

REPORT

GM WELL-TO-WHEEL ANALYSIS OF ENERGY USE AND GREENHOUSE GAS EMISSIONS OF ADVANCED FUEL/ VEHICLE SYSTEMS - A EUROPEAN STUDY



ExxonMobil



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Report

Organizational Matters

The European Well-to-Wheel Study was initiated by General Motors in May, 2001 and initial findings were presented at the Hart World Fuels Conference, Brussels, in May, 2002. The present study is a complement to "*Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis*" published by GM and Argonne National Laboratory in June, 2001. It is supplemented by an "*Annex: Full Background Report*" (published separately) which contains further detail on the European research effort.

GM conducted the European Tank-to-Wheel (vehicle) analysis in its entirety and contracted the European Well-to-Tank (fuel) analysis and integration of fuel and vehicle analyses into overall Well-to-Wheel results to L-B-Systemtechnik GmbH (LBST). Major global energy companies BP, ExxonMobil, Shell, and TotalFinaElf were also active participants in the study, providing particular input and guidance on the Well-to-Tank study.

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Responsibilities for Study Results

LBST assumes responsibility for the Well-to-Tank analysis, the accuracy of which was greatly enhanced through contributions of the GM and energy company participants on the study team.

Responsibility for the Tank-to-Wheel analysis lies exclusively with GM.

The responsibility for stochastic pathway evaluation and the integration of Well-to-Tank and Tank-to-Wheel components into an overall Well-to-Wheel analysis lies with LBST.

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Acronyms

Acronyms

ACEA	European Automobile Manufacturers Association
ANL	Argonne National Lab (US)
BCL	Battelle-Columbus Laboratory
BE	Best estimate
CCGT	Combined cycle gas turbine
CD	Conventional driveline (p. 2)
CGH ₂	Compressed gaseous hydrogen
CH ₄	Methane
CIDI	Compression ignition direct injection
CMG	Compressed methane gas
CNG	Compressed natural gas
CO	Carbon monoxide
CO ₂	Carbon dioxide
CS	Charge sustaining
DI	Direct injection
E100	Ethanol (100%)
ECE	Economic Commission for Europe (a UN organization based in Geneva)
EDC	European driving cycle
ETBE	Ethyl tertiary butyl ether
EU	European Union
FC, FCV	Fuel cell, Fuel cell vehicle
FPFC	Fuel processor fuel cell (vehicle)
FTD	Fischer-Tropsch diesel
FTN	Fischer-Tropsch naphtha
GHG	Greenhouse gas
GM	General Motors Corporation
GWP	Global warming potential

HCL	Hydrocarbon liquid
HDO	Hydro-De-Oxygenation
HEV	Hybrid electric vehicle
HPSP	Hybrid powertrain simulation program
HTU	Hydro Thermal Upgrading
IC, ICE	Internal combustion, Internal combustion engine (vehicle)
LB	Lower bound
LBST	L-B-Systemtechnik GmbH
LCA	Life cycle analysis
LHV	Lower heating value
LH ₂	Liquid hydrogen
LNG	Liquefied natural gas
MCFC	Molten Carbonate Fuel Cell
MeOH	Methanol
MJ	Mega Joule (SI energy unit)
MPa	Mega Pascal (SI pressure unit)
mpg	Miles per US gallon (fuel economy)
MTA	Automated manual transmission
MTBE	Methyl tertiary butyl ether
N, N-fixing	Nitrogen, nitrogen-fixing
N ₂ O	Nitrous oxide
NG	Natural gas
NiMH	Nickel metal hydride (battery)
NVH	Noise-vibration-harshness
NM VOC	Non-methane volatile organic compounds
NO _x	Nitrogen oxides
PNGV	Partnership for a New Generation of Vehicles (US)
ppm	Parts per million
PSA	Pressure swing adsorption

Acronyms

RME	Rape seed methyl ester
SI	Spark ignition
SOC	State of charge
SO _x	Sulfur oxide
TTW	Tank-to-wheel
UB	Upper bound
w%	Weight-percent
WOT	Wide open throttle
WTT	Well-to-tank
WTW	Well-to-wheel
ZEV	Zero-emission vehicle

Executive Summary

Scope of Study

The scope of this study is Europe in 2010.

The study was conducted in three parts:

- Well-to-Tank (WTT): consideration of the fuel from resource recovery to delivery to the vehicle tank,
- Tank-to-Wheel (TTW): assessing vehicle architecture, powertrain and fuels effects,
- Well-to-Wheel (WTW): integration of the WTT and TTW components

The methodology and the tools applied during the compilation of the study are described in Chapter 2 "Methodology, Pre-Selection of Pathways, and Discussion Process" of the Annex "Full Background Report".

Well-To-Tank: LBST evaluated the feedstock and fuel-related stages of fuel production and use, especially the WTT fuel chain efficiency and the WTT greenhouse gas emissions. The main pathways investigated were:

- Crude oil based pathways
- Natural gas based pathways
- Electricity based pathways, and
- Biomass based pathways

A detailed description and analysis of these pathways is provided in Chapter 3 "Fuel Chain Efficiency and Greenhouse Gas Emissions" of the Annex "Full Background Report".

A comparison of the different pathways, mainly their efficiencies and GHG emissions, is included in Chapter 1 of the Report and in Chapter 4 "Fuel Chain Comparison", sub-chapter 4.1 "Comparison of efficiencies for selected pathways (WTT)" of the Annex "Full Background Report". Their feasibility in the near term period (2010), the possible potentials for improvement, as well as their potential for contribution to the vehicle fuel market in Europe are addressed in this chapter.

The fuel pathways selected for more thorough analysis in the study are presented in Table 0-1.

Table 0-1: Selected WTT-Fuel Pathways for WTW-Integration

	Selected Fuel Pathways	
<i>Crude Oil-Based</i>	(1)	Gasoline (sulfur content < 10 ppm)
	(2)	Diesel (sulfur content < 10 ppm)
	(3)	Naphtha (sulfur content < 0.4 ppm)
<i>Natural Gas-Based</i>	(5)	CNG: EU-NG-mix
	(8)	CNG: LNG from remote location
	(10)	MeOH: from remote location
	(12)	FTD: from remote location
	(14)	FTN: from remote location
	(16)	CGH ₂ : EU-NG-mix in central plant (for 70 MPa vehicle tanks)
	(20)	CGH ₂ : EU-NG-mix in onsite production (for 70 MPa vehicle tanks)
	(21)	LH ₂ : EU-NG-mix in central plant
	(23)	LH ₂ : from remote location
	(24) ^[1]	Gasoline, blended with 10 w% MTBE, MTBE from natural gas derived methanol
<i>Electricity-Based</i>	(31)	CGH ₂ : EU-mix electrolysis in regional electrolysis plant (for 70 MPa vehicle tanks)
	(32)	CGH ₂ : wind electrolysis in regional electrolysis plant (for 70 MPa vehicle tanks)
	(37)	CGH ₂ : EU-mix onsite electrolysis (for 70 MPa vehicle tanks)
	(38)	CGH ₂ : CCGT onsite electrolysis (for 70 MPa vehicle tanks)
	(39)	CGH ₂ : wind onsite electrolysis (for 70 MPa vehicle tanks)
	(40)	LH ₂ : EU-mix electrolysis in central electrolysis plant
	(41)	LH ₂ : wind electrolysis in central electrolysis plant
<i>Biomass-Based</i>	(44)	CGH ₂ : gasification of residual woody biomass (for 70 MPa vehicle tanks)
	(48)	CGH ₂ : gasification of woody biomass from plantation of poplar (for 70 MPa vehicle tanks)
	(51)	MeOH: gasification of residual woody biomass
	(53)	E100: enzymatic hydrolysis of lignocellulose (crop residue)
	(55)	E100: enzymatic hydrolysis of lignocellulose (plantation of poplar)
	(60)	E100: conventional fermentation of sugar beet
	(66)	HCL: solids to liquids (diesel/ naphtha) from residual woody biomass via FT-synthesis
	(70) ^[1]	Diesel, blended with 5 w% RME, RME from rape seed
	(79) ^[1]	Gasoline, blended with 10 w% ETBE, ETBE from sugar beet derived ethanol
	(84)	CMG: biogas derived compressed methane gas
	(86)	CGH ₂ : steam reforming of biogas (for 70 MPa vehicle tanks)
(87) ^[1]	Gasoline, blended with 10 w% MTBE, MTBE from residual woody biomass derived Methanol	

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Remark: ¹⁾ in Table 0-1 for the original pathways 24, 70, 79 and 87, ETBE, MTBE and RME have been carried through to the selected pathways only as blending agents.

[The numbering sequence of the originally 88 pathways has been maintained, therefore jumps in the numbering sequence occur in Table 0-1 Selected Fuel Pathways"]

Tank-To-Wheel: Advanced vehicle technologies using various fuels were modeled and their potential for improving fuel consumption and GHG emissions was quantified. These analytical and validated results were provided to LBST in the format needed for the well-to-wheel integration. The results are presented in Chapter 2 of this Report and in Chapter 4 "Fuel Chain Comparison", sub-chapter 4.2 "Tank-to-Wheel Analysis of Powertrains (TTW)" of the Annex "Full Background Report".

Well-To-Wheel: Then LBST, on the basis of its WTT analyses and the GM TTW analyses, performed an integration process generating WTW chains for each fuel and propulsion concept respectively. The description and results of this process are presented in Chapter 3 of this Report and in Chapter 4 "Well-to-Wheel Integration of Fuel Supply Pathways and Powertrains (WTW)" of the Annex "Full Background Report".

Results

The study results were generated with proprietary models, GM using its own vehicle model, and LBST using its own recursively-structured and database-implemented model for the calculation of process modules and pathway chain analyses. The following charts show best estimate values with upper bound and lower bound estimates indicated by error bars.

Well-to-Tank

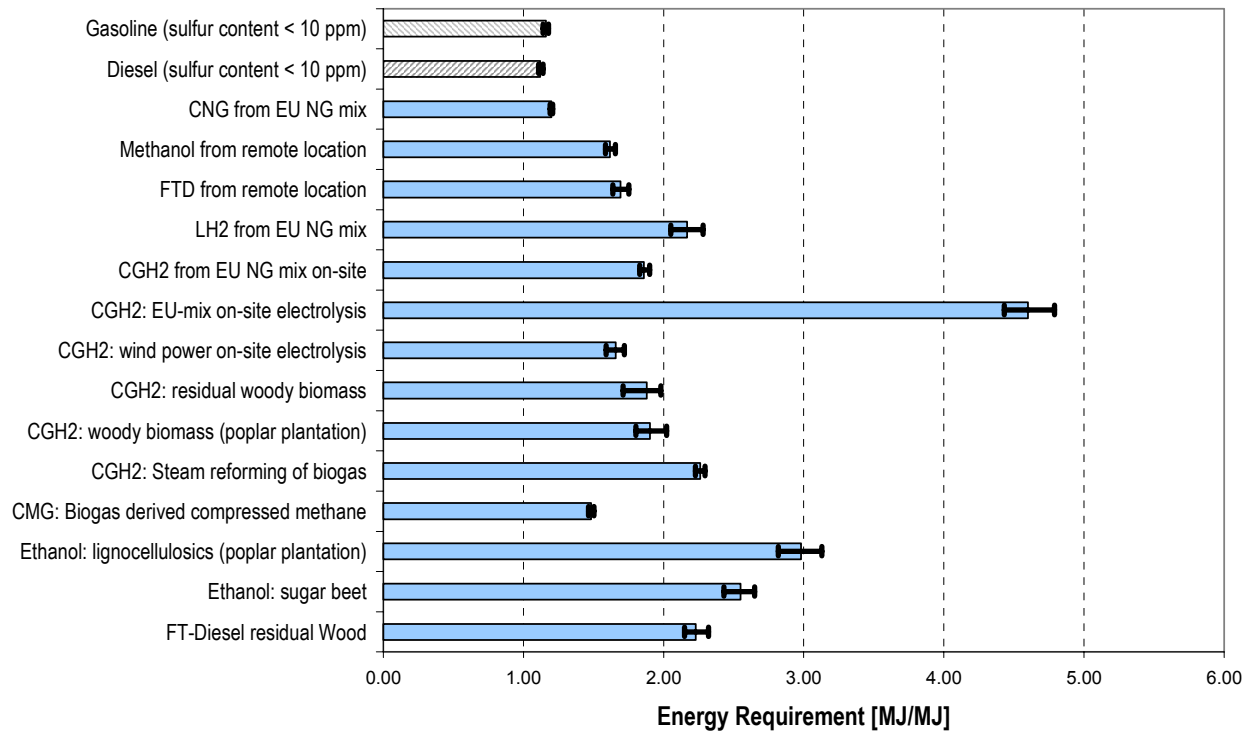
As an example, the energy use and greenhouse gas emissions of a selection of 16 fuel pathways extracted from Table 0-1 are depicted in Figure 0-1 and Figure 0-3. In this report, WTT energy use includes the energy content of the fuel produced as well as energy losses. WTT greenhouse gas emissions are those occurring during fuel production only. Greenhouse gas emissions occurring during fuel use are reported as TTW emissions.

The WTT energy use [Figure 0-1] is lowest for the petroleum-derived fuels, gasoline and diesel, which lie slightly above 1 MJ/MJ. In this range falls also CNG from EU NG Mix. Below 1.5 MJ/MJ falls CMG

(compressed methane gas obtained from anaerobic digestion of biogenic wastes). Between 1.5 and 2.0 MJ/MJ are methanol and FT-diesel derived from remote NG, as well as several CGH₂ production pathways (onsite reforming of NG from EU Mix, onsite electrolysis from wind power, gasification of residual woody biomass and plantation-grown poplar). In the range of 2.0 to 3.0 MJ/MJ fall LH₂ obtained from EU Mix NG, CGH₂ obtained from steam-reformed biogas, FT-diesel from residual woody biomass, and ethanol from sugar beet. Ethanol obtained from poplar plantation is positioned at about 3.0 MJ/MJ. The most inefficient pathway (of the pathways selected) by far, more than 4.5 MJ/MJ, is CGH₂ produced in onsite electrolysis from EU electricity mix [LH₂ from centralized electrolysis using EU electricity mix – not a selected pathway - would be even more energy intensive with 5.4 MJ/MJ]. Conservatively speaking, this pathway is at least three times more energy intensive than the best fuel supply pathways, including some of the best CGH₂ supply methods.

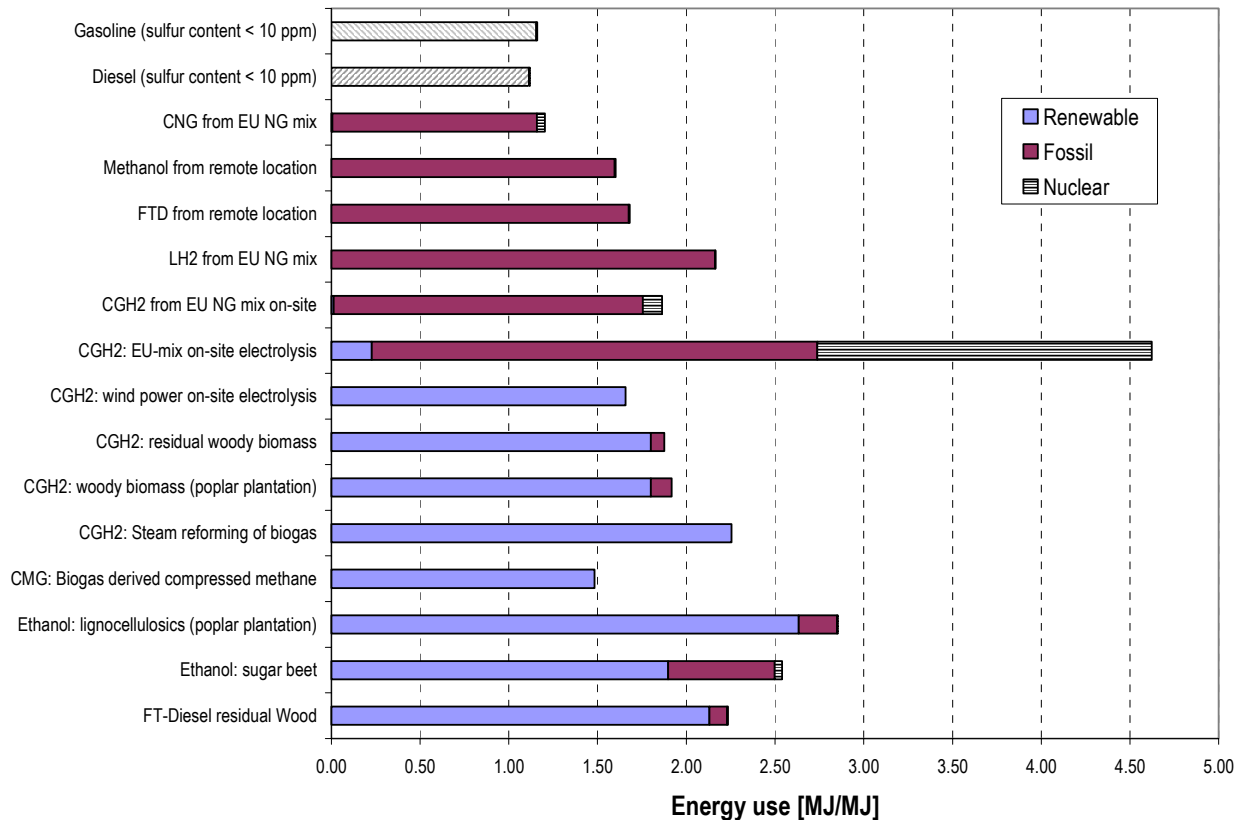
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Figure 0-1: WTT - Energy Use of Selected Pathways



The total energy consumption of the WTT pathways includes the energy content of the produced fuel delivered to the vehicle (i.e. its lower heating value, or LHV). The total energy use includes energy from all sources (non-renewable and renewable). Figure 0-2 shows the shares of renewable, fossil and nuclear energy sources.

Figure 0-2: WTT – Renewable and Non-Renewable Energy Use of Selected Pathways



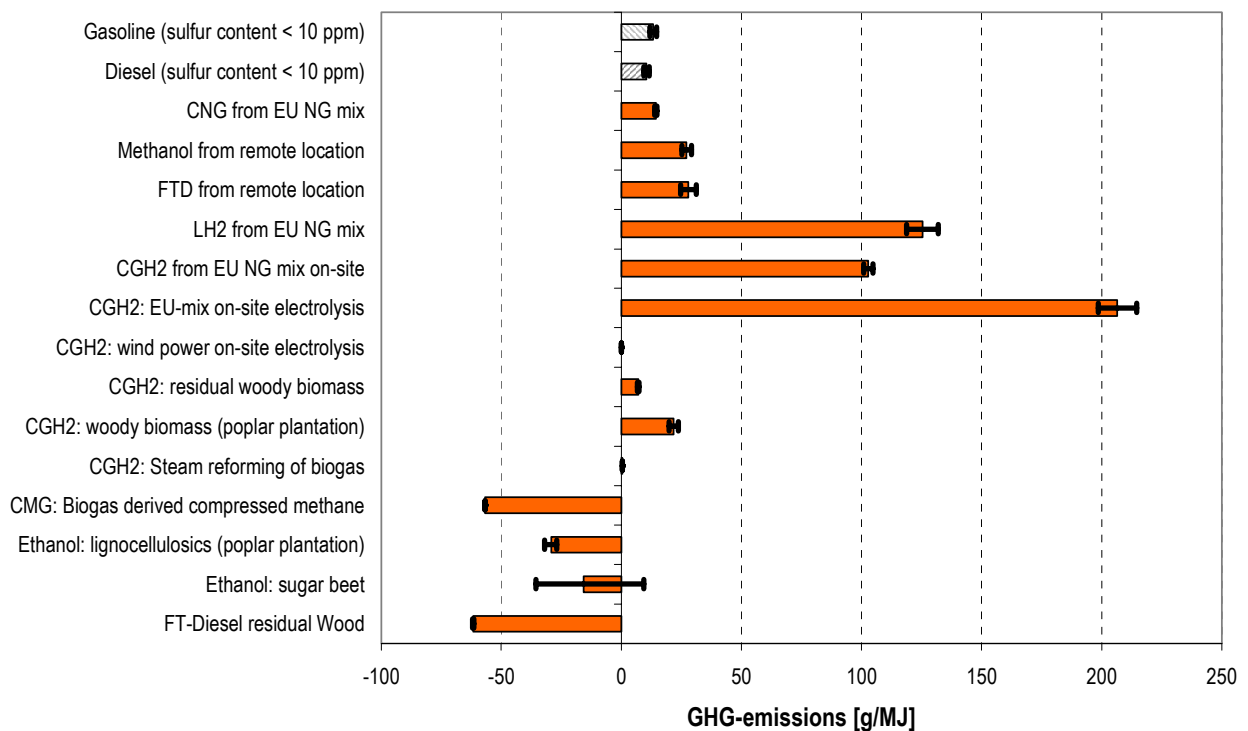
In the presentation of the fuel pathways (WTT) only the GHG emissions emitted during the supply of the final fuel are considered but not the GHG emissions during the combustion of the fuel. GHG emissions consist of CO_2 , CH_4 and N_2O . Negative values reflect sequestration of carbon during plant growth in biomass pathways. The emissions of the carbon content of the fuel occur when the fuel is burnt in the vehicle and then the addition of WTT emissions and TTW emissions will result in positive values for the total WTW emissions.

With respect to WTT GHG emissions, the best pathways are CMG (compressed methane gas) and FT-diesel from residual wood, both with net WTT GHG emissions of less than -50 g/MJ, followed by etha-

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nol from poplar plantation with about -30 g/MJ and ethanol with sugar beet with between about -40 g/MJ and +10 g/MJ. CGH₂ obtained from steam reforming of biogas or from onsite electrolysis using wind power both have almost 0 g/MJ WTT GHG emissions. CGH₂ from residual woody biomass lies in the order of diesel from crude oil and CNG from EU NG Mix is comparable to gasoline from crude oil, i.e. about 15 g/MJ of WTT GHG emissions. Methanol and FT-diesel from remote NG and CGH₂ from poplar plantation grown biomass lie in the order of 25 g/MJ. Significantly higher positioned are LH₂ or onsite CGH₂ obtained from EU NG Mix, both above 100 g/MJ. CGH₂ obtained via onsite electrolysis from EU electricity mix has the highest WTT GHG emissions, about 200 g/MJ.

Figure 0-3: WTT - GHG Emissions of Selected Pathways



Tank-to-Wheel

The base vehicle selected for this study was the 2002 production Opel Zafira minivan using the 1.8L 16V gasoline internal combustion engine (ICE) and a 5-speed manual transmission. Table 0-2 below presents an overview of all the vehicle concepts modeled and alternative fuels considered. A GM proprietary vehicle modeling and simulation tool was used to perform the analysis that employed validated component model input data provided by experts working on the particular technologies. The components in each powertrain were sized to meet a set of vehicle performance requirements typical for European consumers such as launch performance, 0-100 km/h acceleration time, and top vehicle speed. The energy management and control strategies were then optimized over the European Driving Cycle and the vehicle fuel consumption and CO₂ emissions were estimated. The characteristics of the individual powertrain component technologies were based on estimates of efficiency and performance targeted for the 2010 time frame, consistent with Euro IV emission standards. Some of the more complex issues such as cost, packaging needs, and cold start performance considerations were not included at this time because of the surrounding uncertainties and lack of sufficient data at equal levels of integrity for all technologies.

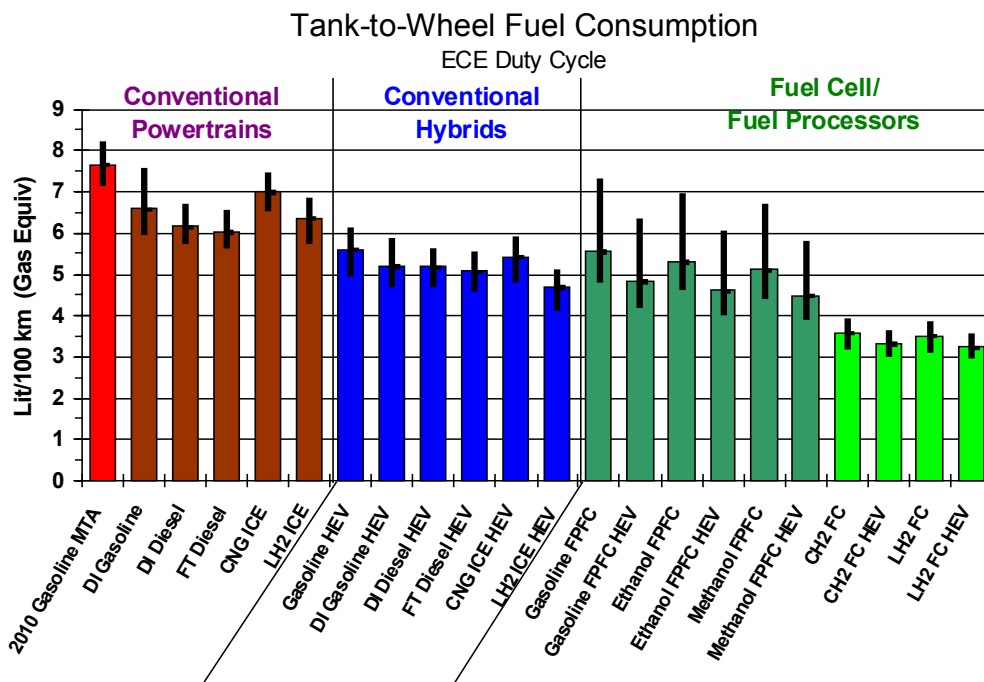
Table 0-2: Vehicle Propulsion Systems in the European Study

	IC Engine	IC Engine Hybrid	Fuel Cell Non-Hybrid	Fuel Cell Hybrid
Gasoline	X	X	X	X
+Advanced Powertrain				
Diesel	X	X		
FT Diesel	X	X		
CNG	X	X		
Methanol			X	X
Ethanol (E100)			X	X
Hydrogen	X	X	X	X

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The major findings of the study in terms of the fuel consumption and greenhouse gas emissions for the above propulsion systems are summarized in Figure 0-4 and Figure 0-5.

Figure 0-4: TTW - Fuel Consumption of Powertrain Technologies



The first bar in the chart represents the conventional powertrain stretched to the 2010 time frame by assuming an upgrade from a manual to an MTA-type (automated manual). This powertrain represents the most mature technology level and currently enjoys the highest market penetration. The hybrid vehicles under consideration are of the parallel architecture type and the battery pack for these systems was sized to meet a 20 km ZEV (Zero Emission Vehicle) range driving the urban cycle in the electric mode on only the battery. Although the battery was sized to drive 20 km on the urban cycle, only a charge-sustaining hybrid strategy was modeled in this study.

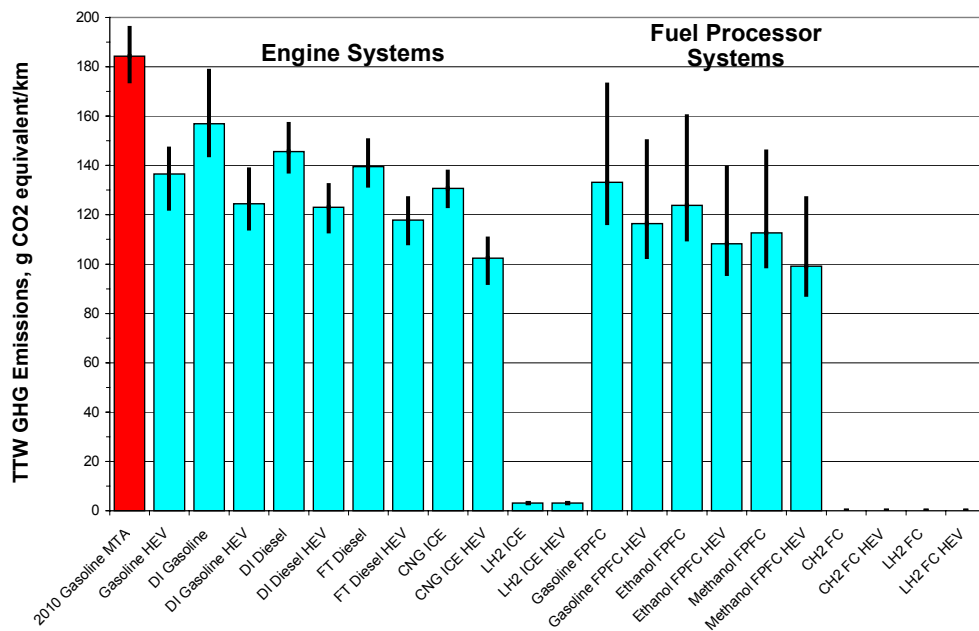
The following conclusions on the potential of the various technologies can be drawn from this bar chart. The greatest reduction in fuel consumption for a conventional powertrain is achieved by combining a direct injection diesel ICE with an advanced wide-ratio range MTA-type 6-speed transmission.

Hybridization of conventional powertrains yields a reduction of 15 to 25%, depending on the engine technology and its part-load efficiency characteristics. Engine downsizing was not possible due to the requirement of 180-km/h continuous vehicle speed operation.

Compared to the 2010 gasoline baseline, fuel cell powered vehicles with direct onboard storage of hydrogen offer the greatest efficiency with a 54% reduction in fuel consumption and the fuel processor systems yield 27% to 33% reductions depending on the fuel used. Hybridization for these concepts also provide a fuel reduction potential due to regenerative braking and off-loading of the ancillary and accessory loads to the battery, however, at a smaller magnitude due to the already high part-load efficiency of the fuel cell systems.

With regard to the GHG emissions, all HEVs were at levels below 140 g CO₂-equivalent/km, the CNG and methanol FPFC HEVs were about 100 g/km, and all the hydrogen-fueled vehicles were at zero or near zero g/km.

Figure 0-5: TTW - GHG Emissions on European Driving Cycle



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Well-to-Wheel

In the Well-to-Wheel analysis, 14 fuels (88 fuel pathways) were combined with 22 vehicle powertrains. Figure 0-6 and Figure 0-7 show the WTW fuel consumption and GHG for selected pathways. Compared to the 2010 gasoline IC engine baseline, the DI Diesel pathway reduced GHG by 20%.

The following examples show additional GHG reductions compared to crude oil DI Diesel powertrains (the benchmark for comparison of future powertrains in Europe). A switch to an IC engine natural gas powertrain, based on EU natural gas mix, can provide a very small GHG reduction. A switch to a fuel cell operating with onboard CGH_2 derived from the EU natural gas mix gives similar WTW energy consumption, but reduces GHG WTW emissions by almost 30%. A switch to CGH_2 derived from wood plantation or from wind power used in the same powertrain configuration, reduces GHG WTW emissions by 85% and 100% respectively, compared with the conventional DI Diesel powertrain.

Examples of results are shown in Figure 0-6 and Figure 0-7 .

Figure 0-6: WTW - Energy Use of Selected Pathways

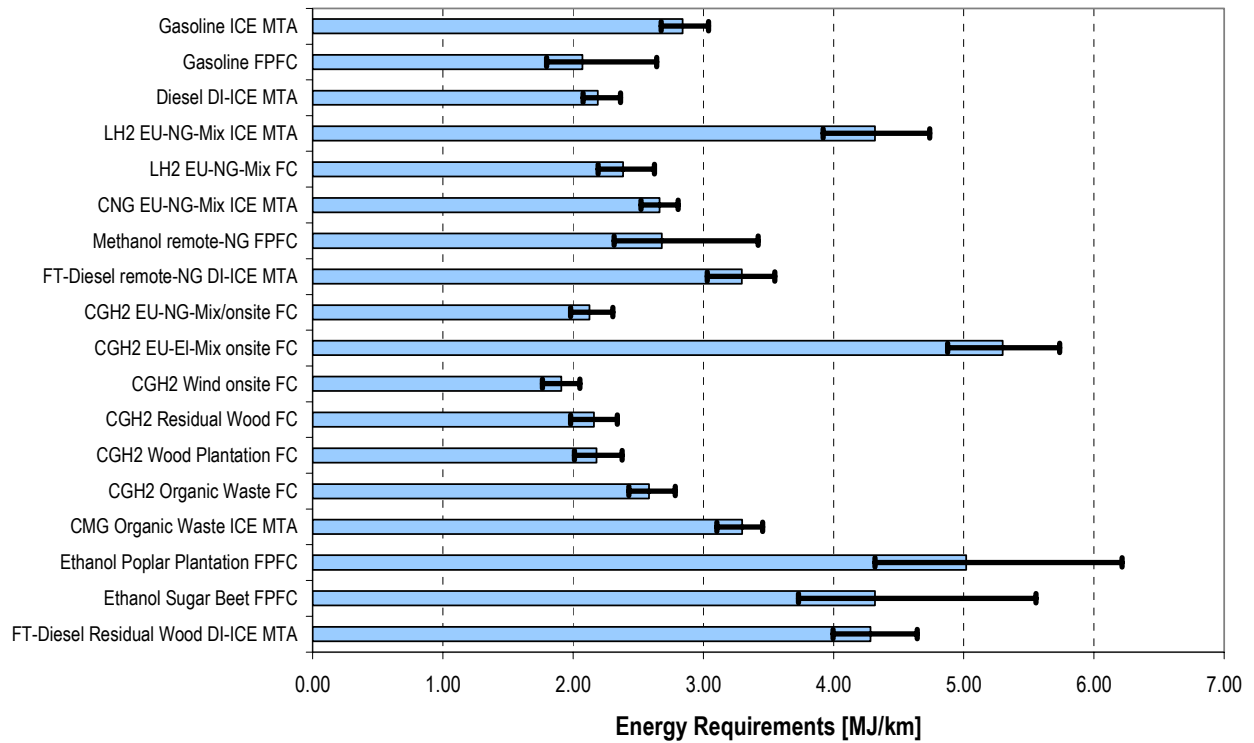


Figure 0-6 shows total energy use and does not differentiate between fossil, nuclear and renewable energy sources.

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Figure 0-7: WTW - GHG Emissions of Selected Pathways

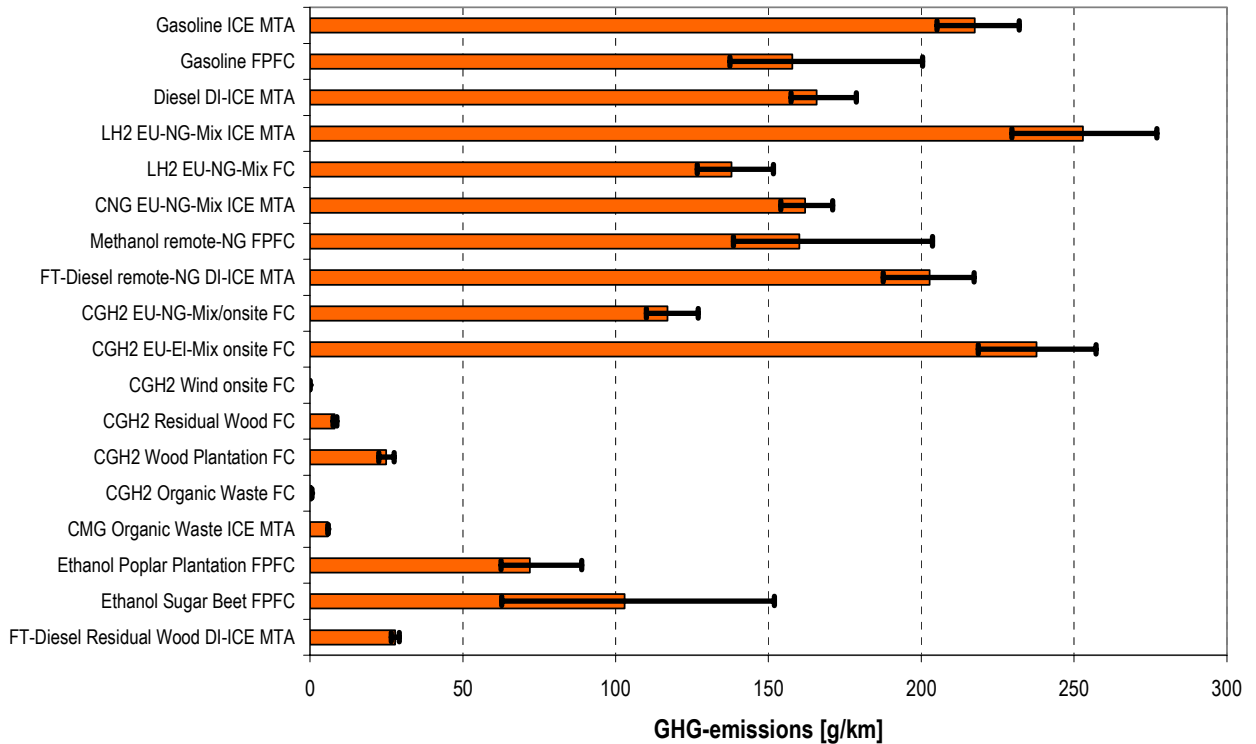


Figure 0-8 shows the WTW energy losses split in WTT and TTW. The graph shows the attribution of energy losses to WTT and to TTW respectively. Internal combustion engine powertrains using petroleum derived fuels have very efficient WTT and less efficient TTW parts, whereas efficient fuel cell powertrains can compensate a significant part or most of the losses incurred during WTT fuel preparation.

Figure 0-8: WTW Energy Loss Split into WTT and TTW

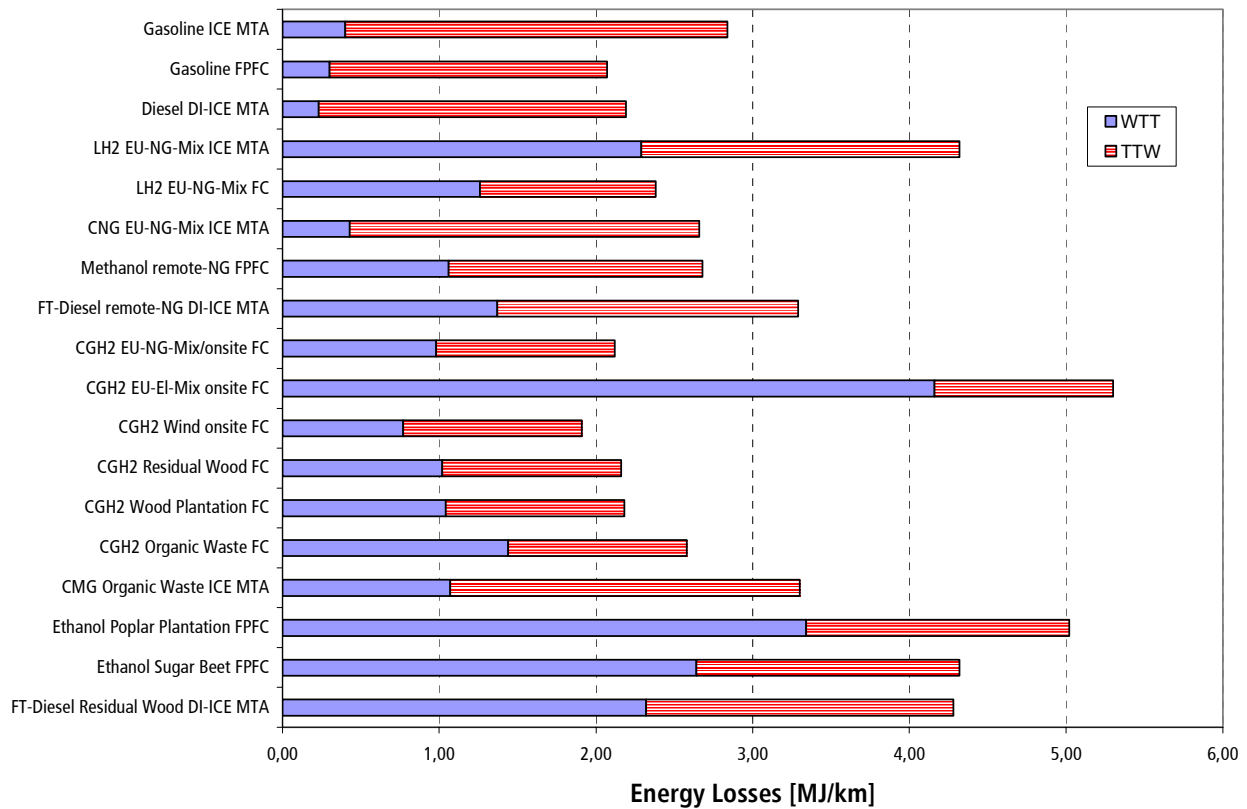
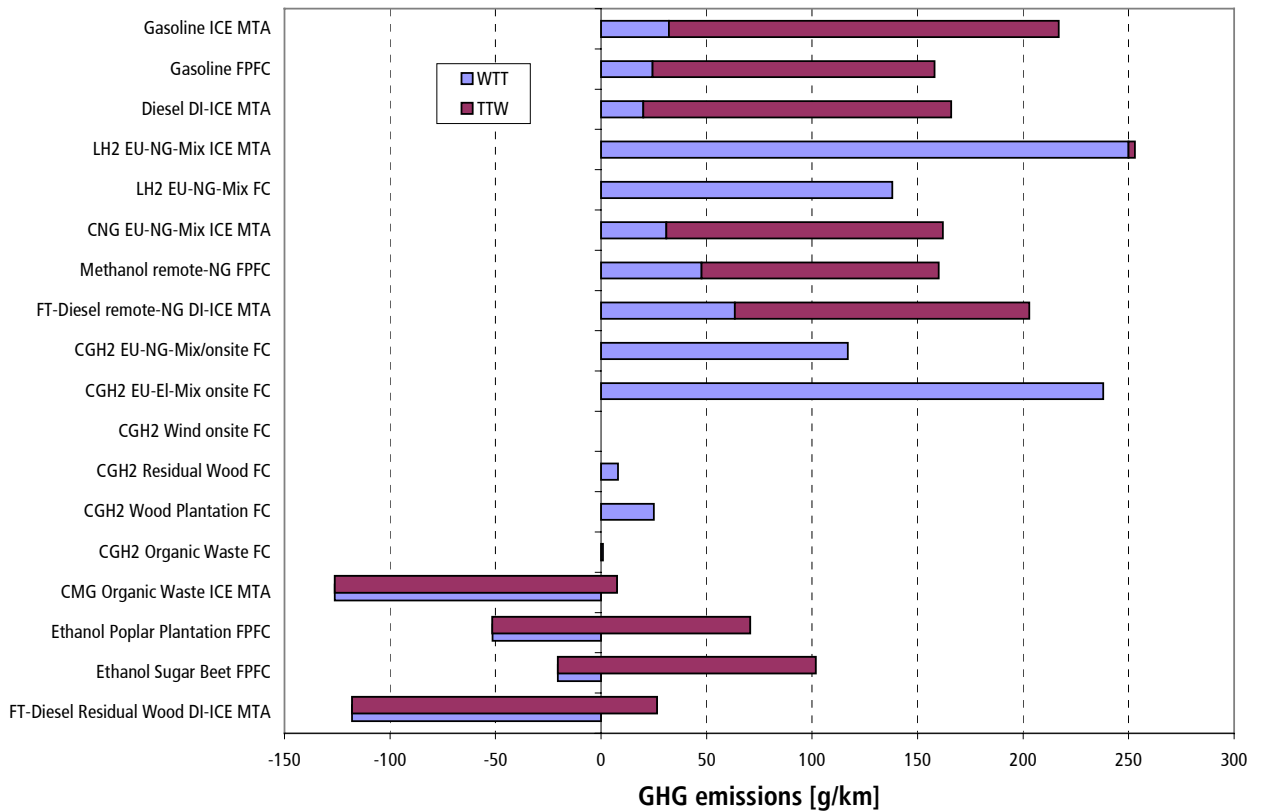


Figure 0-9 shows the WTW GHG emissions split in WTT and TTW. In case of the carbon containing fuels derived from biomass the GHG emissions are negative after fuel supply because CO_2 is removed from the atmosphere during the growth of the plants and the carbon is bound in the delivered fuel. During vehicle operation the carbon bound in the fuel is emitted as CO_2 and the GHG emissions become positive.

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Figure 0-9: WTW GHG emissions, Split into WTT and TTW



The most prominent results are as follows:

Vehicle specific findings:

Hybridization reduces fuel consumption in all propulsion systems, however the benefits are larger for internal combustion (IC) engines than for fuel cells because of the fuel cell’s superior part-load efficiency relative to IC engines.

For non-hybrid powertrains the following findings apply:

Optimized CNG engine vehicles provide GHG emission benefits compared with gasoline IC engine vehicles and are comparable in Well-to-Wheel energy use.

IC engine vehicles fueled with liquid hydrogen from natural gas offer zero vehicle CO₂ emissions, but result in higher WTW GHGs than either conventional gasoline or diesel IC engine vehicles.

Methanol FPFC vehicles running on natural gas derived methanol offer benefits relative to gasoline ICE vehicles and no or only minor benefits relative to diesel ICE vehicles, gasoline processor fuel cell vehicles or monofuel CNG ICE vehicles.

Fuel cell vehicles offer the potential to greatly reduce WTW GHG emissions when fueled with renewable fuels in general. An elimination of WTW GHG emissions can be achieved when FC vehicles are fueled with hydrogen provided by the best renewable pathways.

Fuel specific findings:

The source of natural gas feedstock has a significant impact on GHG emissions for natural gas based pathways.

Hydrogen fuel cell vehicles running on hydrogen from reformed natural gas (with exception of liquid hydrogen produced in remote locations and transported to the EU by ship) offer reduced GHG emissions relative to gasoline and diesel ICE vehicles.

Fischer-Tropsch diesel used in ICE vehicles has higher energy consumption than crude oil-based diesel or gasoline, and higher GHG emissions than conventional diesel but slightly lower than gasoline.

Biofuels offer reduced GHGs, however, the magnitude of improvement depends on the assumptions on N₂O emissions from the crops as reflected by the uncertainty ranges. Processing of biomass by gasification or enzymatic hydrolysis gives lower GHG emissions than conventional biofuels.

Electrolysis-based hydrogen generates high GHG emissions with electricity from traditional electric grid mix, and near-zero GHGs when the electricity is produced renewably.

Comparison with North American study results

Findings of the present work are generally consistent with those of the GM-Argonne North American WTW Study in terms of relative rankings of the fuel-powertrain combinations; absolute WTW values are lower primarily due to the smaller (lower mass) reference vehicle used in the European Study (mini-van instead of truck). Important factors on the Well-to-Tank side were higher oil refining efficiency in Europe and the EU-mix natural gas pathway which was more efficient than the imported LNG pathway used in North America. On the Tank-to-Wheel side, the hydrogen fuel cell in this study benefited from improved fuel cell stack and control system improvements and the CNG ICE for Europe was based on an optimized monofuel vehicle, rather the bi-fuel system used for North America. Hybridization provides a greater benefit on urban type driving, thus in Europe the gasoline hybrid showed greater potential than in North America.

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Conclusions

Many technologies for renewable and alternative fuel supply are already available; some still require further development efforts.

Biomass-derived fuel supply pathways show the highest complexity and the widest range of results depending on applicable cultivation method, fertilizer use, soil and climate conditions. The selection of appropriate pathways for widespread implementation will require careful selection of the suitable farming practice, climatic condition and soil property.

Fuel supply pathways from renewable energy sources in most cases lead to drastically reduced GHG emission, especially in combination with fuel cell powertrains.

With respect to GHG emissions, only hydrogen derived from renewable electricity represents a significant improvement compared to conventional fuels, whereas hydrogen obtained from the European electricity grid mix does not show any benefits. Also, Gas-to-liquid fuel pathways (e.g. Fischer Tropsch Diesel) and methanol do not show any real benefit over diesel powertrains respectively over gasoline FPFC powertrains, whereas noticeable improvements can be obtained in comparison to ICE gasoline powertrains.

Hydrogen as fuel has the advantage of the largest variety of fuel supply pathways from a Well-To-Tank perspective and the highest utilization efficiencies in fuel cell powertrains from a Tank-To-Wheel perspective.

The Well-To-Wheel analysis shows that renewably-produced hydrogen, in combination with fuel cell powertrains, offers an effective strategy for significantly lowering GHG emissions and improving fuel supply diversity.

Preface

Motivation for the Study

The study tries to identify future fuels and corresponding powertrains for passenger cars which may have the technical and environmental potential to complement, and eventually substitute, gasoline and diesel conventional fuels and powertrains. The scope of the study is Europe in 2010.

The study looked at the principal alternative energy sources, including renewables, as possible sources for fuel production. On the vehicle side, a wide variety of hybridized and non-hybridized versions of conventional and advanced powertrains, based on internal combustion and fuel cell technologies, was analyzed.

The research was undertaken in recognition of the growing desire for energy security and the phasing in of renewable energy sources into the primary energy mix, as set forth by the European Commission, and in view of the search for feasible actions within the road transport sector to reduce greenhouse gas emissions.

To this end, comprehensive Well-to-Wheel analyses of fuel supply pathways for possible future fuels and corresponding powertrains were conducted out. The study evaluated fuel production, supply, distribution, and end use in the car along two metrics, both of which are crucial to determining the future quality of Europe's individual and commercial on-road mobility:

- Energy consumption
- Greenhouse gas emissions

Reflecting the present trend of growing numbers of minivans in Europe, the Opel Zafira was chosen by GM as the reference vehicle for the study.

The study is intended to provide advice and assistance to decision makers from different sectors of society and the economy:

- Governments
- Non governmental organizations and other societal groups
- Customers of automobiles and fuel services
- Energy companies active as fuel suppliers
- Automobile manufacturers

Report - Preface

This European Well-to-Wheel Study follows on from an earlier GM-sponsored Well-to-Wheel study undertaken in the North American context, and one of the aims of the present work is to identify possible differences between the two regions.

Key Features of this Study

1. The study is targeted to Europe in 2010
2. It considers only propulsion systems and fuels that can be made technically available by the 2010 target year, assuming foreseeable technology breakthroughs in some cases.
3. "Best estimate" values and associated confidence intervals are assessed for each process or subsystem analyzed. Statistical techniques were applied to characterize the range of expected values of pathways composed of chains of these processes.
4. The study results were generated with proprietary models. GM used its internally-developed vehicle simulation model, and LBST used an in-house recursively structured database model to calculate process modules and pathway chains.
5. Four international energy companies, BP, ExxonMobil, Shell, and TotalFinaElf, participated in the process of discussing and reviewing, either in whole or part, all energy resource recovery and fuel processing stages.
6. The starting point for the vehicle analysis was the current production year Opel Zafira 1.8 L 16V gasoline internal combustion engine (ICE) minivan. The baseline vehicle used for the study projected this 2002 production vehicle to the 2010 time frame by including an advanced powertrain and some anticipated vehicle level improvements. This baseline vehicle was then used as the framework for evaluating conventional drivelines (CD) using advanced ICE technologies (including gasoline direct injection, diesel common rail direct injection, CNG optimized injection, and hydrogen optimized injection), hybridized powertrains using each of the ICE technologies just listed, and non-hybridized and hybridized fuel cell powertrain systems.
7. The fuel pathways (WTT) examined can broadly be broken down as follows: 3 oil-based pathways, 10 natural gas based pathways, 7 electricity-based pathways, and 12 biomass-based pathways. Enumerating all variations (e.g. different pressure levels for hydrogen discharge) leads to a total of 88 fuel pathways considered. The fuels selected and used as "pure fuel" in the vehicle are gasoline, diesel, naphtha, compressed natural gas (CNG), methanol, FT-diesel (FTD), FT-naphtha (FTN), compressed gaseous hydrogen (CGH₂), liquid hydrogen (LH₂), ethanol, and biogas-derived compressed methane gas (CMG). Furthermore,

different fuels used as blending agents for gasoline and diesel have been considered, such as MTBE, ETBE and RME. These 14 fuels (11 pure fuels and 3 blending agents) supplied via 88 fuel pathways (WTT) were paired with 22 vehicles.

8. The study evaluates wind energy as a near term feasible renewable electricity source and provides two different pressure levels for onboard CGH₂ storage.
9. For better consistency with the TTW part, and for compatibility with the North American WTW study, it was decided to exclude energy requirements (so called 'grey energies') for the manufacturing or construction of components, plants or subsystems in the fuel chain analyses.
10. It is recognized that the cost and availability of advanced fuels, as well as the cost of vehicles based on advanced powertrains, will impact their potential for commercial viability. These important questions for future study are, however, beyond the scope of the present work.

Study Format

The study was conducted in three parts:

- Well-to-Tank (WTT): An accounting of energy consumption and GHG emissions over an entire fuel pathway, from primary resource recovery through to delivery of the fuel to the vehicle tank,
- Tank-to-Wheel (TTW): An accounting of the energy consumption and GHG emissions resulting from moving a vehicle through its drive cycle
- Well-to-Wheel (WTW): The combination of WTT and TTW components.

The methodology and the tools applied during the compilation of the study are described in part 1.2 of this report [and Chapter 2 "Methodology, Pre-Selection of Paths, and Discussion Process" of the Annex "Full Background Report"].

Well-To-Tank: LBST evaluated the feedstock and fuel-related stages of fuel production and use, in particular WTT fuel chain efficiency and WTT greenhouse gas emissions. The main pathways investigated were:

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- Crude oil based pathways
- Natural gas based pathways
- Electricity based pathways, and
- Biomass based pathways

A detailed description and analysis of these pathways is provided in part 1.3 [and Chapter 3 "Fuel Chain Efficiencies and Greenhouse Gas Emissions" of the Annex "Full Background Report"].

A comparison of the different pathways with respect to their efficiency and GHG emission characteristics, is presented in part 1.4 of this Report [and Chapter 4 "Fuel Chain Comparison", sub-chapter 4.1 "Comparison of efficiencies for selected pathways (WTT)" of the Annex "Full Background Report"].

Tank-To-Wheel: Advanced vehicle technologies using various fuels were modeled by GM and their potential for improving energy consumption and GHG emissions was quantified. These results were provided to LBST in the format needed for the well-to-wheel integration. The results are presented in Chapter 2 of this Report [and Chapter 4 "Fuel Chain Comparison", sub-chapter 4.2 "Tank-to-Wheel Analysis of Powertrains (TTW)" of the Annex "Full Background Report"].

Well-To-Wheel: LBST performed an integration process generating WTW chains, as applicable, for each pairing of fuel and propulsion concept. The description and results of this process are presented in Chapter 3 of this Report [and Chapter 4 "Well-to-Wheel Integration of Fuel Supply Pathways and Powertrains (WTW)" of the Annex "Full Background Report"].

1 Part 1: Well-to-Tank Analysis of Fuel Supply Pathways – Energy Use and Greenhouse Gas Emissions

1.1 Introduction

A variety of fuels are suitable for use in internal combustion engine vehicles (ICEV), internal combustion engine hybrid electric vehicles (ICEHV), fuel cell electric vehicles (FCV) and fuel cell hybrid electric vehicles (FCHV). These fuels are produced from different primary energy feedstocks by different production processes. The purpose of this study was to evaluate the energy requirements and GHG emissions associated with the production of different vehicle fuels, each based on fossil, non-fossil/non-renewable, or renewable energy sources. The study evaluates technical feasibility for the 2010 timeframe, but does not comprehend cost or availability issues and, therefore, may not be indicative of commercial feasibility of each fuel supply pathway considered.

1.2 Methodology

LBST used its 'E²database' model to conduct the WTT analysis.

E²database bases all calculations on input and output data for a given process (as supplied, for example, by a plant manufacturer). The data are kept in the database with pre-defined interfaces and structures. The front-end is programmed in the Borland Delphi programming environment and the underlying recursive algorithm is simple and transparent. Several processes (e.g. natural gas distribution, natural gas steam reformation, and hydrogen compression) can be combined in an arbitrary way to characterize energy pathways based on input/output relationships. Recursive fuel pathway calculations can be implemented easily. Hence the E²database can calculate complicated fuel supply pathways in a simple manner. Its graphic display, in which processes can be readily added or removed, facilitates simple and easy creation of new fuel supply pathways. Standardized process description, and pathway organization and handling, largely help avoid systematic errors.

For emissions modeling, E²database estimates three major GHGs specified in the Kyoto protocol, namely carbon dioxide [CO₂], methane [CH₄], and nitrous oxide [N₂O]. The CO₂-equivalent of the combined GHG emissions are calculated by the model based on the global warming

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potential (GWP) of each of the three gases. The global warming potentials as indicated by the Intergovernmental Panel on Climate Change (IPCC) were used:

CO₂: 1

CH₄: 21

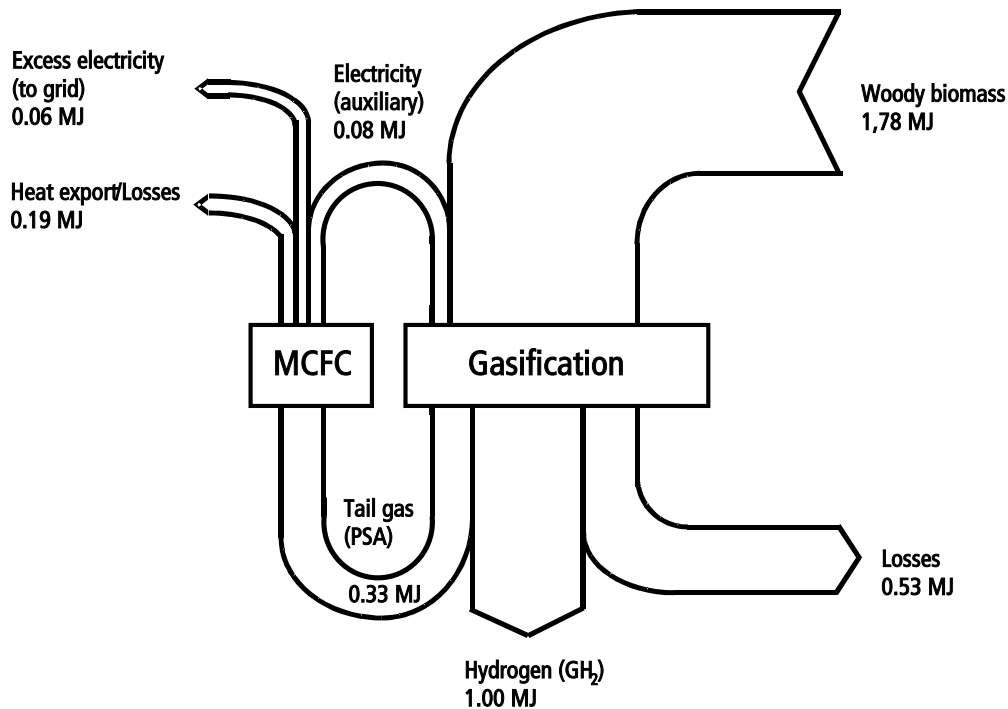
N₂O: 310

The total energy consumption of the WTT pathways includes the energy content of the produced fuel (i.e. its lower heating value, or LHV). The total energy use includes energy from all sources (non-renewable and renewable).

- For crude oil- and natural gas-derived fuels the energy content of the crude oil extracted in the oil fields or the energy content of the natural gas in the gas fields was considered.
- For biomass-derived fuels, we traced the energy use back to the energy content of the crop (e.g. the energy content of sugar beet in case of sugar beet-derived ethanol fuel).
- In case of renewable electricity (e.g. wind power), we traced the energy use back to the energy contained in the electricity generated by renewable power sources.
- For electricity from nuclear power plants, we traced the energy use back to the energy contained in the uranium. The same methodology was applied to the coal in coal-fueled power plants or to the natural gas in natural gas-fueled power plants.

As an example of the calculation process, Figure 1-1 shows the energy flow in a Sankey diagram for hydrogen derived via woody biomass gasification. Note that it excludes upstream processes (e.g. the supply of woody biomass) and downstream processes (e.g. hydrogen compression).

Figure 1-1: Sankey diagram for a biomass-to-hydrogen plant



Biomass is converted to hydrogen by gasification of woody biomass. The tail gas from the pressure swing adsorption plant (PSA) is used in a molten carbonate fuel cell (MCFC) power plant for electricity generation. A part of the electricity generated by the MCFC meets the auxiliary power needs of the biomass-to-hydrogen plant, which consists of biomass gasification, CO-shift and PSA.

There are differences in the methodology used for the energy calculations compared to that used in the GM North American Study:

- In contrast to this study, the GM North American Study WTT energy consumption consists of energy lost during fuel production, so the energy content of the produced fuels is excluded. This is consistent with the "energy losses" in this study.

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- For nuclear power plants, the GM North American Study traces the energy use back to the energy content of generated electricity. In this study the energy use was traced back to the energy content of the uranium.

Stochastic Analysis:

As was the case in the GM North American study, a stochastic tool was implemented to enable quantification of uncertainties through confidence intervals around “best estimates”. For all the key individual processes within a fuel chain (i.e., the main steps of production, conditioning, transport, handling, and discharge), parametric probability values were determined and then implemented to stochastically simulate the range of uncertainty for the overall pathway in question. This permitted the calculation of 20th%-ile, 50th%-ile and 80th%-ile values of its underlying probability distribution. We refer to the 20th%-ile and 80th%-ile values as Lower Bound (LB) and Upper Bound (UB), respectively. The 50th%-ile, or median value is referred to as Best Estimate (BE). For most parameters, normal probability distributions were assumed. For some parameters a triangular distribution was assumed, and for all parameters with an asymmetric probability distribution, an asymmetric triangular distribution was assumed.

1.3 Fuel Supply Pathways

LBST analyzed 44 fuel pathways (88 variants in all) for use in ICE and FC based passenger cars. This section describes the fuel pathways analyzed in the study.

Oil-Based Pathways

A representative European Crude Oil Mix is delivered via maritime vessel from point of origin to a European port (the values assumed are equivalent to a shipping distance of about 7,600 km). Near the port, refining of crude oil to gasoline (< 10 ppm sulfur content), diesel (< 10 ppm sulfur content), and naphtha (< 0.4 ppm sulfur content) is performed. Apart from sulfur, all other properties of diesel and gasoline were assumed to meet the forthcoming European 2005 specifications. Each of these products is delivered via pipeline, inland ship or railroad tank trailer to a depot. Final distribution to the refueling station is assumed to be 150 km via tank trailer truck.

Natural Gas-Based Pathways

Natural gas (NG) resources were used to produce compressed natural gas (CNG), methanol, Fischer Tropsch (FT) hydrocarbons, hydrogen, and MTBE (for blending in gasoline). Three sources of natural gas were considered in this study: European Natural Gas Mix, Russian Gas, and Remote Gas. Each of these sources is defined in more detail in the Annex "Full Background Report".

CNG From European Natural Gas Mix: Natural gas from the European Natural Gas Mix is delivered to a European refueling station. It is compressed from suction pressures of either 4 MPa or 0.1 MPa and dispensed to the vehicle at a discharge pressure of 25 MPa.

CNG From Russian Natural Gas: Russian natural gas is piped for 7,000 km distributed via NG grid to a European refueling station. It is compressed from suction pressures of either 4 MPa or 0.1 MPa and dispensed to the vehicle at a discharge pressure of 25 MPa.

CNG From Remote Gas via LNG: Natural gas is liquefied in remote locations and transported in liquefied form via maritime vessel for 10,200 km, then delivered to a European port and distributed by truck 500 km to the refueling station. There, LNG is evaporated to CNG and dispensed to the vehicle at a discharge pressure of 25 MPa.

Methanol From European Natural Gas: Natural gas from the European Natural Gas Mix is distributed via high pressure grid to a centralized EU methanol synthesis plant. There, it is synthesized to methanol in a completely self-sufficient plant. The methanol fuel is distributed via product pipeline, inland ships or railroad trailer to a depot. A truck transports the methanol 150 km to the refueling station for dispensing to vehicles.

Methanol From Remote Gas: Natural gas from a remote location is converted to methanol onsite in a self-sufficient synthesis plant. Then the methanol is transported via ship over 10,200 km to a European port and stored in a storage plant. A truck transports the methanol 500 km to the refueling station for dispensing to vehicles.

FT-Diesel From European Natural Gas Mix: Natural gas from the European Natural Gas Mix is distributed via high pressure NG grid to a centralized EU FT-Diesel plant. There, it is synthesized to FT-Diesel in a completely self-sufficient plant. The FT-Diesel is distributed via product pipeline, inland ships or railroad trailer to a depot. A truck transports FT-Diesel 150 km to the refueling station for dispensing.

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FT-Diesel From Remote Gas: Remote natural gas is converted to FT-Diesel onsite in a self-sufficient plant with water as an exported by-product. Then, the FT-Diesel is transported via maritime ship for 10,200 km to a European port and stored in a storage plant. A truck transports FT-Diesel 500 km to the refueling station for dispensing.

FT-Naphtha From European Natural Gas Mix: European Natural Gas Mix is distributed via high pressure NG grid to a centralized EU Naphtha plant. There it is synthesized into Naphtha in a completely self-sufficient plant. The naphtha fuel is distributed via product pipeline, inland ships or railroad trailer to a depot. From there, a truck transports the naphtha for 150 km to the refueling station for dispensing.

FT-Naphtha From Remote Gas: Remote natural gas is converted to naphtha onsite in a self-sufficient plant with water as an exported by-product. Then, the naphtha is transported via maritime vessel for 10,200 km to a European port and stored in a storage plant. Then, a truck transports naphtha 500 km to the refueling station for dispensing.

CGH₂ From European Natural Gas Mix: Natural gas from the European Natural Gas Mix is distributed via NG grid to a centralized reformer (with steam export) where it is converted to hydrogen. This hydrogen is distributed via pipeline for 50 km to the refueling station. The hydrogen is compressed from a suction pressure of 1.5 MPa to discharge pressures of either 45 MPa (for 35 MPa @ 15 °C vehicle tanks) or 88 MPa (for 70 MPa @ 15 °C vehicle tanks).

CGH₂ From Russian Piped Natural Gas: Russian natural gas is piped for 7,000 km, then distributed via NG grid for 250 km to a centralized reformer, where it is converted to hydrogen (with steam export). This hydrogen is distributed via pipeline for 50 km to the refueling station. The hydrogen is compressed from a suction pressure of 1.5 MPa to discharge pressures of either 45 MPa (for 35 MPa @ 15 °C vehicle tanks) or 88 MPa (for 70 MPa @ 15 °C vehicle tanks) respectively.

CGH₂ From European Natural Gas Mix via Onsite Production: Natural gas from the European Natural Gas Mix is distributed via NG grid to the refueling station. There, onsite reforming of NG to hydrogen is performed. The hydrogen is compressed from a suction pressure of 1.5 MPa to discharge pressures of either 45 MPa (for 35 MPa @ 15 °C vehicle tanks) or 88 MPa (for 70 MPa @ 15 °C vehicle tanks).

LH₂ From European Natural Gas Mix: Natural gas from the European Natural Gas Mix is distributed via NG grid to a centralized self-sufficient steam reformer plant which uses excess heat in a steam turbine for electricity generation. This electricity is exported to

the liquefaction plant. The other part of the electricity required for H₂-liquefaction is generated by a NG-CCGT. The reformer and liquefaction plant are integrated in the same complex located within the EU. The LH₂ is then transported 300 km by cryogenic truck trailer to the refueling station.

LH₂ From Russian Natural Gas: Russian natural gas is piped for 7,000 km and distributed for 250 km via a NG grid to a centralized self-sufficient steam reformer plant that uses excess heat in a steam turbine for electricity generation. This electricity is exported to the liquefaction plant. The other part of the electricity required for H₂ liquefaction is generated by a NG-CCGT. The reformer and liquefaction plant are integrated in the same complex located within the EU. LH₂ is transported by truck for 300 km to the refueling station.

LH₂ From Remote Gas: Remote NG is converted in a centralized self-sufficient steam reformer plant using excess heat in a steam turbine for electricity generation. This electricity is exported to the liquefaction plant and the other part of the electricity required for H₂ liquefaction is generated by a NG-CCGT. The reformer and liquefaction plant are integrated in the same complex assumed to be remotely located nearby the natural gas field. LH₂ is shipped 10,200 km to Europe and then transported 500 km by cryogenic truck to the refueling station.

MTBE for Blending From European Natural Gas Mix: NG from the European Natural Gas Mix is distributed via high pressure NG grid to a centralized EU methanol synthesis plant. There it is synthesized to methanol in a completely self-sufficient plant. The methanol is transported 150 km by truck to a refinery where it is processed to MTBE for blending with gasoline.

Electricity-Based Pathways

Electricity generation is a process input for many pathways including CGH₂ and LH₂ generation via electrolysis.

Energy supply efficiency and related GHG emissions depend heavily on the origin of the electricity. In the WTT study, LBST considered several pathways: the (average) European Electricity Mix, dedicated combined cycle gas turbine plant (CCGT) fueled from EU-NG-mix, and renewably-generated electricity from wind power (on- and offshore). The European electricity mix is generated from a wide range of primary energy feedstocks, including nuclear, hard coal, natural gas, crude oil, lignite, waste, hydropower, biomass, wind power and geothermal (see Annex Report). Distribution of electricity is assumed to occur at a high voltage level (>

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110 kV) for central plants, at a medium-high voltage level (10-20 kV) for onsite, and at a medium voltage level (0.4 kV) for direct uses.

CGH₂ from regional electrolysis: Electricity from the European Electricity Mix, from onshore and offshore wind power and from the Combined Cycle Gas Turbine (CCGT) plant fed with the representative European natural Gas Mix is delivered into the European electricity grid. The electricity is transmitted at high voltage (> 110 kV) to a large regional electrolysis plant. The H₂ is distributed by pipeline (for a maximum distance of 50 km) to the refueling station and compressed from a suction pressure of 1.5 MPa to a discharge pressures of either 45 MPa (for 35 MPa @ 15 °C vehicle tanks) or 88 MPa (for 70 MPa @ 15 °C vehicle tanks).

CGH₂ from onsite electrolysis: Electricity from the European Electricity Mix, from onshore and offshore wind power, and from the Combined Cycle Gas Turbine (CCGT) plant supplied with the representative European natural Gas Mix is fed into the European electricity grid. The electricity is transmitted via high voltage (> 110 kV) and medium-high voltage (10 - 20 kV) power lines to the filling stations and converted to hydrogen via an onsite electrolysis plant. The H₂ is compressed from a suction pressure of 3.0 MPa to discharge pressures of either 45 MPa (for 35 MPa @ 15 °C vehicle tanks) or 88 MPa (for 70 MPa @ 15 °C vehicle tanks).

LH₂ from electrolysis via central electrolysis plant: Electricity from the European Electricity Mix, onshore and offshore wind power and the Combined Cycle Gas Turbine (CCGT) plant operated with the representative European natural Gas Mix is delivered into the European electricity grid. Electricity is transmitted at high voltage (> 110 kV) to a large regional electrolysis plant. The large-scale liquefaction plant is adjacent to the electrolysis plant and the LH₂ is distributed by truck 300 km to an LH₂ refueling station.

Biomass-Based Pathways

In the WTT study, LBST evaluated fuels produced from woody biomass, other lignocellulosic matter, sugar beets, and oil seeds. CGH₂ and methanol are obtained via the gasification of woody biomass. Compressed methane gas (CMG) is also obtained via biodigestion of waste material to biogas, and from methane extraction. CGH₂ is also obtained by reforming the extracted methane to hydrogen.

Ethanol (E100) is produced from sugar beets by conventional fermentation and distillation and ETBE (e.g. as blending feedstock) is produced from sugar beet-derived ethanol. Ethanol is also produced by enzymatic hydrolysis, fermentation and distillation of lignocellulosic matter,

e.g. sugar beet pulp, crop residue or dedicated crops. Hydrocarbon liquids (HCL, e.g. diesel, naphtha) are produced from residual woody biomass by HTU (Hydro Thermal Upgrading) and Fischer-Tropsch (FT) synthesis. Rapeseed methyl ester (RME) is obtained from rapeseed by extraction and esterification. MTBE is obtained from woody-biomass-derived methanol.

CGH₂ From Residual Woody Biomass via Allothermal Gasification:

Residual woody biomass is collected and transported 50 km to an allothermal gasification plant, where it is gasified to a synthesis gas and then purified to hydrogen via CO-shift and PSA (pressure swing adsorption). The hydrogen is transported through a H₂ pipeline of 10 km to the refueling station. Gaseous hydrogen is compressed from 0.5 MPa to discharge pressures of either 45 MPa (for 35 MPa @ 15 °C in vehicle tanks) or 88 MPa (for 70 MPa @ 15 °C in vehicle tanks).

CGH₂ From Woody Biomass via Allothermal Gasification: Poplar is cultivated, harvested and transported 50 km to an allothermal gasification plant, where it is gasified to a synthesis gas and then purified to hydrogen via CO-shift and PSA (pressure swing adsorption). The hydrogen is transported through a H₂ pipeline of 10 km to the refueling station. Gaseous hydrogen is compressed from 0.5 MPa to discharge pressures of either 45 MPa (for 35 MPa @ 15 °C in vehicle tanks) or 88 MPa (for 70 MPa @ 15 °C in vehicle tanks).

Methanol From Residual Woody Biomass via Gasification and Methanol Synthesis:

Residual woody biomass is collected and transported 50 km to a gasification plant where it is gasified and converted to methanol. The methanol is trucked 150 km to the refueling station and dispensed.

Ethanol From Lignocellulosic Biomass via Enzymatic Hydrolysis: Lignocellulosic biomass, consisting of crop residue (e.g. straw), sugar beet pulp, and dedicated crop plantation (e.g. poplar), is collected and transported 50 km to an ethanol plant. There the biomass is processed by enzymatic hydrolysis, fermentation, and distillation to ethanol. The ethanol is trucked 150 km to the refueling station and dispensed.

Ethanol From Sugar Beet via Fermentation/ Distillation: Sugar beets are cultivated, collected and transported 50 km to an ethanol plant. There the beets are processed to ethanol by fermentation and distillation. The ethanol is trucked 150 km to the refueling station and dispensed. The assumptions on use of by-products, the reference crop system, and field emissions of N₂O can have a dramatic impact on the energy and GHG balances. A number of different scenarios were included to evaluate these effects:

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Agricultural reference systems and N₂O scenarios:

1. Rotational set-aside planted with Egyptian clover with N₂O calculated according to the IPCC guidelines
2. Rotational set-aside planted with rye grass with N₂O calculated according to the IPCC guidelines.
3. Production of ethanol from beets in conjunction with sugar production and N₂O emissions calculated according to Ecobilan (1996)

By-product options considered were:

- (a) Sugar beet pulp used as fuel
- (b) Sugar beet pulp used as animal feed
- (c) Ethanol produced in sugar refinery according to [Ecobilan 1996]

Hydrocarbon Liquids From Residual Woody Biomass:

Residual woody biomass is collected and transported 50 km to a biomass processing plant. There, the biomass is converted to HC-liquids by either HTU (Hydro Thermal Upgrading) with downstream HDO (Hydro-De-Oxygenation) or gasification to synthesis gas and downstream FT Synthesis. The HC-liquids are trucked 150 km to the refueling station and dispensed.

Rapeseed Methyl Ester (RME) From Rape Seed: Rape seed or sunflower seed is cultivated, collected and transported by truck 50 km to an oil processing plant. There the oil is extracted, refined and esterified with methanol. The plant oil ester is transported 150 km for blending with diesel fuel.

ETBE From Sugar Beets via Ethanol: Sugar beets are cultivated, collected and transported 50 km to an ethanol plant. There the biomass is processed, fermented and distilled to ethanol. The ethanol is trucked 150 km to the refinery, processed to ETBE, and used as a gasoline blendstock.

Methane From Organic Waste via Fermentation: Organic waste from households, catering, and the food industry is converted to biogas by fermentation. It is assumed that there is no additional transport of the waste in comparison to current waste disposal. After purification, the methane content is about 95%. The methane is transported to a CNG-filling station by pipeline (e.g. via the natural gas grid) and then compressed to 25 MPa.

CGH₂ From Organic Waste via Fermentation to Methane and Reforming: Organic waste from households, catering and the food industry is converted to biogas by fermentation. It is assumed that there is no additional transport of the waste in comparison to current waste disposal. After purification, the methane content is about 95%. The methane is transported to a refueling station by pipeline (e.g. via the natural gas grid). There it is reformed onsite to hydrogen. Gaseous hydrogen is compressed from 1.5MPa to discharge pressures of either 45 MPa (for 35 MPa @ 15 °C in vehicle tanks) or 88 MPa (for 70 MPa @ 15 °C in vehicle tanks).

MTBE From Residual Woody Biomass Derived Methanol: Residual woody biomass is collected and transported 50 km to a gasification plant where it is gasified and converted to methanol. The methanol is trucked 150 km to the refinery, processed to MTBE, and used as a gasoline blendstock.

GENERAL REMARKS ON BIOMASS-DERIVED PATHWAYS:

Fuel supply pathways based on biomass from residues as well as biomass from plantation have been considered. The plantation of crops generates direct and indirect N₂O emissions at the field. The N₂O emissions are calculated according to the IPCC guidelines of 1996. Additional N₂O emissions are generated by the production of synthetic fertilizers.

Direct N₂O emissions: The formation and decomposition of N₂O in soils depends on various controlling parameters. The main factors are aeration, water content, climate and availability of N and organic material. The amount of N₂O emitted from soils is also influenced by the soil's characteristics, such as soil texture and denitrification activity. Other factors that influence the N₂O emissions from soils are freezing, thawing, drying and rewetting.

Indirect N₂O emissions: The fertilizer N that is not utilized by the crop is either stored in the soil or lost from the system. It is lost through the leaching of nitrate to groundwater or the runoff of soil to surface water, or it is volatilized through ammonia volatilization or nitrification/ denitrification as NO_x, N₂O and N₂. The nitrogen that leaves the agricultural system is eventually either denitrified to N₂, producing a small fraction of N₂O, or stored in sediments of aquatic systems. There is a large bandwidth indicated in the IPCC Guidelines. Therefore, there is a large uncertainty concerning the amount of N₂O used for the calculation of GHG emis-

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sions from biofuels plantation. The use of the default values for the plantation of energy crops provides only a rough estimation of the GHG emissions.

There is also a relationship between the assumed reference system and resulting N₂O emissions. If a N-fixing cover crop were included in a crop rotation system, synthetic fertilizer and therefore indirect emissions of N₂O (e.g. from leaching and runoff) would be saved. If this N-fixing cover crop is replaced by the energy crop, more synthetic fertilizer will be required, not only for the energy crop itself but also for the replaced N-fixing cover crop within the crop rotation system. Thus, a penalty has been applied in when a N-fixing crop is used as the reference system.

For sugar beet and rapeseed plantation the plant residues (e.g. straw) are plowed in for fertilizer, and as a result, the application of synthetic fertilizer can be reduced.

Credits: The conversion of sugar beet to ethanol generates sugar beet pulp as a by-product (the slop - itself a by-product - is processed in a biogas plant). The by-product sugar beet pulp can be used as fuel e.g. for heat generation or as animal fodder. For the calculation of an animal fodder credit it is assumed that the pulp substitutes for soybeans imported from the USA.

For rape seed methyl ester (RME) credits have been considered for the crushed rape seed and the glycerin. The glycerin from the RME-plant substitutes for conventionally produced glycerin in the chemical industry.

Bounds: For variants using IPCC derived N₂O emissions, the lower IPCC values were used to calculate the LB value. The upper value for the UB value and the default value for the BE value were used in the Monte Carlo simulation.

Other assumptions: The transport distance between the conversion plant and the filling station for biomass-derived fuels is generally shorter than that of fossil derived fuels since the biomass conversion plants are smaller and more decentralized. The fuel is transported directly from the biomass conversion plant to the filling station while fossil based fuels are first transported to a depot from which they are finally distributed to the filling stations. Therefore, a 150 km transport distance between conversion plant and filling station is assumed for all liquid fuels.

Agricultural carbon release and sequestration. Long-term set aside land, pasturelands and forests that are converted for agricultural food crops release large amounts of carbon which, due to physical, chemical and biochemical reactions, are converted to CO₂. On the other hand, when land used for food crops is converted to less intensive agriculture such as poplar plantation, carbon sequestration can occur. The volume of these emissions varies depending on modifications of microclimate and soil conditions due to crop selection, soil tillage, mulching, fertilization, irrigation and liming and occurs until a new equilibrium is reached. Because of this uncertainty, we have neglected carbon release and carbon sequestration in this study.

1.4 Results

44 WTT pathways with, in total 88 variants were investigated. From these WTT pathways 32 have been selected for WTW integration. Those pathways selected for WTW integration are highlighted in italics and underlined in Table 1-1, Table 1-2, Table 1-3 and Table 1-4 and listed in Table 3-1.

Oil Based Pathways

Best Estimate energy and greenhouse gas values for production of fuels from crude oil are shown in Table 1-1. Energy inputs and greenhouse gases were highest for gasoline, but relatively low for all three pathways.

Table 1-1: Oil Based Pathways: Energy input, Energy Losses and GHG Emissions (Best Estimate (BE) Values)

Pathway No.		Energy input [MJ/MJ]	Energy losses [MJ/MJ]	GHG [g CO ₂ -equ./MJ]
Crude Based Pathways				
1	<i><u>Gasoline (sulfur content < 10 ppm)</u></i>	1.16	0.16	13.2
2	<i><u>Diesel (sulfur content < 10 ppm)</u></i>	1.12	0.12	10.4
3	<i><u>Naphtha (sulfur content < 0.4 ppm)</u></i>	1.11	0.11	9.9

Natural Gas Based Pathways

Table 1-2 shows best estimate values for the natural gas pathways. Energy losses and greenhouse gas emissions were lowest for the CNG pathway and highest for liquid hydrogen.

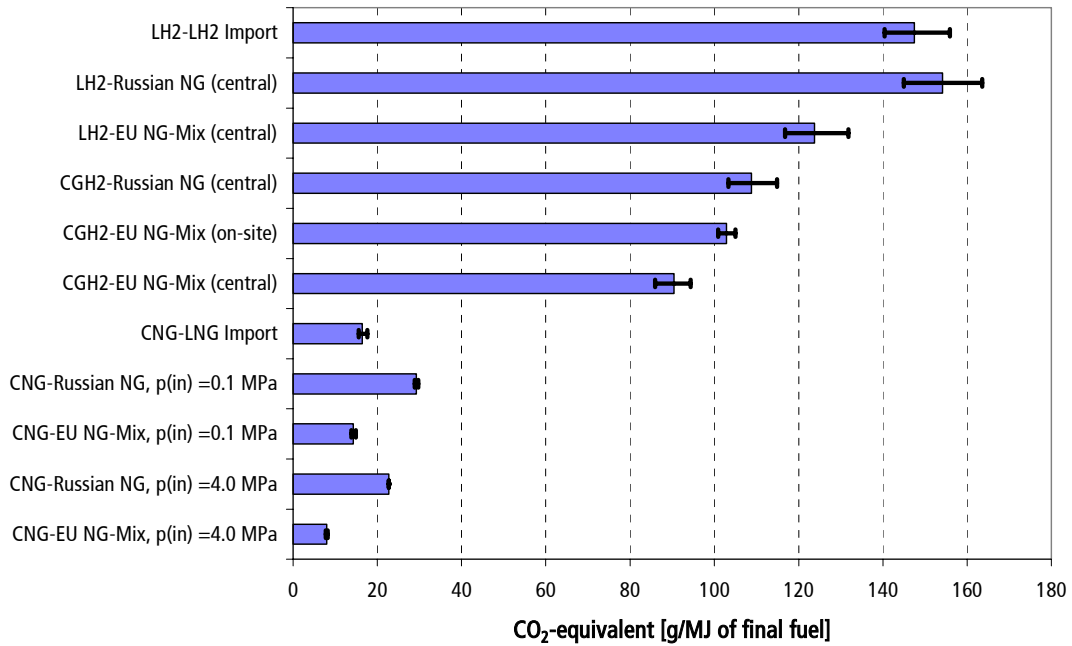
Table 1-2: Natural Gas Based Pathways: Energy input, Energy Losses and GHG Emissions (Best Estimate (BE) Values)

Pathway No.		Energy input [MJ/MJ]	Energy losses [MJ/MJ]	GHG [g CO ₂ -equ./MJ]
Natural Gas Based Pathways				
4	CNG: EU NG mix, p(in) = 4.0 MPa	1.12	0.12	8
5	<u>CNG: EU NG mix, p(in) = 0.1 MPa</u>	1.20	0.20	14
6	CNG from Russian piped NG, p(in) = 4.0 MPa	1.35	0.35	23
7	CNG from Russian piped NG, p(in) = 0.1 MPa	1.43	0.43	29
8	<u>CNG: LNG from remote location</u>	1.24	0.24	16
9	MeOH: from EU NG mix	1.63	0.63	25
10	<u>MeOH: from remote location</u>	1.62	0.62	27
11	FTD: from EU NG mix	1.74	0.74	30
12	<u>FTD: from remote location</u>	1.69	0.69	28
13	FTN: from EU NG mix	1.75	0.75	32
14	<u>FTN: from remote location</u>	1.70	0.70	30
15	CGH ₂ from EU NG mix in central plant (for 35 MPa vehicle tanks)	1.57	0.57	88
16	<u>CGH₂: from EU NG mix in central plant (for 70 MPa vehicle tanks)</u>	1.61	0.61	90

Pathway No.		Energy input [MJ/MJ]	Energy losses [MJ/MJ]	GHG [g CO ₂ -equ./MJ]
17	CGH ₂ : from Russian piped NG in central plant (for 35 MPa vehicle tanks)	1.86	0.86	107
18	CGH ₂ : from Russian piped NG in central plant (for 70 MPa vehicle tanks)	1.90	0.90	109
19	CGH ₂ : EU NG mix in onsite production (for 35 MPa vehicle tanks)	1.83	0.83	101
20	<i>CGH₂: EU NG mix in onsite production (for 70 MPa vehicle tanks)</i>	<i>1.87</i>	<i>0.87</i>	<i>103</i>
21	<i>LH₂: EU NG mix in central plant</i>	<i>2.14</i>	<i>1.14</i>	<i>124</i>
22	LH ₂ : from Russian piped NG in central plant	2.61	1.61	154
23	<i>LH₂: from remote location</i>	<i>2.55</i>	<i>1.55</i>	<i>147</i>
24	<i>MTBE from NG derived methanol (EU NG mix)</i>	<i>1.28</i>	<i>0.28</i>	<i>18</i>

The source of natural gas feedstock has a large impact on GHG emissions for natural gas based pathways. Figure 1-2 shows the supply of CNG, natural gas derived CGH₂ and natural gas derived LH₂ as an example.

Figure 1-2: CNG and Hydrogen from natural gas: WTT GHG emissions



Use of the European NG-Mix offers the lowest energy and GHG use. A significant expansion of natural gas demand by the transport sector would, however, necessitate additional gas imports. Fuel supply pathways based on Russian natural gas generate higher GHG emissions than the EU grid mix, if all other parameters are kept constant (e.g. specification of the delivered fuel, CNG suction pressure, etc.). This results largely from compressor energy requirements along the long pipeline and methane losses.

LNG from remote sources also involves increased energy use and GHG emissions compared with EU grid gas.

Electricity Based Pathways

Table 1-3 shows best estimate values for electricity-based pathways. Electricity produced at the wind power site was defined to be 100% efficient. Based on this definition, pathways producing hydrogen from wind power had the lowest energy losses and lowest greenhouse

gases. The highest energy losses and greenhouse gases were for pathways based on hydrogen generated from EU Mix electricity.

Table 1-3: Electricity Based Pathways: Energy input, Energy Losses and GHG Emissions (Best Estimate (BE) Values)

Pathway No.		Energy input [MJ/MJ]	Energy losses [MJ/MJ]	GHG [g CO ₂ -equ./MJ]
Electricity Based Pathways				
25	Electricity (0.4kV level) from EU electricity mix	2.87	1.87	129
26	Electricity (0.4kV level) from windpower	1.03	0.03	0
27	Electricity (0.4kV level) from CCGT	2.03	1.03	117
28	CGH ₂ : EU mix electrolysis in regional electrolysis plant (for 35 MPa vehicle tanks)	4.59	3.59	206
29	CGH ₂ : wind electrolysis in regional electrolysis plant (for 35 MPa vehicle tanks)	1.65	0.65	0
30	CGH ₂ : CCGT electrolysis in regional electrolysis plant (for 35 MPa vehicle tanks)	3.25	2.25	187
31	<i>CGH₂: EU mix electrolysis in regional electrolysis plant (for 70 MPa vehicle tanks)</i>	<i>4.64</i>	<i>3.64</i>	<i>208</i>
32	<i>CGH₂: wind electrolysis in regional electrolysis plant (for 70 MPa vehicle tanks)</i>	<i>1.66</i>	<i>0.66</i>	<i>0</i>
33	CGH ₂ : CCGT electrolysis in regional electrolysis plant (for 70 MPa vehicle tanks)	3.30	2.30	190
34	CGH ₂ : EU mix onsite electrolyses (for 35 MPa vehicle tanks)	4.60	3.60	207
35	CGH ₂ : wind onsite electrolyses (for 35 MPa vehicle tanks)	1.65	0.65	0
36	CGH ₂ : CCGT onsite electrolyses (for 35 MPa vehicle tanks)	3.26	2.26	188

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Pathway No.		Energy input [MJ/MJ]	Energy losses [MJ/MJ]	GHG [g CO ₂ -equ./MJ]
37	<i>CGH₂: EU mix onsite electrolyses (for 70 MPa vehicle tanks)</i>	4.64	3.64	208
38	<i>CGH₂: wind onsite electrolyses (for 70 MPa vehicle tanks)</i>	1.66	0.66	0
39	<i>CGH₂: CCGT onsite electrolyses (for 70 MPa vehicle tanks)</i>	3.26	2.26	188
40	<i>LH₂: EU mix electrolysis in central electrolysis plant</i>	5.38	4.38	242
41	<i>LH₂: wind electrolysis in central electrolysis plant</i>	1.95	0.95	2
42	LH ₂ : CCGT electrolysis in central electrolysis plant	3.81	2.81	220

Biomass Based Pathways

Table 1-4 displays best estimate energy inputs and greenhouse gas emissions for the biomass pathways. Although energy losses were relatively high, most of the lost energy was renewable. Energy losses and greenhouse gas emissions were generally lower for those pathways involving residual biomass or waste products. This results from the fact that inputs and emissions for the cultivation of the biomass were not required for these pathways. Some of the pathways have negative greenhouse gas emissions due to a credit for carbon sequestered in the biomass via CO₂ uptake. Of the different fuels, RME and MTBE had relatively low energy losses, but these are treated in the study as blending stocks only, and not as pure fuels.

Table 1-4: Biomass Based Pathways: Energy input, Energy Losses and GHG Emissions (Best Estimate (BE) Values)

Pathway No.		Energy input [MJ/MJ]	Energy losses [MJ/MJ]	GHG [g CO ₂ -equ./MJ]
Biomass Based Pathways				
43	CGH ₂ : gasification of residual woody biomass in 10 MW _{th} plant (for 35 MPa vehicle tanks)	1.84	0.84	6.9

Pathway No.		Energy input [MJ/MJ]	Energy losses [MJ/MJ]	GHG [g CO ₂ -equ./MJ]
44	<i><u>CGH₂: gasification of residual woody biomass in 10 MW_{th} plant (for 70 MPa vehicle tanks)</u></i>	1.88	0.88	7.0
45	CGH ₂ : gasification of residual woody biomass in 2.5 MW _{th} plant (for 35 MPa vehicle tanks)	2.08	1.08	8.3
46	CGH ₂ : gasification of residual woody biomass in 2.5 MW _{th} plant (for 70 MPa vehicle tanks)	2.12	1.12	8.5
47	CGH ₂ : gasification of woody biomass from plantation of poplar in 10 MW _{th} plant (for 35 MPa vehicle tanks)	1.89	0.89	21.3
48	<i><u>CGH₂: gasification of woody biomass from plantation of poplar in 10 MW_{th} plant (for 70 MPa vehicle tanks)</u></i>	1.91	0.91	21.7
49	CGH ₂ : gasification of woody biomass from plantation of poplar in 2.5 MW _{th} plant (for 35 MPa vehicle tanks)	2.13	1.13	24.6
50	CGH ₂ : gasification of woody biomass from plantation of poplar in 2.5 MW _{th} plant (for 70 MPa vehicle tanks)	2.16	1.16	25.2
51	<i><u>MeOH: gasification of residual woody biomass (gasifier: BCL)</u></i>	1.87	0.87	-61.8
52	MeOH: gasification of residual woody biomass (gasifier: Framatome)	2.70	1.70	-59.0
53	<i><u>E100: enzymatic hydrolysis of lignocellulose (crop residue)</u></i>	2.78	1.78	-55.7
54	E100: enzymatic hydrolysis of lignocellulose (sugar beet pulp)	4.59	3.59	-70.3
55	<i><u>E100: enzymatic hydrolysis of lignocellulose (plantation of poplar)</u></i>	2.99	1.99	-29.5
56	E100: conventional fermentation of sugar beet (variant 1a)	2.24	1.24	-30.5
57	E100: conventional fermentation of sugar beet (variant	2.58	1.58	-6.1

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Pathway No.		Energy input [MJ/MJ]	Energy losses [MJ/MJ]	GHG [g CO ₂ -equ./MJ]
	1b)			
58	E100: conventional fermentation of sugar beet (variant 1c)	2.20	1.20	3.0
59	E100: conventional fermentation of sugar beet (variant 2a)	2.22	1.22	-34.2
60	<i>E100: conventional fermentation of sugar beet (variant 2b)</i>	2.55	1.55	-15.1
61	E100: conventional fermentation of sugar beet (variant 2c)	2.18	1.18	0.1
62	E100: conventional fermentation of sugar beet (variant 3a)	2.20	1.20	-55.3
63	E100: conventional fermentation of sugar beet (variant 3b)	2.52	1.52	-31.1
64	E100: conventional fermentation of sugar beet (variant 3c)	2.16	1.16	-13.4
65	HCL: solids to liquids (diesel/naphtha) from residual woody biomass via HTU/HDO process	1.94	0.94	-67.4
66	<i>HCL: solids to liquids (diesel/naphtha) from residual woody biomass via FT synthesis</i>	2.23	1.23	-62.0
67	RME: bio-ester from rape seed (variant 1a)	2.13	1.13	-4.4
68	RME: bio-ester from rape seed (variant 1b)	1.76	0.76	-32.2
69	RME: bio-ester from rape seed (variant 2a)	2.07	1.07	-24.3
70	<i>RME: bio-ester from rape seed (variant 2b)</i>	1.70	0.70	-48.0
71	RME: bio-ester from rape seed (variant 3a)	2.14	1.14	1.2
72	RME: bio-ester from rape seed (variant 3b)	1.77	0.77	-26.2

Pathway No.		Energy input [MJ/MJ]	Energy losses [MJ/MJ]	GHG [g CO ₂ -equ./MJ]
73	RME: bio-ester from rape seed (variant 4a)	2.14	1.14	-40.0
74	RME: bio-ester from rape seed (variant 4b)	1.77	0.77	-65.2
75	ETBE from sugar beet derived ethanol (variant 1a)	1.67	0.67	0.3
76	ETBE from sugar beet derived ethanol (variant 1b)	1.79	0.79	10.1
77	ETBE from sugar beet derived ethanol (variant 1c)	1.66	0.66	13.2
78	ETBE from sugar beet derived ethanol (variant 2a)	1.66	0.66	-1.4
79	<i>ETBE from sugar beet derived ethanol (variant 2b)</i>	<i>1.78</i>	<i>0.78</i>	<i>6.3</i>
80	ETBE from sugar beet derived ethanol (variant 2c)	1.65	0.65	12.1
81	ETBE from sugar beet derived ethanol (variant 3a)	1.65	0.65	-8.3
82	ETBE from sugar beet derived ethanol (variant 3b)	1.77	0.77	0.6
83	ETBE from sugar beet derived ethanol (variant 3c)	1.65	0.65	7.1
84	<i>CMG: biogas derived compressed methane gas</i>	<i>1.48</i>	<i>0.48</i>	<i>-56.7</i>
85	CGH ₂ : steam reforming of biogas (for 35 MPa vehicle tanks)	2.24	1.24	0.4
86	<i>CGH₂: steam reforming of biogas (for 70 MPa vehicle tanks)</i>	<i>2.26</i>	<i>1.26</i>	<i>0.4</i>
87	<i>MTBE from residual woody biomass derived methanol (gasifier: BCL)</i>	<i>1.33</i>	<i>0.33</i>	<i>2.0</i>
88	MTBE from residual woody biomass derived methanol (gasifier: Framatome)	1.49	0.49	2.7

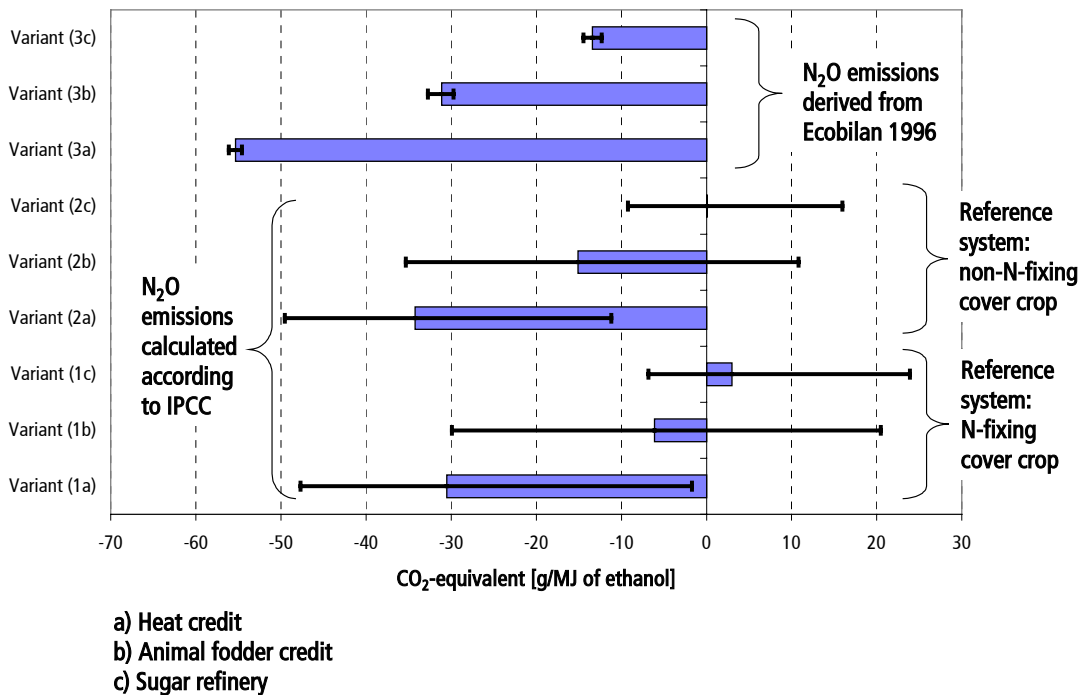
The energy losses shown in the above table consist mostly of renewable energy. Details are shown in Figure 1-7, Figure 1-8 and Figure 1-9.

As previously mentioned, there is wide uncertainty concerning GHG emissions resulting from biomass-derived fuels. This is due principally to N₂O. Figure 1-3 shows the GHG emissions for

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the supply of sugar beet-derived ethanol as an example.

Figure 1-3: Ethanol from sugar beet: WTT GHG emissions¹ (best estimate and bandwidth) depending on different assumptions



¹ Seen from the balance’s viewpoint, negative GHG emissions for fuel supply result from CO₂ absorbed by the plant. For this case (ethanol from sugar beet), if no fossil CO₂ and no other GHGs were emitted the GHG emissions of the ethanol supply would be -71.3 g/MJ of ethanol. Fossil derived CO₂ and other GHGs such as plantation N₂O, lead to higher GHG emissions in the range of -35 to +11 g/MJ of ethanol for variant 2b. During fuel combustion in the vehicle the CO₂ bound in the ethanol will be released, resulting in net positive GHG emissions in any case.

Total Energy Use WTT

Total energy use for fuel production from representative crude oil, natural gas, electricity and biomass-based pathways is presented in Figure 1-4, Figure 1-5 and Figure 1-6. Note that input energy is included in the figures, whether the energy comes from fossil or renewable sources. The efficiency of electricity generation from wind is assumed to be 100%. As a result, the chain starts with the electricity output at the wind power plant.

Fuel supply efficiencies can be calculated as the reciprocal energy use. The Lower Bound and Upper Bound values are depicted using "uncertainty bars". In each of the figures, the first two bars represent the energy use for the supply of gasoline and diesel.

Crude-oil-based fuels and compressed natural gas (CNG) have the lowest energy requirements: 1.14 MJ/MJ to 1.18 MJ/MJ (gasoline), 1.11 MJ/MJ to 1.14 MJ/MJ (diesel), 1.10 MJ/MJ to 1.13 MJ/MJ (naphtha) and 1.19 MJ/MJ to 1.26 MJ/MJ (CNG).

Much higher energy input (in the range of 1.5 MJ/MJ to about 2.0 MJ/MJ) is required for some of the natural gas, electricity and biomass derived fuels. Examples include compressed gaseous hydrogen (CGH₂) via steam reforming of natural gas, compressed methane gas (CMG) from biogas, CGH₂ via electrolysis using wind power or via gasification of woody biomass, liquid hydrogen (LH₂) from wind power, FT-diesel (FTD) and FT-naphtha (FTN) from natural gas, and methanol (MeOH) from natural gas or residual wood.

Ethyl tertiary butyl ether (ETBE) from sugar beet, methyl tertiary butyl ether (MTBE) from residual wood or natural gas and rape seed methyl ester (RME) are not used as dedicated fuels, rather they are used only as blending agents for gasoline or diesel.

Energy inputs in the range of 2.0 MJ/MJ to 2.5 MJ/MJ are required for FTD from residual wood, CGH₂ via steam reforming from biogas and LH₂ from the EU natural gas mix.

Even higher energy inputs of 2.5 MJ/MJ to 3.5 MJ/MJ are needed for the production of LH₂ from remote natural gas, for the production of ethanol from sugar beet, straw and wood plantation, and for electrolytic CGH₂ generated via combined cycle gas turbine power plant (CCGT) plants fueled with EU natural gas mix.

Electrolytic CGH₂ generated centrally and onsite, and centrally-produced LH₂ fall within the 3.5 MJ/MJ to 5.5 MJ/MJ range, when EU electricity mix is assumed as power source.

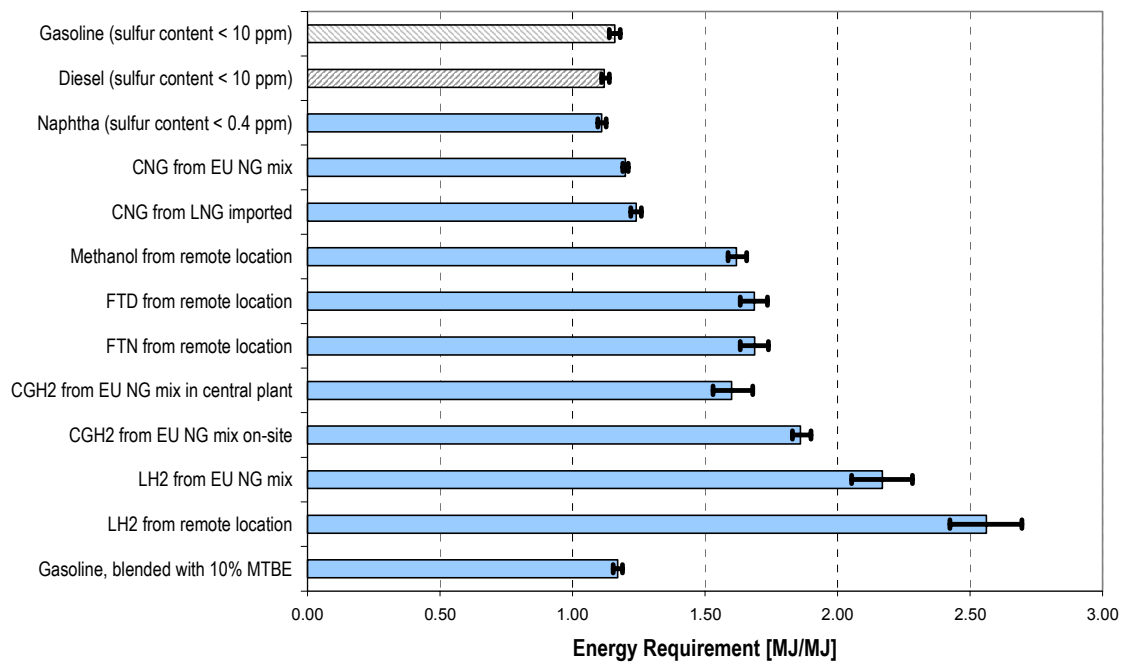
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Total energy use for hydrogen production via electrolysis is reduced when natural gas fired combined cycle gas turbine (CCGT) power plants are used rather than the EU electricity generation mix, because the average efficiency of existing fossil EU power plants is lower than that of large natural gas fired CCGT power plants. However, the energy input for electrolysis remains a significant debit unless renewable electricity is available.

Because of the low volumetric energy density of liquid hydrogen (8.5 MJ/l) compared to that of diesel (36.3 MJ/l), and the additional space needed for cryogenic ship vessels, long distance transport of LH₂ (~ 10,200 km) increases the energy use for the supply of LH₂. Therefore the energy use for the supply of LH₂ via steam reforming of natural gas from the EU natural gas mix is far below that for the supply of LH₂ from steam reforming of remote gas.

Note that the total energy use does not distinguish between the renewable and non-renewable sources. The next section shows the distribution of energy use according to the type of source for selected pathways.

Figure 1-4: WTT - Energy Use of Selected Pathways – Oil Derived Naphtha and Natural Gas Derived Fuels



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Figure 1-5: WTT - Energy Use of Selected Pathways– Electricity Derived Fuels

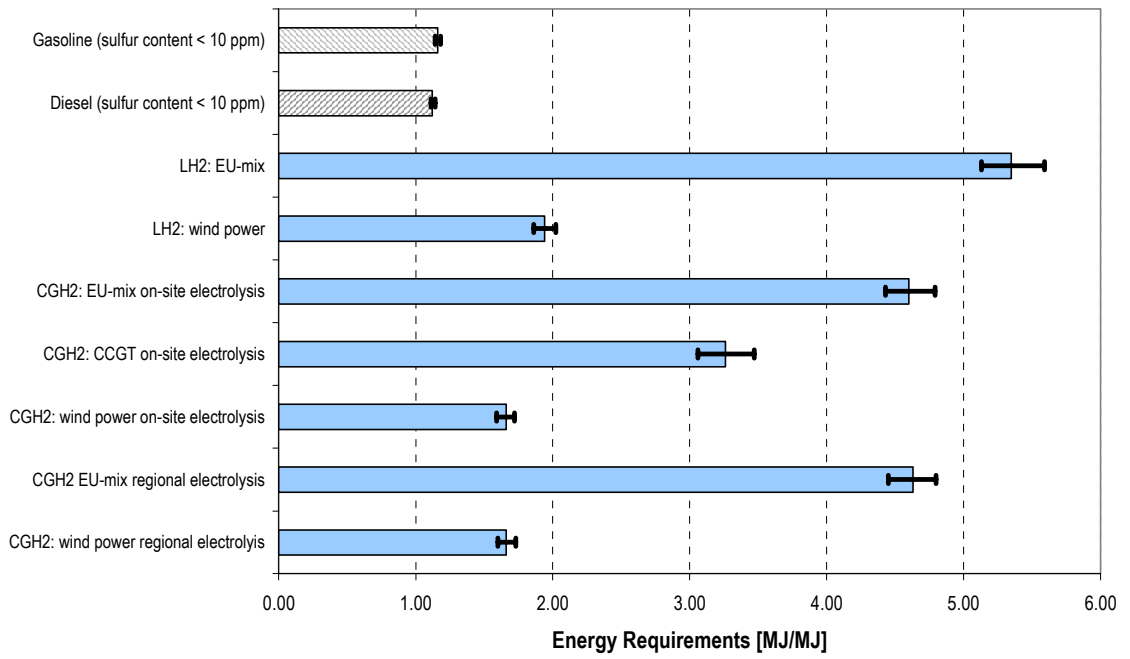
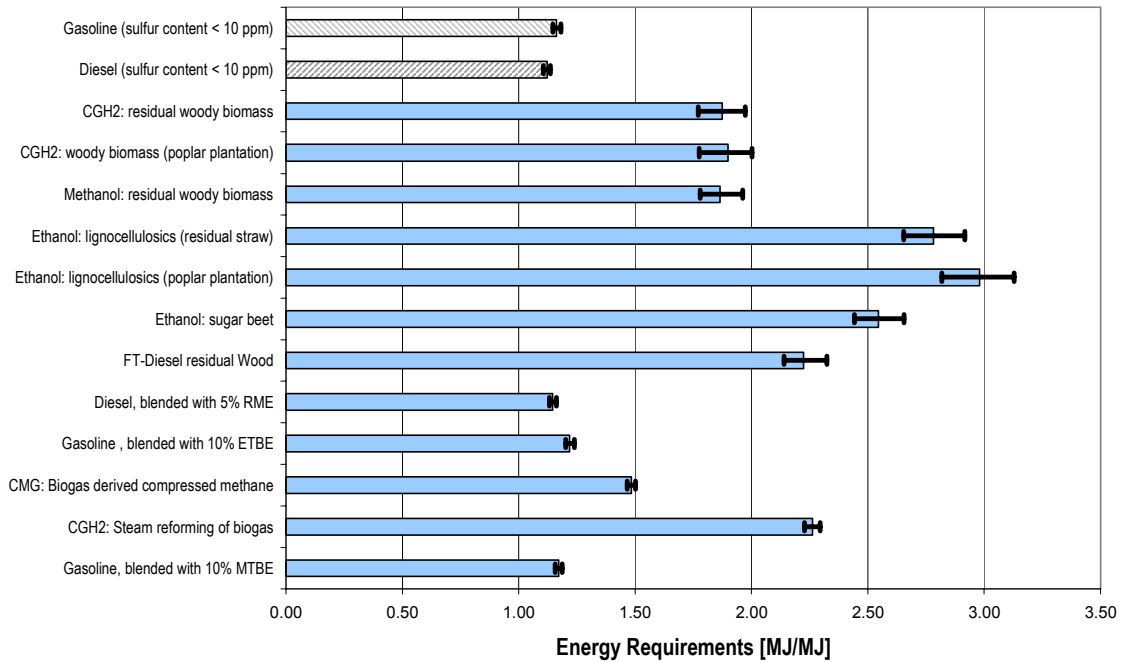


Figure 1-6: WTT - Energy Use of Selected Pathways– Biomass Derived Fuels

Renewable, Fossil and Nuclear Energy Use

The best estimate values for energy use, broken down in renewable, fossil and nuclear parts, are shown for selected pathways in Figure 1-7, Figure 1-8 and Figure 1-9. The first two bars represent the energy use for the supply of gasoline and diesel.

Fossil fuels include crude oil, natural gas (NG) and coal. As mentioned above, the nuclear energy part is derived from the energy content of the uranium.

In case of biomass-derived fuels, the energy use is based on the energy content of the harvested biomass. This is common for woody biomass-derived fuels, but some publications do not consider the energy content of the rapeseed or the sugar beet in producing bio-ester and ethanol, respectively. For the ethanol-from-sugar beets pathway, non-renewable energy use includes cultivation, transport to the ethanol plant, conversion to ethanol, and ethanol distri-

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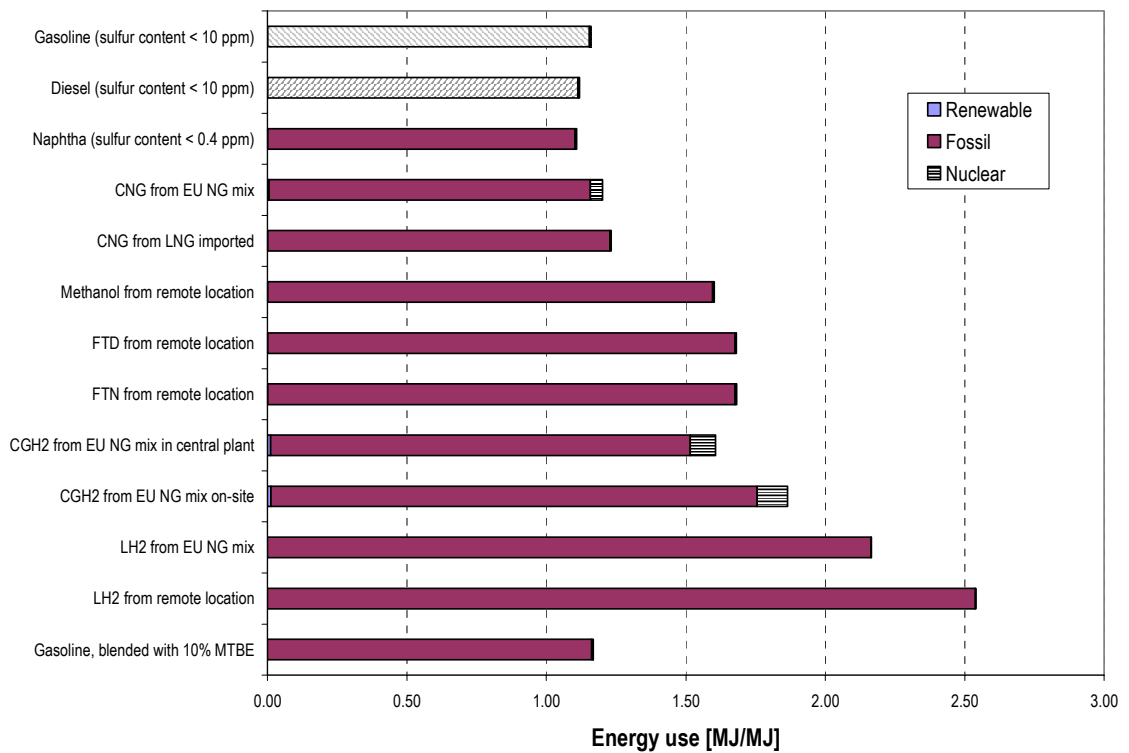
bution, and amounts to about 0.64 MJ/MJ of ethanol.

Figure 1-7 shows that, as expected, oil and natural gas pathway energy consumption results almost entirely from fossil fuels. For electricity-based pathways, as shown in Figure 1-8, the breakdown of energy sources depends on the pathway. About one-half of the European mix energy input is from fossil fuels. About 5% is renewable² and the rest is nuclear. This contrasts to the assumptions for the U.S. electricity mix as taken in the GM North American Study, in which almost 90% of the energy was from fossil fuels.

Energy input to biomass-based pathways, shown in Figure 1-9, was primarily renewable, except for pathways with low concentrations of biomass-based MTBE and RME in gasoline and diesel, respectively. Pathways to fuels from residual woody biomass had the largest proportion (>90%) of renewable energy. Ethanol from sugar beets used about 75% renewable energy.

² ~ 5% of the energy input for electricity generation but ~ 14% of the produced electricity is renewable

Figure 1-7: WTT - Renewable and Non-Renewable Energy Use of Selected Pathways – Oil Derived Naphtha and Natural Gas Derived Fuels (BE)



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Figure 1-8: WTT - Renewable and Non-Renewable Energy Use of Selected Pathways– Electricity Derived Fuels (BE)

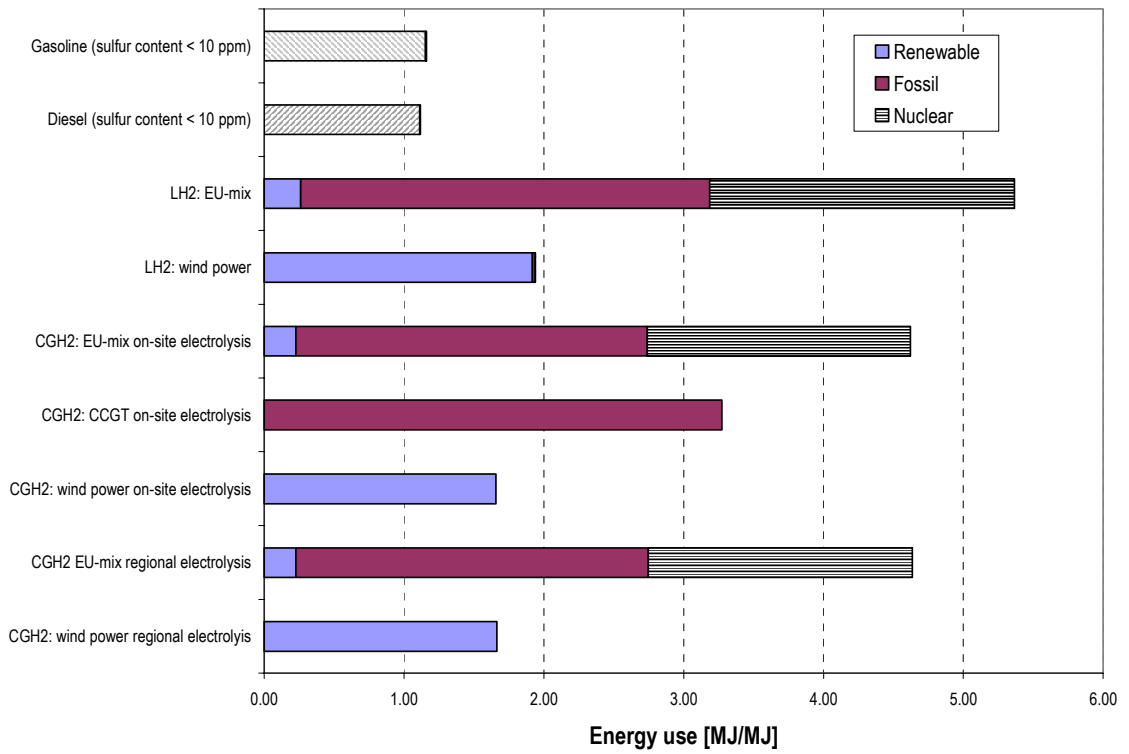
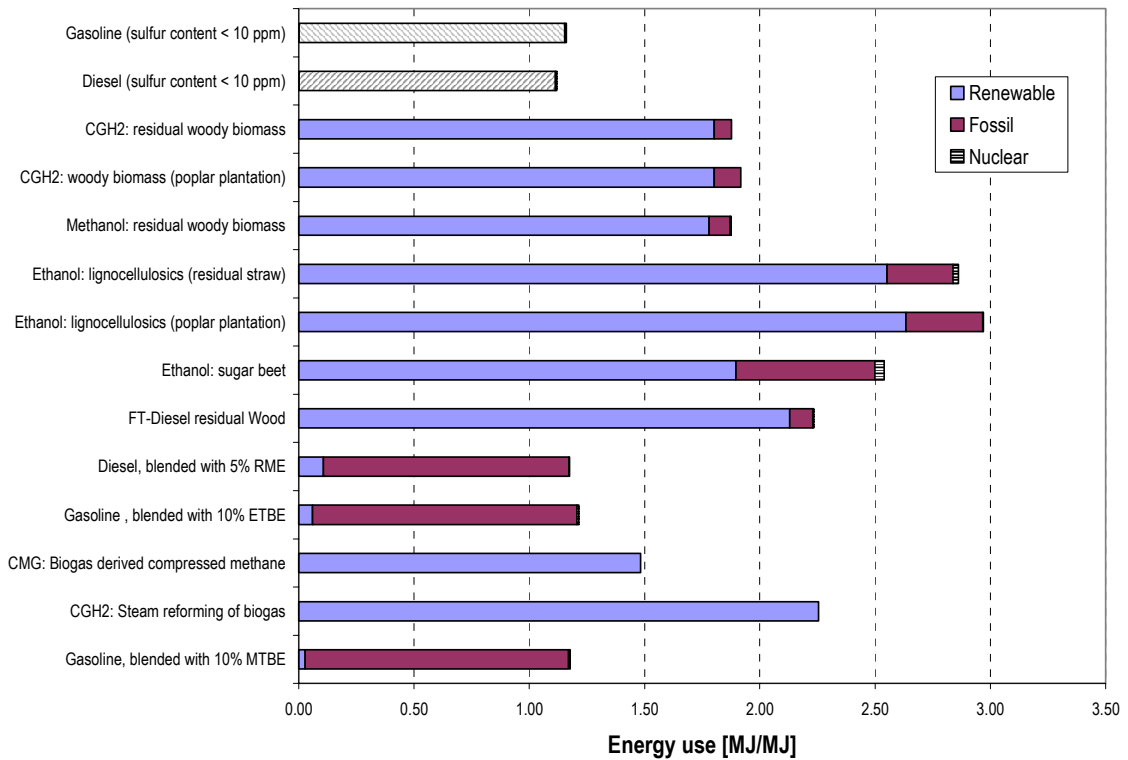


Figure 1-9: WTT - Renewable and Non-Renewable Energy Use of Selected Pathways– Biomass Derived Fuels (BE)



Greenhouse Gas Emissions

WTT GHG emissions for representative oil and natural gas-derived pathways are shown in Figure 1-10. The GHG emissions resulting from the supply of gasoline and diesel from crude oil and CNG from natural gas are relatively low. Methanol and Fischer Tropsch fuels have intermediate WTT GHG emissions, while hydrogen from natural gas pathways have the highest WTT GHG emissions on this chart. For hydrocarbon fuels, most of the carbon is bound to the fuel, so the CO₂ will be emitted during combustion onboard the vehicle. As will be shown later, onboard CO₂ emissions for hydrogen are, by contrast, zero.

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GHG emissions for electricity-based pathways, shown in Figure 1-11, depend on the source of the electricity. GHG emissions are high for the European Mix and CCGT, but near zero for wind power.

Biomass pathway GHG emissions are shown in Figure 1-12. By convention, the WTT CO₂ emissions are negative when the carbon comes from a renewable source. Hence, biomass-derived fuels will have negative WTT GHG emissions when all GHGs produced during the production of a MJ of fuel are lower than the CO₂ absorbed in growing of the biomass.

In some of the biomass pathways (e.g., ethanol from sugar beet, RME from rape seed) N₂O is the most significant driver for the GHG emissions. Based on IPCC, the GHG potential of a gram of N₂O is 310 times that of a gram CO₂. As was discussed earlier, there is a large uncertainty concerning the emissions of N₂O from agricultural lands. For the selected pathways shown in Figure 1-12, the N₂O emissions have been calculated in accordance with IPCC.

The bandwidth, calculated using the Monté Carlo simulation, is also shown in Figure 1-12. The rather large bandwidth seen for the ethanol-from-sugar-beets case results from the N₂O emissions uncertainties indicated in the Revised 1996 IPCC Guidelines. The formation of N₂O in agricultural soils depends on various parameters such as physical characteristics of the soil, aeration of the soil, water content of the soil, climate and the availability of nitrogen.

Figure 1-10: WTT - GHG Emissions of Selected Pathways– Oil Derived Naphtha and Natural Gas Derived Fuels

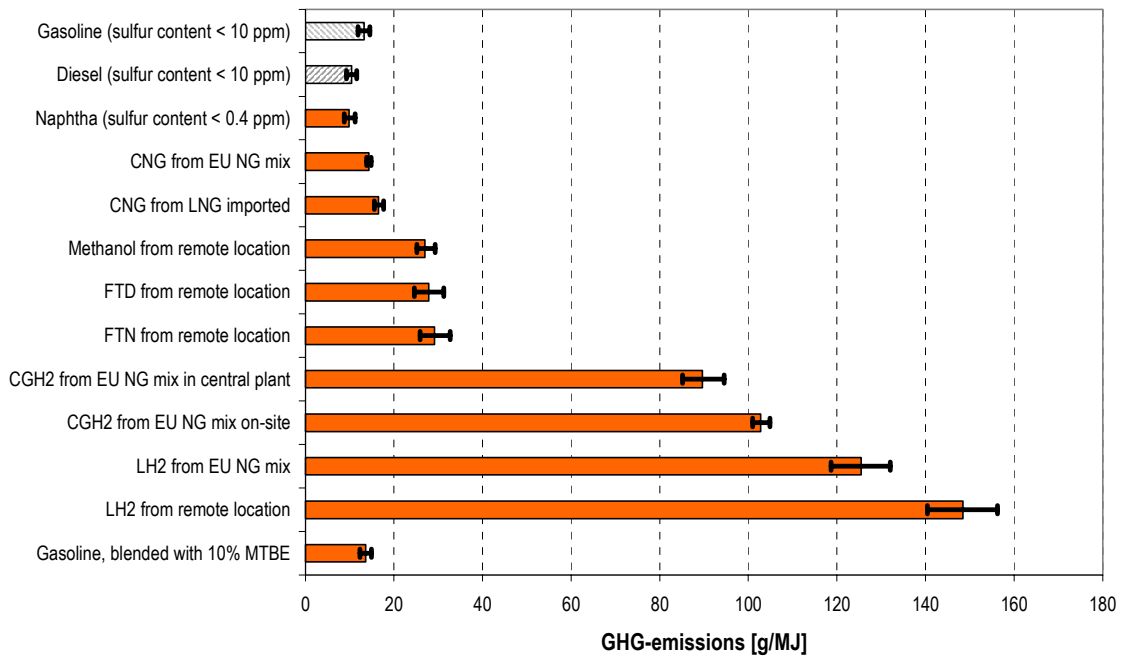


Figure 1-11: WTT - GHG Emissions of Selected Pathways – Electricity Derived Fuels

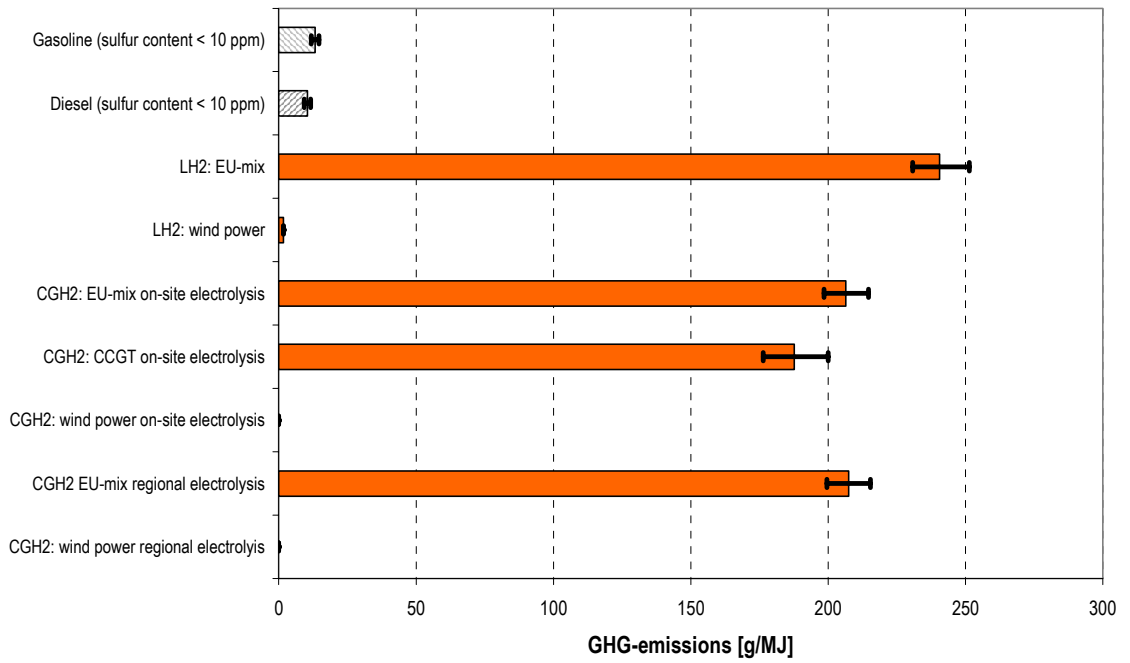


Figure 1-12: WTT - GHG Emissions of Selected Pathways – Biomass Derived Fuels

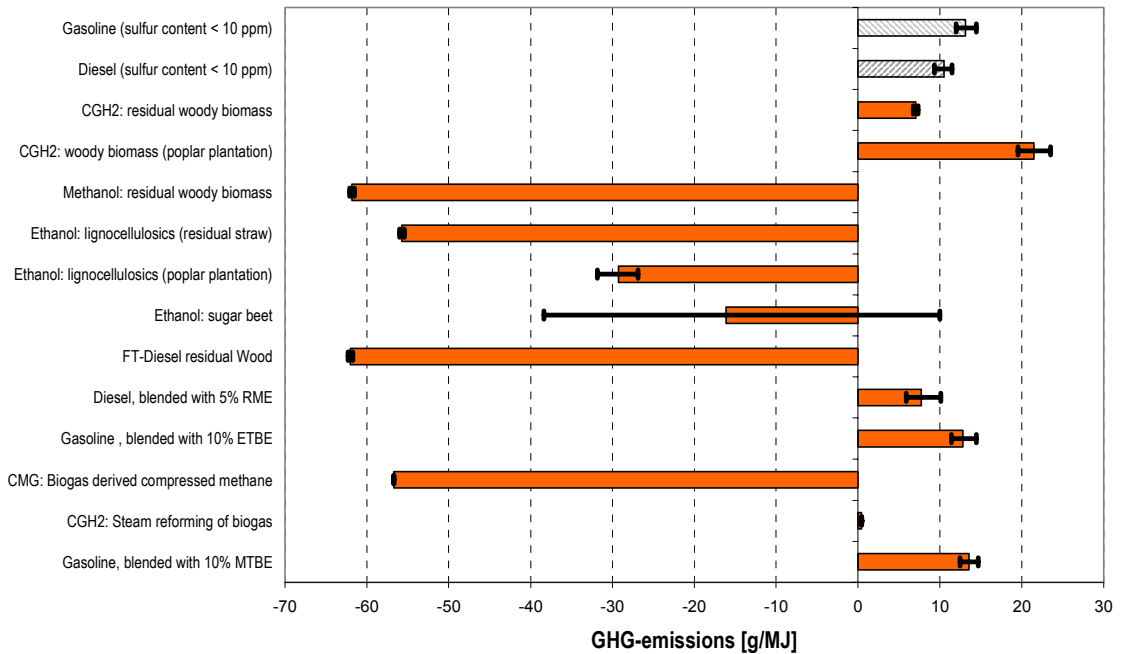


Figure 1-13 and Figure 1-14 show WTT energy consumption and GHG emissions for a subset of pathways. Diesel fuel from oil had the lowest WTT energy consumption, while FT-Diesel from residual wood had the lowest WTT GHG emissions. Hydrogen from European Mix electrolysis had the highest energy consumption and GHG emissions.

Figure 1-13: WTT - Energy Use of Selected Pathways

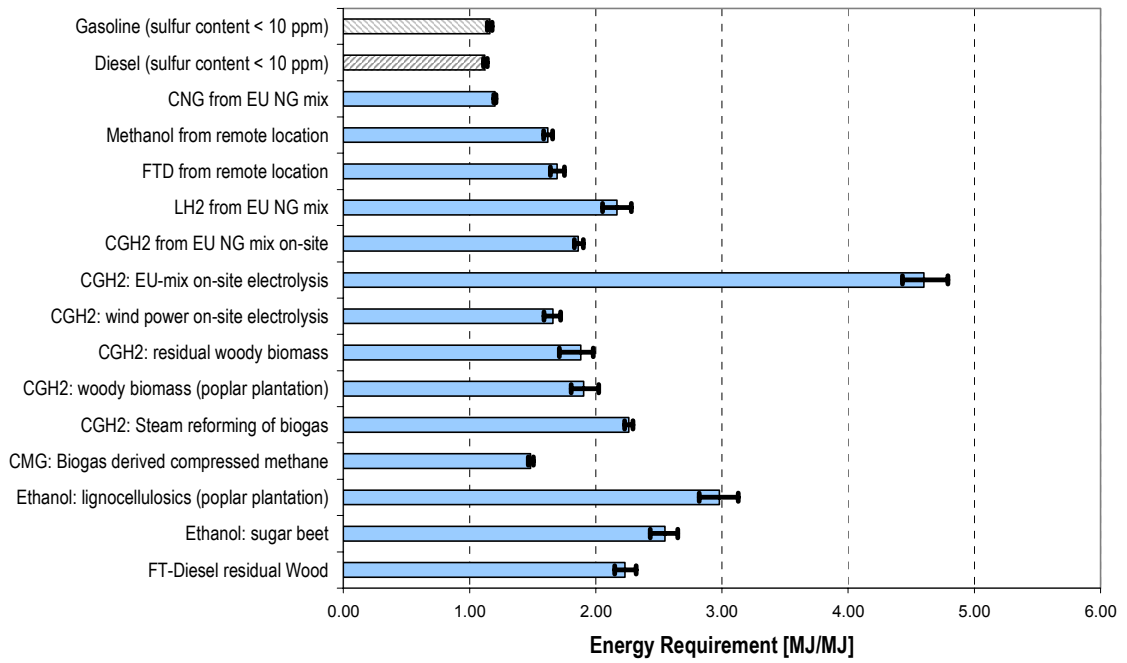
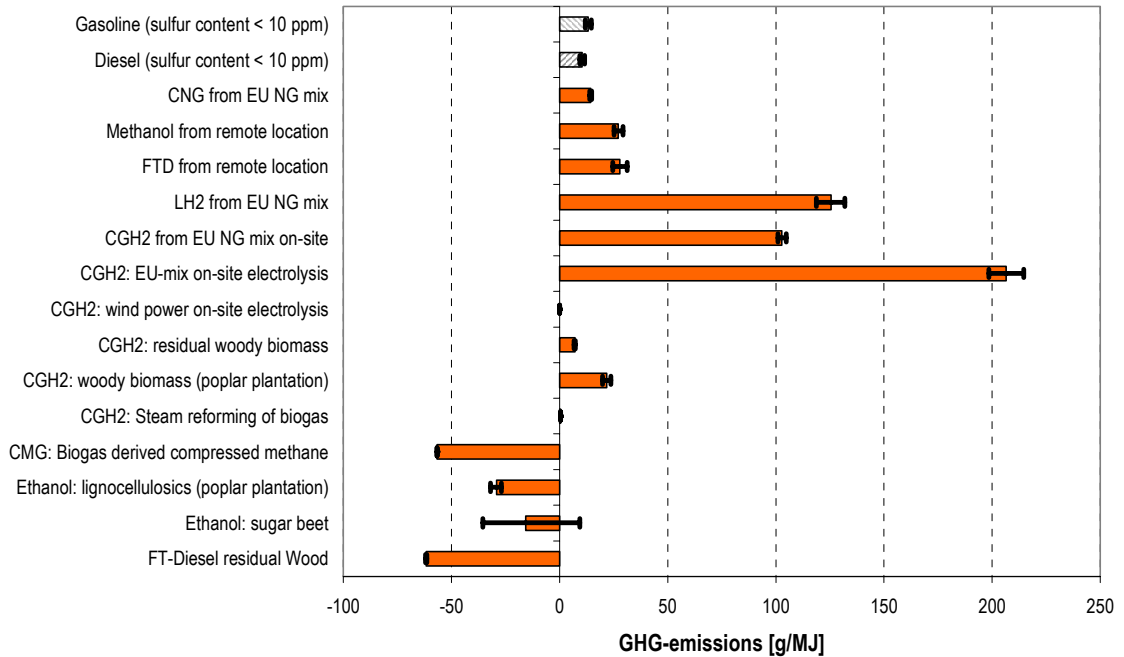


Figure 1-14: WTT - GHG Emissions of Selected Pathways



1.5 Conclusions

Fuels derived from renewable electricity release very low GHG emissions. For the transport of LH₂ they stem only from the truck running on crude oil-based diesel. Production of gasoline, diesel, and natural gas generate relatively low GHG emissions, but most of the CO₂ will be emitted during the use of the fuels (combustion). In contrast, hydrogen from fossil fuels leads to high GHG emissions during fuel supply but essentially zero CO₂ and approximately zero GHGs during fuel use. During hydrogen combustion in internal combustion engines small amounts of GHGs occur as small amounts of N₂O are formed. The use of hydrogen in fuel cell vehicles results in zero GHGs.

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Carbon-containing fuels derived from biomass produce negative GHG emissions during fuel supply, because the carbon is removed from the atmosphere during the growth of the plants and will be emitted as CO₂ during combustion. Therefore, the supply and combustion of the biomass would be CO₂- and GHG-neutral if no external fossil energy or fertilizer were used for cultivation, transport, and processing of biomass. For biomass-derived fuels, GHG emissions are generated largely by N₂O emissions from agricultural land. Furthermore, GHG emissions are generated by the use of fossil energy sources within the biomass-derived fuels supply chain.

Neat RME offers some GHG benefits over oil-derived diesel. This is also true, to a lower extent, for sugar-beet ethanol and ETBE. Biomass-derived methanol and biomass-derived FT-diesel as well as biogas-derived compressed methane gas (CMG) offer higher GHG benefits than sugar-beet ethanol and neat RME. The overall WTT GHG balance for mixtures of oil-derived fuels and bio-components (RME at 5%, and ethanol and ETBE at 10%) offers only minor reductions of GHG emissions in comparison to neat oil-derived fuels.

Vehicle efficiency impacts the overall results, and the CO₂ from combustion needs to be incorporated. Therefore, results from the WTW integration should be considered when evaluating different vehicle/fuel options.

2 Part 2: Tank-to-Wheel Analysis of Powertrains – Energy Use and Greenhouse Gas Emissions

2.1 Introduction

The purpose of this study was to evaluate and quantify the benefits of various fuels in combination with advanced powertrain concepts for the 2010 time frame. The concepts considered in the study included advanced conventional and fuel cell/fuel reformer powertrains as well as their associated hybrid vehicle architectures. The analysis focused on fuel economy and GHG emissions while complying with Euro IV emissions and vehicle performance requirements typical for European consumers.

At this time, the study did not take cost, packaging requirements, and cold-start performance into consideration. Thus, the results of the study may not be indicative of commercial feasibility of each propulsion system. The results do, however, provide a relative comparison among the conventional and more advanced non-conventional propulsion system technologies. It should also be noted here that the advanced conventional vehicle concepts (e.g., common rail direct injection diesel engines) currently considered state-of-the-art technologically, have yet not enjoyed a major penetration into the vehicle market.

The vehicle platform selected for the study was the current 2002 production Opel Zafira minivan with the 1.8L gasoline internal combustion engine (ICE) and a 5-speed manual transmission. This vehicle is also available on the market with a diesel and a CNG IC engine. The baseline vehicle used for this study projected this 2002 production vehicle to the 2010 time frame by including an advanced powertrain (such as an MTA – automated manual transmission) and some anticipated vehicle level improvements (such as a reduction in vehicle mass). Within this vehicle framework, additional powertrain technologies were then assessed. These included: various advanced ICE technologies (gasoline direct injection, diesel common rail direct injection, CNG optimized injection, hydrogen optimized injection) in conjunction with conventional drives (CD), more advanced transmissions, hybridized drivetrains for these ICE technologies, non-hybrid and hybrid fuel cell systems using onboard hydrogen storage and onboard reforming (of gasoline, methanol, and ethanol).

2.2 Methodology

The GM proprietary Hybrid Powertrain Simulation Program (HPSP) was employed to model and analyze all the vehicle propulsion systems included in the study. An extensive database of proprietary and validated component maps allowed modeling of each conventional and advanced vehicle architecture and powertrain technology. These component maps were used in simulation models to establish the vehicle performance capability and the fuel consumption, energy requirements, and greenhouse gas emissions on the European Driving Cycle (EDC). This cycle comprehends both a city driving mode (characterized by low vehicle speed and low engine load) and a more aggressive, high speed driving mode (maximum speed of 120 km/h).

The European Driving Cycle (EDC) was used in the study. This cycle includes a low vehicle speed segment (also referred to as the UDC – Urban Driving Cycle), Figure 2-1, representing urban driving and a high speed highway driving segment (also referred to as the EUDC – Extra Urban Driving Cycle) shown in Figure 2-2.

Figure 2-1: European Urban Driving Cycle (UDC)

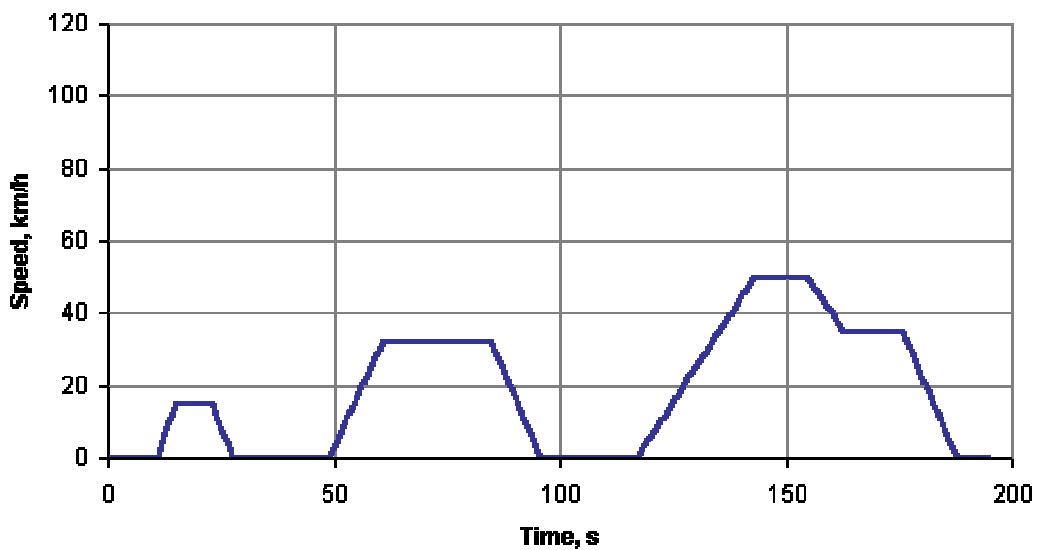
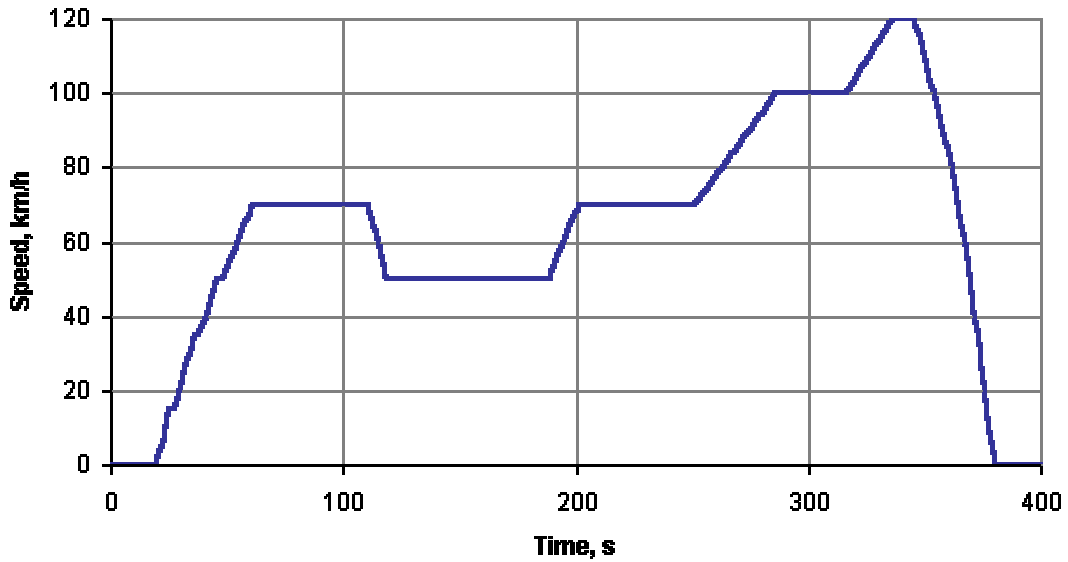
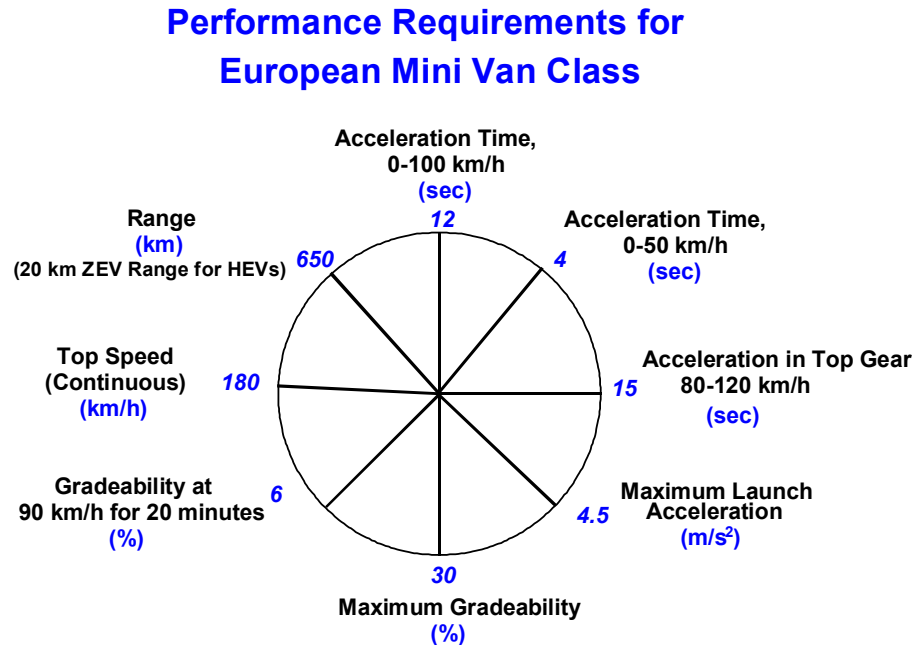


Figure 2-2: European Extra Urban Driving Cycle

The spider chart Figure 2-3 below in presents the performance requirements imposed on each vehicle concept evaluated in this study. The powertrain was first sized in terms of power and torque capacity to meet these performance criteria. The energy management and control strategies were subsequently optimized to yield the lowest fuel consumption on the driving cycle.

Figure 2-3: Vehicle Performance Requirements



The vehicle performance requirements were based on current gasoline ICE-equipped vehicles and customer performance expectations of future powertrains. A 20 km ZEV (Zero Emission Range) was imposed on the hybrid vehicles to provide these concepts with the ability to drive in a European inner city without actually running the engine.

The vehicle mass of each concept was adjusted based on estimates of added or eliminated components. Emissions targets for criteria pollutants for all vehicle concepts were based on Euro IV requirements. Powertrain efficiency and related CO₂-emissions were driven by the ACEA self-commitment of 140 g/km for 2008 and the European Commission requirement aiming at 120 g/km for 2012.

2.3 Propulsion Systems

The Table 2-1 below provides an overview of the vehicle architectures and fuels included in the study.

Table 2-1 Vehicle Propulsion Systems in European Study

	IC Engine	IC Engine Hybrid	Fuel Cell Non-Hybrid	Fuel Cell Hybrid
Gasoline	X	X	X	X
	+Advanced Powertrain			
Diesel	X	X		
FT Diesel	X	X		
CNG	X	X		
Methanol			X	X
Ethanol (E100)			X	X
Hydrogen	X	X	X	X

The powertrain and fuel combinations include conventional and hybrid drives using ICEs running on various fuels as well as electric drives in hybrid and non-hybrid architectures for fuel processor and fuel cell systems.

The fuels include a wide range of conventional and alternatives under consideration. Advanced Powertrain refers to a Direct Injected Gasoline ICE with an MTA (automated manual transmission). The Hybrid concepts are parallel architectures using advanced electric drives and NiMH (Nickel Metal Hydride) batteries. The fuel reformer and fuel cell systems incorporate recent advances to deal with issues of mass, transient response, and optimized management of the ancillary loads.

A dominant factor influencing the fuel consumption of any vehicle is the strategy imple-

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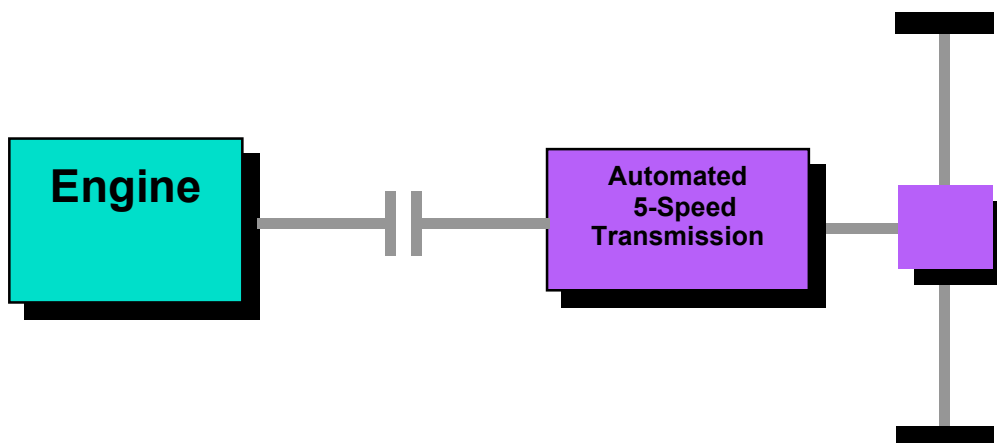
mented for controlling the energy distribution on the duty cycle. The vehicle simulation models for each of the concepts presented implement energy management and control strategies incorporating real-world constraints on engine or power source operation. These constraints reflect customer driveability and pleaseability criteria (e.g., engine ramping rates, engine speed constraints to assure vehicle response, engine operating regions to meet emission targets).

The trade-offs between performance, fuel consumption, and emissions are treated in a consistent manner for all concepts, thus allowing for robust fuel consumption comparisons as well as technology rankings.

Conventional Drives

The CD (Conventional Drive) powertrain depicted in Figure 2-4 consists of an IC (Internal Combustion) engine with a five speed manual transmission implementing an automated gearshift control (in contrast to a manual shift) in accordance with prescribed ECE cycle requirements. This assumption was used for all the conventional vehicles using gasoline, diesel, CNG, and hydrogen fuels. The transmission is shifted to optimize fuel consumption within driveability and emissions constraints. The engine is not allowed to drop to very low operating speeds which impacts vehicle performance at moderate and high vehicle speeds, and similarly, the engine does not operate near the WOT torque to avoid operating in regions of high emissions.

Figure 2-4: Conventional Drive (CD) Powertrain



The engine technologies represented in the study are based on data from various sources. An engine-specific fuel shut-off strategy with appropriate delays and speed constraints is implemented during deceleration periods. The engine characteristics and assumptions were geared towards maintaining consistency for the comparison of the technologies.

The Direct Injection (DI) Gasoline ICE was based on a next generation Opel prototype test engine using control strategies, constrained by NVH and emission requirements, for operating the engine in the stratified, or homogeneous, region.

The DI Diesel / FT Diesel ICE was based on the Opel advanced common rail direct injection technology maximizing engine efficiency and meeting emission requirements.

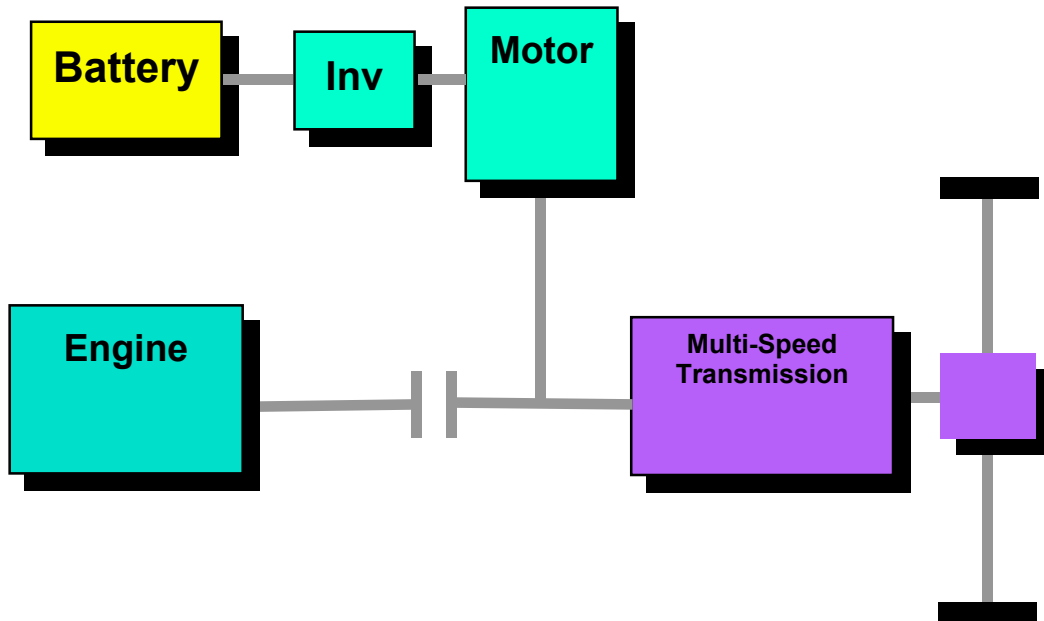
The MONOFUEL CNG ICE was based on the next generation Opel prototype turbocharged, monovalent or monofuel, high compression ratio engine optimized for CNG operation.

The LH₂ ICE was based on an estimated map constructed from efficiency benefits and power output predictions published by BMW and sized to meet the vehicle performance requirements used in the present study.

Hybrid Drives

The Hybrid Electric Vehicle (HEV) architecture used in this study, and shown in Figure 2-5, is a Parallel Input Power Assist kinematic configuration with an electric drive at the input to the transmission. The battery was sized to meet the 20 km ZEV (Zero Emission Vehicle) Range specified in the vehicle performance requirements. A full size engine was necessary to meet the sustained top vehicle speed requirement of 180 km/h. The electric motor was sized to follow the duty cycle performance demands without the engine.

Figure 2-5: Parallel HEV



The IC engine and transmission assumptions and input data are the same as in the Conventional Drive concepts. The electric motors and NiMH batteries are based on the next generation technologies demonstrated in the GM Precept PNGV vehicle.

A charge sustaining control strategy was implemented wherein the battery state-of-charge (SOC) at the end of the driving cycle was always returned to the level it was at when the cycle commenced. The engine is always turned off at standstill and the battery is used to launch the vehicle to about 35 – 40 km/h depending on the battery SOC. At high acceleration demands, the battery launch is turned off and the vehicle is launched with the engine and/or with battery assist.

Depending on the engine characteristics and the specific electric component sizes for each HEV, the engine control and energy management strategy for each vehicle was optimized to provide high engine efficiency without incurring excessive losses in the motor and battery. During braking, the engine is disconnected from the transmission and shut-off to maximize energy recovery. However, at vehicle speeds above ~70 km/h, the engine remains connected to the transmission, thereby assuring adequate performance in the event of sudden demand

for acceleration. In general, both Torque Control and Power Sharing strategies are used over different vehicle speed ranges.

- Engine Torque Control:

The engine operates within a band specified as fraction of maximum torque at each speed. The engine torque fraction is generally given as a function of battery SOC so that as the battery SOC increases, the torque fraction is allowed to decrease while the engine still operates in an efficient region. If the engine output exceeds the instantaneous cycle demand, energy is stored in the battery. If the engine output is less than the instantaneous demand, the battery assists the engine. Engine Torque Control is generally most effective at low and moderate vehicle speeds over which the engine loading would normally be low.

- Engine/Battery Power Sharing:

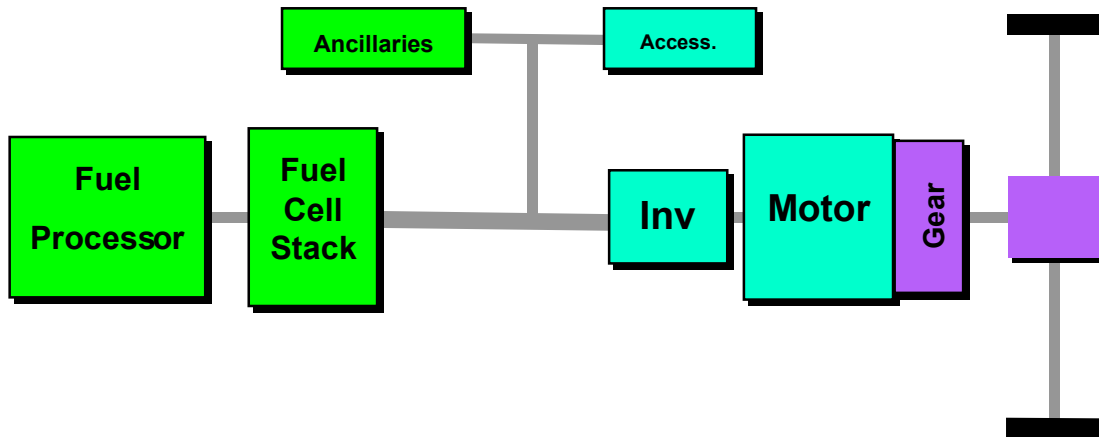
The engine and battery each share a fraction of the load. If the SOC decreases, the engine share is allowed to increase. Engine/Battery Power Sharing is most effective at high vehicle speeds wherein engine loading is normally favorable and the engine load may be reduced somewhat without adversely affecting engine efficiency.

Alternative architectures to this Parallel HEV have also been assessed (e.g., Toyota Prius, Honda Insight, GM Precept Next Generation Vehicle).

Fuel Cell and Fuel Processor Systems

Fuel Cell systems with onboard hydrogen storage in direct electric drives architectures and gasoline and methanol Fuel Processor (FPFC) systems shown in Figure 2-6 were among the concepts included in the study.

Figure 2-6: Fuel Cell/Fuel Processor Powertrain



Fuel cell stack and fuel processor component maps were based on small- to full-scale component maps predicted with GM proprietary modeling tools and validated on the GM HydroGen-1 Fuel Cell Vehicle. However, significant development would be required to scale up these state-of-the-art components to the power levels required for the expected vehicle performance imposed in this study. More specifically, breakthroughs in the areas of thermal and water management, fuel processor dynamics, and startup/warm-up for the fuel processor systems would be needed.

The dominant metric that determines the fuel cell capacity is the requirement for a top vehicle speed of 180 km/h. The motor capacity is determined by requirements for maximum acceleration of 4.5 m/s^2 and 0-100 km/h time of 12 seconds. A 2-speed gear reduces the motor corner power requirement and allows the specified vehicle performance requirements to be met with a motor of reasonable size. The losses incurred in the 2-speed gear are more than offset by the improved average motor efficiency.

At standstill, the fuel cell is turned off and the vehicle accessory load is powered by a small service battery. During deceleration, the fuel cell is turned off after a 5-second delay and the transient response of the stack is sufficient to avoid lags on the standard duty cycles.

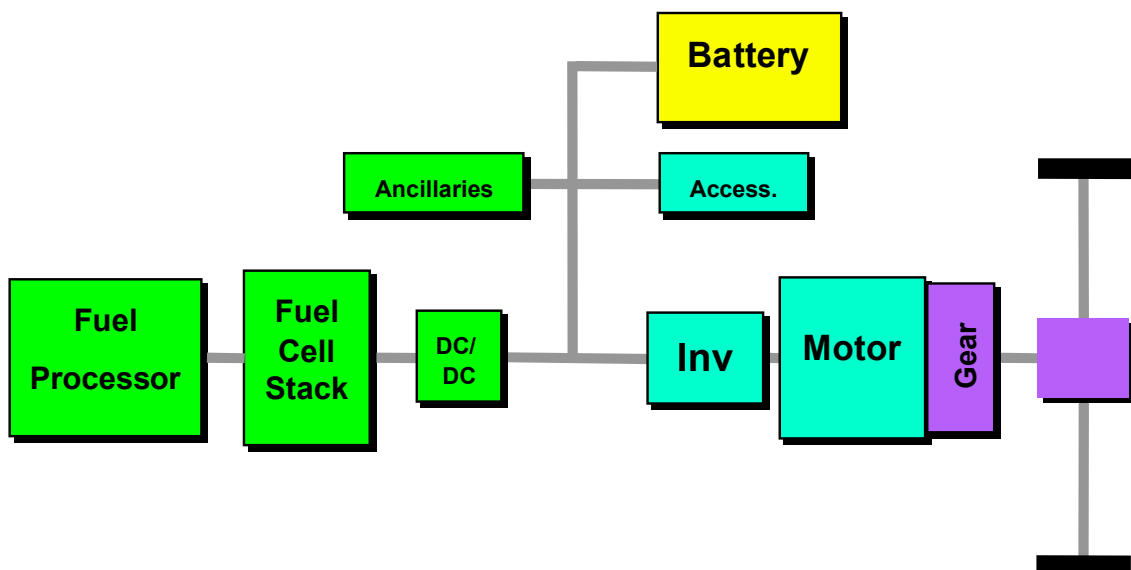
The electric motor inverter operates at the fuel cell stack output voltage and is characterized by detailed three-dimensional maps (comprehending speed, torque and voltage) thus accounting for the effect of varying stack voltage on motor efficiency and capacity.

In the reformer systems, a hydrogen buffer is used to minimize fuel waste at low output power levels. Excess hydrogen is compressed by the ancillary compressor and stored in this small buffer for later use.

Fuel Cell and Fuel Processor Hybrids

Hybridization of these fuel cell systems as shown in Figure 2-7 provides additional possibilities for improvement in fuel economy, although the relative gain of a fuel cell hybrid will be less than that of an engine hybrid.

Figure 2-7: Fuel Cell HEVs



The installed fuel cell capacity is determined by the sustained 180 km/h top vehicle speed. The motor is sized by the 4.5 m/s² launch acceleration and the 0-100 km/h maximum time requirement. The battery size is determined by the 20 km/h ZEV requirement. However, for the H₂ FC HEV vehicle (already a ZEV concept), the battery is sized to optimize the fuel consumption while still meeting all performance constraints.

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Having a battery in the system allows the overall load to be shared between the battery and the fuel cell system. Thus, at very low cycle requirements, the fuel cell and reformer may be shut-off completely, thereby avoiding the low efficiency operating region of the fuel cell/fuel processor system at very low power levels. Similarly, at high cycle requirements, the accessory and ancillary loads may be off-loaded from the fuel cell to the battery, thereby reducing inefficient operation of the fuel cell system at high power levels.

The best overall energy management strategy is one that tends to minimize the use of the fuel cell to recharge the battery. At high battery SOC, the fuel cell system is turned off and the vehicle operates from battery energy only. When the battery SOC drops below a specified level, the fuel cell is turned on providing the necessary road load.

A judicious combination of turning the fuel cell system off at standstill and low power and transferring the accessory and ancillary loads to the battery at high power allows the fuel cell system to operate at near optimum efficiency for most of the cycle without incurring excessive battery and motor losses.

2.4 Results

Table 2-2 and Table 2-3 summarize the fuel economy/consumption and vehicle performance predictions for all the propulsion system concepts included in this study.

Table 2-2: Gasoline Equivalent Fuel Economy/Consumption and Performance Predictions: ICE

	EDC (mpg)	EDC (l/100 km)	Engine Efficiency	Vehicle Efficiency	Time, s 0-100 km/h	% Reduction from Baseline
2002 Production Gasoline Vehicle	28.9	8.15	21.0%	18.2%	11.6 s	+6%
Baseline 2010 Gasoline CD	30.7	7.66	22.5%	19.4%	11.6 s	Baseline
Gasoline HEV	41.9	5.61	30.5%	28.6%	9.0 s	-27%
DI Gasoline CD	35.7	6.59	25.2%	22.6%	11.4 s	-14%
DI Gasoline HEV	45.3	5.19	32.9%	30.9%	8.8 s	-32%
DI Diesel CD	38.2	6.16	28.5%	25.5%	11.8 s	-20%
DI Diesel HEV	45.4	5.18	34.8%	32.6%	9.4 s	-32%
FT DI Diesel CD	39.0	6.03	29.1%	26.0%	11.8 s	-21%
FT Diesel HEV	46.3	5.07	35.5%	33.3%	9.4 s	-34%
CNG ICE CD	33.6	7.00	25.8%	22.9%	11.4 s	-9%
CNG ICE HEV	43.4	5.42	33.0%	31.8%	9.1 s	-29%
H2 ICE CD	36.9	6.37	27.7%	24.2%	11.7 s	-17%
H2 ICE HEV	50.1	4.70	37.7%	34.9%	9.1 s	-39%

CD - Conventional Drive using 5-Speed MTA Transmission, DI - Direct Injection ICE
HEV - Parallel Hybrid Electric Vehicle with Charge Sustaining (CS) Control Strategy

Table 2-3: Gasoline Equivalent Fuel Economy/Consumption and Performance Predictions: FC

	EDC (mpg)	EDC (l/100 km)	Engine Efficiency	Vehicle Efficiency	Time, s 0-100 km/h	% Reduction from Baseline
2010 Gasoline Baseline Vehicle	30.7	7.66	22.5%	19.4%	11.6 s	Baseline
Gasoline FPFC	42.3	5.56	37.8%	28.9%	10.8 s	-27%
Gasoline FPFC HEV	48.6	4.84	39.2%	35.2%	10.0 s	-37%
Ethanol FPFC	44.4	5.30	39.7%	30.4%	10.8 s	-31%
Ethanol FPFC HEV	51.1	4.61	41.1%	36.9%	10.0 s	-40%
Methanol FPFC	46.1	5.11	41.5%	31.9%	11.1 s	-33%
Methanol FPFC HEV	52.4	4.49	42.6%	38.4%	10.2 s	-41%
CH ₂ FC	65.6	3.59	56.6%	44.3%	10.7 s	-53%
CH ₂ FC HEV	71.0	3.31	55.6%	48.9%	9.5 s	-57%
LH ₂ FC	67.1	3.51	56.6%	44.3%	10.4 s	-54%
LH ₂ FC HEV	72.6	3.24	55.6%	48.9%	9.3 s	-58%

FPFC - Fuel Processor + Fuel Cell FC - Fuel Cell

HEV - Hybrid Electric Vehicle w/ Charge Sustaining (CS) Control Strategy

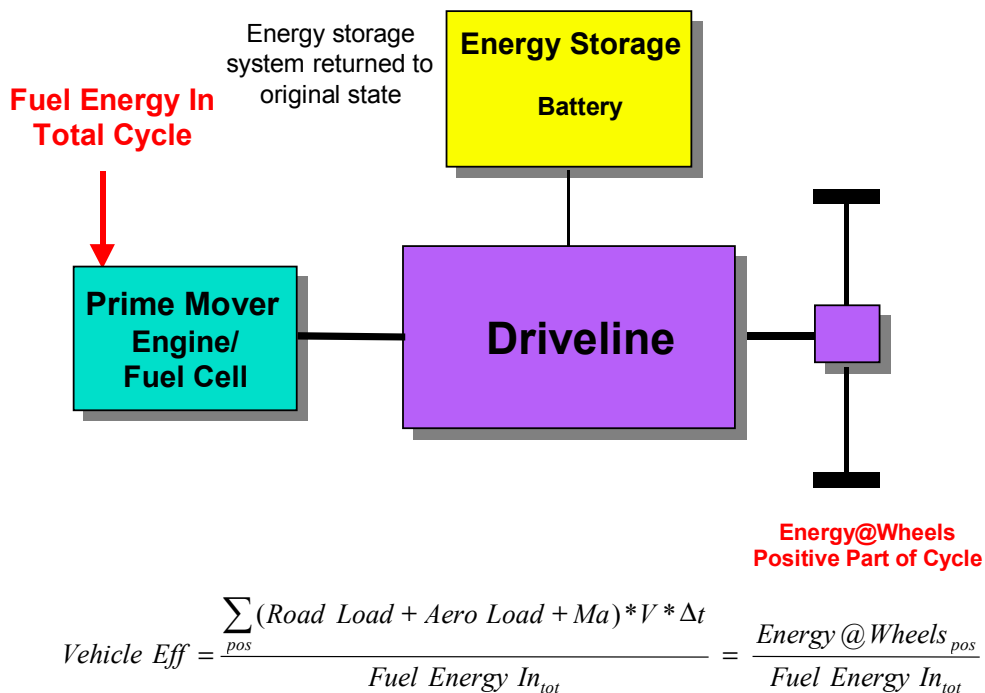
Fuel consumption and fuel economy in the tables above are reported on a gasoline-equivalent basis. These tables also report the average engine and vehicle efficiency (defined in Figure 2-8, below) on the ECE duty cycle for each powertrain concept.

The only performance metric included in the tables is the 0-100 km/h acceleration time. On

first glance at this column, it is noticeable that the acceleration times vary between 8 to 12 seconds begging the question: How are these concepts comparable on an equal performance basis? As stated previously, all the performance metrics in Figure 2-3 had to be met for each powertrain concept and the 0-100 km/h time was never the dominant constraint in sizing any of the powertrain components. The launch acceleration and the top vehicle speed requirements dominated the power and torque requirements and the 0-100 km/h time shown was the performance value which resulted.

The fuel economy (mpg) and fuel consumption (l/100 km) results represent the Best Estimate or 50%-tile, cases of the powertrain technologies and, given all the input assumptions, it is assumed that each of them will meet Euro IV emission targets.

Figure 2-8 : Vehicle Efficiency Definition



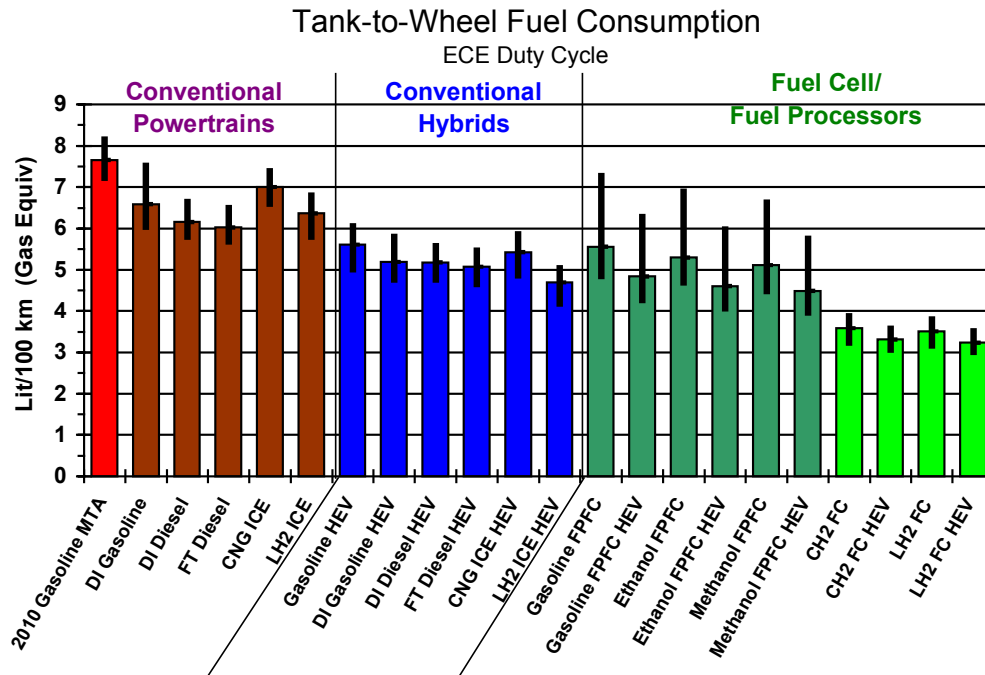
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Figure 2-9 captures the results of Table 2-2 and Table 2-3 in a bar chart format. The bars are the 50%-tile cases and the lines superimposed on the bars represent the Lower Bound and Upper Bound scenarios for each concept. These were also generated with simulation models based on input data and assumptions capturing the uncertainties of the various technologies.

The Upper Bound scenarios include assumptions on the performance/efficiency map and/or mass of any particular component. For the Conventional Drive vehicles this means that the current state-of-the-art technology level for engines and transmissions are maintained without further improvements. For the Conventional Hybrids and Fuel Reformer/Fuel Cell vehicles, these bounds incorporate higher masses and lower efficiencies of components (e.g., electric motors, batteries) not yet mass-produced or as mature as a mechanical transmission or IC engine.

The Lower Bound scenarios are based on assumptions that the expectations of these technologies will exceed their targets for the 2010 time frame. For the Conventional Vehicles it is assumed that at the vehicle level some mass reduction will be implemented and at the powertrain level the MTA transmission will be improved with the use of a wider ratio spread, providing additional overdrive, and an additional gear to maintain customer pleaseability requirements. For the Conventional Hybrids and Fuel Reformer/Fuel Cell vehicles these bounds include reductions in component mass and improvements in efficiencies.

Figure 2-9: Fuel Consumption of Powertrain Technologies



The 2010 Gasoline MTA, the Baseline Vehicle for this study, assumes a conservative upgrade to an MTA transmission, and also assumes that a best effort will be made to achieve the highest engine efficiency without a change in technology level. This powertrain represents a very mature level of technology and currently enjoys the highest market penetration. With continuous improvements, these powertrains have the potential to contribute to a large reduction in CO₂ emissions. The Upper Bound scenario for this concept would be the current 2002 Production vehicle meaning that no change would have been made to this powertrain by the 2010 time frame. All other IC engines included represent major changes in the engine technologies and require continuous engineering development in order to reach higher levels of maturity and market penetration.

The asymmetrical ranges for some of the technologies reflect a compounding effect that results when a number of uncertainties are lumped together. The range for the DI Gasoline ICE shows such an asymmetrical range and captures the uncertainty regarding lean operation while meeting emission and NVH (Noise-Vibration-Harshness) requirements. The two DI Die-

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sel ICEs show the greatest improvement due to the high efficiency exhibited by the compression ignition engine. The benefits of the monofuel CNG ICE are partially attributed to its optimized monovalent fuel system and to its downsized turbocharged design.

The conventional IC engine HEV concepts reflect a fuel consumption reduction commensurate with the engine technology characteristics and the inherent benefits of hybridization discussed above. Thus, engine technologies with poor part-load efficiency and high idle consumption yield a greater improvement in fuel consumption as demonstrated by the gasoline ICE in contrast to the diesel ICE. All of the HEVs also show an improvement in the 0-100 km/h performance time due to the battery assist complementing their full size engines. It should also be noted here that the benefits due to hybridization are very much a function of the duty cycle, thus, urban-type stop-and-go driving yields much higher gains than does highway-type continuous high speed driving.

The last set of bars on the chart represent the fuel cell system concepts in direct electric drive and their counterpart hybrid architectures. The first six are fuel processor systems reforming gasoline, ethanol, and methanol fuel, while the last four use onboard stored liquid or compressed hydrogen. The wide uncertainty ranges of the reformer concepts in contrast to the narrow ranges for the fuel cell systems with onboard hydrogen storage should be noted. The reformer systems reflect uncertainties in efficiency and mass in a number of components comprised in these complex drivetrains, while the fuel cell systems reflect a lower uncertainty in efficiency and mass, although they face other challenges such as hydrogen storage, mass production, and market readiness. All of these concepts show a significant reduction in fuel consumption relative to the gasoline baseline vehicle, but overlap in their uncertainty ranges. Due to the high part-load efficiency of fuel cells, benefits resulting from their hybridization are less significant than those seen for hybridized ICEs.

Table 2-4 captures the results in Table 2-2 and Table 2-3 on an energy consumption (MJ/km) basis, and includes the Lower Bound (LB), Best Estimate (BE) and Upper Bound (UB) scenarios.

Table 2-4: Energy requirements (TTW) of vehicles selected for WTW calculation

	LB [MJ/km]	BE [MJ/km]	UB [MJ/km]
Gasoline MTA (Gasoline 2010 Base-line)	2.30	2.44	2.59
Gasoline HEV MTA	1.59	1.78	1.92
DI Gasoline MTA	1.92	2.09	2.39
DI Gasoline HEV MTA	1.51	1.65	1.84
DI Diesel MTA	1.85	1.96	2.11
DI Diesel HEV MTA	1.51	1.65	1.77
FT Diesel MTA	1.81	1.92	2.07
FT Diesel HEV MTA	1.48	1.61	1.74
MONOFUEL CNG ICE MTA	2.10	2.23	2.35
MONOFUEL CNG ICE HEV MTA	1.54	1.72	1.86
H ₂ ICE MTA	1.85	2.03	2.16
H ₂ ICE HEV MTA	1.33	1.49	1.60
Gasoline and naphtha FPFC	1.54	1.77	2.31
Gasoline and naphtha FPFC HEV	1.35	1.54	1.99
Methanol FPFC	1.43	1.62	2.10
Methanol FPFC HEV	1.26	1.43	1.83
Ethanol FPFC	1.49	1.68	2.19
Ethanol FPFC HEV	1.29	1.47	1.90
CGH ₂ FC	1.07	1.14	1.23
CGH ₂ FC HEV	1.02	1.05	1.14
LH ₂ FC	1.05	1.12	1.21
LH ₂ FC HEV	1.00	1.03	1.12

The bar chart in Figure 2-10 below shows the CO₂ predictions for the powertrains in Table 2-4. The CO₂ g/km is calculated based on the carbon consumption of each propulsion system by the formula:

$$g \text{ CO}_2/\text{km} = l \text{ gasoline equivalent} / \text{km} * 31.756 \text{ MJ/l gasoline} * g \text{ fuel CO}_2/\text{MJ}$$

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where the $g\ CO_2$ for the various fuels from combustion in $g\ fuel\ CO_2/MJ$ is defined as:

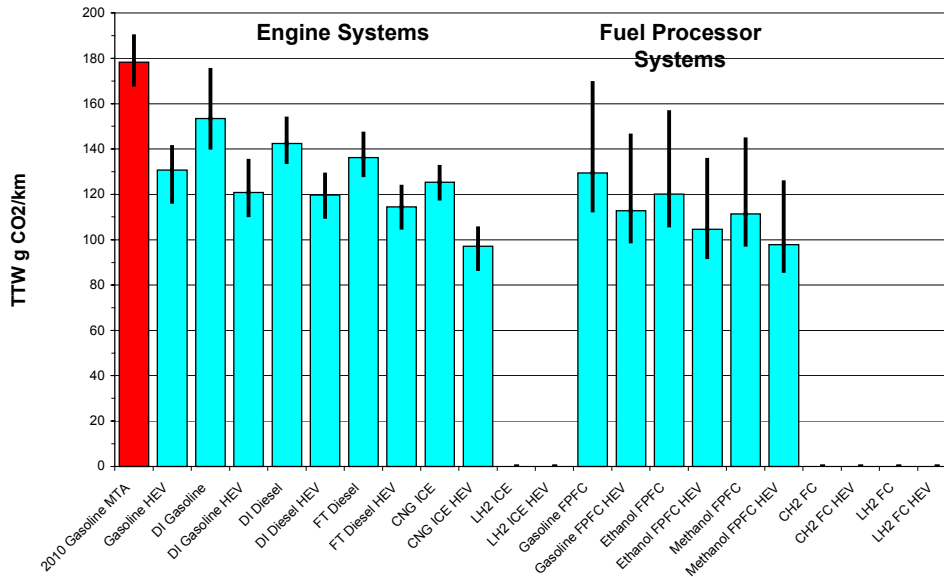
Table 2-5 Fuel Properties

Fuel	g CO₂/MJ	Fuel	g CO₂/MJ
Gasoline	73.4	Naphtha	70.7
Diesel	72.8	CMG	56.9
FT diesel	70.7	ETBE blended gasoline	73.2
FT naphtha	69.5	MTBE blended gasoline	73.2
CNG	56.4	RME blended Diesel	73.0
H ₂	0.00	ETBE	71.4
Ethanol	71.3	MTBE	71.1
Methanol	68.6	RME	76.7

The TTW emissions of the vehicles fueled with naphtha, FT naphtha, CMG, ETBE blended and MTBE blended gasoline and RME blended diesel are not shown in Figure 2-10 and Figure 2-11 but considered in the WTW integration.

Naphtha and FT naphtha are only used in FC vehicles with onboard fuel processors (FPFC). The energy consumption of the FPFC vehicles fueled with naphtha and FT-naphtha is assumed to be equivalent to that of the gasoline fueled FPFC vehicles. The energy consumption of the ICE vehicles fueled with compressed methane gas (CMG) from biogas is equivalent to that of the CNG vehicles. ETBE, MTBE and RME are only used as blending agents for gasoline and diesel. ETBE- and MTBE-blended gasoline is only used in gasoline ICE vehicles but not in gasoline fueled FPFC vehicles. The energy consumption of the ICE vehicles fueled with ETBE-blended and MTBE-blended gasoline is equivalent to that of the vehicles fueled with pure gasoline. The energy consumption of ICE vehicles fueled with RME-blended diesel is equivalent to that of the ICE vehicles fueled with pure diesel.

Figure 2-10: TTW - CO₂ Emissions on European Driving Cycle



During the combustion of fuels in IC engines, and during onboard reforming, small amounts of non-CO₂ GHGs such as CH₄ and N₂O are also released. The total greenhouse gases are calculated by adding the impact of methane and N₂O to the CO₂ emissions. Assumed CO₂ equivalents are 21 g CO₂ per g methane and 310 g CO₂ per g N₂O. Unfortunately, data for methane and N₂O emissions of propulsion technology are not extensive. Based on GM experience, literature sources, and judgment of advanced after-treatment impacts, the following values were used:

Table 2-6: Non CO₂ GHG emissions

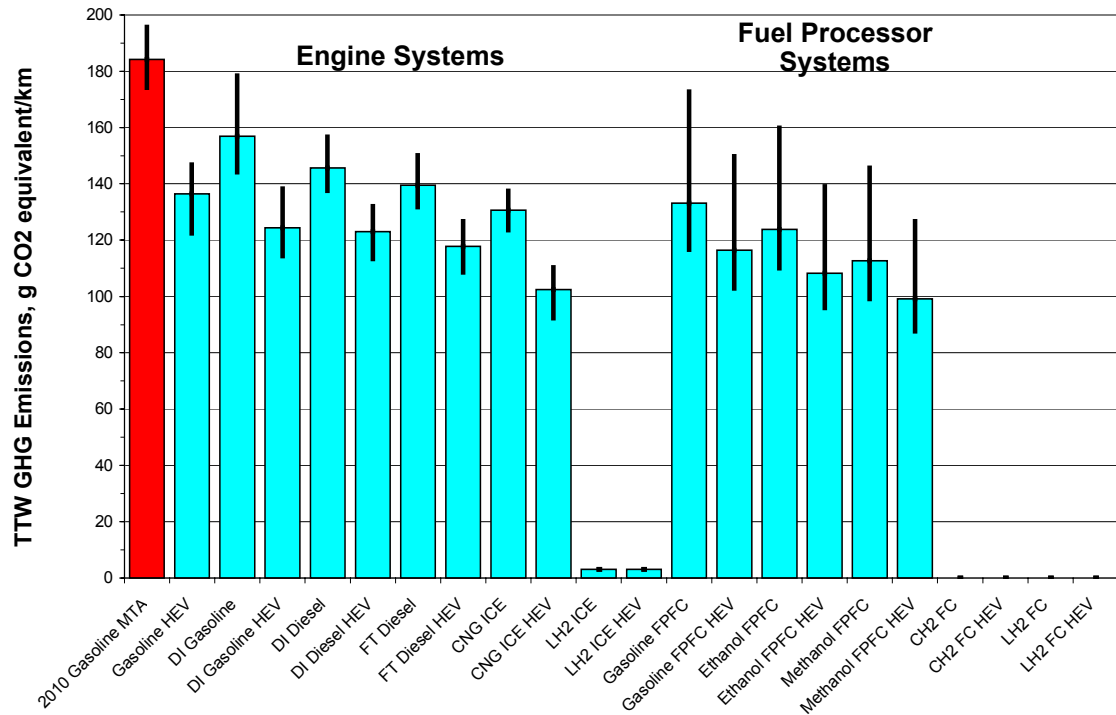
	CH ₄ [g/km]	N ₂ O [g/km]
Gasoline conventional drive SI (baseline)	0.020	0.0174
Diesel conventional drive CIDI	0.010	0.0099
CNG conventional drive and HEV SI	0.124	0.0087
H ₂ ICE SI	0.000	0.0099

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	CH ₄ [g/km]	N ₂ O [g/km]
Gasoline parallel SIHEV charge-sustaining (CS)	0.020	0.0174
Diesel parallel CIDI HEV CS	0.010	0.0099
Gasoline and naphtha fuel processor FCV	0.124	0.0035
Gasoline and naphtha fuel processor FC HEV	0.124	0.0035
Methanol fuel processor FCV	0.012	0.0035
Methanol fuel processor FC HEV	0.012	0.0035
Ethanol fuel processor FCV	0.124	0.0035
Ethanol fuel processor FC HEV	0.124	0.0035
GH ₂ FCV/LH ₂ FCV	0.000	0.0000
GH ₂ FC HEV/LH ₂ FC HEV	0.000	0.0000

Figure 2-11 below presents these predicted GHG emissions for each of the powertrains.

Figure 2-11: TTW - GHG Emissions on European Driving Cycle



It is assumed that FPFC vehicles fueled with naphtha and FT naphtha emit the same amounts of non CO₂-GHGs as gasoline-fueled FPFC vehicles. The emissions of non-CO₂ GHGs (CH₄, N₂O) of vehicles fueled with the blended fuels are equivalent to those fueled with the pure fuels. The emissions of non-CO₂ GHGs of vehicles fueled with CMG are assumed to be equivalent to those of the vehicles fueled with CNG.

Table 2-7: Greenhouse Gas Emissions (TTW) of Vehicles for Selected Pathways

	LB [g/km]	BE [g/km]	UB [g/km]
Gasoline MTA (Gasoline 2010 Baseline)	175	185	196
Gasoline HEV MTA	123	136	147
Gasoline-10% MTBE/ETBE MTA	174	184	195
Gasoline-10% MTBE/ETBE HEV MTA	122	136	146
DI Gasoline MTA	147	159	181
DI Gasoline HEV MTA	117	127	141
DI Diesel MTA	138	146	157
DI Diesel HEV MTA	113	123	132
DI Diesel-5% RME MTA	138	146	157
DI Diesel-5% RME HEV MTA	114	124	132
FT Diesel MTA	132	140	150
FT Diesel HEV MTA	108	118	127
Monofuel CNG ICE MTA	124	131	138
Monofuel CNG ICE HEV MTA	92	102	110
H ₂ ICE MTA	3	3	3
H ₂ ICE HEV MTA	3	3	3
Gasoline FPFC	117	134	173
Gasoline FPFC HEV	103	117	150
Naphtha FPFC	113	129	167
Naphtha FPFC HEV	99	113	144
Methanol FPFC	99	112	145

	LB [g/km]	BE [g/km]	UB [g/km]
Methanol FPFC HEV	88	99	127
Ethanol FPFC	110	123	160
Ethanol FPFC HEV	96	109	139
CGH ₂ FC	0	0	0
CGH ₂ FC HEV	0	0	0
LH ₂ FC	0	0	0
LH ₂ FC HEV	0	0	0

2.5 Conclusions

The following conclusions for the Tank-to-Wheel or vehicle portion of this study are based on the results presented in the previous section.

Conventional powertrain technologies such as diesel ICEs together have the potential to reduce vehicle fuel consumption by about 20%. The greatest improvement in fuel economy for a conventional powertrain is achieved by combining a direct injection diesel ICE with a wide-ratio MTA-type 6-speed transmission.

Hybridization of these conventional powertrains, while meeting customer requirements, yields an additional 16% to 26% reduction, depending on the engine technology and its efficiency characteristics. Due to the performance metric of 180 km/h continuous vehicle speed operation, engine downsizing strategies could not be considered, so their effects are not included in the benefits shown here. All the hybrid vehicles, however, are capable of a 20 km ZEV driving range at duty cycle performance demands.

Fuel cell powered vehicles with direct onboard storage of hydrogen offer the greatest improvement with a 54% reduction in fuel consumption over the 2010 Baseline vehicle. This improvement is attributed to the very high average operating efficiency of the fuel cell stack and the low ancillary loads. The fuel processor systems yield 27% to 33% reductions depending on the fuel used, and hybridization has the potential of decreasing this further by ~12%. The fuel cell vehicles with onboard hydrogen storage do not show significant benefits with hybridization because of the already high part-load efficiency of the fuel cell. The benefits are mainly due to regenerative braking and off-loading of the ancillary and accessory loads to the battery.

The TTW GHG emissions for all HEVs were less than 140 g CO₂-equivalent/km on the European Driving Cycle. The CNG and Methanol FPFC HEVs were about 100 g/km and the hydrogen concepts at zero or near zero levels.

These energy consumption and emission predictions are strictly at the vehicle and powertrain level for the 2010 time frame and must now be examined at in the context of the overall Well-to-Wheel picture.

3 Part 3: Well-to-Wheel Integration of Fuel Supply Pathways and Powertrains – Energy Use and Greenhouse Gas Emissions

3.1 Introduction

Part 1 of this report presented energy use and greenhouse gas (GHG) emissions on a well-to-tank (WTT) basis for 32 selected fuel pathways (from a total of 88, including the different variants). For Part 2, researchers from GM quantified the energy use of 22 advanced powertrain systems (tank-to-wheel [TTW] analysis) (see Table 2-2 and Table 2-3). Integrating the 32 fuel supply pathways with the 22 powertrain systems yields 96 fuel/vehicle options.

This part of the report combines the results of Parts 1 and 2 into an analysis of well-to-wheel (WTW) energy efficiency and GHG emissions — providing an overall view of these alternative fuel/vehicle pathways.

3.2 Methodology

The total WTW energy use is calculated by multiplying the WTT energy requirements with the fuel consumption of the vehicle. In contrast with the GM North American Study, here the energy requirements for fuel supply include the LHV of the fuel available in the vehicle tank. The vehicle GHG emissions are derived from the carbon content of the fuel used in the vehicle, and the fuel consumption and the emissions of CH₄ and N₂O generated by the combustion onboard the vehicle. The total GHG emissions are calculated by multiplying the WTT GHG emissions in gram per MJ with the energy consumption of the vehicle in MJ per km, to which are added the TTW GHG emissions in gram per km. 44 WTT pathways with, in total 88 variants were investigated.

Table 3-1 lists selected pathways for WTW integration which results will be presented in this report. The Annex – Full Background Report provides results for all pathways.

Table 3-1: Selected WTT-Fuel Pathways for WTW-Integration

Selected Fuel Pathways	
<i>Crude Oil-Based</i>	
(1) ^(*)	Gasoline (sulfur content < 10 ppm)
(2)	Diesel (sulfur content < 10 ppm)
(3)	Naphtha (sulfur content < 0.4 ppm)
<i>Natural Gas-Based</i>	
(5)	CNG: EU-NG-mix
(8)	CNG: LNG from remote location
(10)	MeOH: from remote location
(12)	FTD: from remote location
(14)	FTN: from remote location
(16)	CGH ₂ : EU-NG-mix in central plant (for 70 MPa vehicle tanks)
(20)	CGH ₂ : EU-NG-mix in onsite production (for 70 MPa vehicle tanks)
(21)	LH ₂ : EU-NG-mix in central plant
(23)	LH ₂ : from remote location
(24) ^(**)	Gasoline, blended with 10 w% MTBE, MTBE from natural gas derived methanol
<i>Electricity-Based</i>	
(31)	CGH ₂ : EU-mix electrolysis in regional electrolysis plant (for 70 MPa vehicle tanks)
(32)	CGH ₂ : wind electrolysis in regional electrolysis plant (for 70 MPa vehicle tanks)
(37)	CGH ₂ : EU-mix onsite electrolysis (for 70 MPa vehicle tanks)
(38)	CGH ₂ : CCGT onsite electrolysis (for 70 MPa vehicle tanks)
(39)	CGH ₂ : wind onsite electrolysis (for 70 MPa vehicle tanks)
(40)	LH ₂ : EU-mix electrolysis in central electrolysis plant
(41)	LH ₂ : wind electrolysis in central electrolysis plant
<i>Biomass-Based</i>	
(44)	CGH ₂ : gasification of residual woody biomass (for 70 MPa vehicle tanks)
(48)	CGH ₂ : gasification of woody biomass from plantation of poplar (for 70 MPa vehicle tanks)
(51)	MeOH: gasification of residual woody biomass
(53)	E100: enzymatic hydrolysis of lignocellulose (crop residue)
(55)	E100: enzymatic hydrolysis of lignocellulose (plantation of poplar)
(60)	E100: conventional fermentation of sugar beet
(66)	HCL: solids to liquids (diesel/ naphtha) from residual woody biomass via FT-synthesis

Selected Fuel Pathways	
(70) ^[**]	Diesel, blended with 5 w% RME, RME from rape seed
(79) ^[**]	Gasoline, blended with 10 w% ETBE, ETBE from sugar beet derived ethanol
(84)	CMG: biogas derived compressed methane gas
(86)	CGH,: steam reforming of biogas (for 70 MPa vehicle tanks)
(87) ^[**]	Gasoline, blended with 10 w% MTBE, MTBE from residual woody biomass derived Methanol

Remarks: ^[*] For gasoline and diesel, the properties used (with the exception of sulfur content) were assumed to meet the forthcoming European 2005 specifications

^[**] For the original pathways 24, 70, 79 and 87, ETBE, MTBE and RME have been carried through to the selected pathways only as blending agents.

[The numbering sequence of the originally 88 pathways has been maintained, therefore jumps in the numbering sequence occur in Table 3-1 "Selected Fuel Pathways"]

3.3 Results

Table 3-2 shows the well-to-wheel (WTW) energy requirements of different fuel pathway/powertrain combinations.

Table 3-2: WTW - Energy Requirements (BE Values) of different fuel supply pathway/power train combinations in [MJ/km]

Fuel	Powertrain			
	Conventional [MTA]	Conventional Hybrid	Fuel Cell Non-Hybrid	Fuel Cell Hybrid
Gasoline	2.84 (SI) – 2.45 (DI)	2.07 (SI) – 1.92 (DI)	2.07	1.79
Diesel DI Crude Oil	2.19	1.84	--	--

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	Powertrain			
Fuel	Conventional [MTA]	Conventional Hybrid	Fuel Cell Non- Hybrid	Fuel Cell Hybrid
Naphtha Crude Oil	--	--	1.97	1.73
FT-Diesel Remote-NG Residual Wood	3.29 4.28	2.73 3.60	-- --	-- --
FT-naphtha Remote-NG	--	--	3.03	2.57
CNG/CMG EU-NG-Mix Russian NG from LNG CMG from Waste	2.66 3.18 2.77 3.30	2.09 2.44 2.12 2.55	-- -- -- --	-- -- -- --
Methanol Remote-NG Residual Wood	-- --	-- --	2.68 3.10	2.37 2.66
Ethanol (E100) Residual Straw Poplar Plantation Sugar Beet	-- -- --	-- -- --	4.77 5.02 4.32	4.17 4.47 3.75

Fuel	Powertrain			
	Conventional [MTA]	Conventional Hybrid	Fuel Cell Non- Hybrid	Fuel Cell Hybrid
Hydrogen – CGH₂				
– <i>Central</i>				
--- EU-NG-Mix	3.24	2.38	1.84	1.73
--- Russian NG	3.83	2.80	2.16	2.00
--- EU-Electricity	9.32	6.88	5.30	4.93
--- Wind-Electricity	3.31	2.48	1.91	1.76
– <i>Onsite</i>				
--- EU-NG-Mix	3.78	2.77	2.12	1.98
--- EU-Electricity	9.32	6.84	5.30	4.93
--- EU-CCGT-Electr.	6.55	4.82	3.74	3.49
--- Wind-Electricity	3.31	2.45	1.91	1.76
– <i>Decentralized</i>				
--- Residual Wood	3.74	2.77	2.16	2.02
--- Poplar plantation	3.83	2.84	2.18	2.05
--- Organic Waste	4.58	3.37	2.58	2.38
Hydrogen - LH₂				
- <i>Central</i>				
--- NG EU-Mix	4.32	3.21	2.38	2.26
--- Remote NG/LH ₂	5.14	3.85	2.85	2.66
--- EU-Electricity	10.74	7.93	6.00	5.60
--- Wind-Electricity	3.92	2.87	2.16	2.02

Table 3-3 shows the well-to-wheel (WTW) GHG emissions of different fuel pathway/powertrain combinations.

Table 3-3: WTW - GHG emissions (BE Values) of different fuel supply pathway/power train combinations in [g/km]

Fuel	Powertrain			
	Conventional [MTA]	Conventional Hybrid	Fuel Cell Non-Hybrid	Fuel Cell Hybrid
Gasoline	217 (SI) - 188 (DI)	160 (SI) - 149 (DI)	158	137
Diesel DI Crude Oil	166	140	--	--
Naphtha Crude Oil	--	--	152	134
FT-Diesel Remote-NG Residual Wood	203 28	168 24	-- --	-- --
FT-naphtha Remote-NG	--	--	181	154
CNG/CMG EU-NG-Mix Russian NG from LNG CMG from Waste	162 195 168 6	127 151 131 6	-- -- -- --	-- -- -- --
Methanol Remote-NG Residual Wood	-- --	-- --	160 13	142 11
Ethanol (E100) Residual Straw Poplar Plantation Sugar Beet	-- -- --	-- -- --	29 72 103	25 65 91

Fuel	Powertrain			
	Conventional [MTA]	Conventional Hybrid	Fuel Cell Non-Hybrid	Fuel Cell Hybrid
Hydrogen – CGH₂				
– <i>Central</i>				
--- EU-NG-Mix	184	136	103	96
--- Russian NG	223	164	124	115
--- EU-Electricity	421	312	238	221
--- Wind-Electricity	3	3	0	0
– <i>Onsite</i>				
--- EU-NG-Mix	211	156	117	109
--- EU-Electricity	422	309	238	222
--- EU-CCGT-Electr.	380	280	215	202
--- Wind-Electricity	3	3	0	0
– <i>Decentralized</i>				
--- Residual Wood	17	13	8	8
--- Poplar Plantation	47	35	25	23
--- Organic Waste	4	4	1	0
Hydrogen - LH₂				
- <i>Central</i>				
--- NG EU-Mix	253	189	138	131
--- Remote NG/LH ₂	301	226	165	154
--- EU-Electricity	486	360	270	252
--- Wind-Electricity	7	6	2	2

From the perspective of minimizing total GHG emissions, the most effective WTW pathways for all powertrains (i.e., conventional ICEs and conventional hybrids, fuel cell non-hybrids and fuel cell hybrids) are FT-diesel, CNG/CMG, methanol and hydrogen, all derived from renewable resources. More specifically, the results are as follows:

- For the conventional and conventional hybrid vehicles the combinations FT-diesel and hydrogen (all from residual wood), compressed methane gas (CMG) derived from organic

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waste, and hydrogen from organic waste or from wind electricity (hydrogen-ICE), are among the most effective WTW pathways.

- For the hybrid and non-hybrid fuel cell vehicles, the most effective WTW pathways include 2 for the methanol FPFC, 2 for the ethanol FPFC and 12 for the hydrogen FCV (10 of which are for CGH₂ alone).

The following charts show the energy use and GHG emissions of the selected WTW pathways including the MTBE-, ETBE- and RME-blended oil-derived gasoline or diesel.

Figure 3-1: WTW - Energy Use of Selected Pathways – Crude Oil Derived Fuels

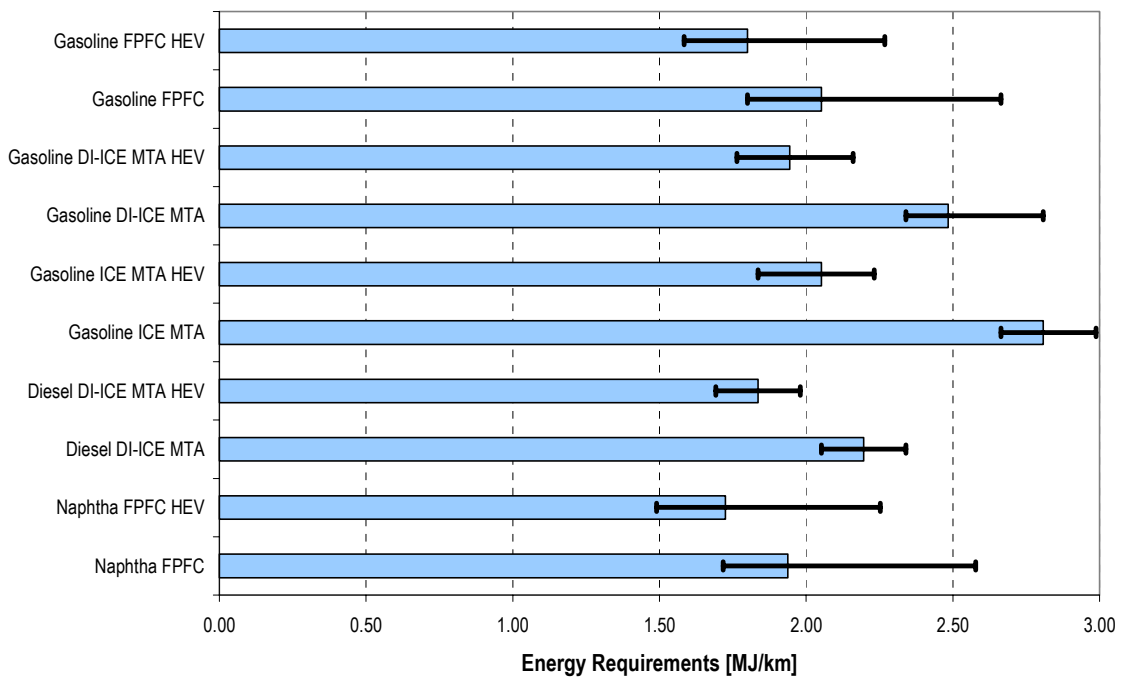


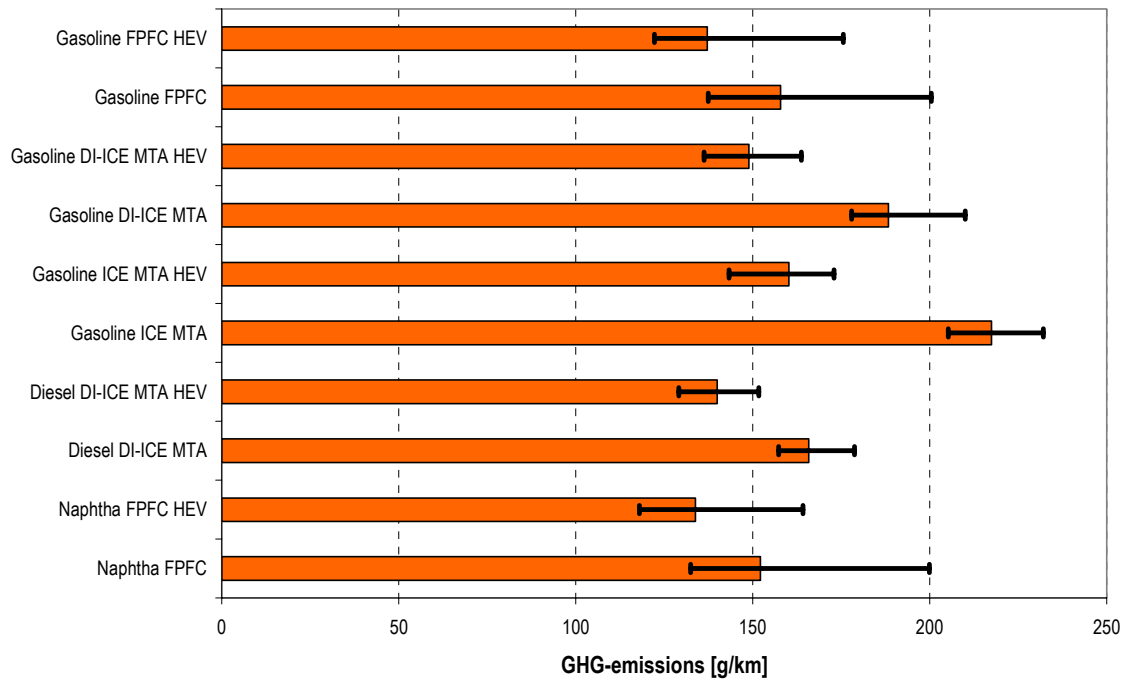
Figure 3-2: WTW - GHG Emissions of Selected Pathways – Crude Oil Derived Fuels

Figure 3-3: WTW - Energy Use of Selected Pathways – NG-Derived Fuels: CNG, Methanol, Gasoline blended with 10% MTBE, FT-Diesel, FT-naphtha

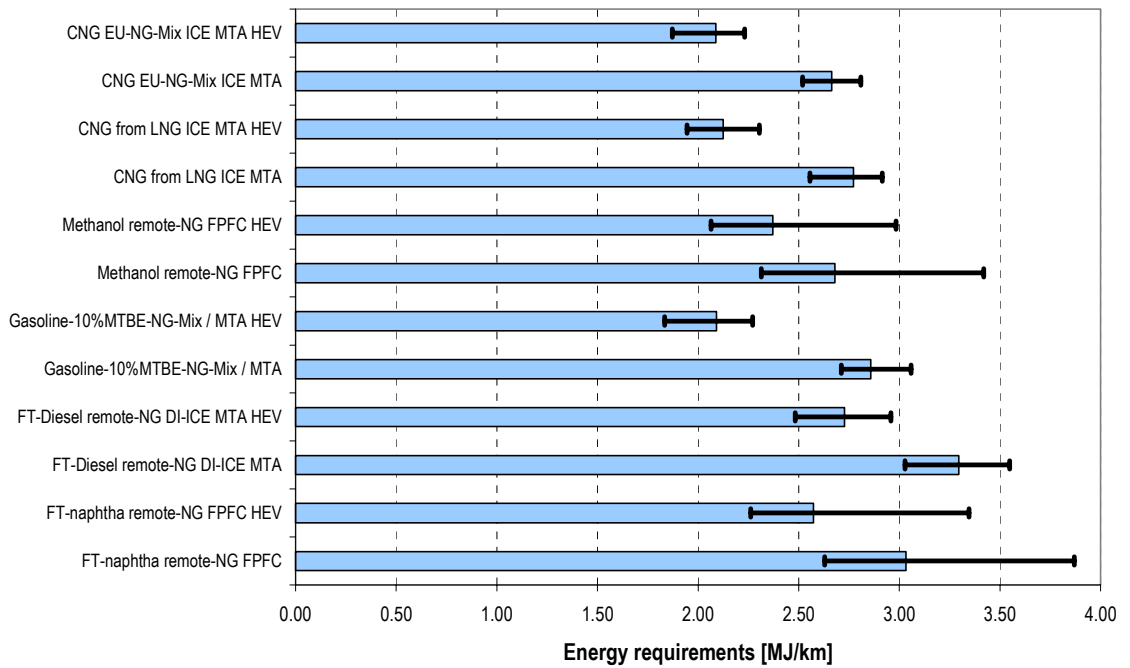


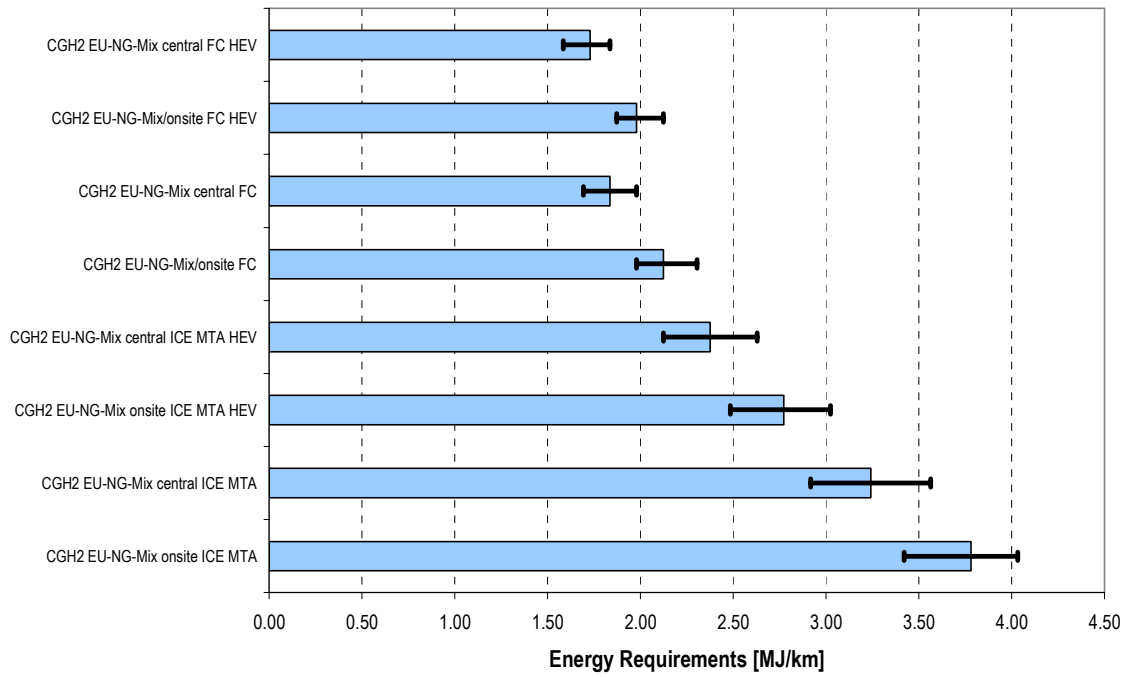
Figure 3-4: WTW - Energy Use Selected Pathways – NG-Derived Fuels: CGH₂

Figure 3-5: WTW - Energy Use of Selected Pathways – NG-Derived Fuels: LH₂

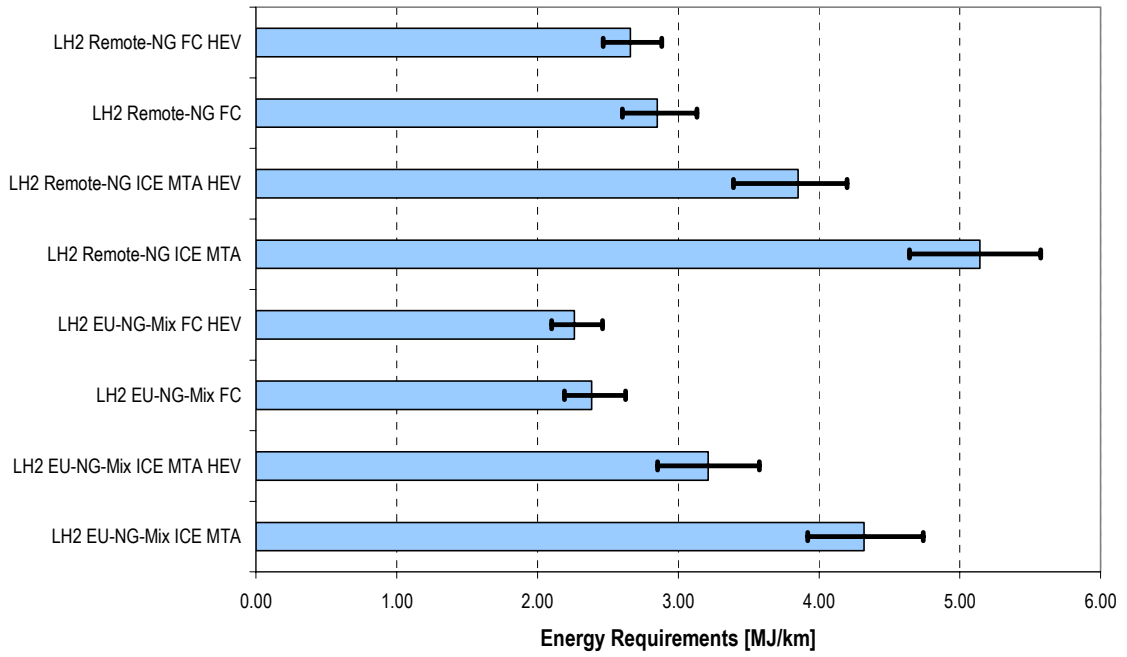


Figure 3-6: WTW - GHG Emissions of Selected Pathways – Natural Gas Derived Fuels: CNG, Methanol, Gasoline blended with 10% MTBE, FT-Diesel

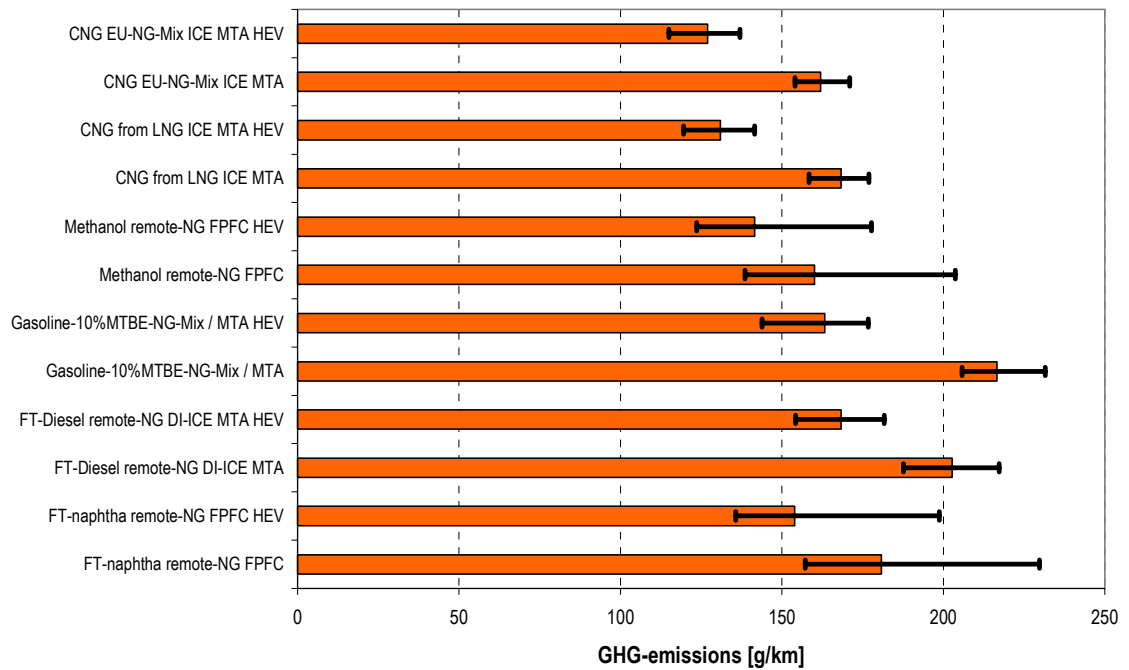


Figure 3-7: WTW - GHG Emissions of Selected Pathways – NG-Derived Fuels: CGH₂

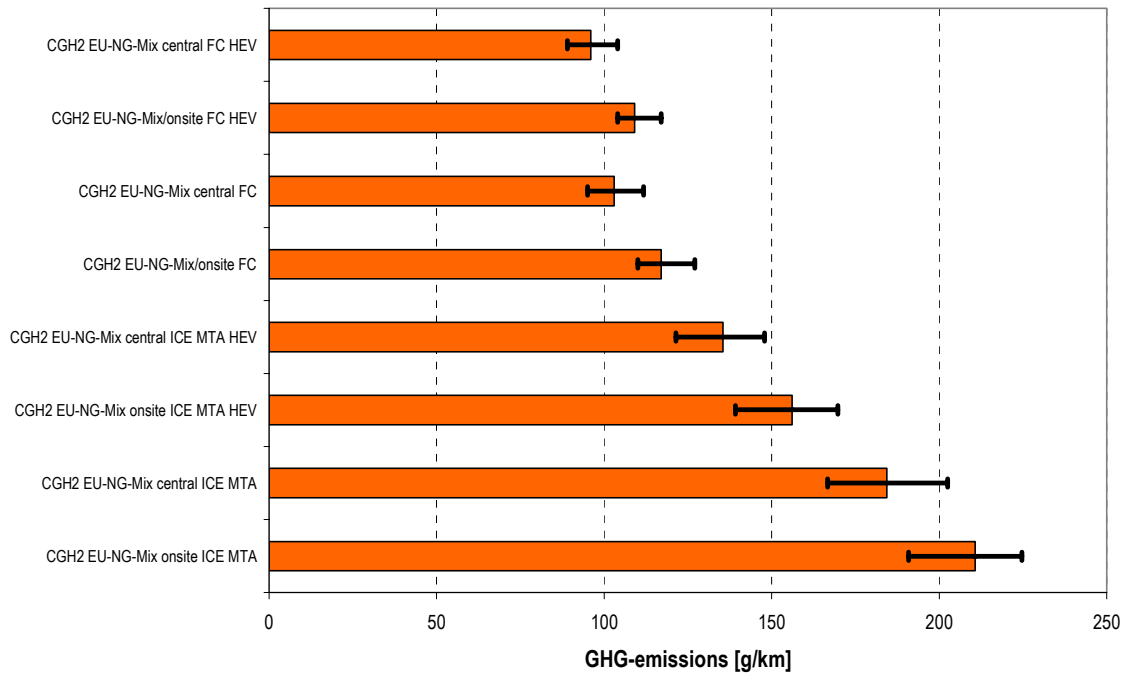


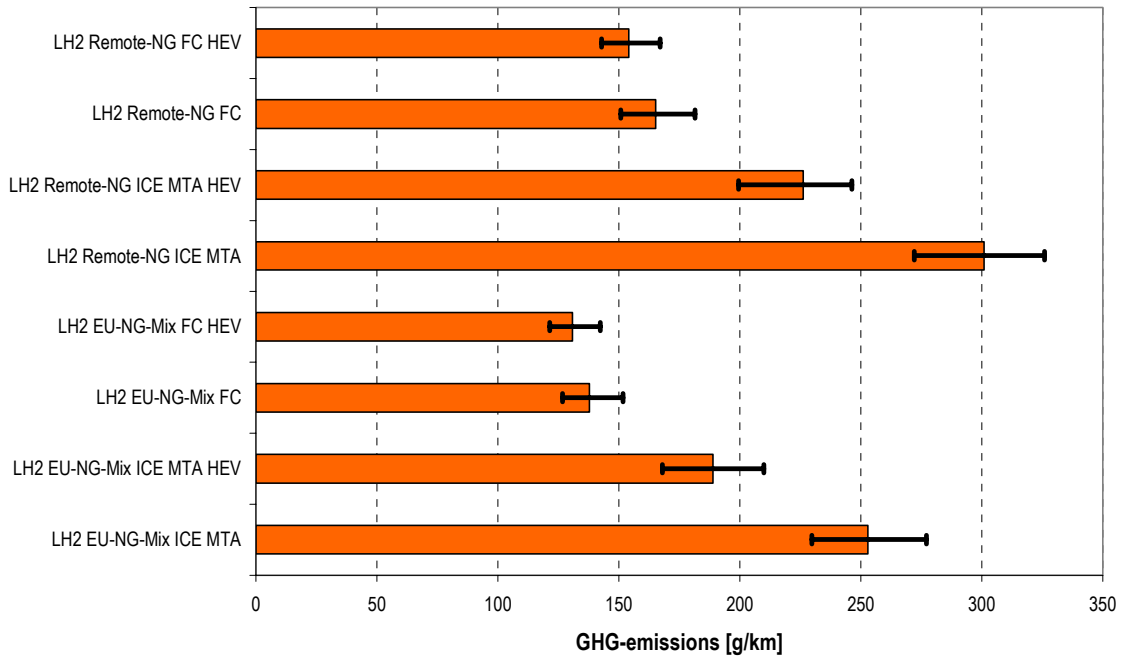
Figure 3-8: WTW - GHG Emissions of Selected Pathways – NG-Derived Fuels: LH₂

Figure 3-9: WTW - Energy Use of Selected Pathways – Electricity Derived Fuels: CGH₂ from regional Electrolysis

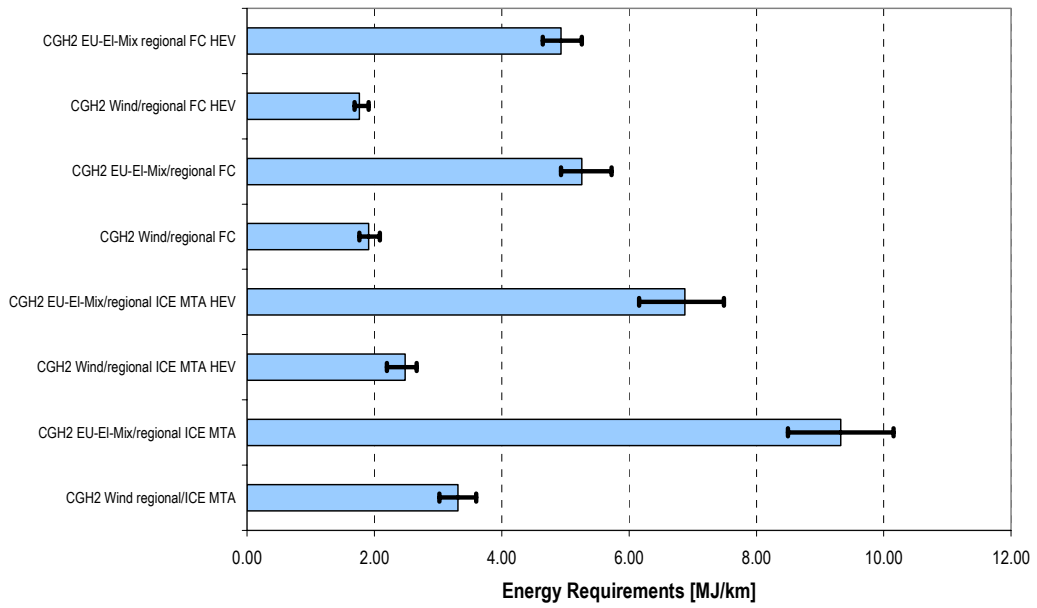


Figure 3-10: WTW - Energy Use of Selected Pathways – Electricity Derived Fuels: CGH₂ from on-site Electrolysis

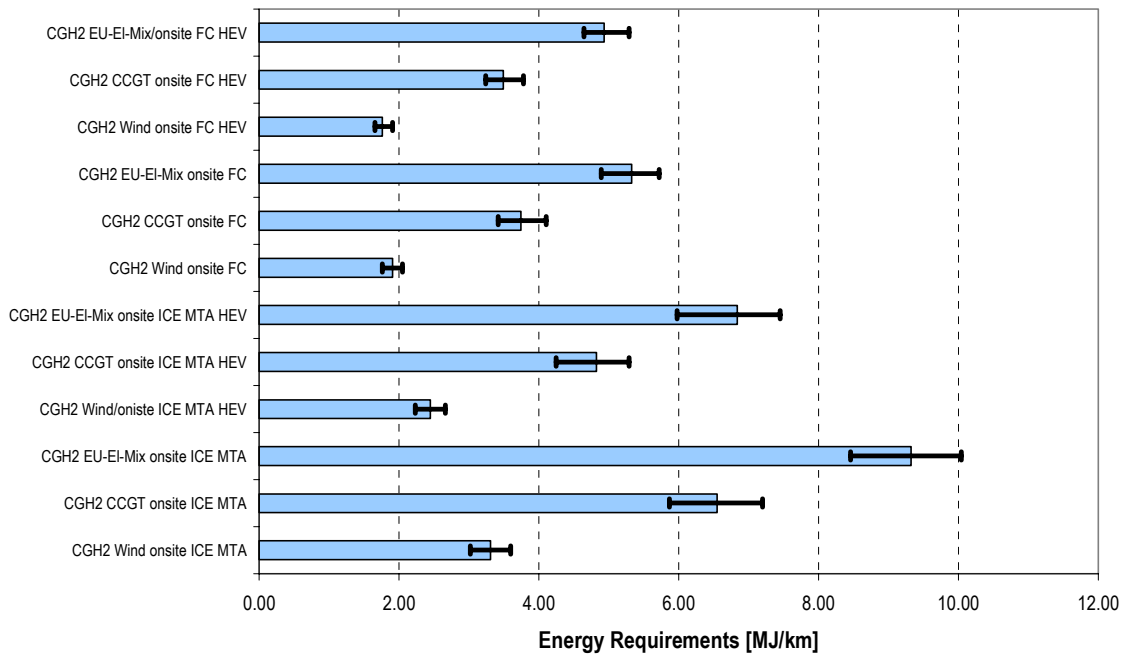


Figure 3-11: WTW - Energy Use of Selected Pathways – Electricity-Derived Fuels: LH₂

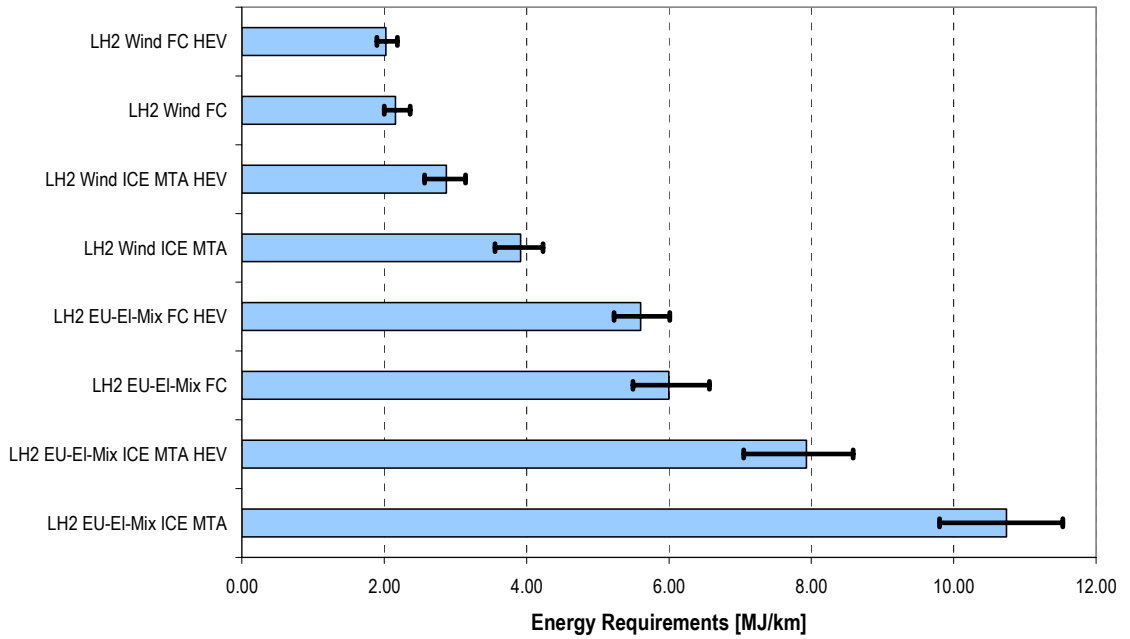


Figure 3-12: WTW - GHG Emissions of Selected Pathways – Electricity Derived Fuels: CGH₂ from regional Electrolysis

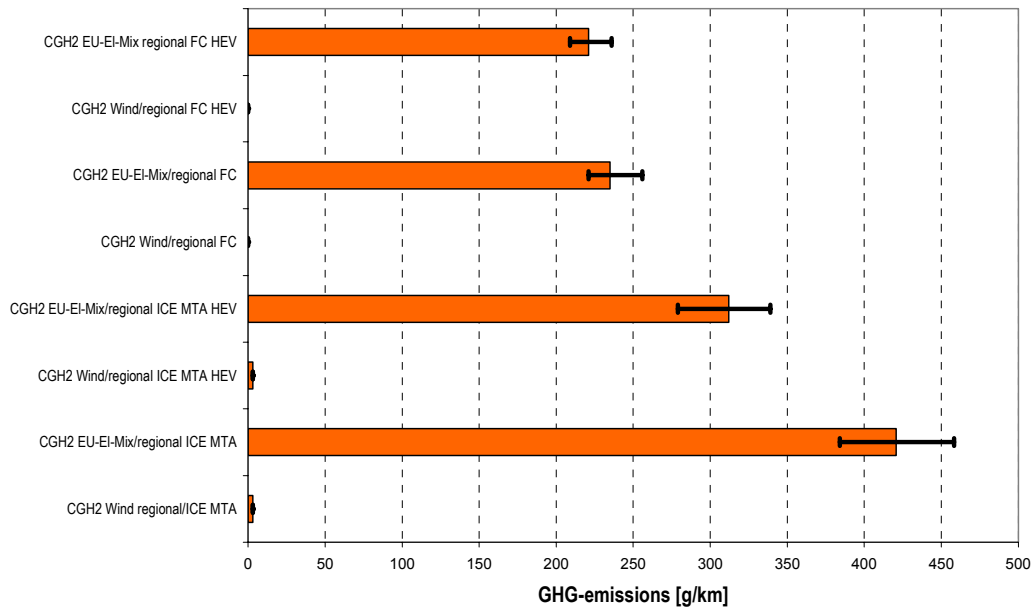


Figure 3-13: WTW - GHG Emissions of Selected Pathways – Electricity Derived Fuels: CGH₂ from on-site Electrolysis

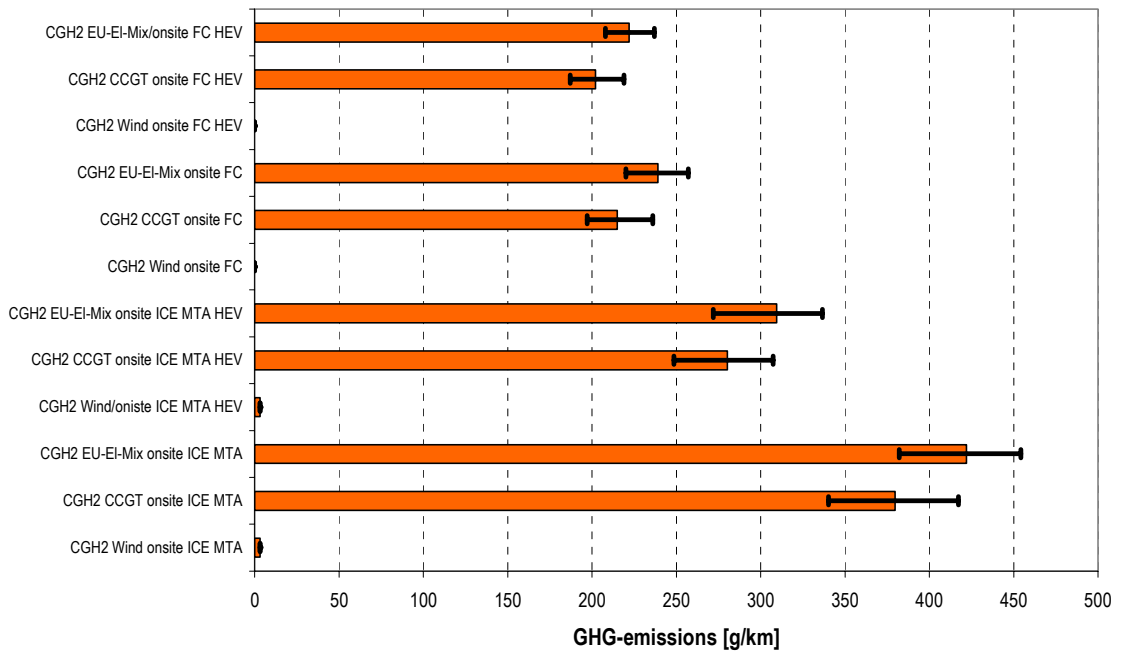


Figure 3-14: WTW - GHG Emissions of Selected Pathways – Electricity-Derived Fuels: LH₂

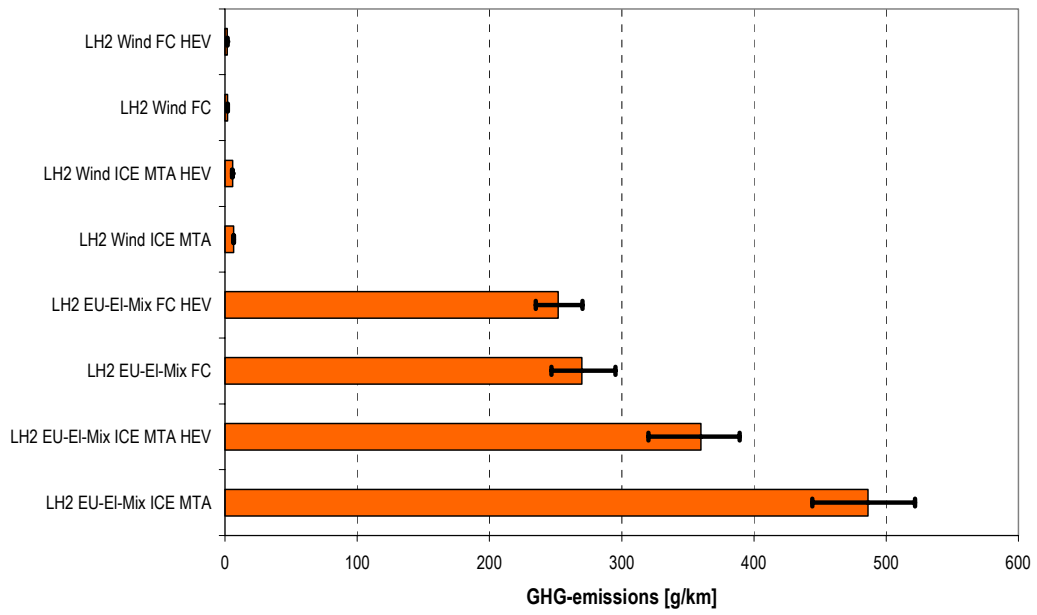


Figure 3-15: WTW - Energy Use of Selected Pathways – Biomass Derived Fuels: CGH₂

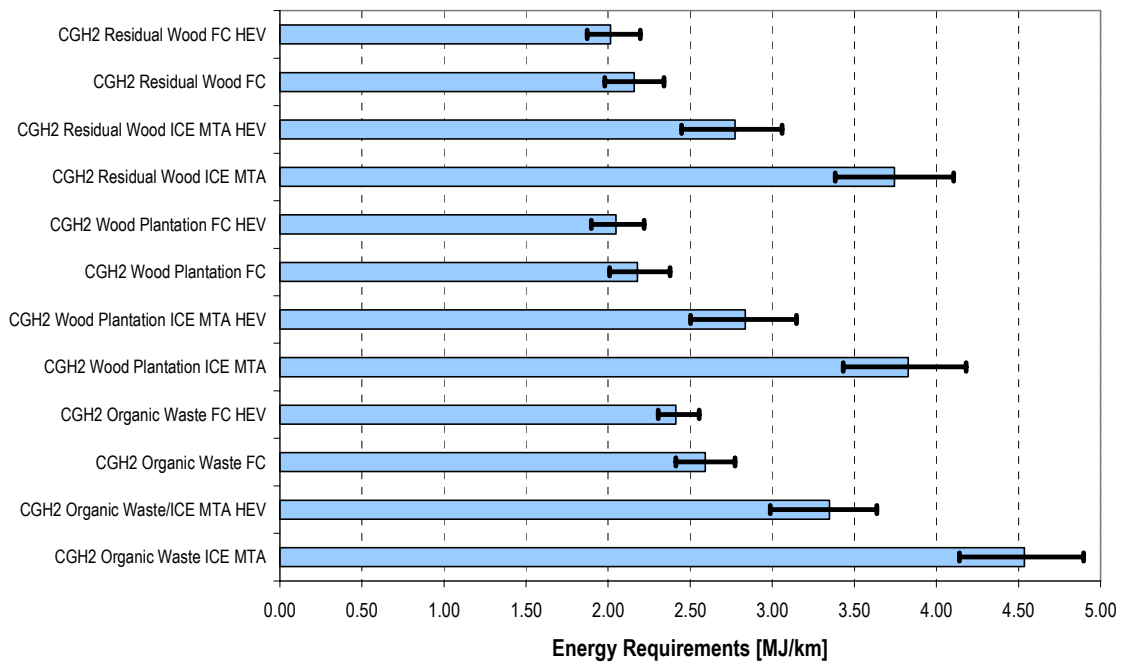


Figure 3-16: WTW - Energy Use of Selected Pathways – Biomass Derived Fuels: Methanol, Ethanol, FT-Diesel, Compressed Methane Gas (CMG)

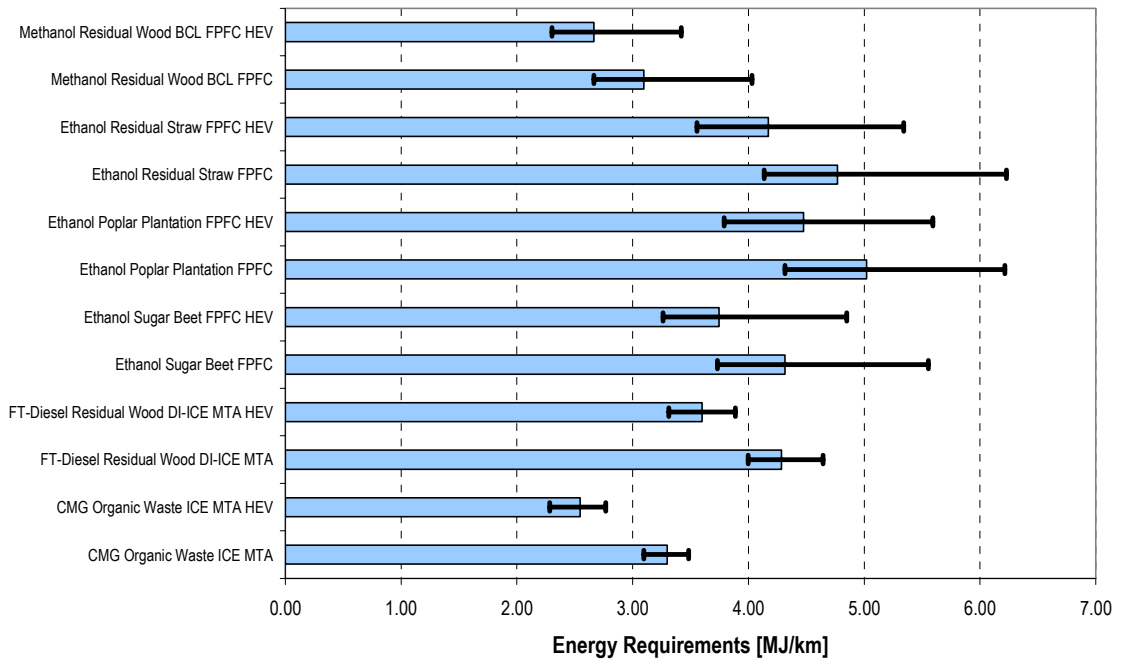


Figure 3-17: WTW - Energy Use of Selected Pathways – Biomass Derived Fuels: Gasoline and Diesel, blended with MTBE, ETBE and RME

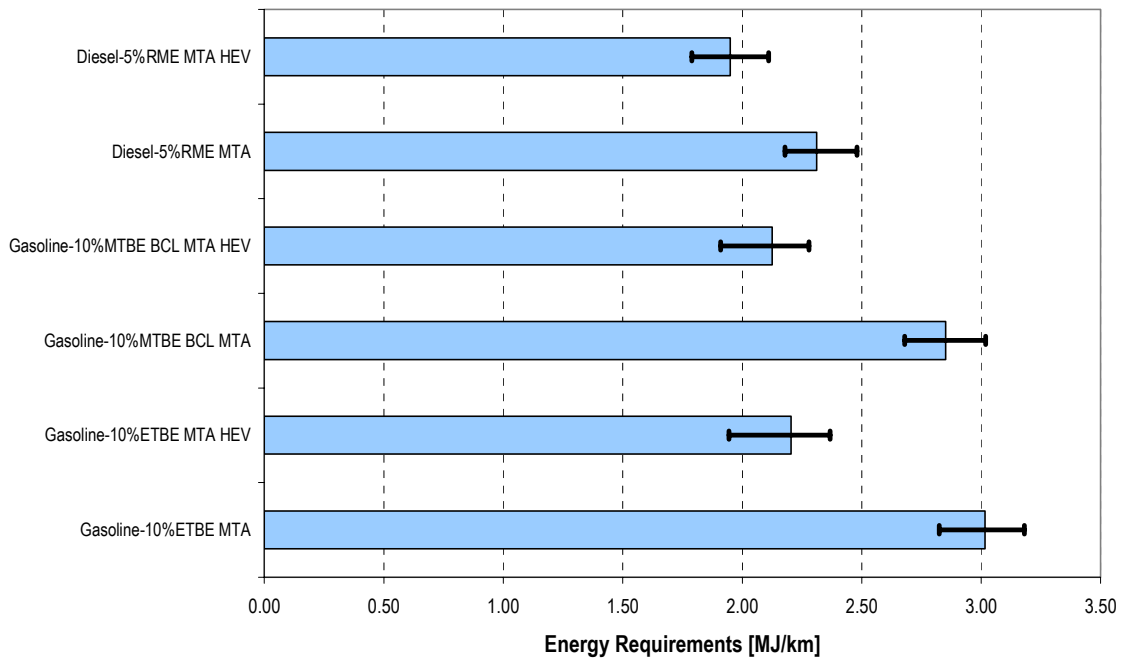


Figure 3-18: WTW - GHG Emissions of Selected Pathways – Biomass-Derived Fuels: CGH₂

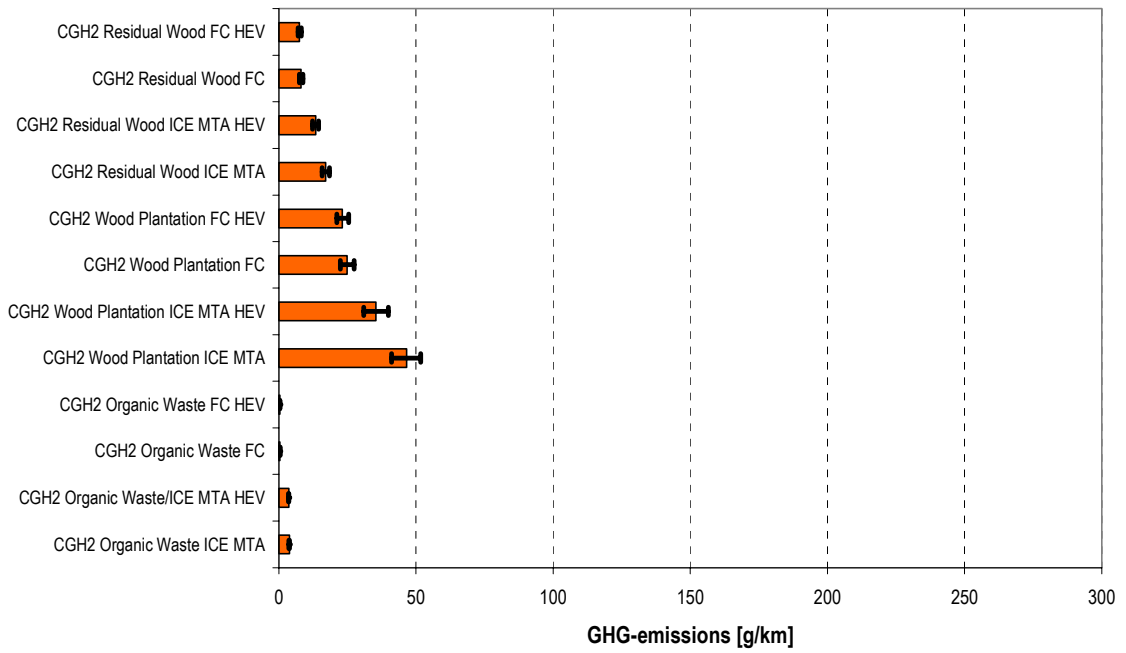


Figure 3-19: WTW - GHG Emissions of Selected Pathways – Biomass-Derived Fuels: Methanol, Ethanol, FT-Diesel, Compressed Methane Gas (CMG)

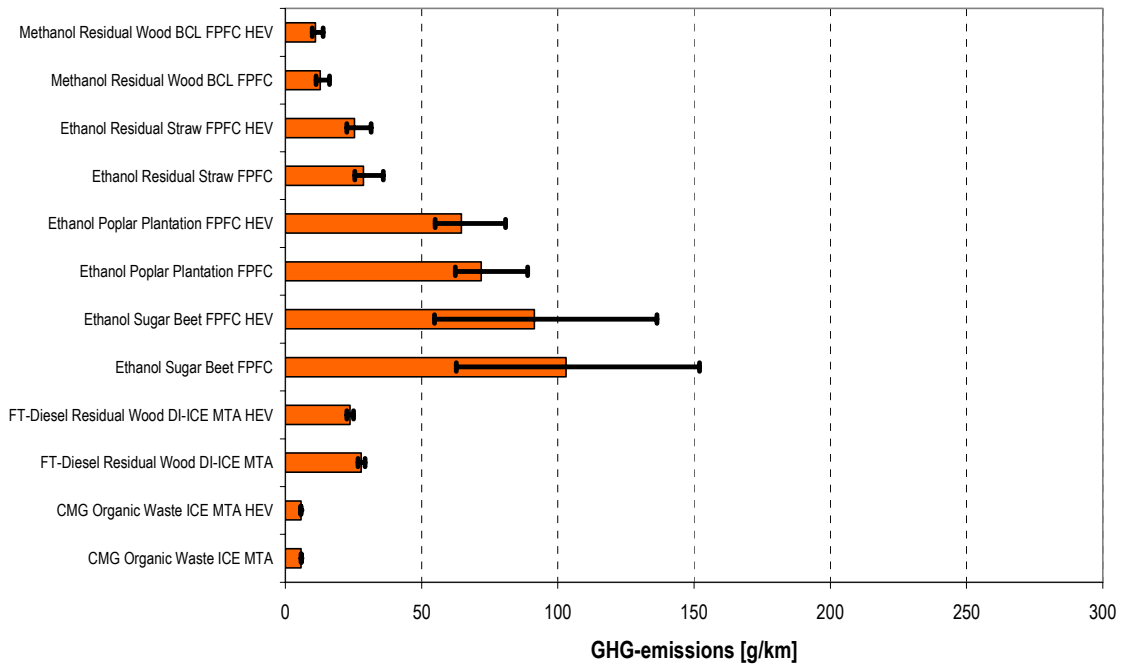


Figure 3-20: WTW - GHG Emissions of Selected Pathways – Biomass Derived Fuels: Gasoline and Diesel, blended with MTBE, ETBE and RME

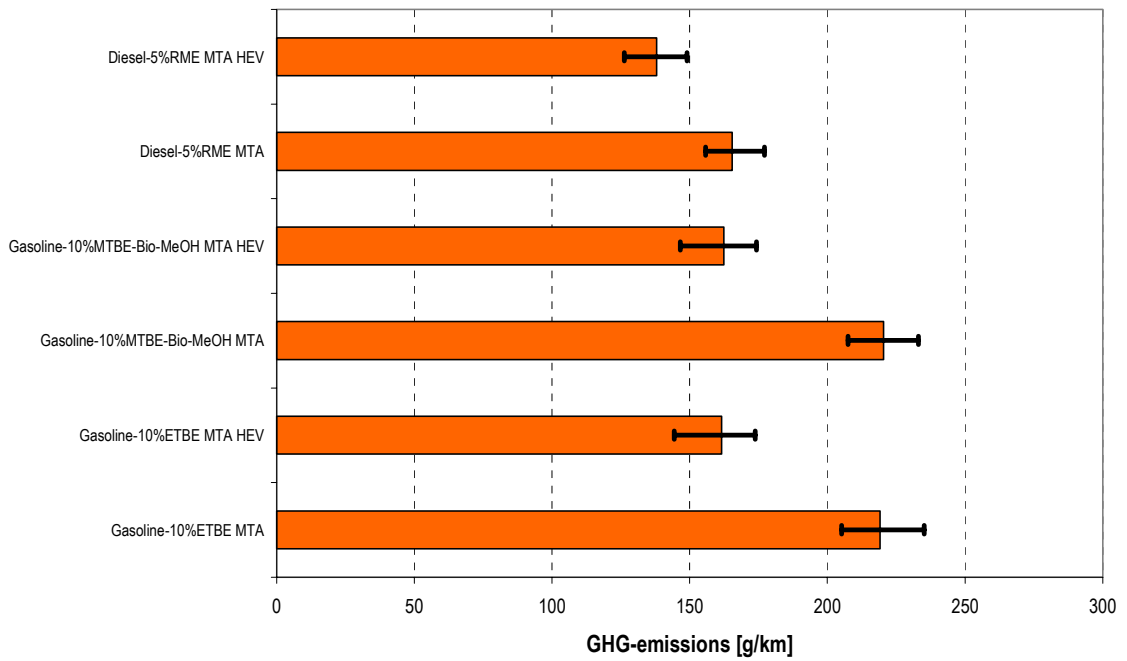


Figure 3-21: WTW - Energy Use of Selected Pathways

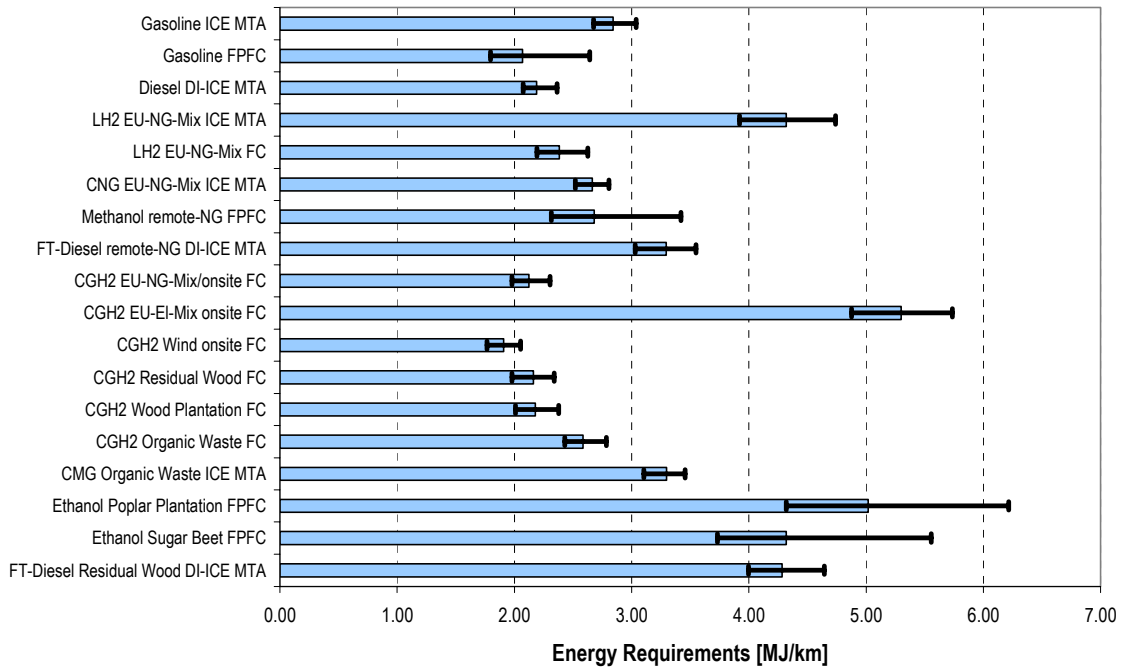


Figure 3-22: WTW - GHG Emissions of Selected Pathways

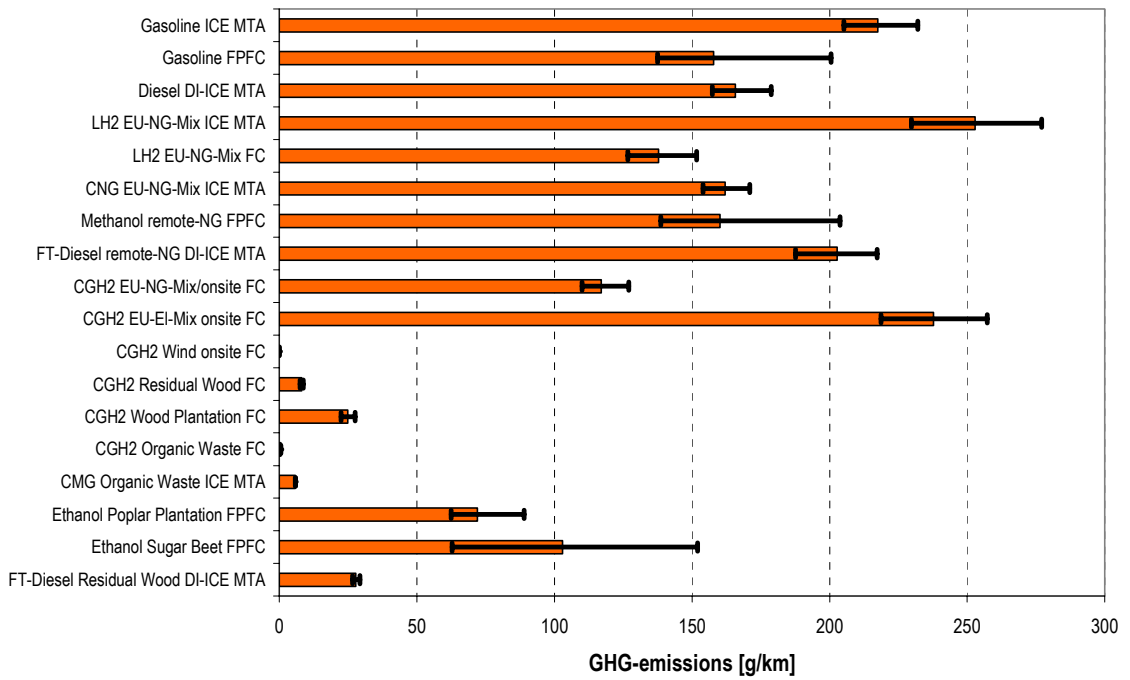


Figure 3-23: WTW Energy Loss Split into WTT and TTW

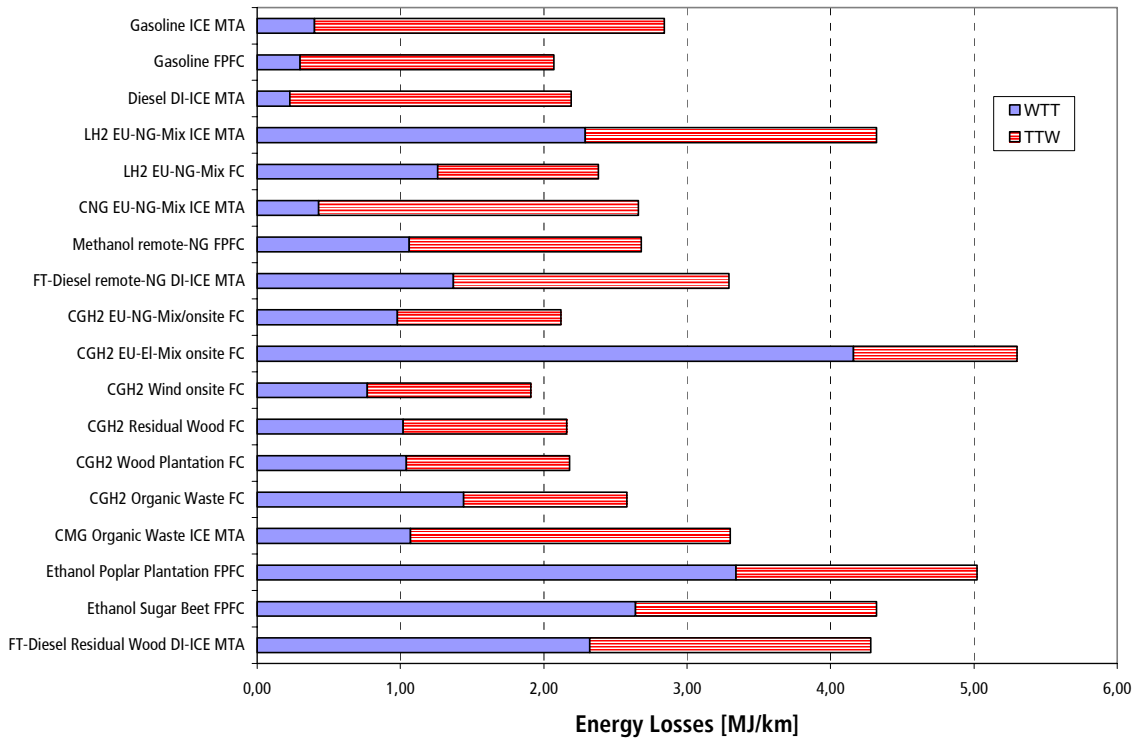
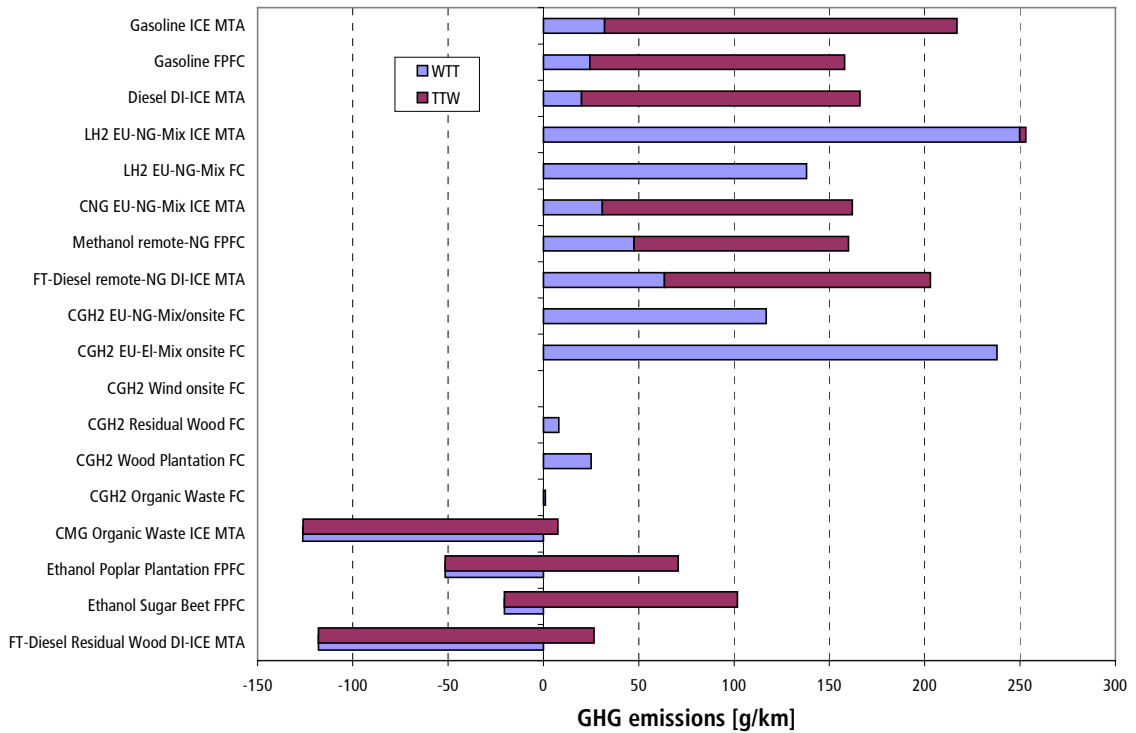


Figure 3-24: WTW GHG Emissions Split into WTT and TTW



3.4 Conclusions

In the overall well-to-wheel analysis 14 fuels were combined with 22 vehicle powertrains. The most prominent results are as follows:

Vehicle-specific findings:

Hybridization reduces fuel consumption in all propulsion systems, however the benefits are larger for internal combustion (IC) engines than for fuel cells because of the fuel cell's superior part-load efficiency relative to IC engines.

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Optimized CNG engine vehicles can provide GHG emission benefits compared with gasoline IC engine vehicles depending on the source of the natural gas, though they do not provide a real benefit on well-to-wheel energy use.

IC engine vehicles fueled with liquid hydrogen from natural gas offer zero vehicle CO₂ emissions, but result in higher WTW GHGs than either conventional gasoline or diesel IC engine vehicles.

Methanol FPFC vehicles running on remote natural gas derived methanol offer benefits relative to gasoline ICE vehicles and no or only minor benefits relative to diesel ICE vehicles, gasoline processor fuel cell vehicles or monofuel CNG ICE vehicles.

Fuel cell vehicles offer the lowest TTW energy consumption and the potential to reduce or eliminate WTW GHG emissions per km, when they are fueled with hydrogen from renewable sources.

Fuel-specific findings:

The source of natural gas feedstock has a significant impact on GHG emissions for natural gas based pathways.

Fuel cell vehicles running on compressed hydrogen from reformed natural gas offer reduced GHG emissions relative to gasoline and diesel ICE vehicles.

Fischer-Tropsch diesel used in ICE vehicles has higher energy consumption than crude oil-based diesel or gasoline, and higher GHG emissions than conventional diesel but slightly lower than gasoline.

Biofuels offer reduced GHGs, however, the magnitude of improvement depends on the assumptions on N₂O emissions from the crops as reflected by the uncertainty ranges. Processing of biomass by gasification or enzymatic hydrolysis gives lower GHG emissions than conventional biofuels.

Electrolysis-based hydrogen generates high GHG emissions when the electricity comes from the traditional electric grid mix, and near-zero GHGs when the electricity is produced renewably.

Comparison with North American study results

Findings of the present work are generally consistent with those of the GM-Argonne North American WTW Study in terms of relative rankings of the fuel-powertrain combinations. Of

course, the absolute WTW values are lower for Europe primarily due to the smaller (lower mass) minivan used in the European Study compared to the truck used in North America.

On the Well-to-Tank side, the oil pathways benefited from higher refining efficiency in Europe than in North America; this resulted primarily from the higher ratio of diesel to gasoline fuel produced in Europe. However, natural gas pathways based on the EU-mix were also more efficient than those used for the Well-to-Wheel integration in the North American study, which were based on imported LNG. As expected, the ethanol from sugar beets pathway shown in this study showed smaller reductions of GHGs than the lignocellulosic ethanol pathways shown in the North American Study.

Differences on the Tank-To-Wheel side are attributed to the vehicle used for the study, the base engine technologies, and the driving cycles on which the vehicle were simulated. Hybridization provides a greater benefit on urban type driving, thus in Europe the gasoline – hybrid showed greater potential than in North America. The CNG ICE vehicle was more attractive in the European study because of its optimized monofuel engine in contrast to the dual-fuel ICE used in the North American study. The hydrogen fuel cell vehicle in the European study benefited from improvements achieved in the efficiency map and control strategy in the time elapsed between the two studies. However, because of the improvements in the non-hybridized fuel cell vehicle in Europe, the resulting benefits due to hybridization were smaller in Europe than in North America.

General Comment

It is important to note that the WTW estimates provide two key dimensions for assessing the attractiveness of future fuels and powertrains - namely those of energy consumption and GHG emissions. Cost, fuel feedstock availability, and infrastructure considerations, however, are clearly other dimensions that will play a role in determining the overall attractiveness of future transport systems.

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L B S T

L-B-Systemtechnik

L-B-Systemtechnik GmbH – Company Profile

L-B-Systemtechnik is the commercial sister company of the non-profit Ludwig-Bölkow-Systemtechnik GmbH, which is owned by the Ludwig-Bölkow-Foundation. Solar and hydrogen energy supply options and clean transportation concepts are the major fields of our activities since more than one decade.

LBST supports industry, politics and non-governmental organisations

- in the identification of new products and services,
- in the development of strategies for the introduction of new products and concepts,
- with system studies,
- in finding new partners – networking,
- in the project management and co-ordination of projects,
- with strategic consultancy services.

LBST has established HyWeb – the Hydrogen and Fuel Cell Information System in the Internet under www.HyWeb.de/english.

Main fields of activities in the energy sector are renewable energies, improvement of energy efficiency, mitigation of negative greenhouse effects, the introduction of solar/ renewable hydrogen and fuel cells. Main fields of activity in the transportation sector are improved railroad systems and interlinkage with road transport, alternative propulsion concepts for road vehicles and environmentally acceptable traffic concepts for metropolitan areas. In the case of clean fuels and energy carriers, the main efforts of LBST lie in advancing the wide-spread use of hydrogen and natural gas, the latter being regarded as a transition fuel to hydrogen. Since the early 1990s, increased efforts are made into the investigation of stationary and mobile fuel cell applications including related infrastructure components and systems. LBST is furthermore active in several project coordination activities, among them hardware projects for stationary and mobile PEM fuel cell applications.

An interdisciplinary team of about 15 specialists works on scenarios and technology assessments, develops strategy papers and feasibility studies, initiates new projects, coordinates joint projects and provides strategic consultancy.