Life Cycle Analysis of Hydrogen Fuel

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Overview

- Principles of Life Cycle Assessments (LCA)
- Hydrogen Fuel Pathways
- Life Cycle Analysis of Hydrogen Fuel Pathways: Results
- Conclusions

Principles of Life Cycle Assessments (LCA)

- The Scope
- Methodological Difficulties and Limitations
- The Data

Life Cycle Assessment (LCA) - The Scope

Life Cycle Assessment (LCA):

The comprehensive analysis of the environmental impact caused by a product during its life cycle, comprising its

- **Production**
- **Use**
- **Disposal**

Environmental impact is mainly caused by the consumption / transformation of materials and energies (a definition of LCA is given in ISO 14040 ff). Therefore LCA looks at

- **material flows,**
- **energy use, and**
- **associated emissions (especially greenhouse gas emissions).**

Costs are not an issue within LCA! But costs are certainly a main consideration in decision making.

Life Cycle Assessment (LCA) of Hydrogen Fuel

LCA of HYDROGEN FUEL has to analyse material flows, energy flows and emissions, caused by

(1) the production of the fuel supply infrastructure and of the vehicles,

(2) the production of the hydrogen fuel,

(3) the use of the fuel (therefore the vehicle has to be included in the analysis!),

(4) the dismantling and disposal of supply infrastructure and vehicles.

Topics (2) and (3) are addressed in Well-To-Tank and in Tank-To-Wheel analyses.

A comprehensive LCA should also investigate topics (1) and (4). But this is often not done, due to

- **a difficulty of data collection and /or**
- **a presumption that the effects are of minor importance**

(we will show some relevant data for topics (1), (2) and (3) later).

LCA: Methodological Difficulties and Limitations

LCA has to cope with a number of difficulties, e.g.:

- **relevant data are uncertain and may vary to some extent,**
- **or are not available in some cases,**
- **some technologies considered are still under development,**
- **it is not always clear, where to draw the boundary for the analysis (also there is the problem of by-products and credits),**
- **there is practically an infinite number of possible fuel pathways,**
- **but only few make sense (which then is already a result of an LCA).**

But despite the theoretical and practical limitations of LCA, this is the best method we have to assess and compare different energy systems.

LCA will always be work in progress. But it helps our understanding of energy systems and gives orientation where to look for the more sustainable solutions.

LCA: Data Sources and Tools

Many institutions are working on LCA and providing relevant data and tools:

- **GEMIS,**
- **Oekoinventare von Energiesystemen (ETH-ESU),**
- **Studies and tools developed by various research institutions (IKARUS, Greet model by ANL, E2database by LBST, MIT, etc.).**

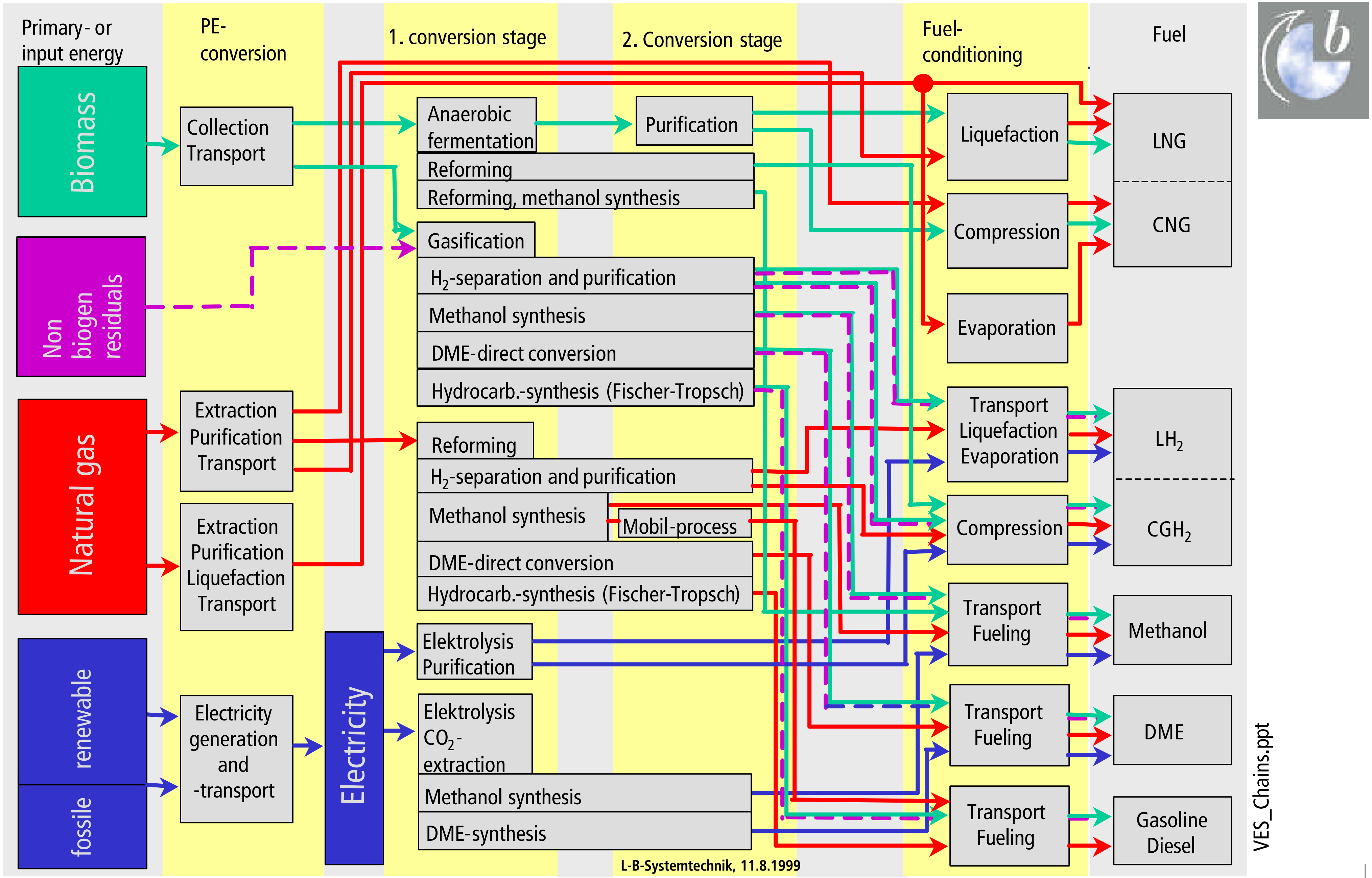
Transparency of data and methods is a precondition for a rational discussion of LCA results.

Hydrogen Fuel Pathways

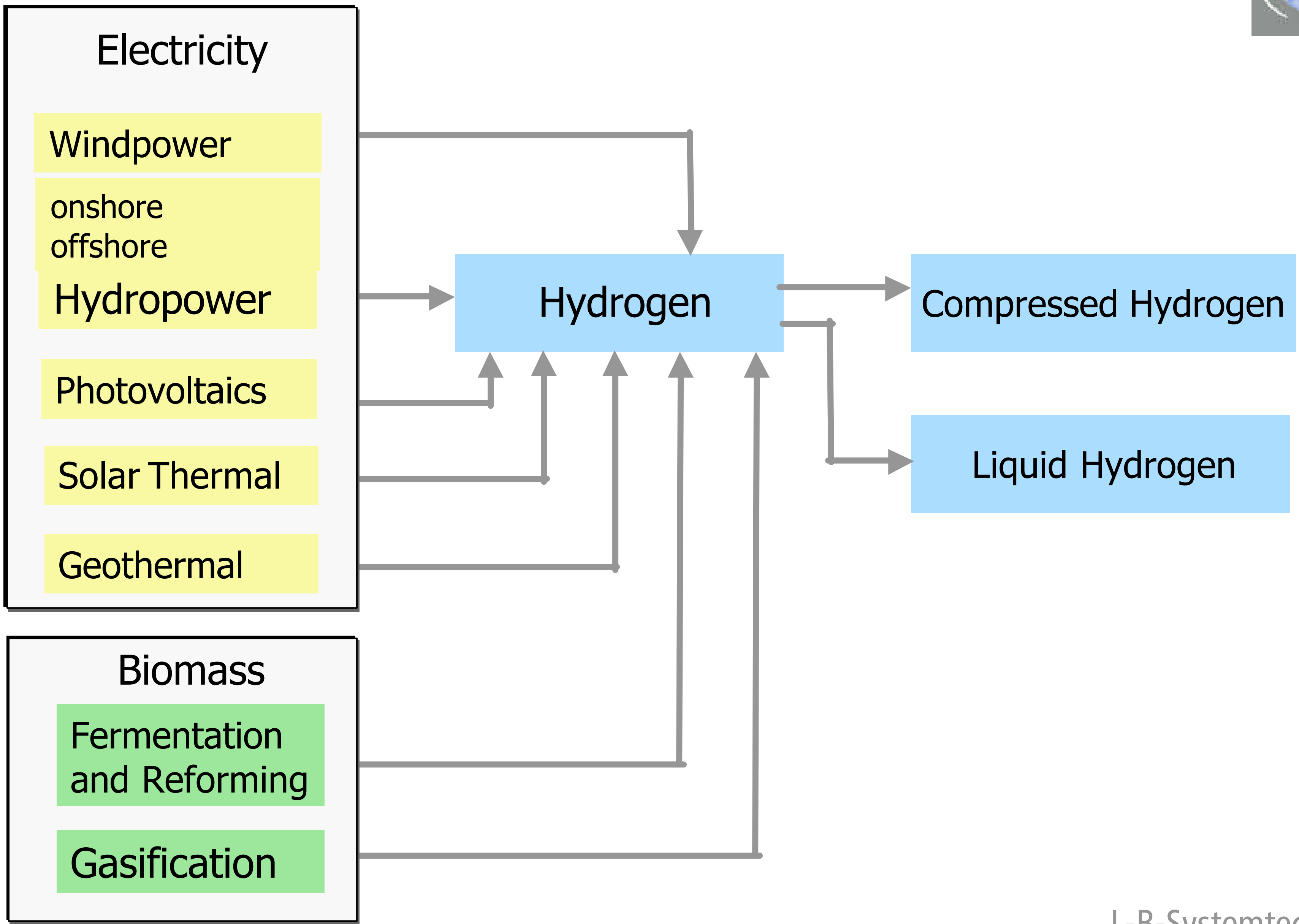
- Fuel Supply (Well-To-Tank)
- Fuel Usage - The Vehicle (Tank-To-Wheel)

Fuel Supply Pathways Including Hydrogen

Crude Oil	Gasoline
	Diesel
Coal	Gasoline
	Methanol
	Hydrogen
Natural Gas	CNG
	Methanol
	FT-Diesel, FT-Naphtha
	Hydrogen (CGH_2, LH_2)
Renewable Electricity	Hydrogen (CGH_2, LH_2)
Electricity (fossil, nuclear)	Hydrogen (CGH_2, LH_2)
Biomass (Lignocellulose)	Hydrogen (CGH_2, LH_2)
	Methanol
	Ethanol
	FT-Diesel, FT-Naphtha
Biomass (Sugar Beet)	Ethanol
Biomass (Rape Seed)	Plant Oil
	RME
Biogas	CMG from Biogas
	Hydrogen (CGH_2)

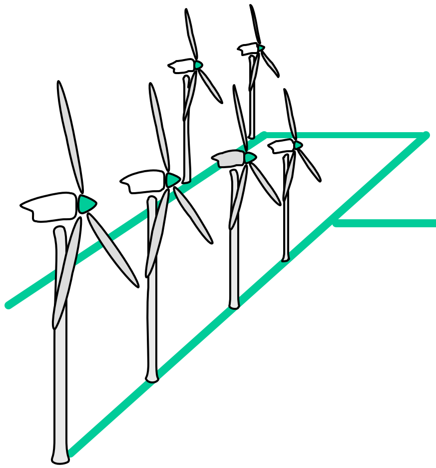

Primary- or input energy
PE-conversion
1. conversion stage
2. Conversion stage
Fuel-conditioning
Fuel
Biomass
Non biogen residuals
Natural gas
renewable
fossile
Collection Transport
Extraction Purification Transport
Extraction Purification Liquefaction Transport
Electricity generation and -transport
Electricity
Anaerobic fermentation
Purification
Reforming
Reforming, methanol synthesis
Gasification
H_2-separation and purification
Methanol synthesis
DME-direct conversion
Hydrocarb.-synthesis (Fischer-Tropsch)
Reforming
H_2-separation and purification
Methanol synthesis
Mobil-process
DME-direct conversion
Hydrocarb.-synthesis (Fischer-Tropsch)
Elektrolysis Purification
Elektrolysis CO_2-extraction
Methanol synthesis
DME-synthesis
Liquefaction
Compression
Evaporation
Transport Liquefaction Evaporation
Compression
Transport Fueling
Transport Fueling
Transport Fueling
LNG
CNG
LH_2
CGH_2
Methanol
DME
Gasoline Diesel
L-B-Systemtechnik, 11.8.1999
VES_Chains.ppt

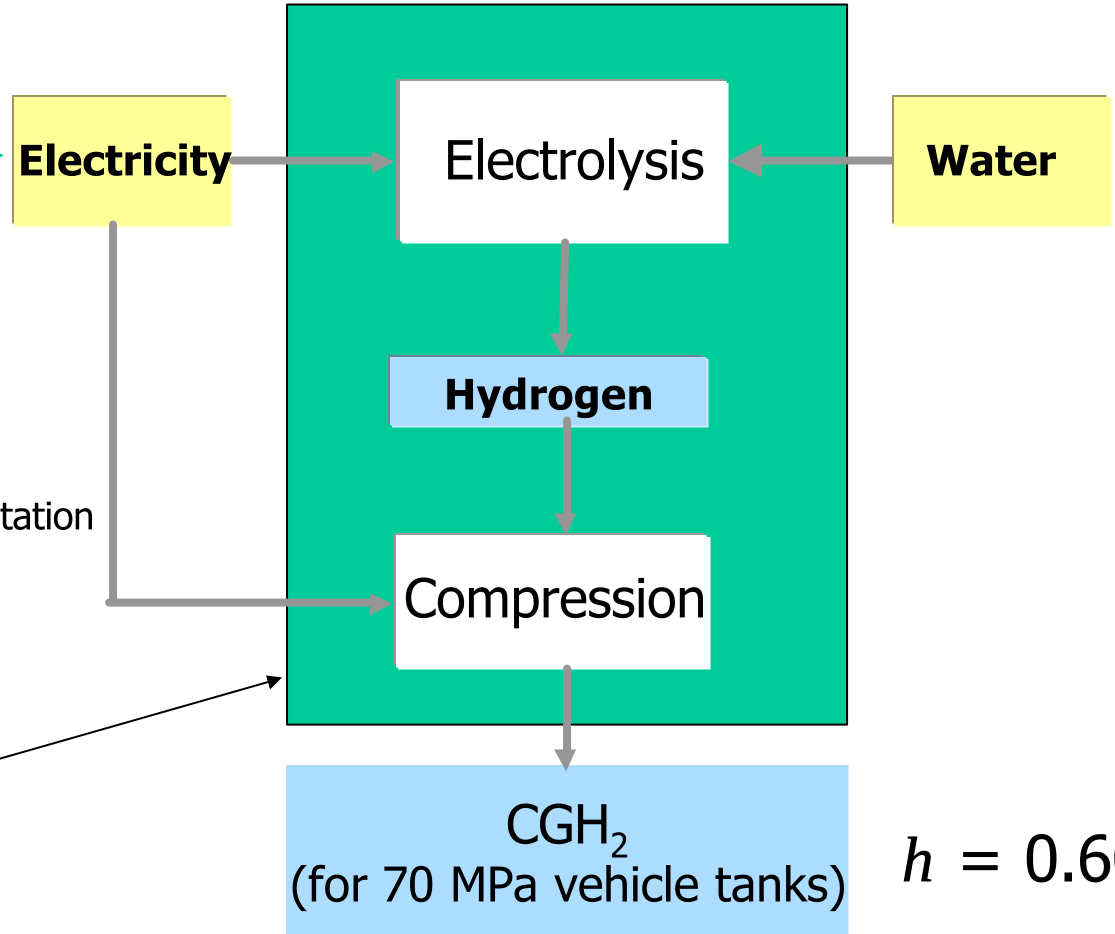
Renewable Hydrogen Fuel Pathways



Electricity-based Compressed Hydrogen (CGH_2)

Compressed hydrogen from renewable electricity
Example: Wind Power



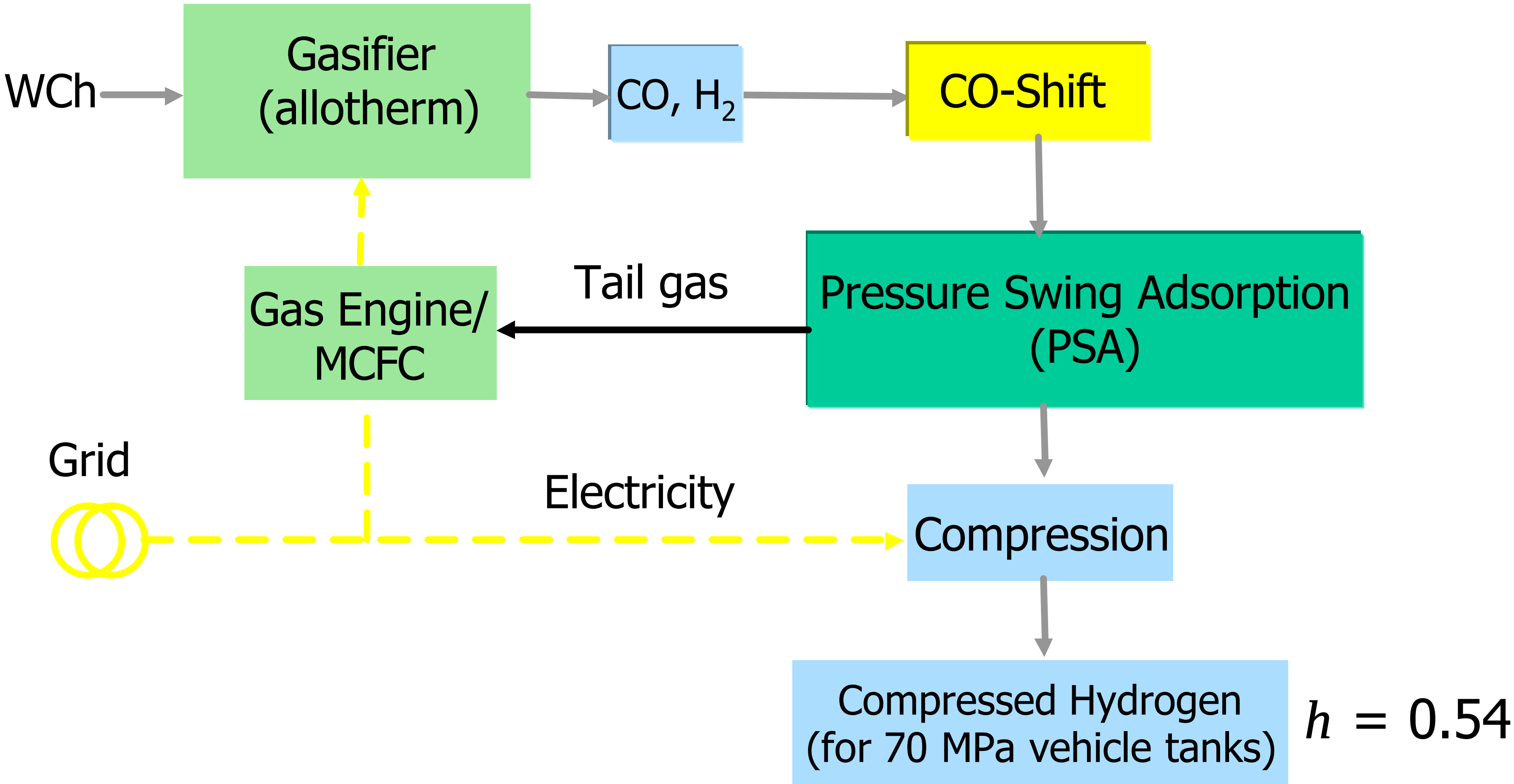


Concept for a CGH_2-Refueling Station (Hydrogen Systems)

$h = 0.60$

Fuels from Biomass: Compressed Hydrogen of Lignocellulose

Example: Gasification of Wood Chips (WCh)



Vehicle Types Considered in the GM WTW-Study

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

Vehicles with different drive-trains and efficiencies

All vehicles based on Opel Zafira	ECE (mpg)	ECE (l/100km)	Engine Efficiency	Vehicle Efficiency	Time, s 0-100kph	% Reduction from Baseline
2002 Production Gasoline Vehicle	28.9	8.15	21.0%	18.2%	11.6 s	+6%
2010 Gasoline Baseline w/MTA	30.7	7.66	22.5%	19.4%	11.6 s	Baseline
Gasoline HEV MTA	41.9	5.61	30.5%	28.6%	9.0 s	-27%
DI Gasoline w/ CV	33.1	7.10	23.6%	21.0%	11.4 s	
DI Gasoline w/ MTA	35.7	6.59	25.2%	22.6%	11.4 s	-14%
DI Gasoline HEV MTA	45.3	5.19	32.9%	30.9%	8.8 s	-32%
DI Diesel w/ CV	35.4	6.64	26.6%	23.6%	11.8 s	
DI Diesel w/ MTA	38.2	6.16	28.5%	25.5%	11.8 s	-20%
DI Diesel HEV MTA	45.4	5.18	34.8%	32.6%	9.4 s	-32%
H2 ICE w/ CV	34.6	6.79	25.9%	22.6%	11.7 s	
H2 ICE w/ MTA	36.9	6.37	27.7%	24.2%	11.7 s	-17%
H2 ICE HEV MTA	50.1	4.70	37.7%	34.9%	9.1 s	-39%
CH2 FC	65.6	3.59	56.6%	44.3%	10.7 s	-53%
CH2 FC HEV	71.0	3.31	55.6%	48.9%	9.5 s	-57%
LH2 FC	67.1	3.51	56.6%	44.3%	10.4 s	-54%
LH2 FC HEV	72.6	3.24	55.6%	48.9%	9.3 s	-58%

CV - MT5 w/ manual shift; MTA - 5-Speed w/ auto shift; DI - Direct Injection
HEV - Parallel Hybrid Electric Vehicle with Charge Sustaining Control Strategy

Source: GM 2002

Vehicle Types Considered in the MIT Study

	Fuel consumption [$l_{gasoline\ equiv}$/(100 km)]	CO_2 [g/km]
ICE Gasoline Baseline	5.4	128
ICE Gasoline Advanced	4.8	114
ICE Gasoline Hybrid	3.3	78
ICE Diesel Advanced	4.1	96
ICE Diesel Hybrid	2.9	67
FC H_2	2.1	0
FC H_2 hybrid	1.8	0

[MIT 2003] Weiss, M., A.; Heywood, J., B.; Schafer, A.; Natarajan, V., K.; MIT: Comparative Assesment of Fuel Cell Cars; February 2003

For these vehicles the energies and emissions for the manufacturing were calculated. For reasons of comparability and consistency these vehicles were used for the calculation of the results shown in the next chapter.

Life Cycle Analysis of Hydrogen Fuel Pathways:

Results

Life Cycle Analyses with LBST Involvement

TES - Transport Energy Strategy [1998 - 2001]

GM WTW-Study - "Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems - A European Study" [2001 - 2002]

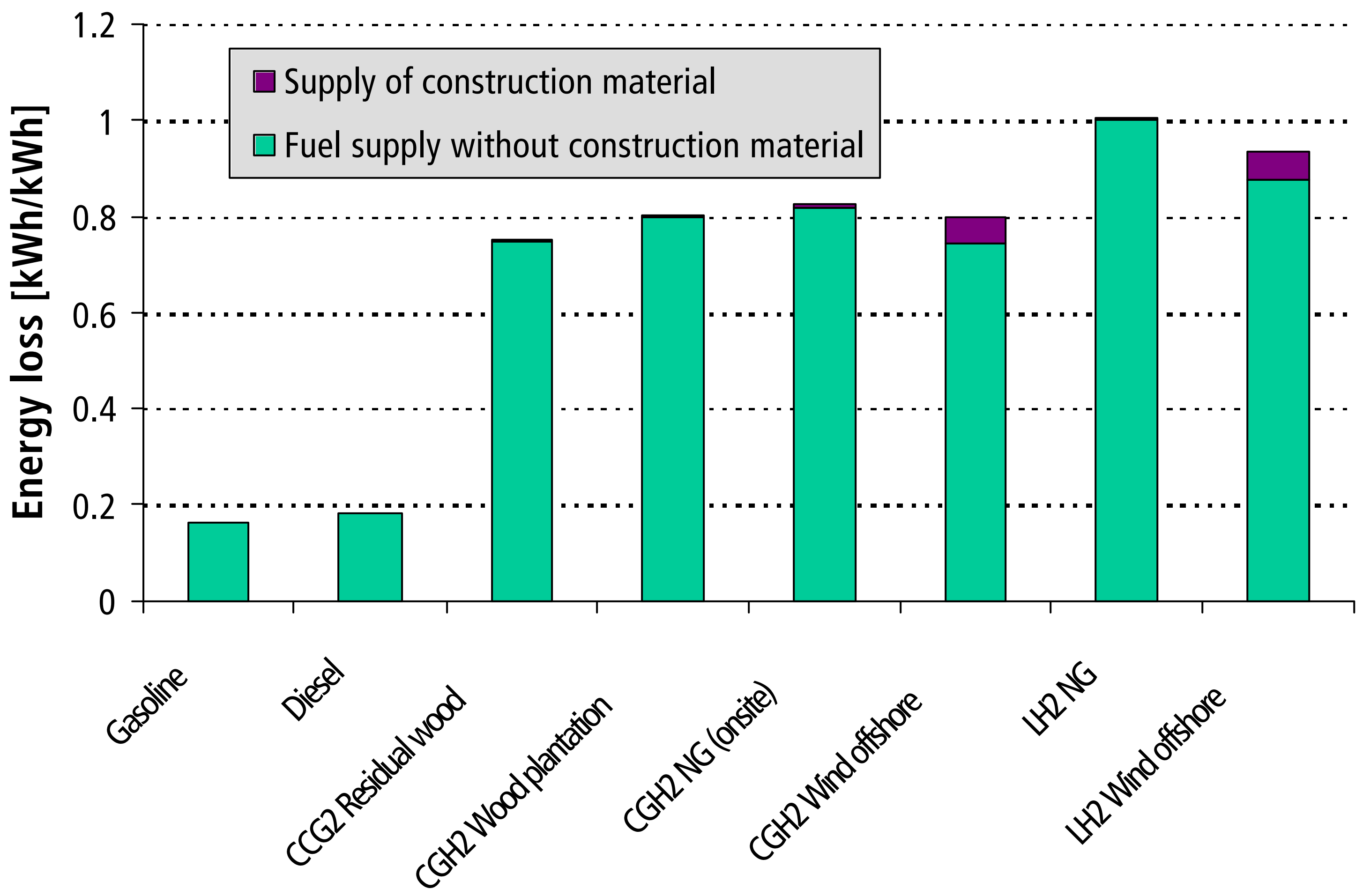
BStMLU-Studie - "Vergleich verschiedener Antriebskonzepte im Individualverkehr im Hinblick auf Energie- und Kraftstoffeinsparung“ (Comparison of different passenger car propulsion concepts with regard to energy and fuel savings) [2001 - 2002]

FCSHIP - “Fuel Cell Technology in Ships” [2002 - 2004]

EUCAR/JRC/CONCAWE - Well-to-Wheels Assessment of Alternative Road Transport Fuels - Well-to-Tank [2002 - 2003]

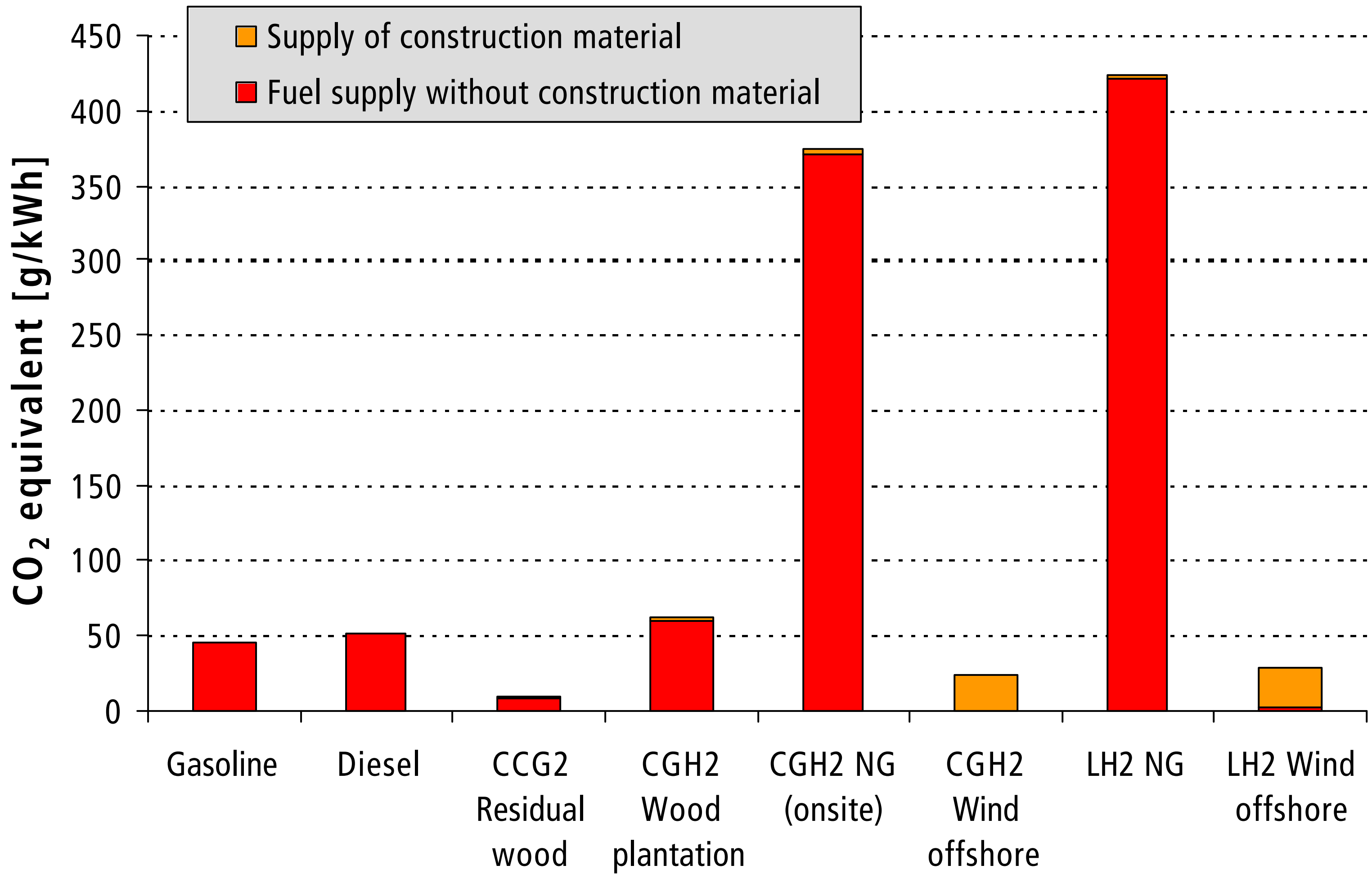
HyWays - “European Hydrogen Energy Roadmap Activity” [presumably from 2004 on]

Energy Loss of Fuel Supply (WTT) - per Energy Content



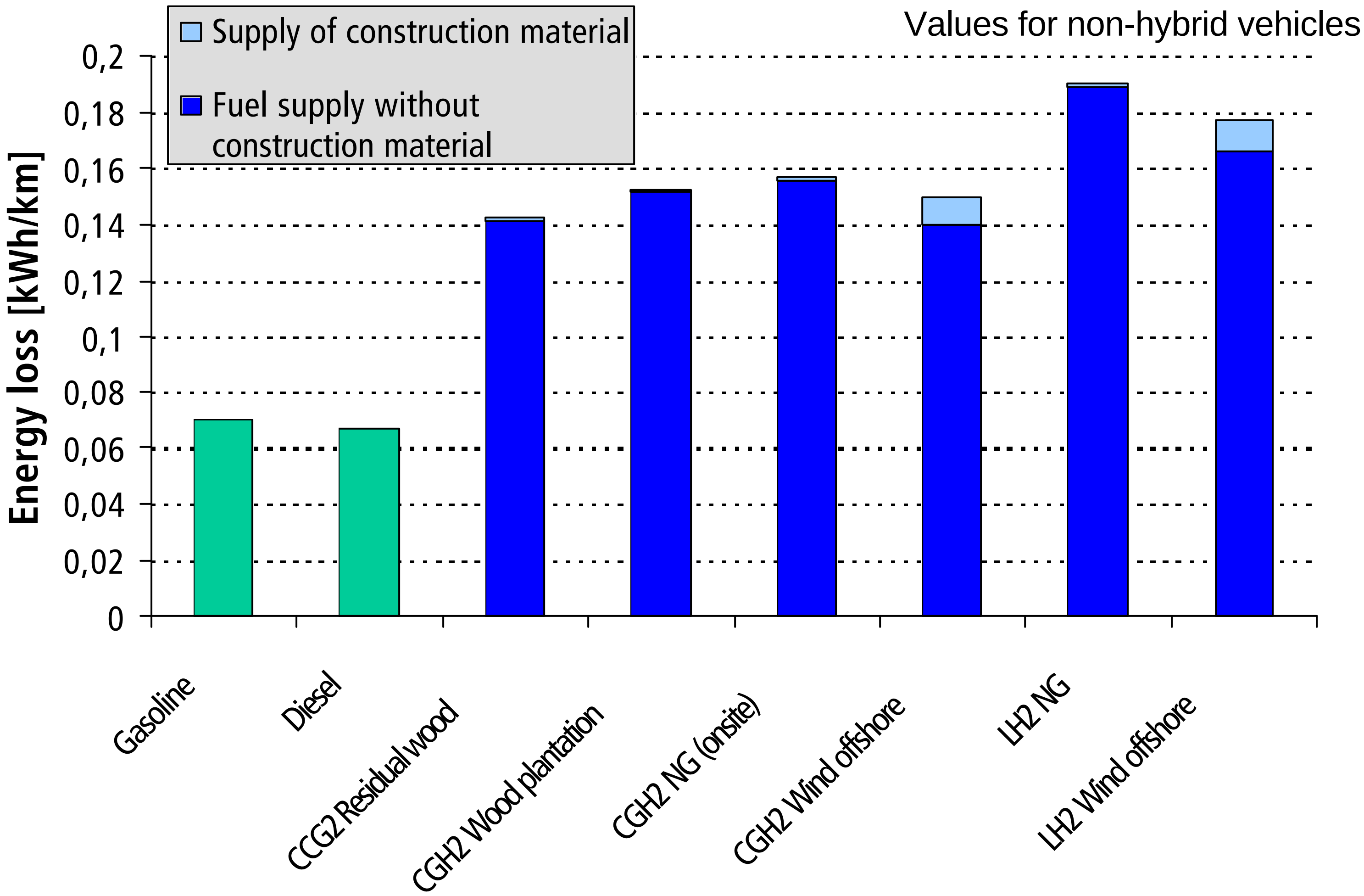
Source LBST, Energy requirements and GHG emissions for construction material: preliminary estimate

GHG Emissions of Fuel Supply (WTT) - per Energy Content



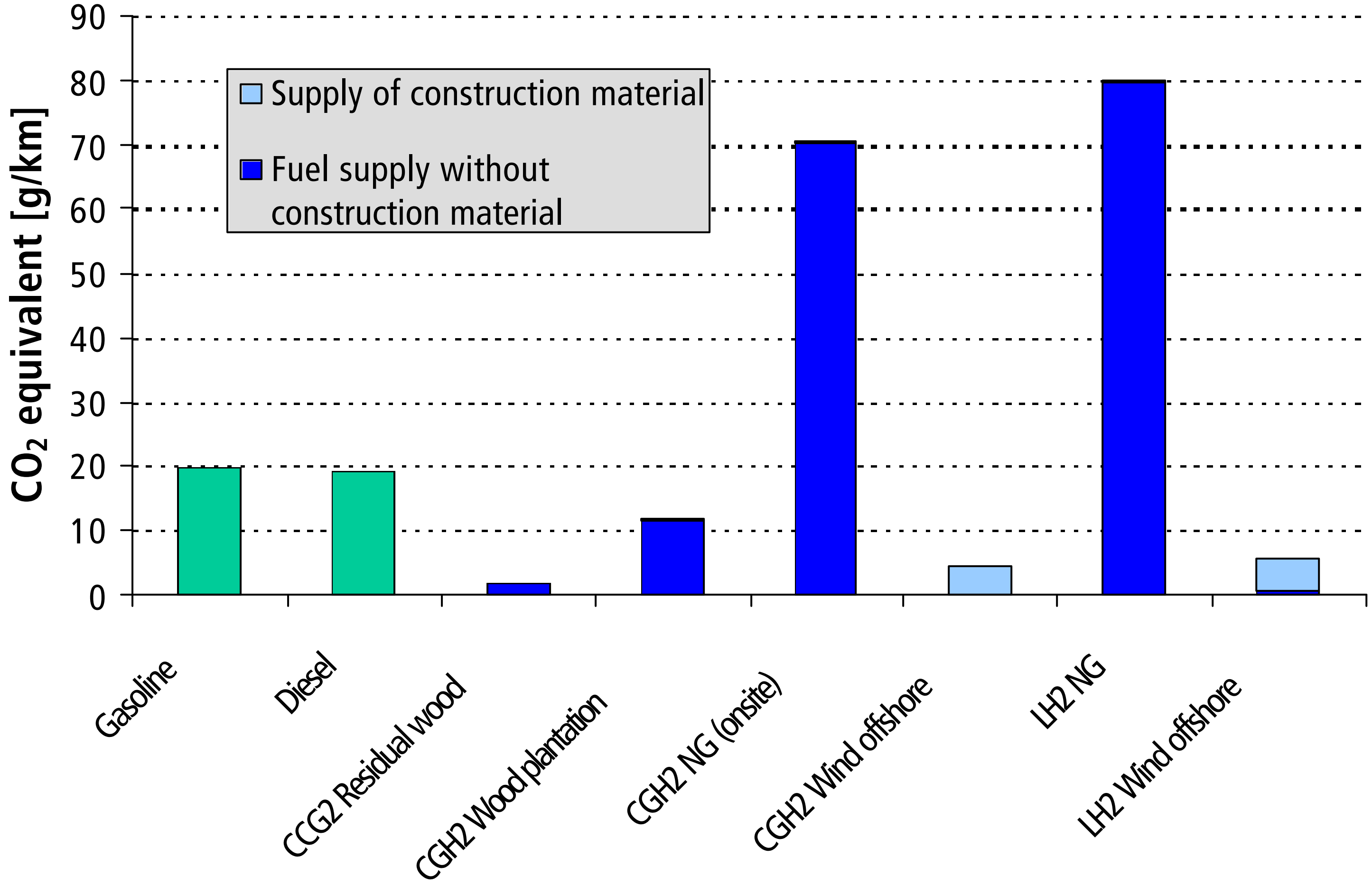
Source LBST, Energy requirements and GHG emissions for construction material: preliminary estimate

Energy Loss of Fuel Supply (WTT) - per Vehicle-km



Fuel consumption vehicle: [MIT 2003] Weiss, M., A.; Heywood, J., B.; Schafer, A.; Natarajan, V., K.;
MIT: Comparative Assesment of Fuel Cell Cars; February 2003
Fuel supply: LBST

GHG Emissions of Fuel Supply (WTT) - per Vehicle-km



Fuel consumption vehicle: [MIT 2003] Weiss, M., A.; Heywood, J., B.; Schafer, A.; Natarajan, V., K.;
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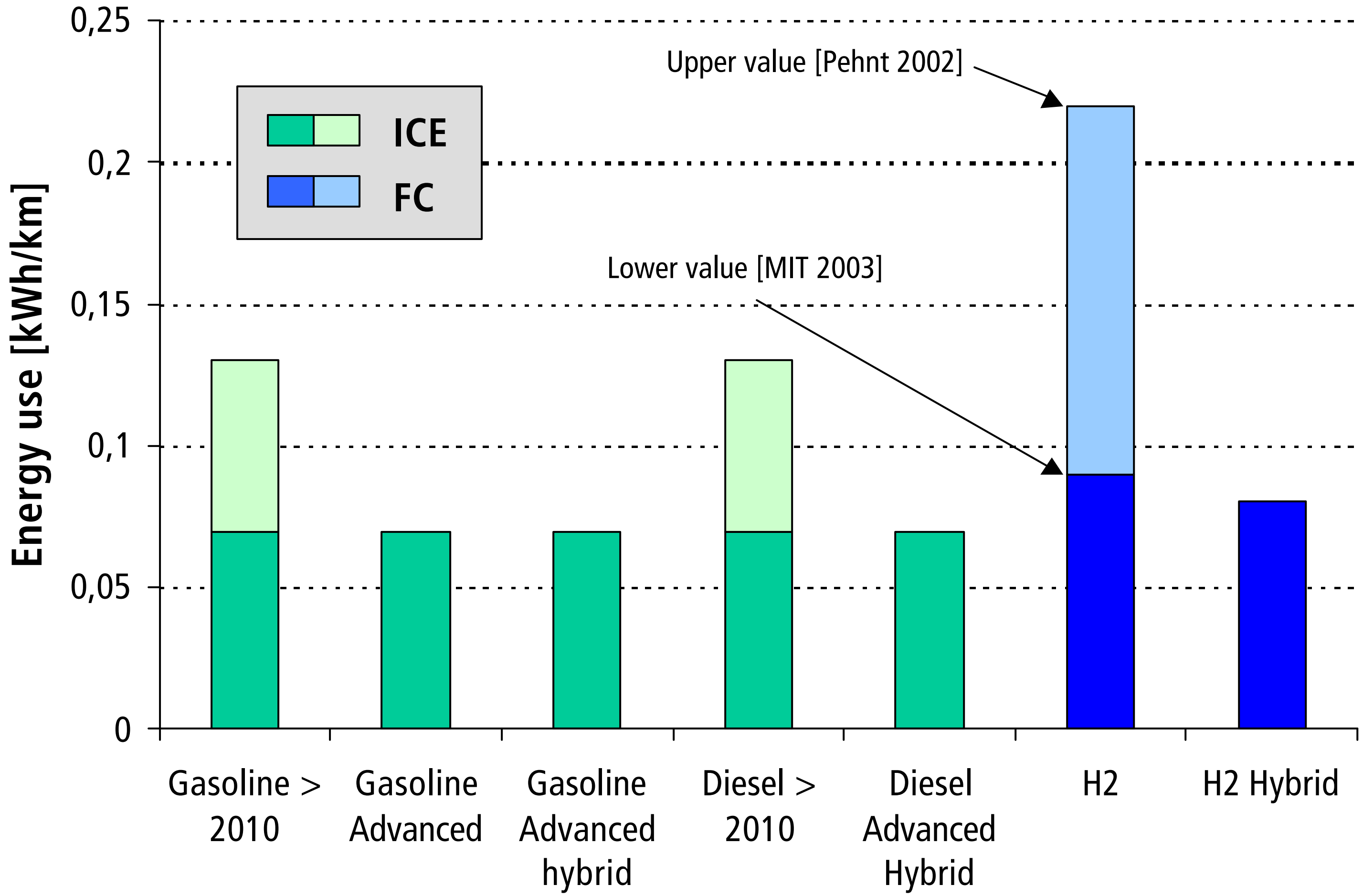
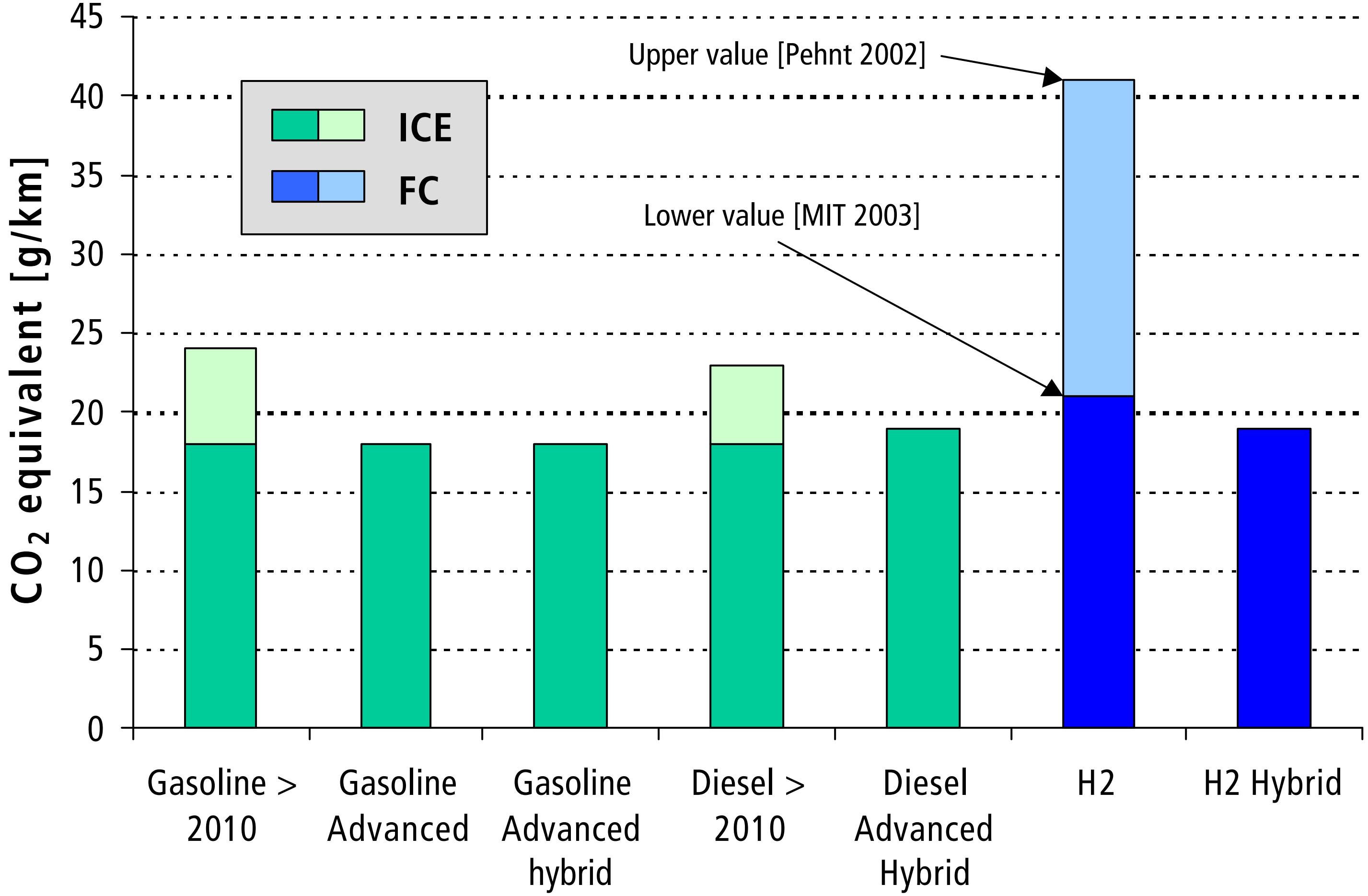
Energy use for Vehicle Manufacturing



[MIT 2003] Weiss, M., A.; Heywood, J., B.; Schafer, A.; Natarajan, V., K.; MIT: Comparative Assesment of Fuel Cell Cars; February 2003
[Pehnt 2002]Pehnt, M.: Ganzheitliche Bilanzierung von Brennstoffzellen in der Energie- und Verkehrstechnik; VDI Verlag, Düsseldorf 2002

GHG Emissions of Vehicle Manufacturing



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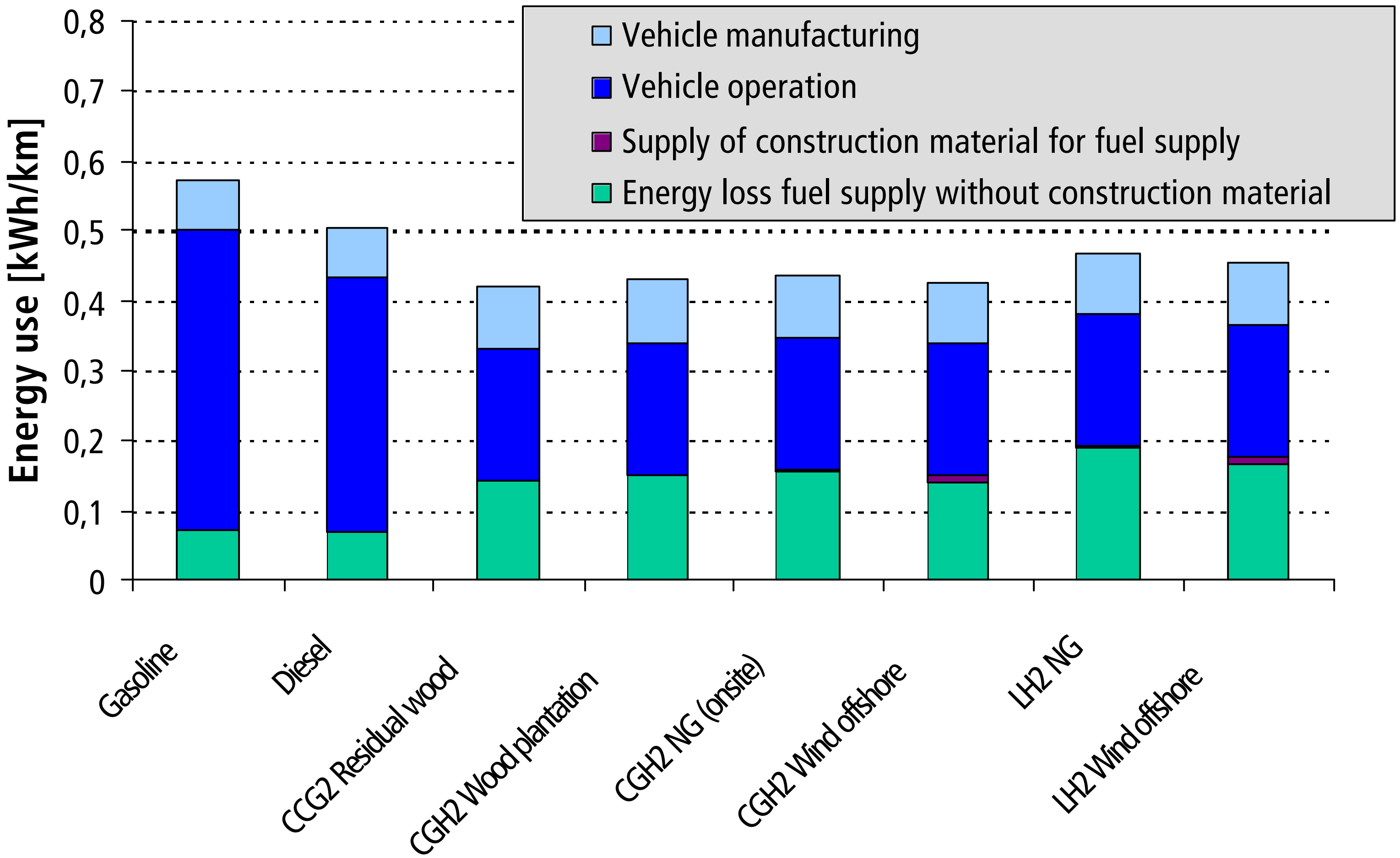
Energy Use Well-To-Wheel: Non-hybrid Vehicles



Fuel consumption of vehicles and energy requirements and GHG emissions for vehicle manufacturing:
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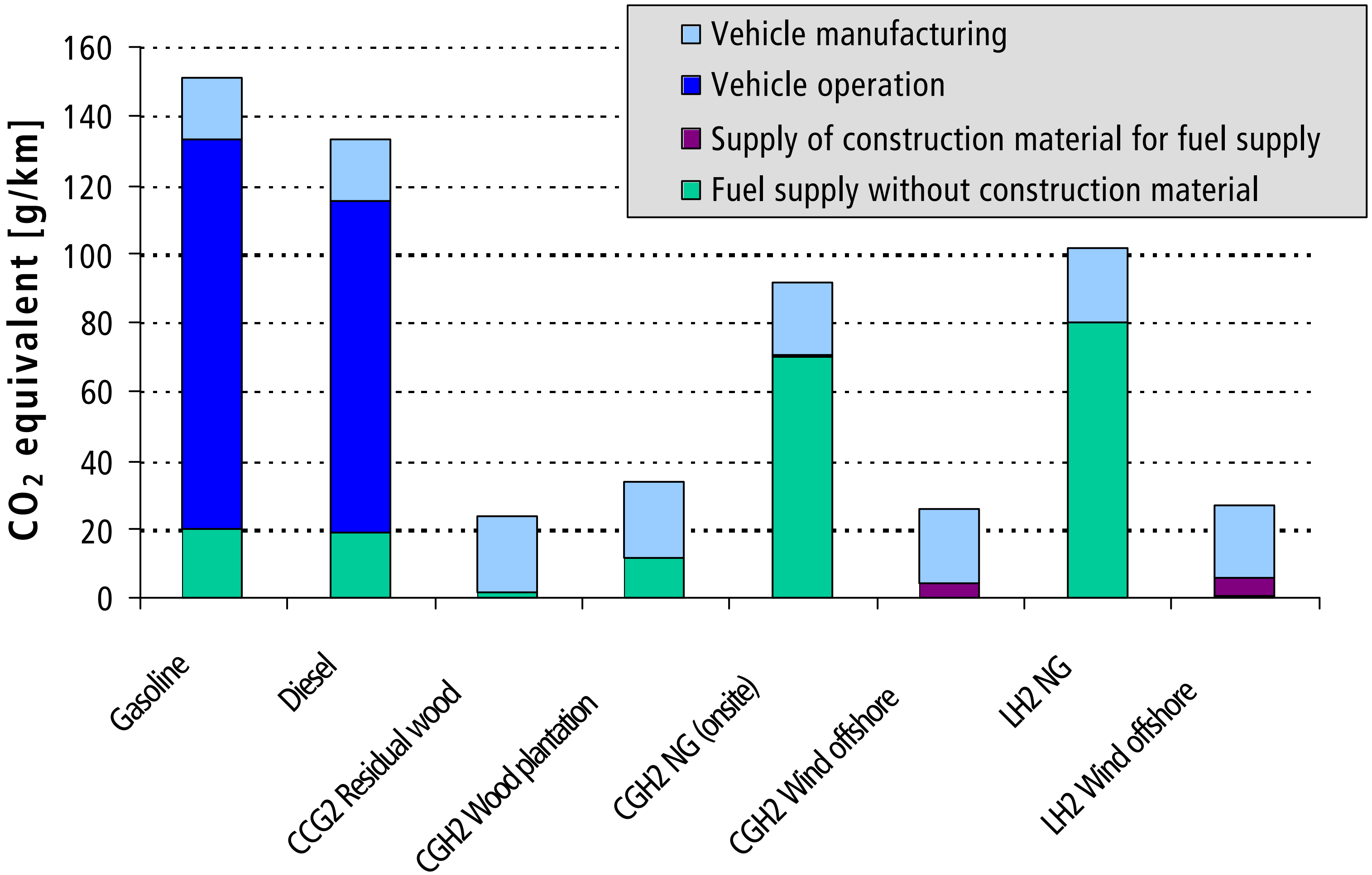
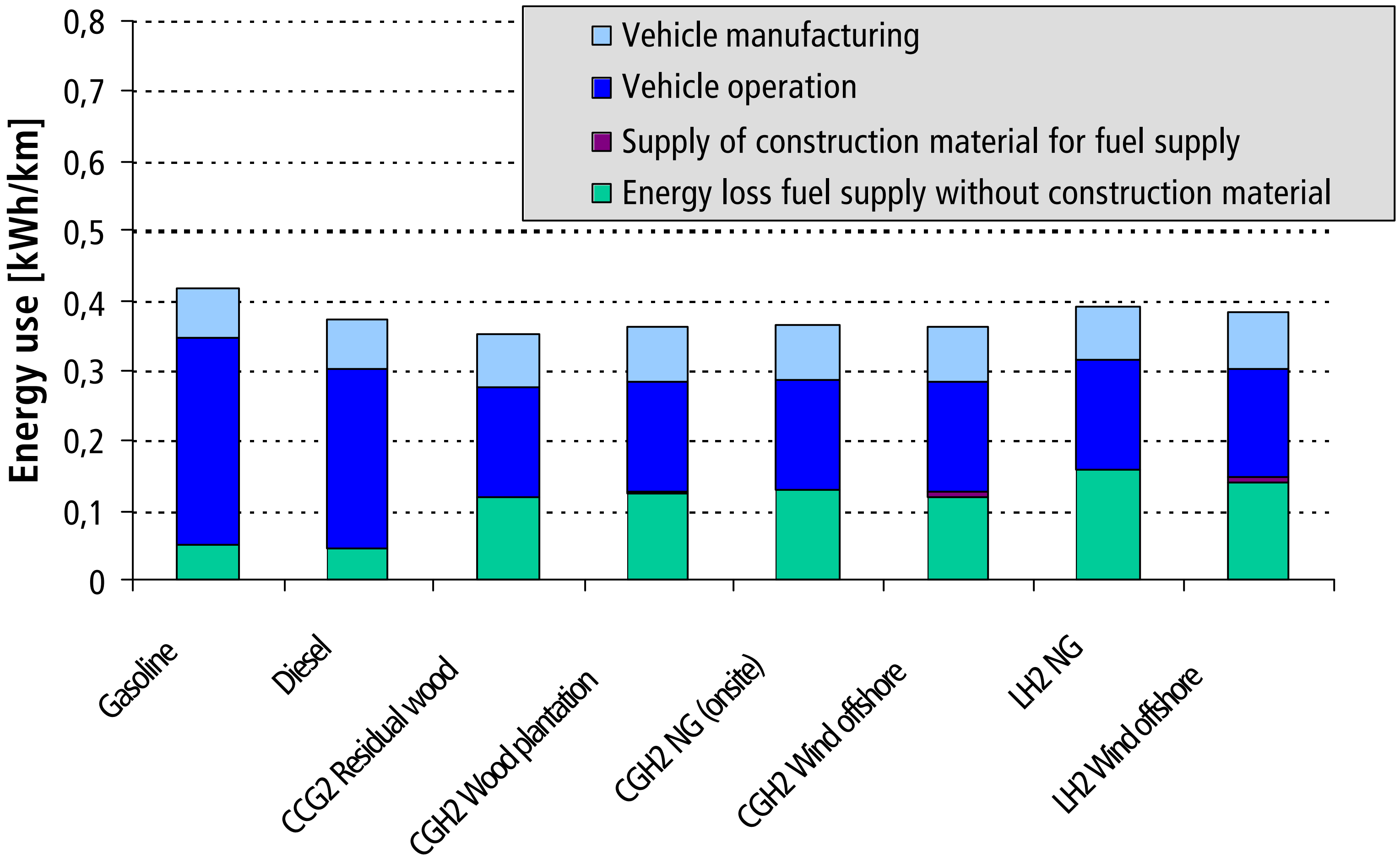
Fuel supply: LBST

GHG Emissions Well-To-Wheel: Non-hybrid Vehicles



Fuel consumption of vehicles and energy requirements and GHG emissions for vehicle manufacturing: [MIT 2003] Weiss, M., A.; Heywood, J., B.; Schafer, A.; Natarajan, V., K.; MIT: Comparative Assesment of Fuel Cell Cars; February 2003
Fuel supply: LBST

Energy Use Well-To-Wheel: Hybrid Vehicles



Fuel consumption of vehicles and energy requirements and GHG emissions for vehicle manufacturing:
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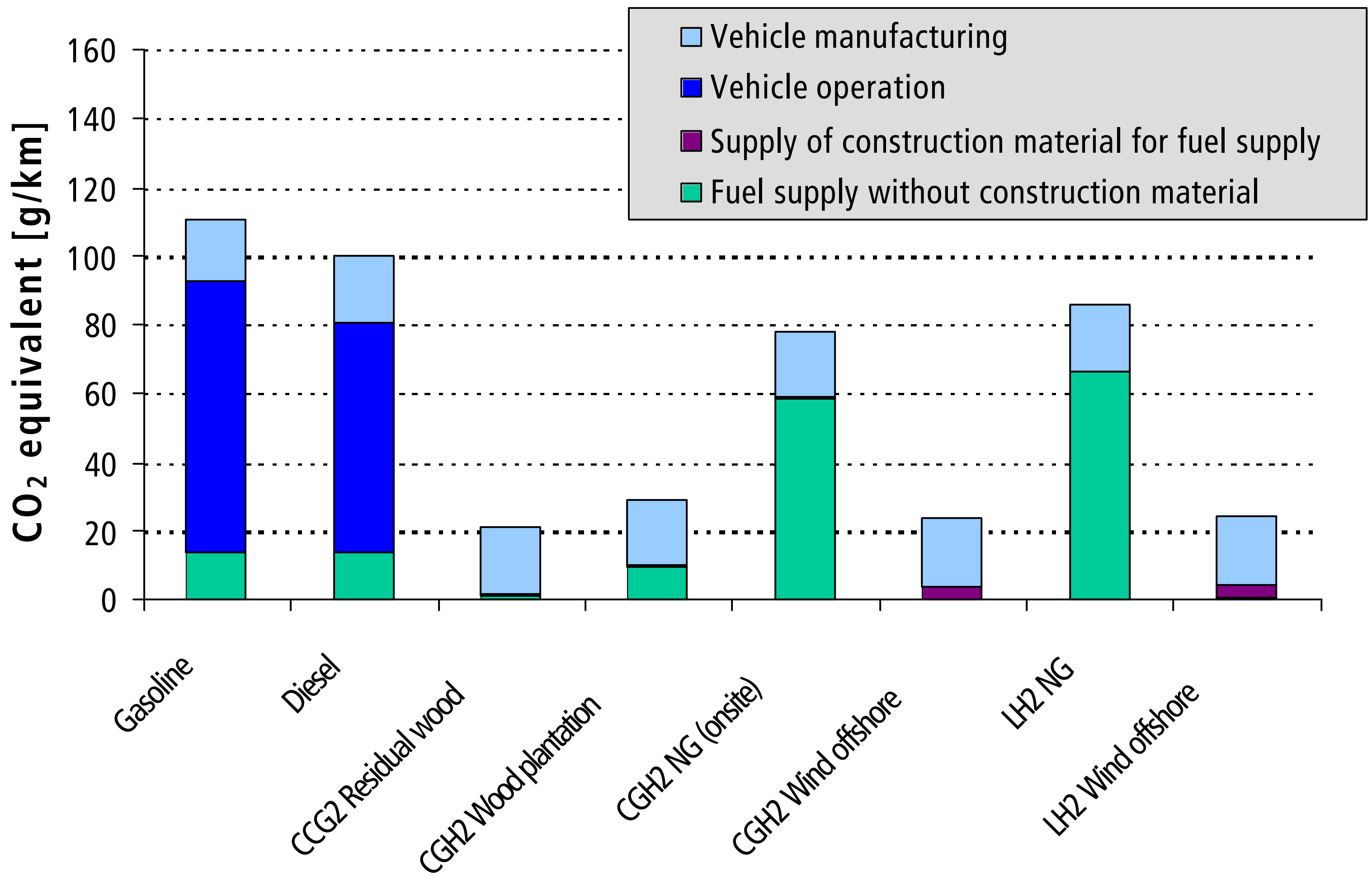
MIT: Comparative Assesment of Fuel Cell Cars; February 2003
Fuel supply: LBST

GHG Emissions Well-To-Wheel: Hybrid Vehicles



Fuel consumption of vehicles and energy requirements and GHG emissions for vehicle manufacturing:
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Fuel supply: LBST

Results of Life Cycle Analyses

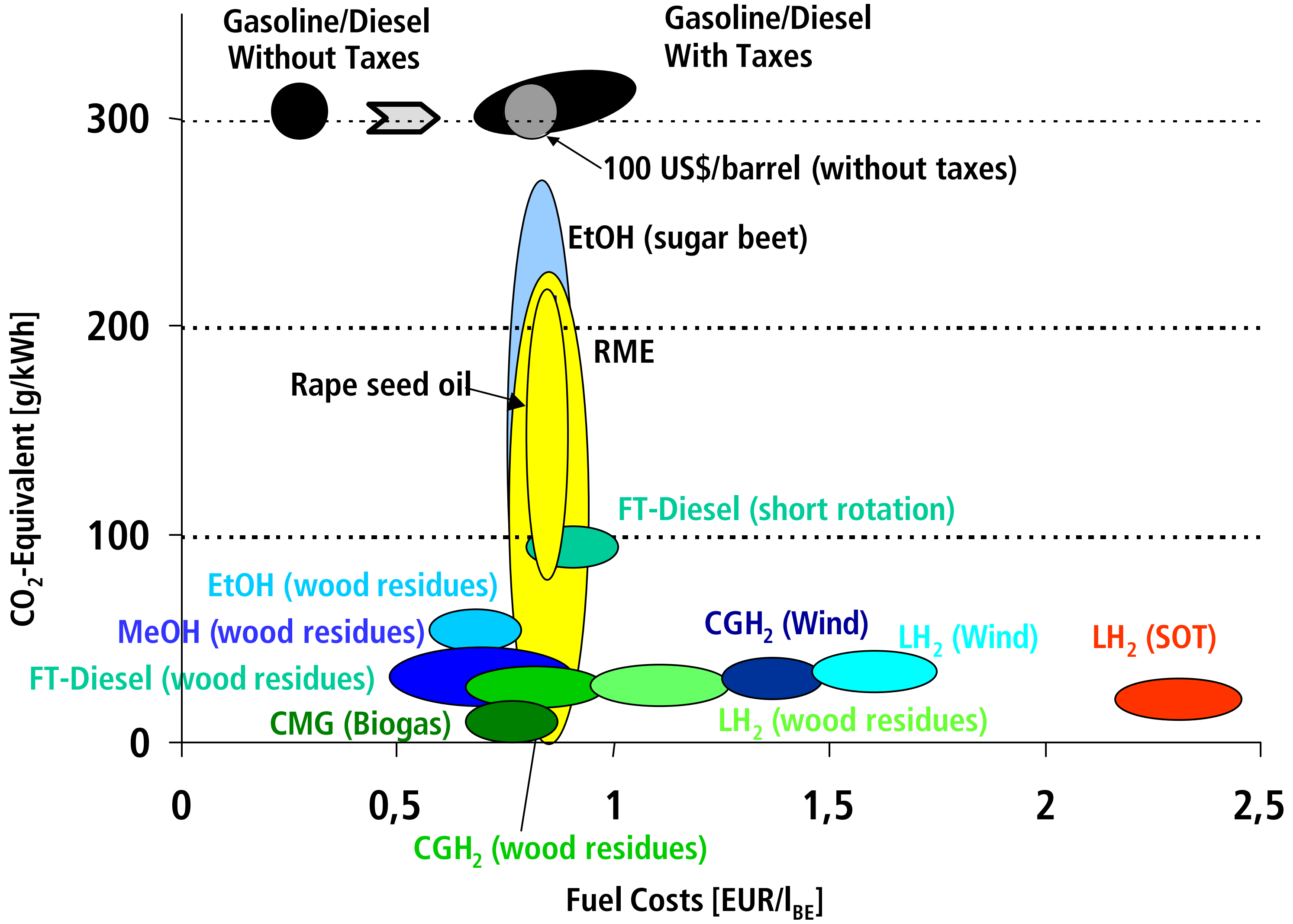
- WTT analyses may result in different conclusions than WTW analyses.
- The advantage of hydrogen fuel depends to a great extent on the fuel supply chain and becomes obvious only in the WTW context.
- A complete and adequate LCA of fuels is not possible without taking into account the vehicle and its powertrain.
- Hydrogen has the highest feedstock flexibility of all fuels.
- Renewable energy derived hydrogen is the superior fuel pathway regarding GHG emissions.

Life Cycle Analyses (Cont.'d)

- Energy requirements for the manufacturing of components and of vehicles do not change the overall trends in the development of energy efficiencies and GHG emissions in the well-to-wheels context

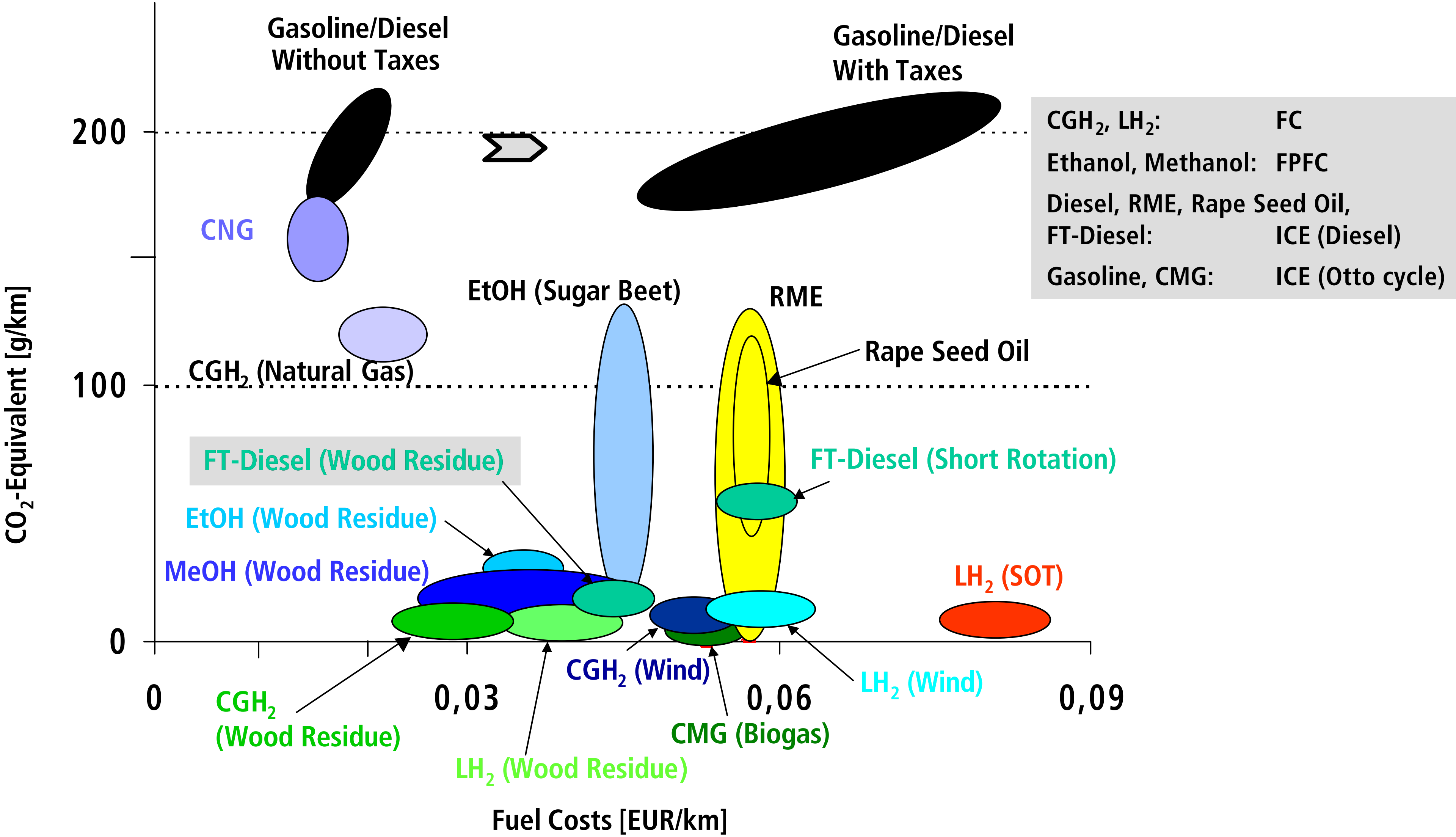
- An LBST study also has shown that advanced vehicle concepts (like Hypercar^{TM}) when adapted for everyday use are not anymore really superior in performance and LCA-criteria to advanced 'conventional' vehicle designs

Fuel Costs Normalized on 1 Liter of Gasoline (H_u = 8,9 kWh/l)



CGH_2 from Natural Gas
(onsite SR):
370 g/kWh
0.62 EUR/l_{GE})

Fuel Costs per km-Driven in Europe



Assessments and Conclusions

Conclusions

- LCA results for fuel chains are not very much affected by the inclusion of the energies needed for providing the fuel infrastructure.
- To a lesser extent this is also true for the vehicle. The consideration of energies and emissions associated with the production of vehicles does not change the ranking of WTW analyses which only consider fuel production and fuel use.
- There still remain uncertainties regarding energies needed for the production of fuel cell vehicles. But even rather high estimates would only add appr. another 20 g of GHG emissions per vehicle-km.

Conclusions (Cont.'d)

- Hydrogen fuels used in an appropriate way are the preferred option for sustainable fuels in transportation
  - flexible (e.g. feedstock)
  - environmentally beneficial
  - allowing a smooth transition from fossil to renewable energy sources