Well-to-Wheels analysis of future automotive fuels and powertrains in the European context

A joint study by

EUCAR / JRC / CONCAWE

Summary of Results

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Outline

- Objectives
- Pathways
- Vehicle Assumptions
- Overall results: WTW energy/GHG, costs
- Specific results
  - Conventional liquid fuels
  - CNG
  - Alternative liquid fuels
  - DME
  - Hydrogen
- Potential for conventional fuel substitution and CO₂ avoidance
- Conclusions
Study Objectives

- Establish, in a transparent and objective manner, a consensual well-to-wheels energy use and GHG emissions assessment of a wide range of automotive fuels and powertrains relevant to Europe in 2010 and beyond.

- Consider the viability of each fuel pathway and estimate the associated macro-economic costs.

- Have the outcome accepted as a reference by all relevant stakeholders.
Well-to-Wheels Pathways

**Resource**
- Crude oil
- Coal
- Natural Gas
- Biomass
- Wind
- Nuclear

**Fuels**
- Conventional
  - Gasoline/Diesel/Naphtha
- Synthetic Diesel (F-T)
- CNG
- Hydrogen (compressed / liquid)
- Methanol
- DME
- Ethanol
- FAME

**Powertrains**
- Spark Ignition:
  - Gasoline, CNG, Ethanol, \( H_2 \)
- Compression Ignition:
  - Diesel, DME, FAME
- Fuel Cell
- Hybrids:
  - SI, CI, FC
- Hybrid Fuel Cell + Reformer
## Well-to-Tank Matrix

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Gasoline, Diesel, Naphtha (2010 quality)</th>
<th>CNG</th>
<th>Hydrogen (comp., liquid)</th>
<th>Synthetic diesel (Fischer-Tropsch)</th>
<th>DME</th>
<th>Ethanol</th>
<th>FAME</th>
<th>Methanol</th>
<th>Electricity</th>
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<tbody>
<tr>
<td>Crude oil</td>
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<tr>
<td>Natural gas</td>
<td>Piped</td>
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<td>X</td>
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<td>X</td>
<td>X</td>
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<td>X</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>Biomass</td>
<td>Woody waste</td>
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<td>X</td>
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<tr>
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<td>Farmed wood</td>
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<td>X</td>
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<tr>
<td></td>
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<td>Rapeseed</td>
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<td>Electricity</td>
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</table>
## Tank-to-Wheels Matrix

<table>
<thead>
<tr>
<th>Fuels and Fuel Blends</th>
<th>PISI</th>
<th>DISI</th>
<th>DICI</th>
<th>Hyb. SI</th>
<th>Hyb. DICI</th>
<th>FC</th>
<th>Hyb. FC</th>
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</thead>
<tbody>
<tr>
<td><strong>Gasoline</strong></td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
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<tr>
<td><strong>Diesel</strong></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
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<tr>
<td><strong>CNG (dedicated)</strong></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Diesel 95% / FAME 5%</strong></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gasoline 95% / EtOH 5%</strong></td>
<td>X</td>
<td>X</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td><strong>Methanol</strong></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td><strong>FAME</strong></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>DME</strong></td>
<td>X</td>
<td></td>
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<td></td>
<td>X</td>
<td></td>
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<tr>
<td><strong>F-T Diesel</strong></td>
<td>X</td>
<td></td>
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<tr>
<td><strong>Naphtha</strong></td>
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<td>X</td>
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<tr>
<td><strong>Hydrogen, compressed</strong></td>
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<td></td>
<td>X</td>
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<td>X</td>
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<tr>
<td><strong>Hydrogen, liquid</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Vehicle Assumptions

- The simulations of GHG emissions and energy use were based on a model vehicle representing the European C-segment and on the New European Driving Cycle (NEDC). The model vehicle results are not representative of the EU fleet.

- When necessary, the vehicle platform was adapted to ensure that each fuel and powertrain combination met a set of minimum performance criteria (speed, acceleration, gradability etc). The criteria reflect European customer expectations.

- Compliance with Euro III / IV was ensured for the 2002 / 2010 case.

- No assumptions were made with respect to availability and market share of the vehicle technology options proposed for 2010 and beyond.

- Heavy duty vehicles (truck and busses) were not considered in the study.
Overall Results – GHG Emissions vs. Energy Use
Overall Results – GHG Emissions vs. Energy Use

- Chart shows WTW GHG emissions versus total WTW energy input:
  - Energy includes renewable energy, GHG emissions reflects fossil fuel use
  - Performance of current Gasoline ICE is highlighted
  - Data points cluster on lines representing the energy source material
  - Wide spread along each line according to the fuel pathway and vehicle option considered

- Large variations in N$_2$O emissions influence GHG emissions from conventional biomass fuels

- Advanced biomass fuels, together with wind and nuclear offer largest GHG emission reductions
General Observations: WTW

- A Well-to-Wheels analysis is the essential basis to assess the impact of future fuel and powertrain options.
  - Both fuel production pathway and powertrain efficiency are key to assessing GHG emissions and energy use.
  - A common methodology and data-set have been developed, providing a basis for the evaluation of pathways. Data can be updated as technologies evolve.

- Results must further be evaluated in the context of volume potential, feasibility, practicality, costs of the fuels pathways investigated.

General observations and the main conclusions are presented using the following scheme:

- Points pertaining to energy use and GHG emissions are in normal font and with a square bullet.
- Additional points involving feasibility, availability and costs are in italic and with an arrow bullet.
Overall Results – Costs of CO₂ avoided

The cost estimates in this study are based on the following assumptions:

- In a business as usual scenario - 5% of the conventional EU-25 fleet (marginal diesel and gasoline) will emit ca 37 Mt CO₂eq/a in 2010 (280 M vehicles, fleet average consumption 137 g CO₂/km, 16000 km/a average mileage, 140 Mt/a of gasoline and 60 Mt/a of diesel)

- If this portion of the EU transportation demand were hypothetically to be replaced by alternative fuels and powertrain technologies, the GHG savings vs. incremental costs would be as indicated

- CO₂ avoided costs are calculated from incremental capital and operating costs for fuel pathway and vehicle
Overall Results – Costs of CO₂ avoided

The reference case is gasoline + diesel in the expected demand ratio in 2010. 5% corresponds to 37 Mt/a CO₂eq.
General Observations: Costs

- A shift to renewable / low carbon sources is currently costly
  - However, high cost does not always result in high GHG emission reductions
  - At comparable costs GHG savings can be considerably different and vice versa

- In a 5% replacement scenario significant GHG emission reductions can be achieved by using fuels from biomass at a cost of 200-300 €/ton CO$_2$ avoided
Specific Results: WTW

The results are reviewed in detail for the following fuels and a range of applicable powertrains:

- Liquid fuels from crude oil
- Compressed natural gas
- Alternative liquid fuels (including biomass sources)
- Di-methyl ether (DME)
- Hydrogen
Conventional Fuels from Crude Oil

WTW energy (MJ / 100 km)

WTW GHG (g CO2eq / km)

Gasoline 2002
Conv. Diesel 2002
Conv. Diesel 2010
Conv. Diesel 2010 hyb.
no DPF
Gasoline 2010 hyb.
Gasoline 2010
PISI
DISI
Conv. Diesel 2010 hyb.
Conventional Fuels from Crude Oil

**Energy**

- Conv. Diesel DICI Hyb.
- Conv. Diesel DICI+DPF Hyb.
- Gasoline DISI Hyb.
- Gasoline PISI Hyb.
- Conv. Diesel DICI
- Conv. Diesel DICI+DPF
- Gasoline DISI
- Gasoline PISI
- Conv. Diesel DICI
- Gasoline DISI
- Gasoline PISI

**GHG**

- Conv. Diesel DICI Hyb.
- Conv. Diesel DICI+DPF Hyb.
- Gasoline DISI Hyb.
- Gasoline PISI Hyb.
- Conv. Diesel DICI
- Conv. Diesel DICI+DPF
- Gasoline DISI
- Gasoline PISI
- Conv. Diesel DICI
- Gasoline DISI
- Gasoline PISI

MJ / 100 km

2002

2010

g CO₂eq / km

2002

2010
Conventional Fuels / Vehicle Technologies

- Developments in engine and vehicle technologies will continue to contribute to the reduction of energy use and GHG emissions:
  - In the timeframe 2002 to 2010, higher energy efficiency improvements are predicted for the gasoline and CNG engine technology (PISI) than for the diesel engine technology.
  - Hybridization of the conventional engine technologies can provide further GHG emission and energy use benefits.

  - Hybridisation technologies would increase the complexity and cost of the vehicles.
Compressed Natural Gas (CNG)
Compressed Natural Gas (CNG)
Compressed Natural Gas (CNG): key points

- The origin of the natural gas and the supply pathway are critical to the overall WTW energy use and GHG emissions.
- Today the WTW GHG emissions for CNG lie between gasoline and diesel, approaching diesel in the best case.
- Beyond 2010, greater engine efficiency gains are predicted for CNG vehicles, especially with hybridization:
  - WTW GHG emissions becomes better than those of diesel.
  - WTW energy use remains higher than for conventional fuels.
- The cost of CO₂ avoided is relatively high as CNG requires specific vehicles and a dedicated distribution and refueling infrastructure:
  - Targeted application in fleet markets may be more effective than widespread use in personal cars.
Alternative Liquid Fuels

- Conv. diesel
- Syndiesel: GTL
- RME
- SME
- EtOH: wood
- EtOH: wheat
- EtOH: sugar
- Gasoline
- DME: NG
- DME: wood
- Syndiesel: BTL

Common basis: 2010
PISI or DICI DPF (not for DME)
Alternative Liquid Fuels: Conventional Biofuels

**Energy**

- SME: glycerine as animal feed
- SME: glycerine as chemical
- RME: glycerine as animal feed
- RME: glycerine as chemical
- Conv. Diesel DICI+DPF
- EtOH: W Wood
- EtOH: F wood
- EtOH: Wheat, no straw
- EtOH: Sugar beet, pulp to heat
- EtOH: Sugar beet, pulp to EtOH
- EtOH: Sugar beet, pulp to fodder
- Gasoline PISI

**GHG**

- SME: glycerine as animal feed
- SME: glycerine as chemical
- RME: glycerine as animal feed
- RME: glycerine as chemical
- Conv. Diesel DICI+DPF
- EtOH: W Wood
- EtOH: F wood
- EtOH: Wheat, no straw
- EtOH: Sugar beet, pulp to heat
- EtOH: Sugar beet, pulp to EtOH
- EtOH: Sugar beet, pulp to fodder
- Gasoline PISI

**MJ / 100 km**

**g CO2eq / km**
Alternative Liquid Fuels: Syndiesel

![Energy Chart]

- DME: Farmed wood
- DME: Waste wood
- DME: Remote synthesis
- Syndiesel: Farmed wood
- Syndiesel: Waste wood
- Syndiesel: Remote GTL
- Conv. diesel DICI+DPF

![GHG Chart]

- DME: Farmed wood
- DME: Waste wood
- DME: Remote synthesis
- Syndiesel: Farmed wood
- Syndiesel: Waste wood
- Syndiesel: Remote GTL
- Conv. diesel DICI+DPF
A number of routes are available to produce alternative liquid fuels that can be used neat or in blends with conventional fuels in the existing infrastructure and vehicles.

Conventionally produced bio-fuels such as ethanol and FAME provide some GHG benefits but are energy intensive compared to conventional crude oil-based fuels.

- The GHG balance of conventional biofuels is particularly uncertain because of N$_2$O emissions.

Potential volumes of ethanol and FAME are limited. The cost/benefit depends of the specific pathway, by-product usage and N$_2$O emissions.
Alternative Liquid Fuels: key points (2)

- GTL processes enable high quality diesel fuel to be produced from natural gas. However, the WTW GHG emissions are higher than for conventional diesel fuel
  - Only limited GTL volumes can be expected to be available by 2010 and beyond

- New processes are being developed to produce synthetic fuels from biomass (BTL) with lower overall GHG emissions, though still high energy use
  - BTL processes have the potential to save substantially more GHG emissions than current bio-fuel options at comparable cost
    - Issues such as land and biomass resources, material collection, plant size, efficiency and costs, may limit the application of these processes
Di-Methyl Ether (DME)

- DME can be produced from natural gas or biomass at lower energy use and GHG emissions than other GTL or BTL fuels
  
  - Implementation costs would be much higher as DME would require specifically designed engines and a dedicated distribution and refuelling infrastructure
Hydrogen

WTW energy (MJ/100 km)

0 200 400 600 800 1000 1200

WYW GHG (g CO2eq/km)

0 200 400 600 800

Hydrogen technologies:
- Gasoline
- Diesel
- Hyd ex NG, ICE
- Hyd ex NG, FC
- Hyd ex NG+ely, ICE
- Hyd ex NG+ely, FC
- Hyd ex coal, ICE
- Hyd ex coal, FC
- Hyd ex coal+ely, ICE
- Hyd ex coal+ely, FC
- Hyd ex bio, ICE
- Hyd ex bio, FC
- Hyd ex bio+ely, ICE
- Hyd ex bio+ely, FC
- Hyd ex wind+ely, ICE
- Hyd ex wind+ely, FC
- Hyd ex nuclear, ICE
- Hyd ex nuclear, FC
- Hyd ex EU-mix elec, ICE
- Hyd ex EU-mix elec, FC
- Hyd ind (Ref+FC)

Crude oil
Natural gas
Eu-mix coal
Eu-mix elec
Biomass (advanced)
Wind, Nuclear
Hydrogen: key points (1)

- Many potential production routes exist and the results are critically dependent on the pathway selected.

- If hydrogen is produced from natural gas:
  - WTW GHG emissions savings can only be achieved if hydrogen is used with fuel cell vehicles
  - The WTW energy use / GHG emissions are higher for hydrogen ICE vehicles than for conventional fuels and CNG vehicles

- In the short term, natural gas is the only viable and cheapest source of large scale hydrogen. WTW GHG emissions savings can only be achieved if hydrogen is used in fuel cell vehicles albeit at high costs

- Hydrogen ICE vehicles will be available in the near-term at a lower cost than fuel cells. Their use would increase GHG emissions as long as hydrogen is produced from natural gas
Hydrogen: key points (2)

- Electrolysis using EU mix electricity results in higher GHG emissions than producing hydrogen directly from NG.

- Hydrogen from non-fossil sources (biomass, wind, nuclear) offers low overall GHG emissions.
  - *Renewable sources have a limited potential for the foreseeable future and are at present expensive.*
  - *More efficient use of renewables may be achieved through direct use as electricity rather than road fuels application.*
Hydrogen: key points (3)

- Indirect hydrogen through on-board reformers offers little GHG benefit compared to advanced conventional powertrains or hybrids

  - On-board reforming could offer the opportunity to establish fuel cell vehicle technology with the existing fuel distribution infrastructure

  - Large scale central hydrogen production (from coal or gas) offers the potential for CO₂ capture and sequestration

  - The technical challenges in distribution, storage and use of hydrogen lead to high costs. Also the cost, availability, complexity and customer acceptance of vehicle technology utilizing hydrogen technology should not be underestimated.
Overall Results – GHG Emissions vs. Energy Use

New approaches such as
- Renewable Fuels
- Carbon Capture & Sequestration
Offer GHG savings but are generally more energy intensive
Alternative use of primary energy resources - Biomass

Where could the biomass come from?

- **Agricultural Surplus land**
  - Sugar beet
  - Wheat grain
  - Oil seeds
  - Wood
  - Ethanol
  + Ethanol
  Or FAME
  Or Syn diesel(*)
  Or DME

- **Set aside**
  - Wheat grain
  - Oil seeds
  - Wood
  - Ethanol
  Or FAME
  Or Syn diesel
  Or DME

- **Forestry residues**
  - Wood waste
  - Ethanol
  Syn diesel
  Or DME

- **Agricultural wastes**
  - Straw
  - Ethanol
Alternative use of primary energy resources - Biomass

Potential for conventional fuels substitution with biomass-derived fuels

- Gasoline
- Diesel
- Max ethanol
- Max FAME + Syn diesel
- Max Syn diesel
- Max DME

WTT basis EU-25

% net renewable energy

61%
73%
91%
91%
8360
Alternative use of primary energy resources - Biomass

Potential for CO₂ avoidance with biomass-derived fuels

WTW basis EU-25

Mt CO₂eq/a avoided

Max ethanol
Max FAME + Syn diesel
Max Syn diesel
Max DME
Hydrogen (ICE)
Hydrogen (FC)

Hydrogen
Naphtha
DME
Syn diesel
FAME
EtOH cel.
EtOH conv
Potential for CO₂ avoidance from 1 ha of land

- Wood to DME
- Wood to FT diesel
- Wood to C-H₂, Ely (O/S), FC
- Wood to C-H₂ (O/S), FC
- Wood to C-H₂ (cen), ICE
- Wood to C-H₂ (cen), FC
- Oilseeds to FAME
- Wood to EtOH
- Wheat to EtOH
- Sugar beet to EtOH
- Wood to elec, conv (vs Coal, state-of-the-art)
- Wood to elec, IGCC (vs Coal, state-of-the-art)
- Wood to elec, IGCC (vs NG CCGT)

Reference case: 2010 ICE with Conventional fuel
Alternative use of primary energy resources – Natural gas

Potential for CO₂ avoidance from 1 MJ extracted gas

Reference case: 2010 ICE with Conventional fuel
Alternative use of primary energy resources - Wind

Potential for CO₂ avoidance from 1 MJ wind electricity

- C-H₂, Ely (cen), ICE
- C-H₂, Ely (cen), FC
- Electricity (vs Coal, state-of-the-art)
- Electricity (vs NG, CCGT)

Reference case: 2010 ICE with Conventional fuel

g CO₂ avoided / MJ wind electricity
Conclusions

- A shift to renewable/low fossil carbon routes may offers a significant GHG reduction potential but generally requires more energy. The specific pathway is critical.

- No single fuel pathway offers a short term route to high volumes of "low carbon" fuel.
  - Contributions from a number of technologies/routes will be needed.
  - A wider variety of fuels may be expected in the market.
  - Blends with conventional fuels and niche applications should be considered if they can produce significant GHG reductions at reasonable cost.

- Transport applications may not maximize the GHG reduction potential of renewable energies.

- Optimum use of renewable energy sources such as biomass and wind requires consideration of the overall energy demand including stationary applications.
Well-to-Wheels analysis of future automotive fuels and powertrains in the European context

The study report is available on the WEB:
http://ies.jrc.cec.eu.int/Download/eh

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