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

concawe

EUCAR
EUROPEAN COUNCIL FOR AUTOMOTIVE R&D

WTW

Version 2c

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

A joint study by **EUCAR / JRC / CONCAWE**

EFV GENEVA

Friday 06/06/2008

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.

  - Focus on 2010+
  - Marginal approach for energy supplies

Well-to-Wheels Pathways

Resource

Crude oil

Coal

Natural Gas

Biomass

Wind

Nuclear

Fuels

Conventional Gasoline/Diesel/Naphtha

Synthetic Diesel

CNG (inc. biogas)

LPG

MTBE/ETBE

Hydrogen (compressed / liquid)

Methanol

DME

Ethanol

Bio-diesel (inc. FAEE)

Powertrains

Spark Ignition: *Gasoline, LPG, CNG, Ethanol, H_2*

Compression Ignition: *Diesel, DME, Bio-diesel*

Fuel Cell

Hybrids: *SI, CI*, FC

Hybrid Fuel Cell + Reformer

MJ non renewable primary input / *MJ* in the tank

WTT Pathways Decomposition

GXCH: Compressed Hydrogen from piped or remote NG

		Total primary energy consumed	CO2	CH4	N2O	CO2 eq
		MJ/MJ	g/MJ	g/MJ	g/MJ	g/MJ
GPCH1a	**Piped NG, 7000 km, on-site reforming**					
	NG Extraction & Processing	0.04	2.0	0.15	0.000	5.1
	NG Transport	0.29	15.0	0.33	0.001	22.1
	NG Distribution	0.01	0.8	0.00	0.000	0.8
	On-site reforming	0.52	83.9	0.02	0.000	84.5
	On-site delivery	0.20	7.7	0.02	0.000	8.2
	Total chain	1.07	109.4	0.52	0.001	120.7
GPCH1b	**Piped NG, 4000 km, on-site reforming**					
	NG Extraction & Processing	0.04	1.8	0.14	0.000	4.6
	NG Transport	0.14	7.1	0.19	0.000	11.1
	NG Distribution	0.01	0.8	0.00	0.000	0.8
	On-site reforming	0.52	83.9	0.02	0.000	84.5
	On-site delivery	0.20	7.7	0.02	0.000	8.2
	Total chain	0.91	101.3	0.37	0.001	109.3
GMCH1	**NG EU-mix, 1000 km, on-site reforming**					
	NG Extraction & Processing	0.04	1.7	0.1	0.0	4.4
	NG Transport	0.03	1.7	0.0	0.0	2.7
	NG Distribution	0.01	0.8	0.0	0.0	0.9
	On-site reforming	0.52	85.8	0.0	0.0	86.4
	On-site delivery	0.20	7.7	0.0	0.0	8.2
	Total chain	0.81	97.8	0.22	0.001	102.5

GHG(g) in CO2 eq. / MJ in the tank

Tank-to-Wheels Matrix

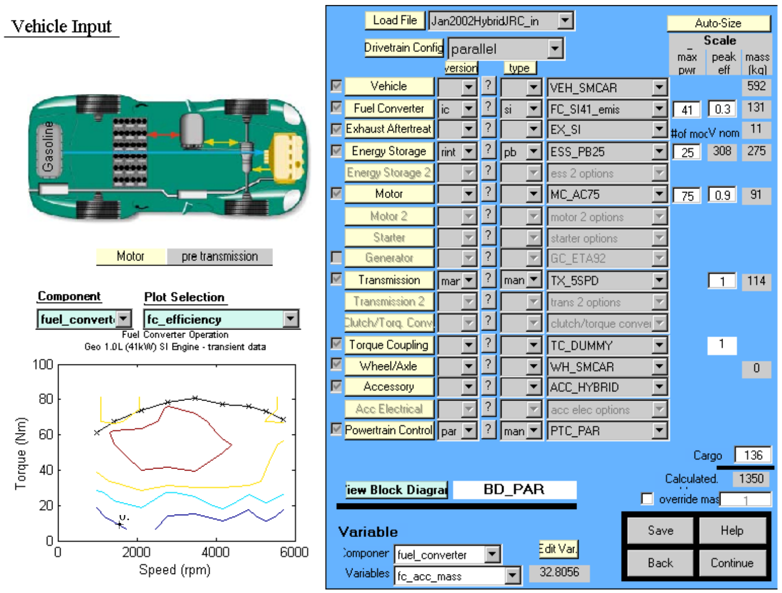
Powertrains	PISI	DISI	DICI	Hybrid PISI	Hybrid DISI	Hybrid DICI	FC	Hybrid FC	Ref. + hyb. FC
Fuels									
Gasoline	2002 2010+	2002 2010+		2010+	2010+				2010+
Diesel fuel			2002 2010+			2010+			2010+
LPG	2002 2010+								
CNG Bi-Fuel	2002 2010+								
CNG (dedicated)	2002 2010+			2010+					
Diesel/Bio-diesel blend 95/5			2002 2010+			2010+			
Gasoline/Ethanol blend 95/5	2002 2010+	2002 2010+			2010+				
Bio-diesel			2002 2010+			2002 2010+			
MTBE/ETBE	2002 2010+	2002 2010+		2002 2010+	2002 2010+				
DME			2002 2010+			2010+			
FT Diesel fuel			2002 2010+			2010+			
Methanol									2010+
Naphtha									2010+
Compressed hydrogen	2010+			2010+			2010+	2010+	
Liquid hydrogen	2010+			2010+			2010+	2010+	

Vehicle Assumptions

Advisor Freeware Model

◎Vehicles simulations with **ADVISOR** Freeware
◎The entire vehicle + powertrain must be described

◎Data collection from manufacturers and others, helped by a data logger (sample below)



VEHICLE DEFINITION

Variable name	Type	Unit	ADVISOR name	FIAT Multipla
First coefficient of rolling resistance	Scalar	--	*veh_1st_rrc*	0.01
Second coefficient of rolling resistance	Scalar	s/m	*veh_2nd_rrc*	0.00
Coefficient of aerodynamic drag	Scalar	--	*veh_CD*	0.36
Vehicle frontal area	Scalar	m^2	*veh_FA*	2.60
Height of the vehicle center of gravity	Scalar	m	*veh_cg_height*	0.50
Fraction of total vehicle mass	Scalar	--	*veh_front_wt_fraction*	0.60
Distance between front and rear axle	Scalar	m	*veh_wheelbase*	2.67
Mass of the vehicle without components	Scalar	kg	*veh_glider_mass*	900
Test mass including fluids, passengers and cargo	Scalar	kg	*veh_mass*	unknown
Cargo mass	Scalar	kg	*veh_cargo_mass*	200

FUEL CONVERTER - CONVENTIONAL

Variable name	Type	Unit	ADVISOR name	FIAT Multipla
Engine size (cylinder displacement)	Scalar	L	*fc_disp*	1.9
Vector of engine speed used to index other variables	Vector	rad/s	*fc_map_spd*	73-605
Vector of engine torque used to index other variables	Vector	N*m	*fc_map_trq*	0.0-144
Fuel use indexed by engine speed and torque	Matrix	g/s	*fc_fuel_map*	14-100
Engine out CO indexed by engine speed and torque	Matrix	g/s	*fc_co_map*	0-100
Engine out HC indexed by engine speed and torque	Matrix	g/s	*fc_hc_map*	0-100
Engine out NOx indexed by engine speed and torque	Matrix	g/s	*fc_nox_map*	0-100
Engine out PM indexed by engine speed and torque	Matrix	g/s	*fc_pm_map*	0-100
Fuel density	Scalar	g/L	*fc_fuel_den*	749
Lower heating value of the fuel	Scalar	J/g	*fc_fuel_lhv*	42600
Rotational inertia of the engine	Scalar	$kg{*}m^2$	*fc_inertia*	0.1
Maximum torque output indexed by engine speed	Vector	N*m	*fc_max_trq*	113-144
Fraction of waste heat that goes to exhaust	Scalar	--	*fc_ex_pwr_frac*	0.4
Engine coolant thermostat set temperature	Scalar	C	*fc_tstat*	96
Average heat capacity of engine	Scalar	J/kg/K	*fc_cp*	500
Average heat capacity of hood and engine	Scalar	J/kg/K	*fc_h_cp*	500
Surface area of hood and engine compartment	Scalar	m^2	*fc_hood_area*	1.5

Main OUTPUTS:
On the European Cycle (ECE-EUDC), the results concern:

- *MJ/km* necessary to perform the NEDC cycle
- GHG(g/km) in CO2 eq.emitted along the cycle

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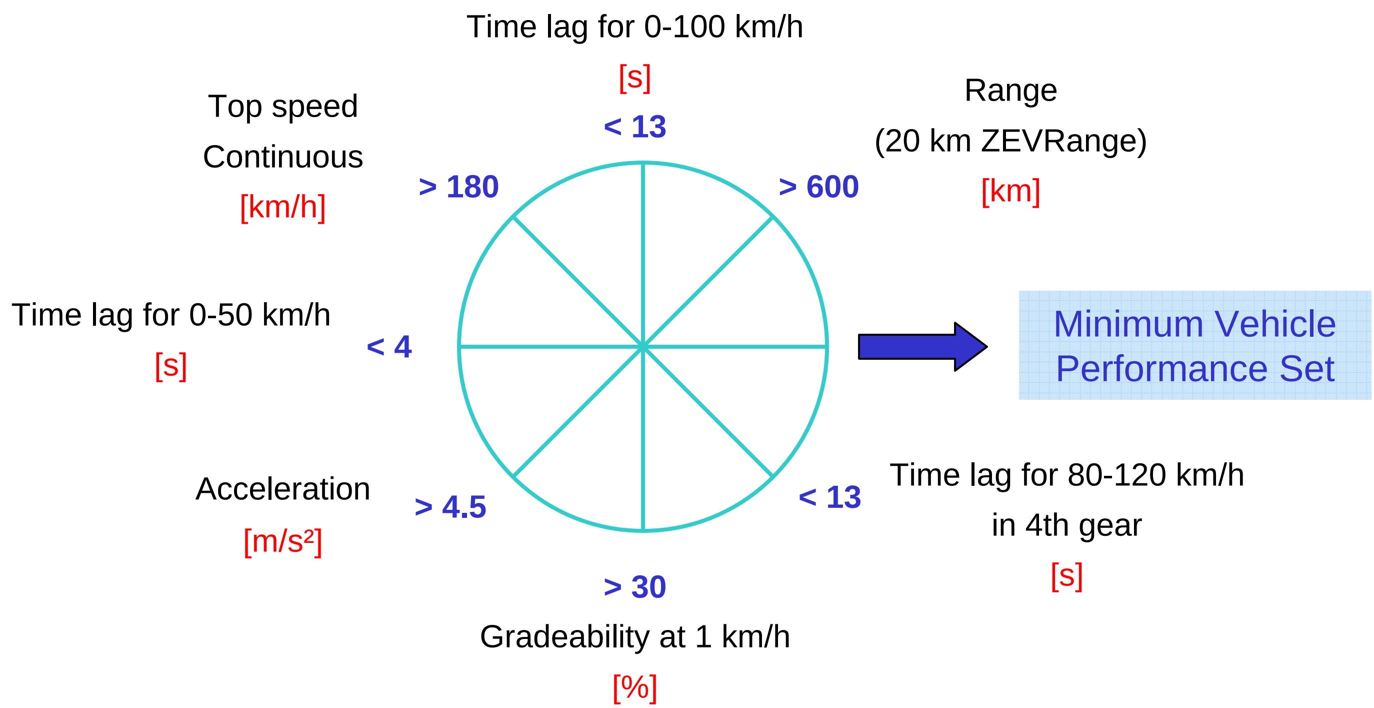
✓ All technologies fulfil at least minimal customer performance criteria



✓ "Vehicle / Fuel" combinations comply with emissions regulations

- **The 2002 vehicles comply with Euro III**
- **The 2010[+] vehicles comply with EU IV**

Vehicle Assumptions

- Simulation of GHG emissions and energy use calculated for a model vehicle
  - Representing the European C-segment (4-seater Sedan)
  - Not fully representative of EU average fleet
- No assumptions were made with respect to availability and market share of the vehicle technology options proposed for 2010+
- Heavy duty vehicles (truck and buses) not considered in this study

➲Version 2c Technology Up-dates

CNG fuel consumption maps

- CNG bi-fuel
  - Fuel consumption map calculated from
    - "% comparison" map (NG v. Gasoline)
    - Combined with the reference 1.6 l gasoline PISI map
  - The bi-fuel engine achieves slightly higher efficiency on CNG than on gasoline, because the ECU calibration can be adjusted to take advantage of the higher octane.

- CNG dedicated
  - fuel consumption map calculated
    - New efficiency map of the bi-fuel engine
    - Efficiency increased by 3 points v. bi-fuel version to account for higher compression ratio
  - For the dedicated engine, it is possible in addition to increase the compression ratio, giving a further efficiency improvement

2002 CNG vehicle performance

		CNG PISI		*Target*
		Bi-fuel	Dedicated	
Time lag for 0-50 km/h	s	**4.5**	3.9	*<4*
Time lag for 0-100 km/h	s	**13.6**	11.8	*<13*
Time lag for 80-120 km/h in 4th gear	s	**13.8**	11.4	*<13*
Time lag for 80-120 km/h in 5th gear	s	18.6	15.1	-
Gradeability at 1 km/h	%	44	52	*>30*
Top speed	km/h	184	193	*>180*
Acceleration	m/s^2	**3.8**	4.4	*>4.0*

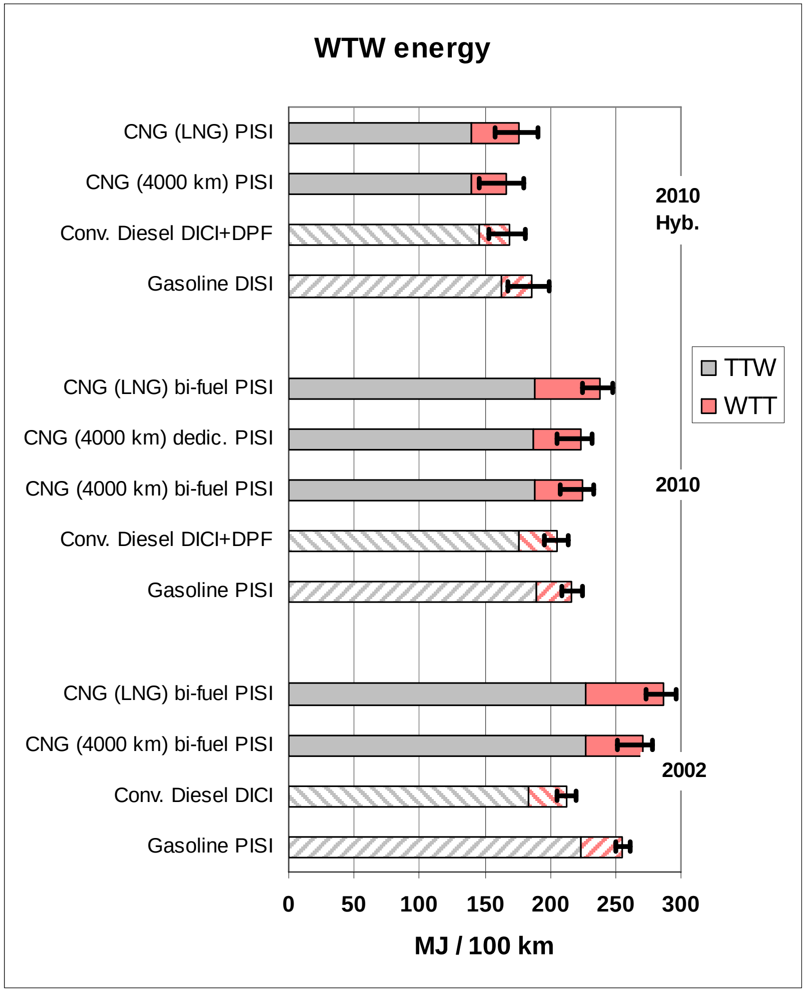
CNG Bi-fuel is still not meeting all performance criteria

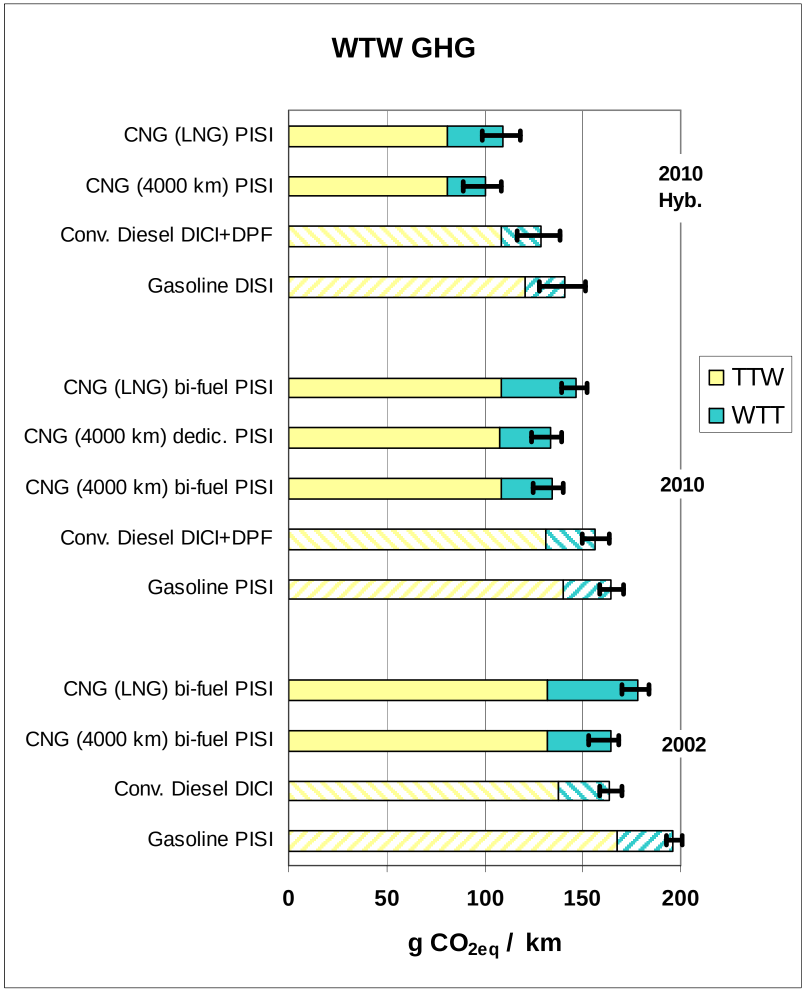
	Fuel consumption (/100 km)			GHG emissions (g CO_2 eq/km)				Engine efficiency	Vehicle efficiency
	MJ	l (*)	kg	as CO_2	as CH4	as N2O	Total	%	%
PISI conventional									
1.6 CNG BiFuel	226.9	7.05	5.03	127.8	3.4	0.9	132.1	19.5	17.3
1.9 CNG dedicated	222.8	6.92	4.94	125.5	3.4	0.9	129.8	19.8	17.6
Gasoline 1.6 l	223.5	6.95	5.21	166.2	.8	.9	167.9	18.7	16.6

GHG TTW reductions (v. gasoline)

- CNG BF vehicle: - 21 % (performance criteria not met)
- CNG Dedicated: - 23 % (performance criteria met)

Compressed Natural Gas (CNG)





Stop & Start

- On the NEDC, fuel consumption during vehicle stop is calculated
- It represents 7.5 % of the total fuel consumption
- Remarks
  - ❐ Energy to restart the engine is not taken into account ↘
  - ❐ The slight modification in engine warm up is not taken into account ↘
- The maximum potential can't be fully retained for "real life" configurations
  - ❐ 3 % is a more realistic figure, Potentially applicable on all 2010 ICE configurations

Hybrid optimisation

- As previously reported in the study, the hybrid technology, when applied to standard size power trains, has the potential to improve the fuel economy by around 15 %
- However, further improvements may be expected through additional optimisation of the power ratio between the thermal and electric motors
- A theoretical evaluation was carried out in the up-date in order to address this issue
- Objective: “adjust” the thermal engine/electric motor power ratio
    - To decrease fuel consumption and CO_2 emissions
    - While still meeting all standard performance criteria

Results for the “optimised” hybrid configuration

	Fuel consumption (/100 km)			GHG emissions (g CO2 eq/km)			
	MJ	l	kg	as CO_2	as CH4	as N2O	Total
PISI hybrid							
Gasoline 1.6 l	161.7	5.02	3.74	118.7	0.4	0.5	119.6
Gasoline 1.28 l	152.9	4.75	3.54	112.2	0.4	0.5	113.1

Fuel consumption and CO_2 emissions decrease by approximately 5%

Hybrid configuration optimisation

- Thermal Engine / Displacement Optimisation:
  - 1,6 litre → 1,28 litre
  - Fuel consumption reduction: about 5 %
  - Fully complying with performance criteria

- Electric Motor / Power Optimisation:
  - 14 kW → 30 kW (still 1,28 l PISI ICE)
  - Fuel consumption reduction: 1 to 2 %
  - Fully complying with performance criteria

Hybrid configuration optimisation: outcome

- Theoretical hybrid power train simulations (thermal and electric motors) indicate that some 6% additional fuel economy improvement is potentially achievable from the basic 2010 hybrid PISI gasoline vehicle
- This additional potential 6% improvement is assumed to be applicable to all power trains and fuel types covered by the study
- This potential has been recognised by an increase of the variability range for hybrid fuel consumption

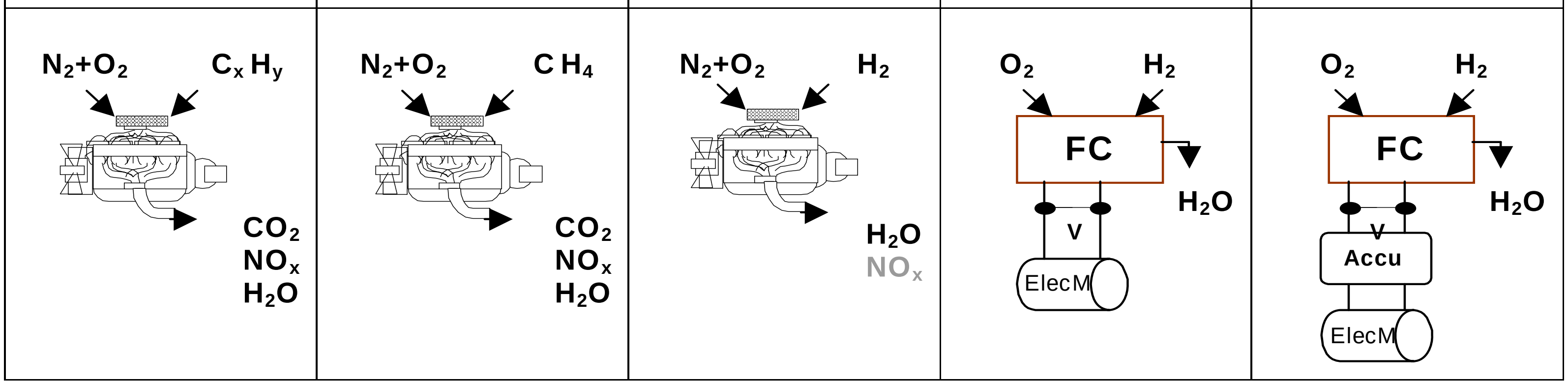
Hydrogen from NG : ICE and Fuel Cell

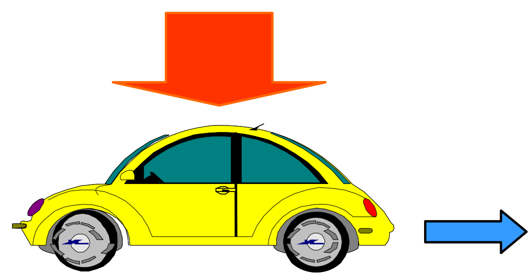
H2 from NG 4.000 KM

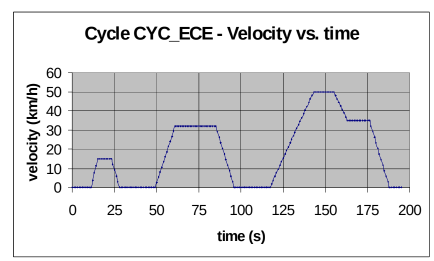
Well-to-Wheels analysis

H2 from NG: H2 ICE & FC vs 'Best' Conventional Pathways

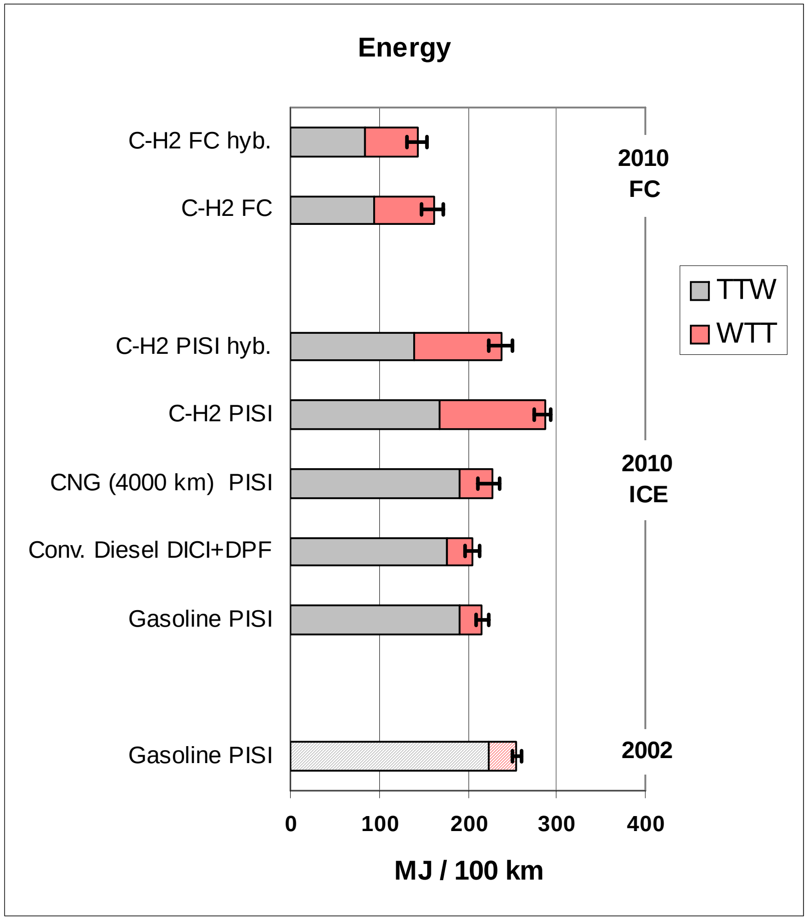
ICE Diesel CIDI	ICE CNG SI	ICE H_2 SI	FC H_2	Hybrid FC H_2

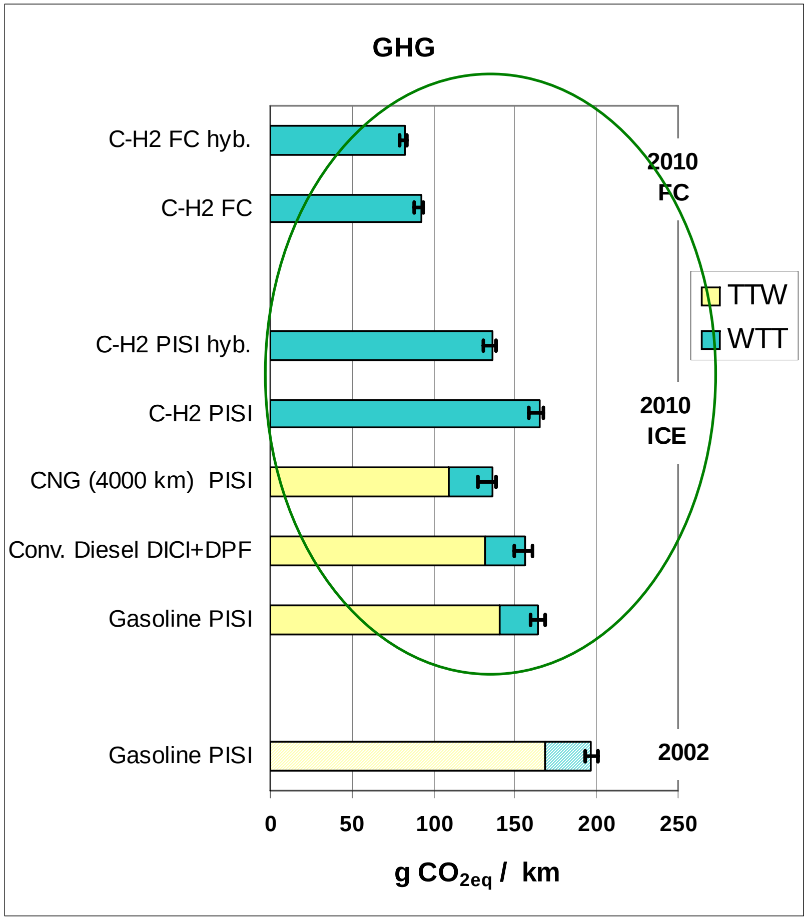






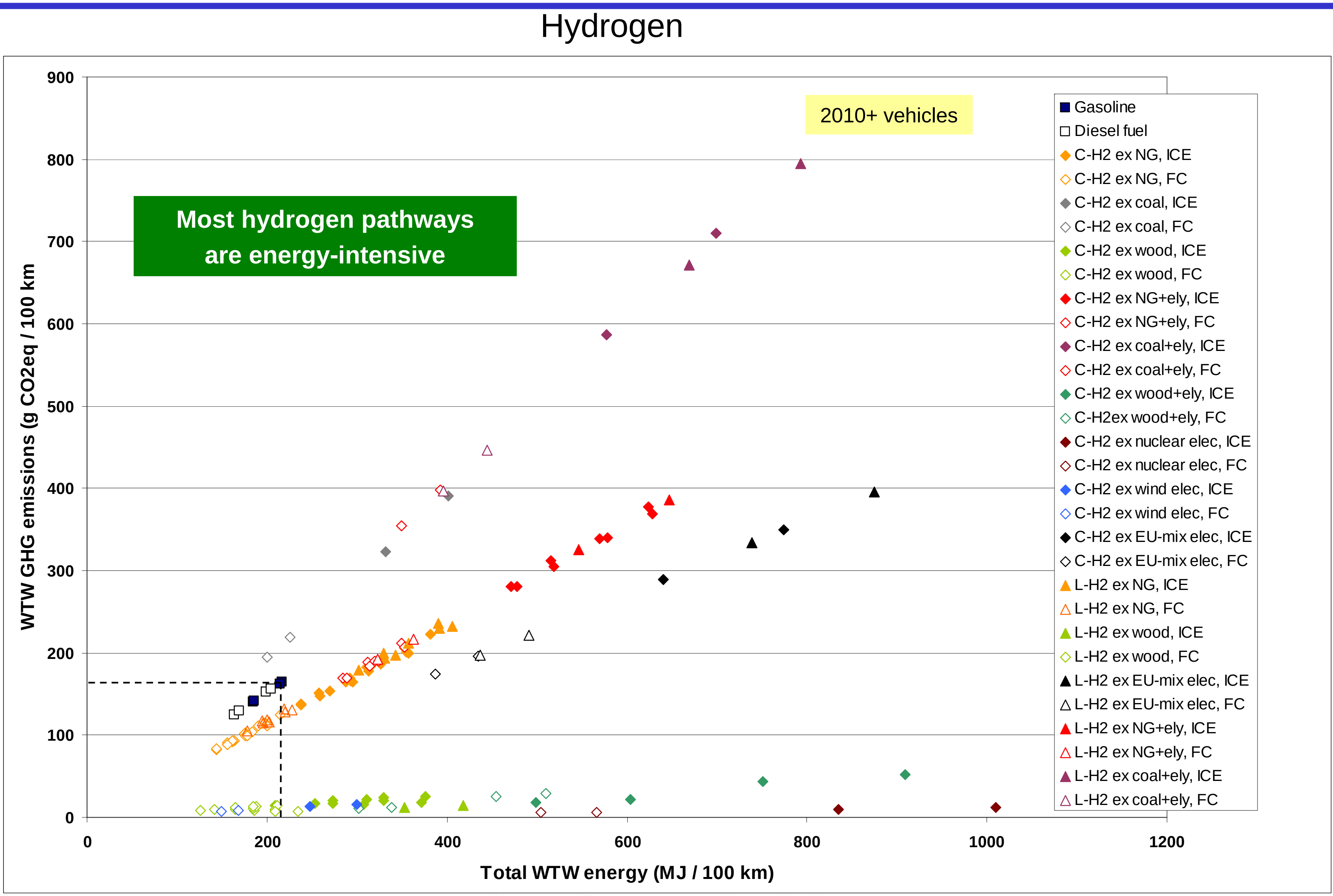
Hydrogen from NG : ICE and Fuel Cell





If hydrogen is produced from NG, GHG emissions savings are only achieved with fuel cell vehicles

Overall picture: GHG versus total energy



Hydrogen: Key Points

- **Many potential production routes exist and the results are critically dependent on the pathway selected.**
- **Electrolysis using EU mix electricity results in higher GHG emissions than producing hydrogen directly from NG**
- ***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***
- ***On-board reforming could offer the opportunity to establish fuel cell vehicle technology with the existing fuel distribution infrastructure***
- ***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.***

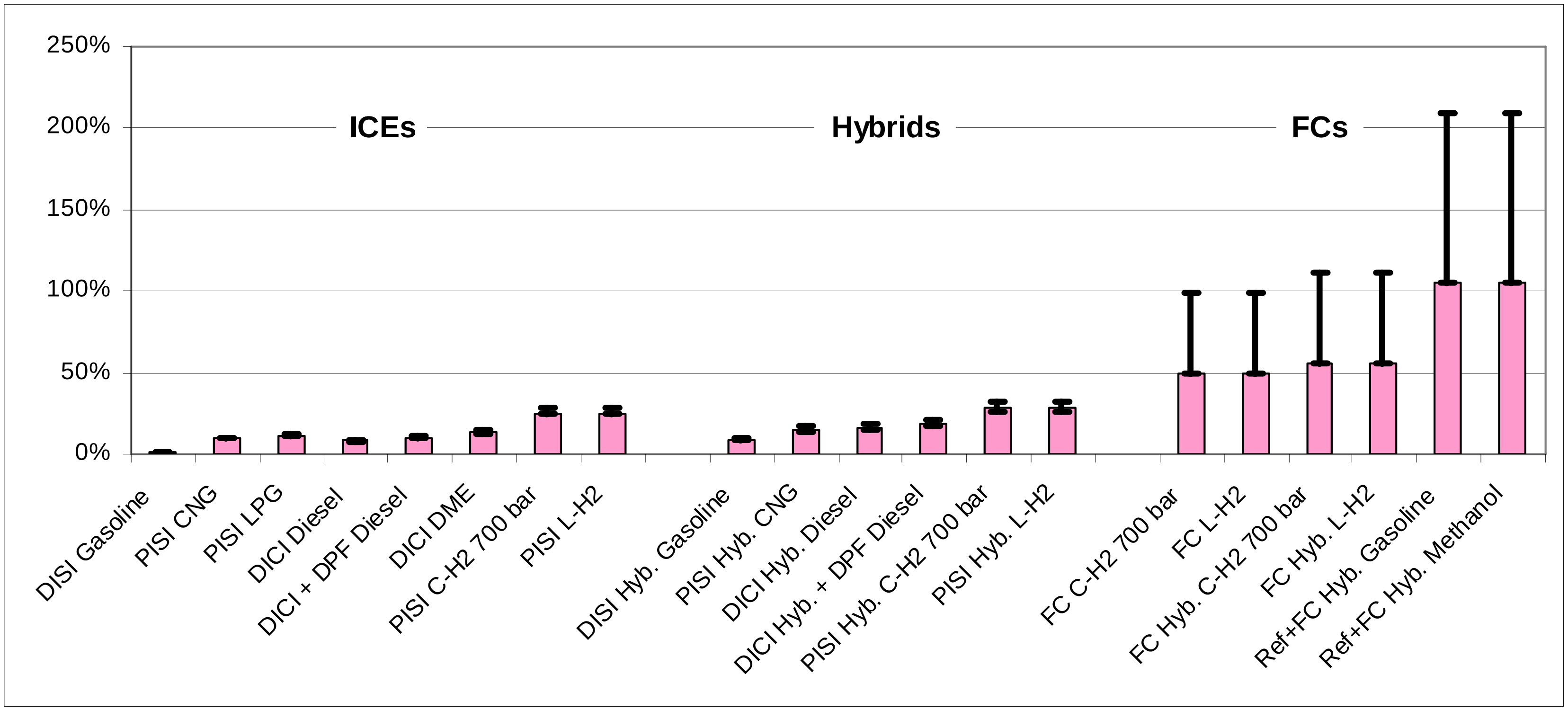
Cost of fossil fuels substitution and CO_2 avoided

- Some cost elements are dependent on scale (e.g. distribution infrastructure, number of alternative vehicles etc)
- As a common calculation basis we assumed that 5% of the relevant vehicle fleet (SI, CI or both) converts to the alternative fuel
  - This is not a forecast, simply a way of comparing each fuel option under the same conditions
  - If this portion of the EU transportation demand were to be replaced by alternative fuels and powertrain technologies, the GHG savings vs. incremental costs would be as indicated
- Costs of CO_2 avoided are calculated from incremental capital and operating costs for fuel production and distribution, and for the vehicle

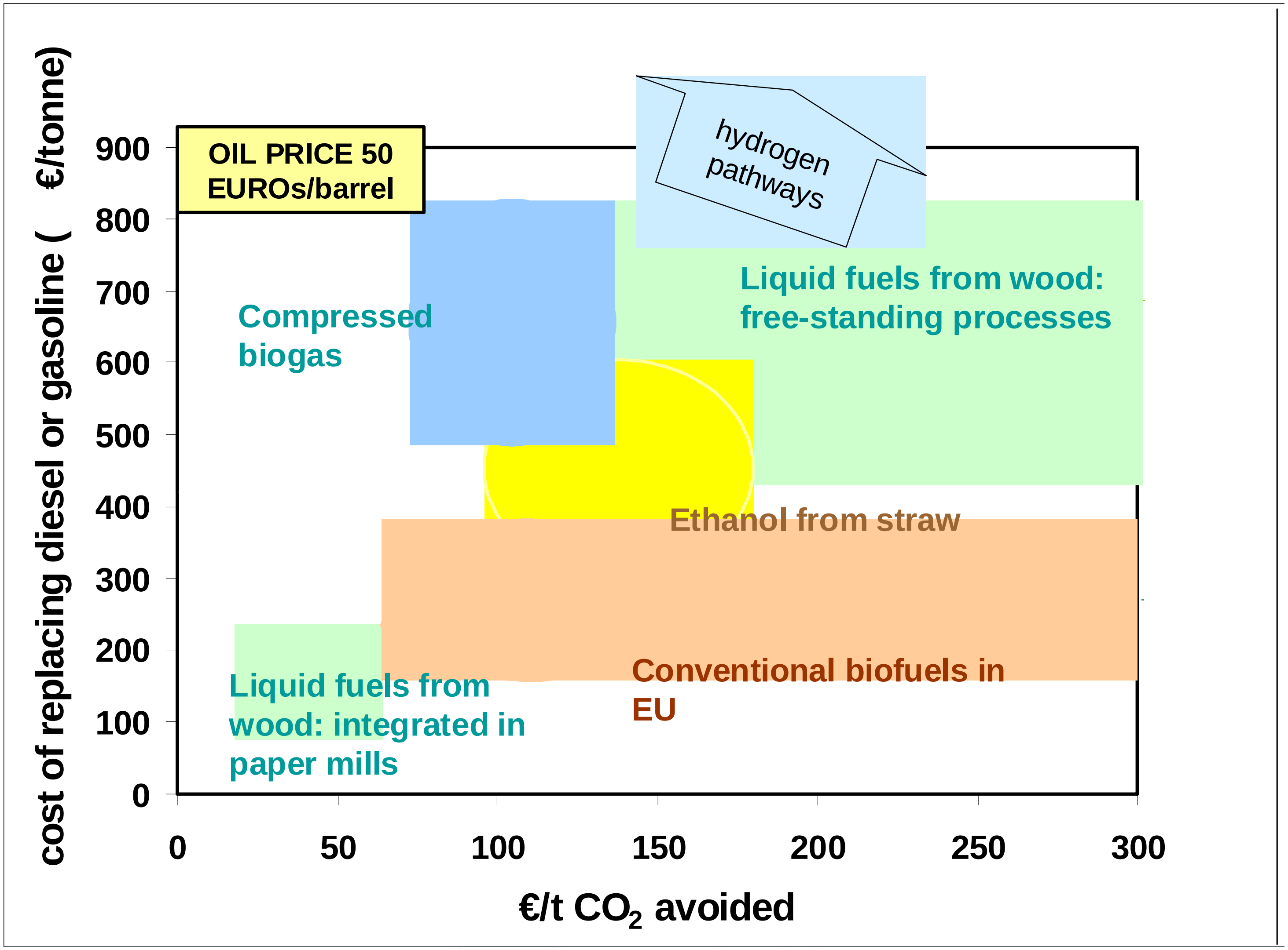
The costs, as calculated, are valid for a steady-state situation where 5% of the relevant conventional fuels have been replaced by an alternative. Additional costs are likely to be incurred during the transition period, especially where a new distribution infrastructure is required.

Additional cost of alternative 2010+ vehicles

Base: Gasoline PISI



Overall picture: GHG mitigation Costs



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 vary considerably
- The cost of CO_2 avoidance using conventional biofuels is around
  - 150-300 €/ton CO_2 when oil is at 25 €/bbl
  - 50-200 €/ton CO_2 when oil is at 50 €/bbl
- Syn-diesel, DME and ethanol from wood have the potential to save substantially more GHG emissions than current bio-fuel options at comparable or lower cost per tonne of CO_2 avoided.
  - Issues such as land and biomass resources, material collection, plant size, efficiency and costs, may limit the application of these processes

General Observations: Costs

- For CNG, the cost of CO_2 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
- The technical challenges in distribution, storage and use of hydrogen lead to high costs.
  - The cost, availability, complexity and customer acceptance of vehicle technology utilizing hydrogen should not be underestimated

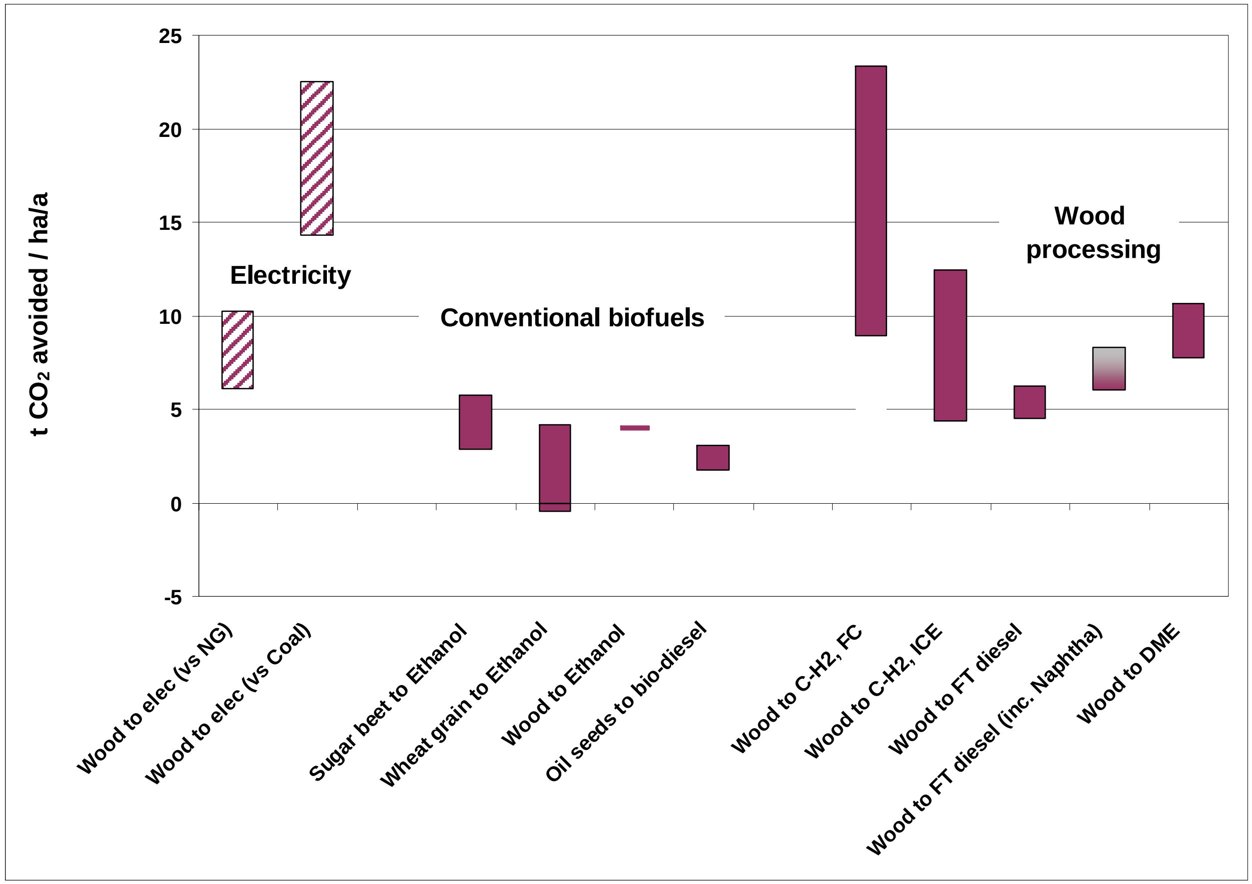
Alternative use of primary energy resources - Biomass

Potential for CO_2 avoidance from 1 ha of land

CO_2 savings per hectare are better for advanced biomass than ethanol or biodiesel

Using biomass for electricity generation offers even greater savings

Reference case: 2010 ICE with Conventional fuel



Wood gasification or direct use of biomass for heat and power offers greatest GHG savings

Conclusions

- A shift to renewable/low fossil carbon routes may offer 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
  - More efficient use of renewables may be achieved through direct use as electricity rather than road fuels applications

JEC Study History

Version 1: 2001 – 2003

- Version 1 published December 2003
- Workshop at JRC 2004 to review and start of updates

Version 2: 2004 – 2005

- Version 2a published May 2006
- Biomass availability workshop May 2006
- Version 2b published December 2006
- Version 2c published May 2007 after small corrections

Version 3: 2007 – 2008

Publication expected summer 2008

Version 4: 2008 – 2010

Expected end 2010

What this type of WTW study can bring in the debate ?

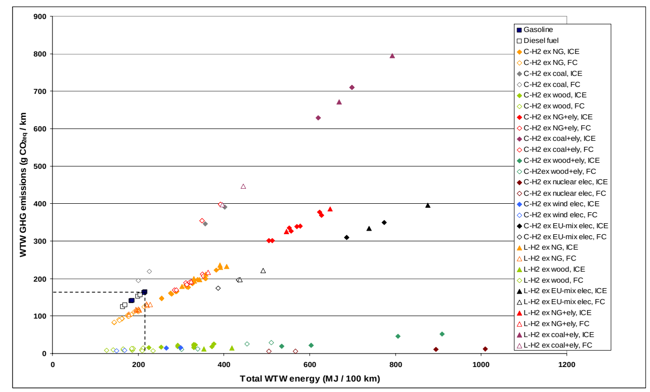
Ways to encourage the fuels performances in term of sustainability are curently analyzed (Europe-California-UK: Carbon Reporting under the Renewable Transport Fuel Obligation).

As shown in the study, conventional pathways (Gasoline/Diesel) present WTT GHG emissions in a relatively low range, around 15 % of the WTW emissions. Road TTW GHG emissions are prevalent. The GHG reduction at WTT fuels side is helping, but in a limited way.

When playing with Bio/Renewable fuels, WTW thinking is mandatory, as the «road side» emissions are the same (e.g. Diesel vehicle fuelled by fossil Diesel or BioDiesel). Only the WTW assessment is taking into account the CO2 loop.

What this type of WTW study can bring in the debate ?

The results regarding Hydrogen applications are a good example to look at possible future « Fuels Certifications ». The study is clearly showing that there are various way to generate and use hydrogen for vehicles propulsion, including the dirty one's.



When H2 will be sold on the road, certificates could be adopted, constraining the producers to comply with GHG emissions limits

$$\left[\frac{\text{GHG (gr } CO_2 \text{ eq.)}}{\text{MJ of Energy Sold}}\right]$$

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The study report will be available on the WEB:

http://ies.jrc.cec.eu.int/WTW

For questions / inquiries / requests / notes

to the consortium,

please use the centralised mail address:

infoWTW@jrc.it