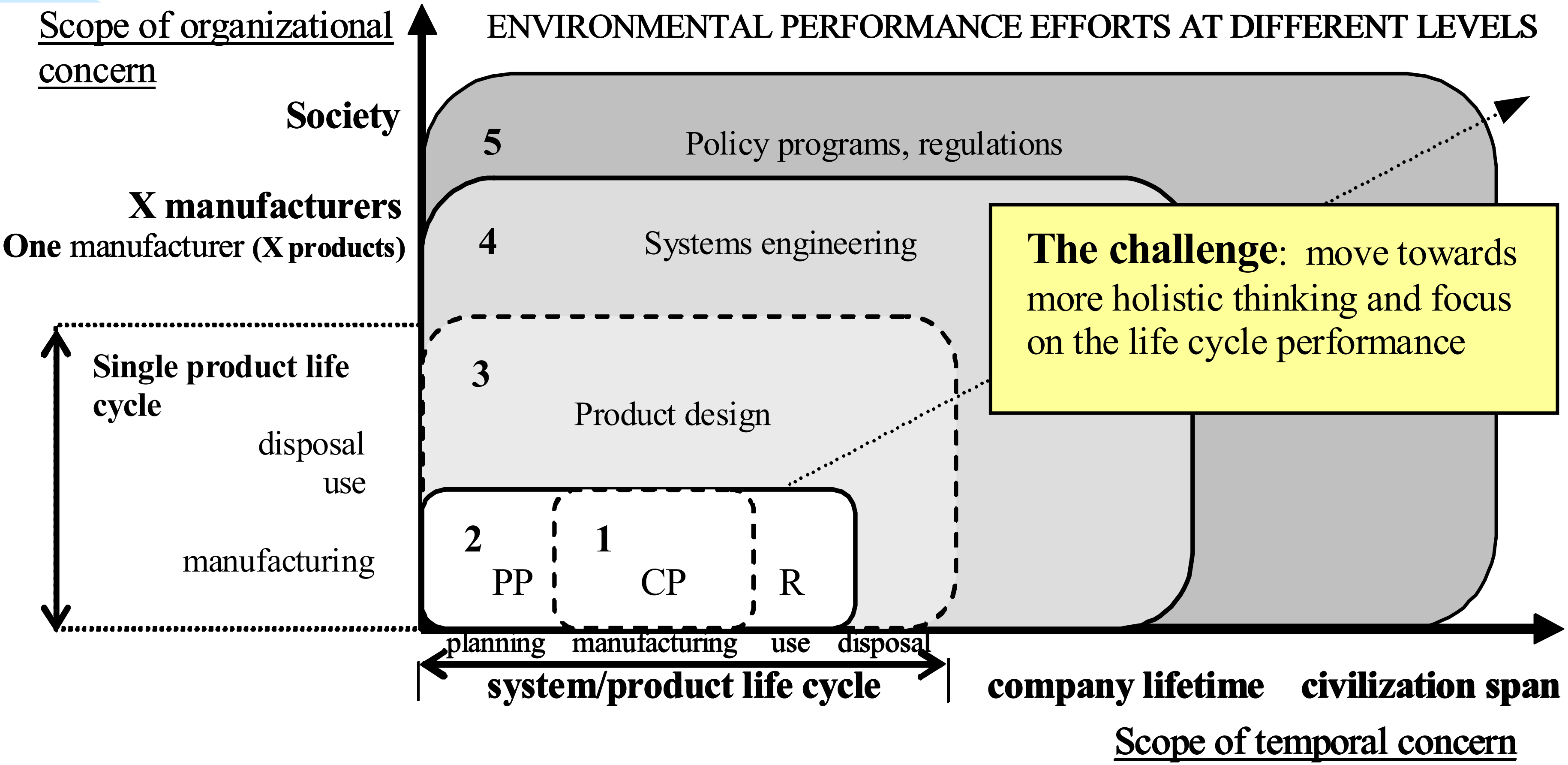
# Product strategies into increased design spaces



ENVIRONMENTAL PERFORMANCE EFFORTS AT DIFFERENT LEVELS

Scope of organizational concern

**Society**

**X manufacturers**

**One** manufacturer **(X products)**

**Single product life cycle**

disposal
use
manufacturing

5 Policy programs, regulations

4 Systems engineering

3 Product design

2 PP

1 CP

R

planning manufacturing use disposal

**system/product life cycle**

**company lifetime** **civilization span**

**Scope of temporal concern**

**The challenge**: move towards more holistic thinking and focus on the life cycle performance

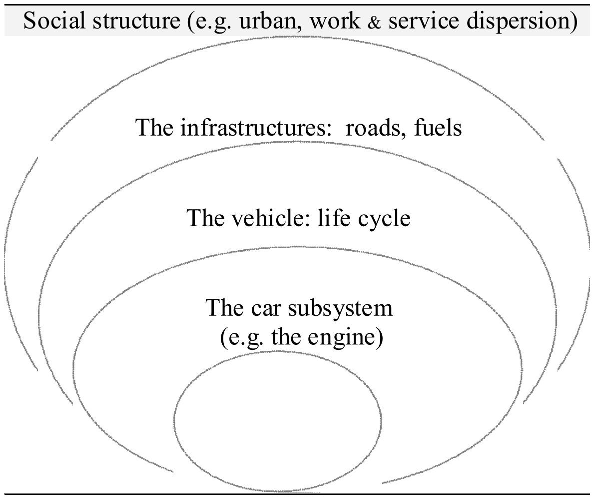
(1&2) Process oriented tools (cleaner manufacture of the vehicles)

(3) Product oriented tools (DfE of vehicles, LC concepts, Eco-labeling)

(4&5) System levels: Industrial ecology (management of vehicles at the end of life)
Sustainable mobility (consumption patterns, driving behavior, life styles)

# **The four** hierarchical **stages** of eco-design and innovation:

- Improvement and redesign of products: often not enough improvements through techs (with existing products)
- Function and systems innovation: major changes in the lifestyles and infrastructure (with the key role of industrial designers)
  - Perform enviro-metrics of the current solutions to develop alternatives, while strategies force critical analysis of the product, the underlying needs, the way they are fulfilled, and generate innovative concepts



Social structure (e.g. urban, work & service dispersion)

The infrastructures: roads, fuels

The vehicle: life cycle

The car subsystem
(e.g. the engine)

E.g. the automotive technological system:

1.- **Product improvement** of specific aspects:
i.e. fuel economic engines or catalytic converters

2.- **Redesign product** environmental-profile as a whole:
i.e. reducing the weight, material diversity or ease disassembly at the end of its useful life

3.- **Function fulfillment** of transport needs in a different way:
i.e. hybrid cars or integrating distinct transport modes

4.- **Sustainable** mobility **systems innovation**:
i.e. rethink the whole concept with new infrastructures, working at home or more versatile public transport

**MJ/passenger·km**

| | Private | Public |
|---|---|---|
| Madrid | **2,71** | **0,71** |
| Barcelona | **2,25** | **0,37** |

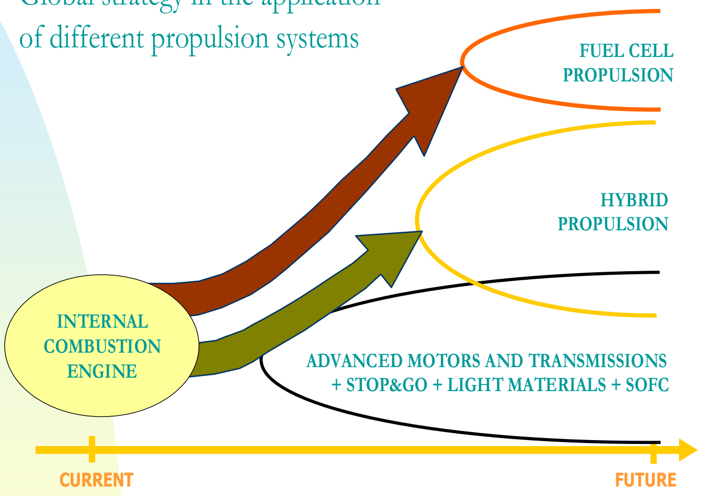
# Improvement and redesign of vehicles

- Nearly all vehicles run with oil fuels, where the gasoline autos are less contaminant but the diesel engines are better in energy efficiency (less fuel consumption per km)

  Main concerns are related to GHGs and air quality; modern cars are considerably more fuel efficient and less contaminant than in the past (90%), while new regulations and increases of the fuel prices address to further improvements in a near future:

  - Some of the new E.U. targets for the road vehicles during the next years are:
    - Reduction of emissions from 163 $g_{CO2}$ /km (current avg.) to 140 (by 2008) and less than 130 (by 2012)
    - Zero emissions of SOx with new processes in refineries (by 2009)
    - Substitution of 20% petrol with alternative fuels (by 2020)
  - Significant improvements to the automobile have been made in terms of fuel consumption and toxic emissions, while increasing attention is directed towards recycling strategies for end-of-life vehicles
  - E.g. better injection, lean engines (A/F>14,6), recirculation of exhaust, increase the number of gears, new motors with compressor and turbos, \`stop and go´ systems for traffic jams
  - Substitution of metals, material reduction and recycle contribute to environmental profiles of vehicles
  - Other improvements are aerodynamics, recuperative systems in motor and braking and \`low rolling resistance´ tyres, with silicate which decreases wheel energy losses (reducing fuel consumption)
  - Control measures for gasoline and diesel exhausts include sensors, catalysts and cartridge filters (to reduce 90% of fine carbon particulates)

- Moreover, there is much debate surrounding the future potential contributions of alternative fuels and propulsion technologies such as hybrid and fuel-cell vehicles:
  - **Alternative fuels** derived from bioethanol or vegetal oils in conventional, adapted or dual-carburant motors are cheaper and cleaner, as well as the LPGs and natural gas vehicles (e.g. $< 0{,}9$ €/kg$_{CNG}$)
  - **Hybrid cars**, which duplicate the motor and storage systems (electrical and explosion) are more expensive but reduce the urban pollution and CO$_2$ (with good road performance); electrical vehicles with Li-ion batteries or solar prototypes with gallium cells are also in the stands
  - The `**Fuel Cell Vehicle**´ vs ICVs is the best solution to minimize all environmental impacts, specially if the hydrogen can be produced from renewables (hydro, photovoltaic, etc)



Global strategy in the application of different propulsion systems

FUEL CELL PROPULSION

HYBRID PROPULSION

INTERNAL COMBUSTION ENGINE

ADVANCED MOTORS AND TRANSMISSIONS + STOP&GO + LIGHT MATERIALS + SOFC

CURRENT

FUTURE

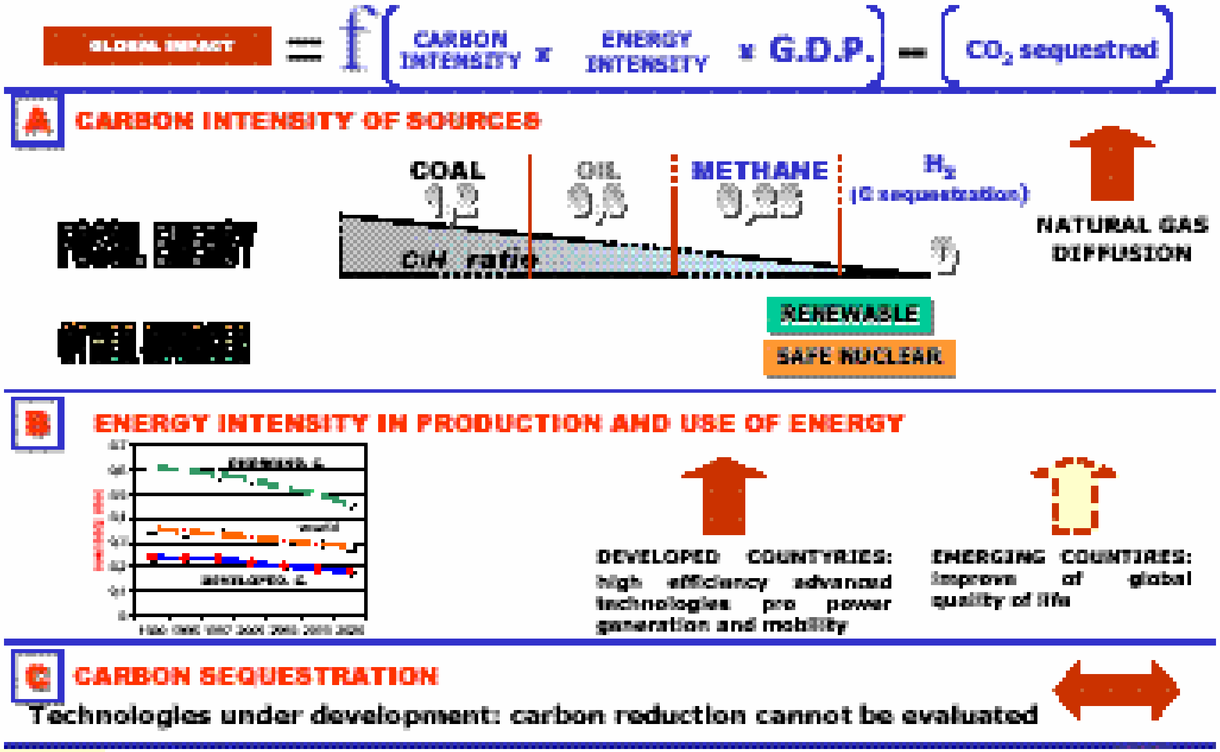
Fuel.cell vehicle in California

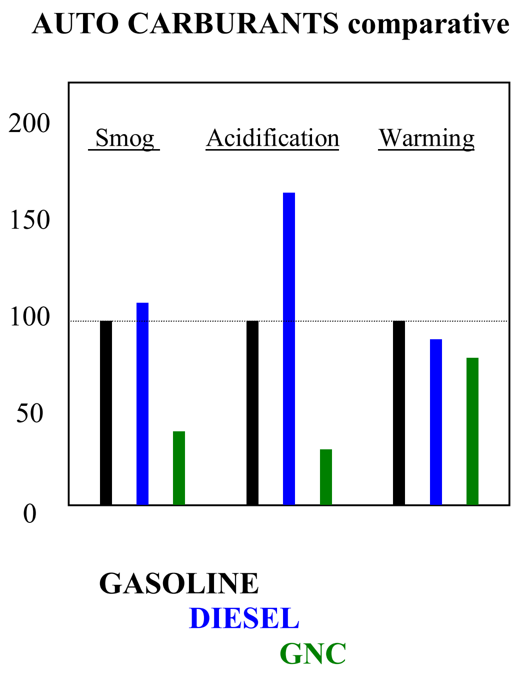
Ethanol bus in Stockholm

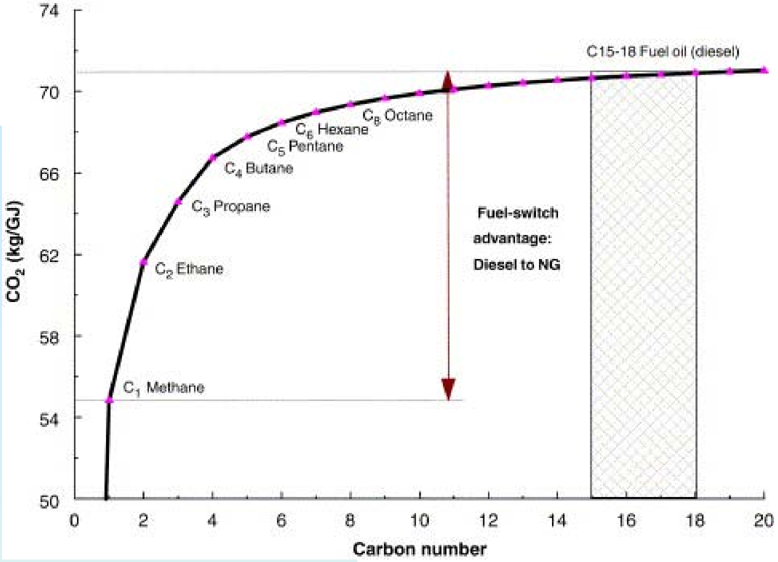
Hybrid bus in London

# Hydrocarbon fuels

- Carbon: $C + O_2 = \mathbf{CO_2} + 404\ \text{kJ}$ $\{\Delta\Sigma(\Delta H_f^o)\}$ (109 g/MJ)
- Octane: $1/8\ C_8H_{18} + (1+9/16)O_2 = \mathbf{CO_2} + 9/8\ H_2O + 634\ \text{kJ}$ ( 69 g/MJ)
- Methane: $CH_4 + 2\ O_2 = \mathbf{CO_2} + 2\ H_2O + 802\ \text{kJ}$ ( 55 g/MJ)







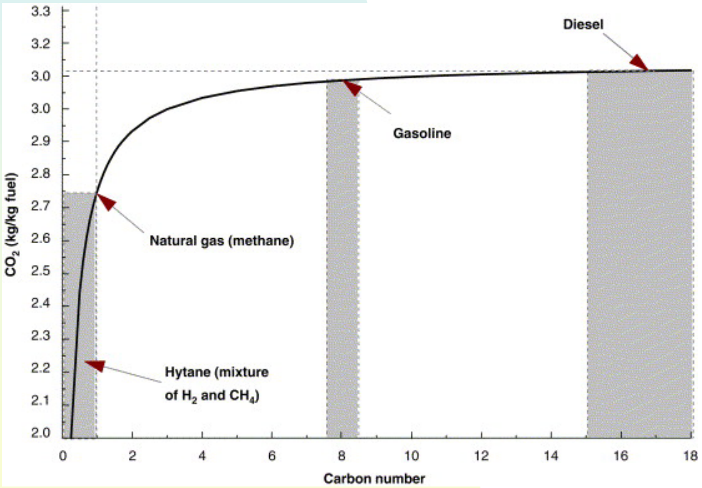


Table.- Energy density of common automotive fuels at various states, based on lower heating values

| Fuel | MJ/kg | MJ/l |
|---|---|---|
| **Gasoline** | **42.5** | **32.7** |
| **Diesel** | **42.5** | **37.7** |
| **LPG** | **48.0** | **24.4** |
| **Methane** | **50.0** | **0.035** |
| **Natural gas** (a) | **38–50** | **0.032–0.037** |
| **Gaseous methane at 248 bar, CNG** | **50.0** | **8.7** |
| **Liquid methane at -162ºC, LNG** | **50.0** | **21.6** |
| **Hydrogen at 248 bar** | **120.0** | **2.5** |
| **Hydrogen at 700 bar** | **120.0** | **7.1** |
| **Hydrogen at -250ºC** | **120.0** | **8.5** |

(a) Methane usually makes up from 80% to 99% of the natural gas in volume. The balance is composed of varying amounts of methane, ethane (2.7–4.6%), and gases like carbon dioxide (1–5%), nitrogen (0.1–15%), He, Ar, hydrogen, carbon monoxide, and sometimes hydrogen sulphide (<5ppm on a mass basis)

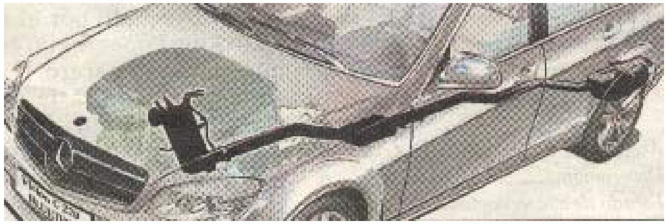
Fig. 1. $CO_2$ formation in kg $CO_2$ per GJ fuel by a complete conversion of basic hydrocarbons by carbon number. *Note*: the environmental impact of the fuels of fig. per produced energy service results from multiplying the amount of emission with the inverse thermal efficiency of the actual technology used for the conversion.

Fig. 2. CO2 emission by carbon number per kg fuel formed in anyone process that fully converts the fuel versus carbon number. A zero emission associated with pure hydrogen is reckoned at the tail end only. A substantial reduction is further achievable by mixing natural gas and hydrogen (hytane).

# Diesel turbo engines

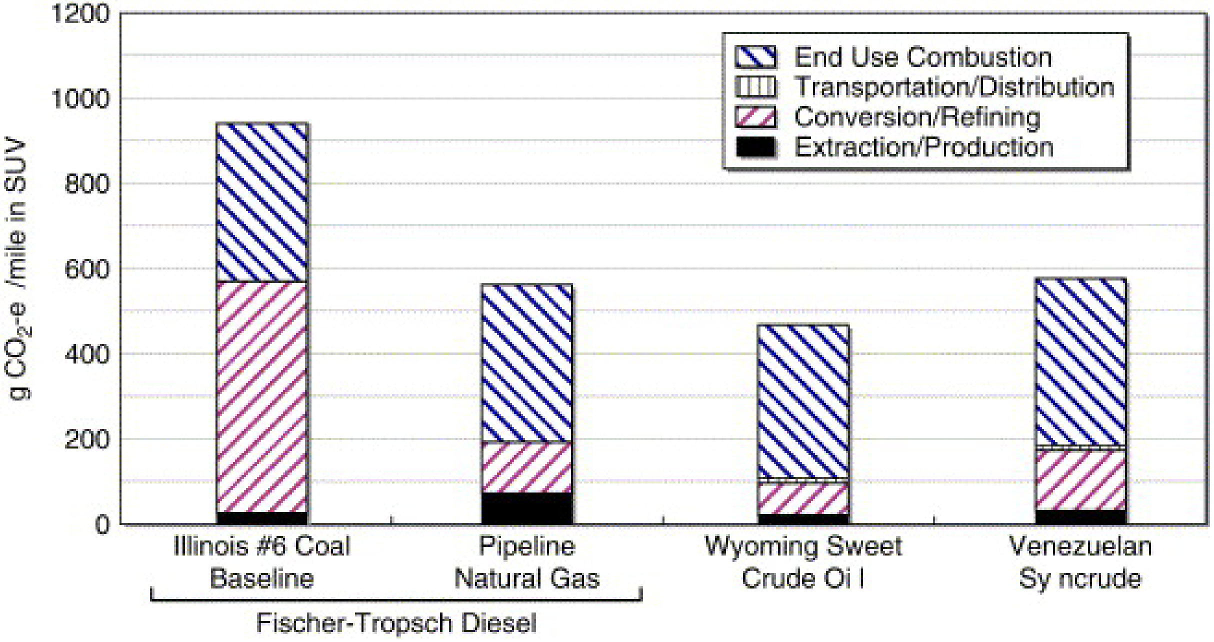
- They are faster and consume less fuel than gasoline autos, but new emission rules would increase costs by converting them nearly in `chemical plants´ to clean exhaust gases
  - Diesel mechanics continue evolving to design propulsions of more power, with less consumption and noise; nowadays, the 08-CDi turbo-diesel of the new `Smart model´ consume only 3,3 l and emits 88 g/km of $CO_2$

  - Though emitting less $CO_2$, they produce $NO_x$ and particulates, which require new drives and catalytic devices for NOx (EU-5), as well as filters to reduce 90% particles by burning at 500ºC

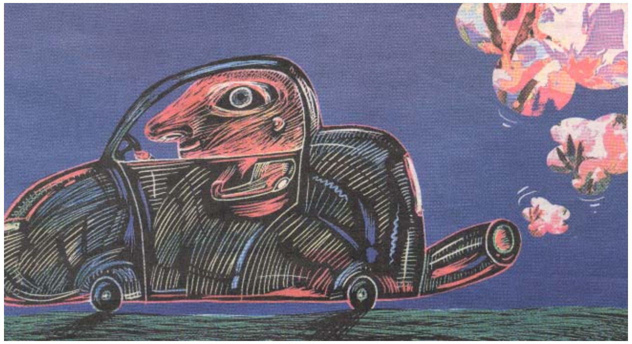


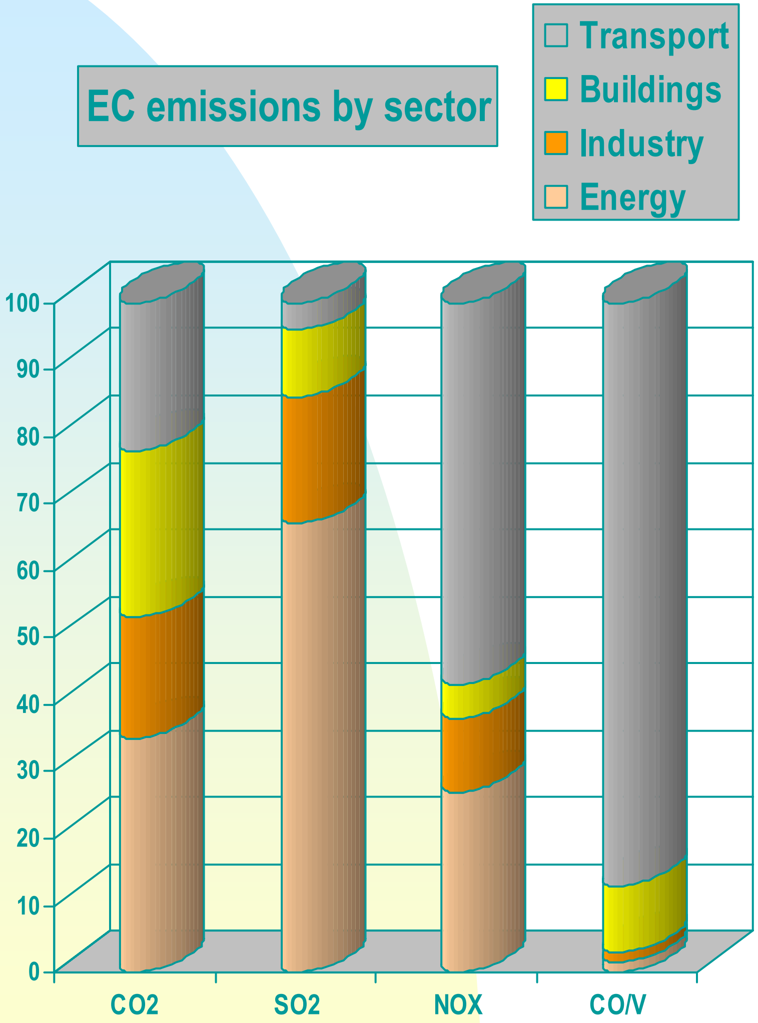
| Energy consumption and $CO_2$ eq. emissions of several carburetants in a Volvo 740-GL | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Life cycle** | **Gas-oil** | | **Gasoline** | | **Methanol** | | **Methane** | |
| | MJ/km | $g_{CO2}$/km | MJ/km | $g_{CO2}$/km | MJ/km | $g_{CO2}$/km | MJ/km | $g_{CO2}$/km |
| Extraction | 0,15 | 17 | 0,17 | 18 | 0,12 | 13 | 0,12 | 10 |
| Refining | O,14 | 10 | 0,22 | 15 | 0,85 | 51 | 0,12 | 7 |
| Distribution | 0,08 | 7 | 0,10 | 8 | 0,15 | 12 | 0,29 | 41 |
| Operation | 2,52 | 205 | 2,87 | 225 | 2,42 | 186 | 2,87 | 187 |
| **Total** | **2,89** | **239** | **3,36** | **266** | **3,54** | **263** | **3,40** | **245** |

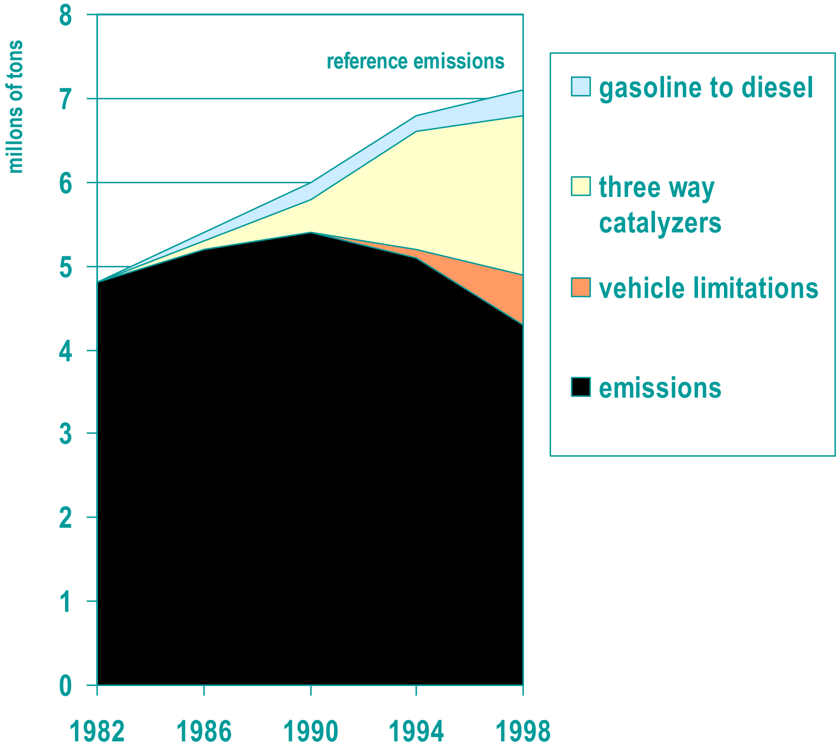
**Fig. Greenhouse-gas emissions per vehicle mile for a suburban utility vehicle with diesel fuel produced from different feedstocks**



# Reduction in road transport smog emissions (UE)

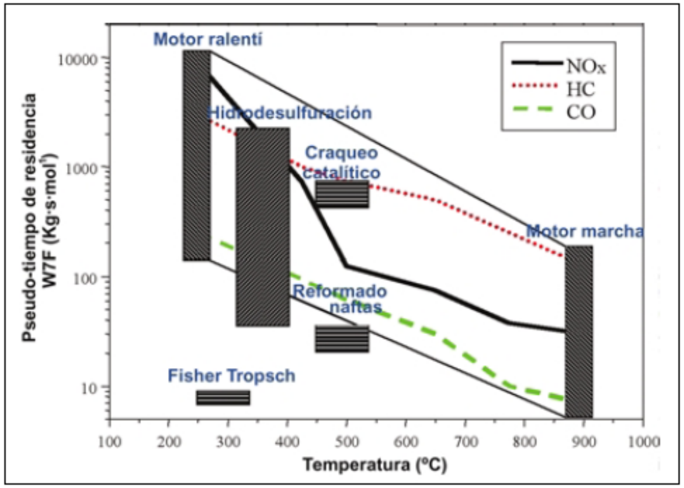




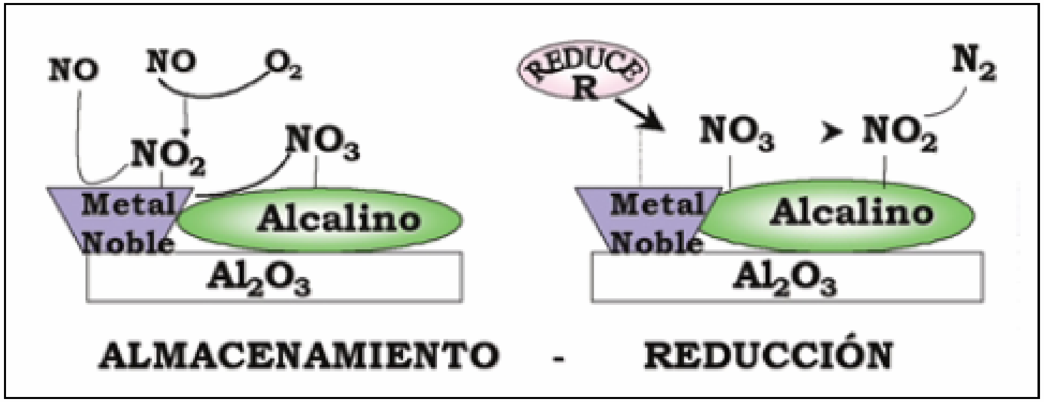


# Exhaust catalysts in vehicles

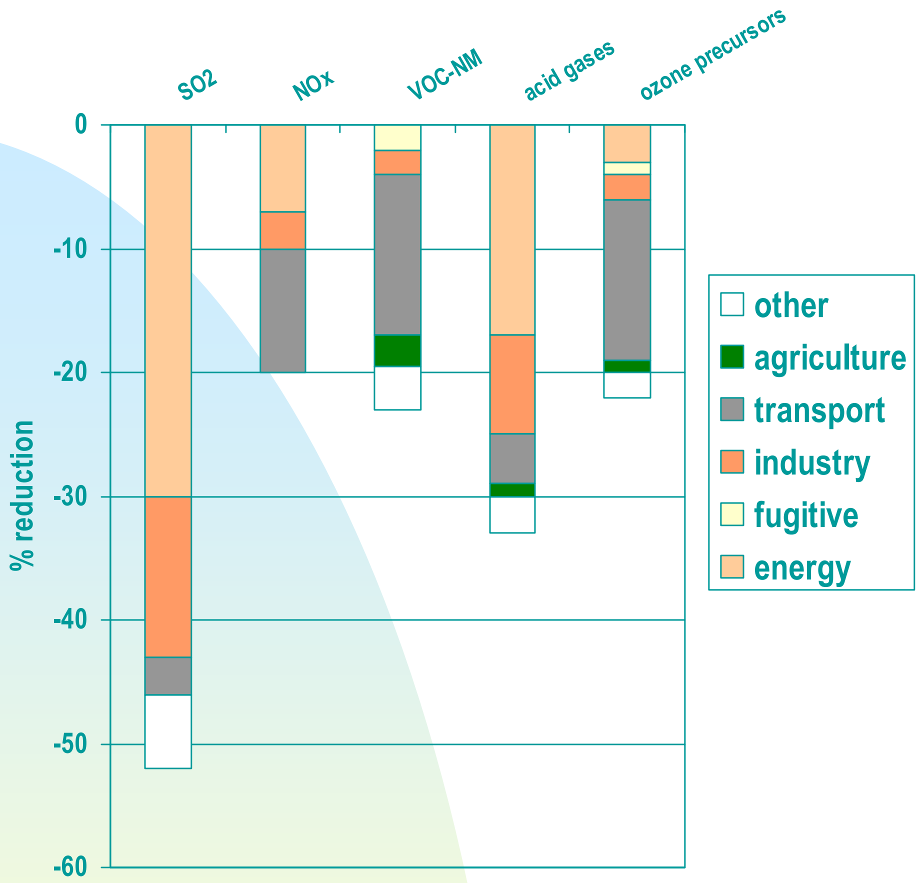
- Main problem in catalyst development are variable conditions in motors, to reach high conversion and selectivities (as compared with other chemical and refinery processes)

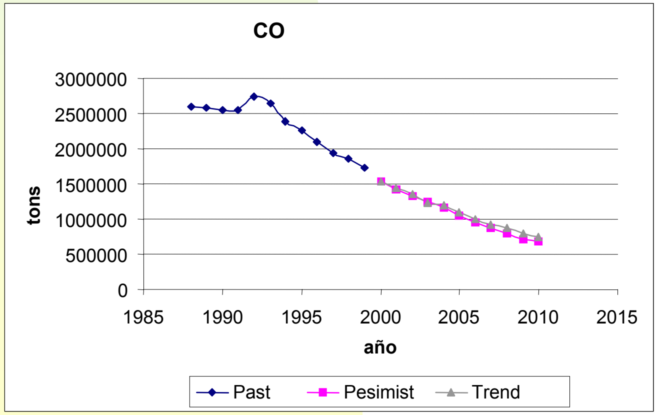


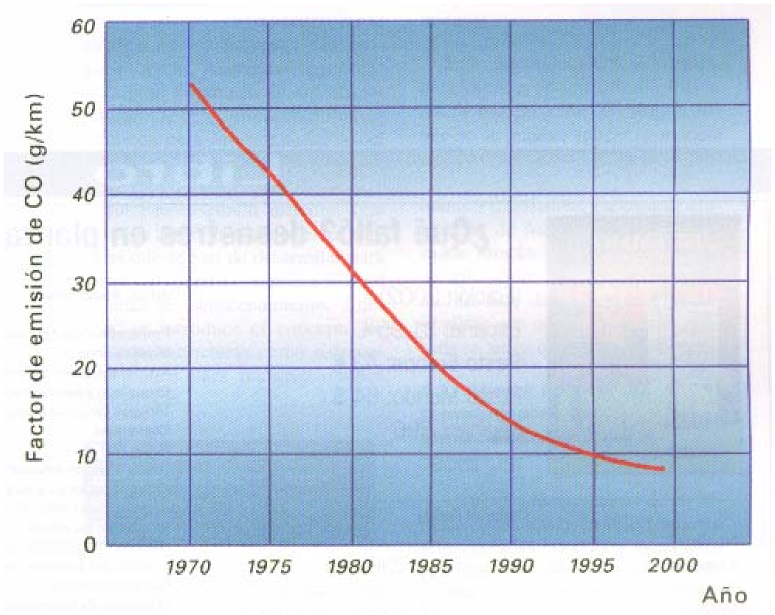
- The `Three way catalysts´ eliminate CO, HCs and NOx from cars exhaust (by NSCR) in stoichiometric A/F conditions (λ=1), which are transformated in $CO_2$, $H_2O$ and $N_2$ (ceramics impregnated with metals)
- For lean engines (λ>1) the alternative are NSR catalysts which operate in cycles of NOx storage in the surface (as nitrite and nitrate) and short rich-fuel stages (with NOx reduction and catalyst regeneration); by formulations which incorporate the double function: oxidation of metal and accumulative capacity of alkaline component, dispersed on a porous monolithic support (e.g. $Pt/Ba/Al_2O_3$)

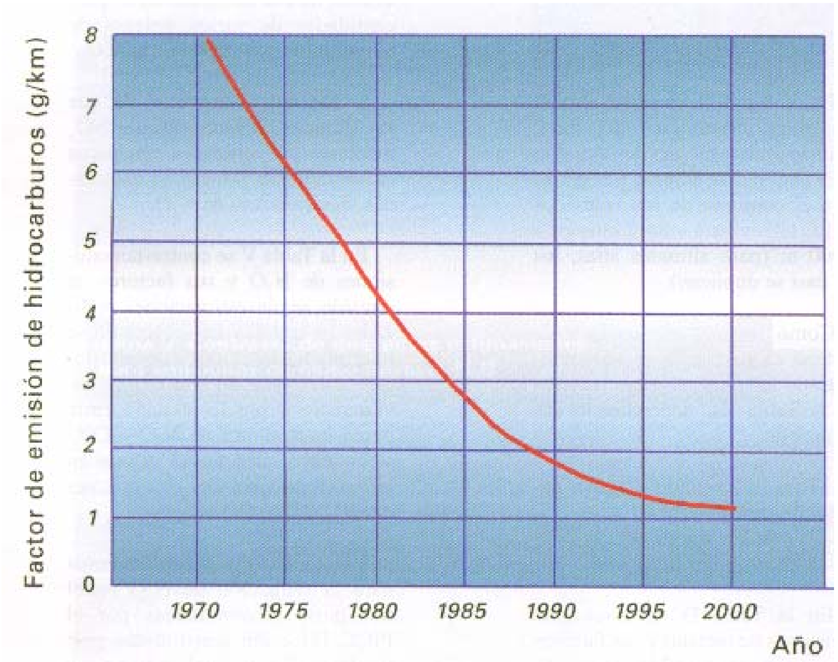


**Ing. Quím. nº:** 440
Octubre 2006

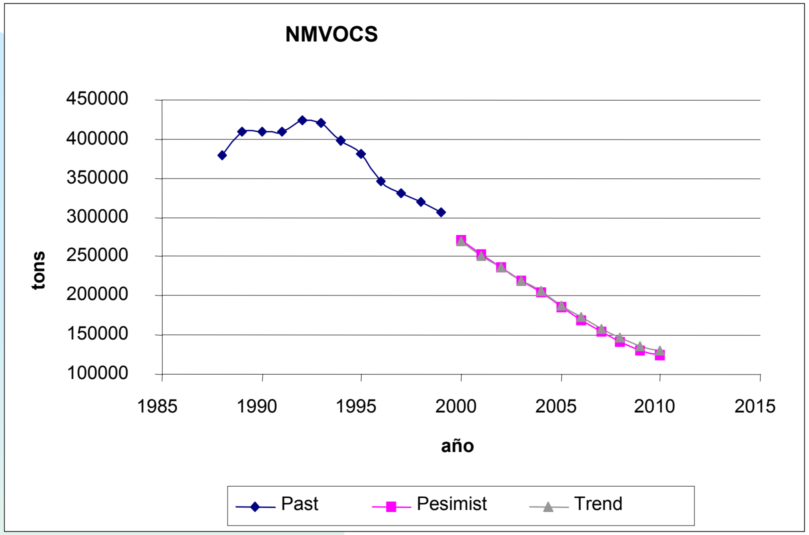

SO2
NOx
VOC-NM
acid gases
ozone precursors
% reduction
0
-10
-20
-30
-40
-50
-60
other
agriculture
transport
industry
fugitive
energy

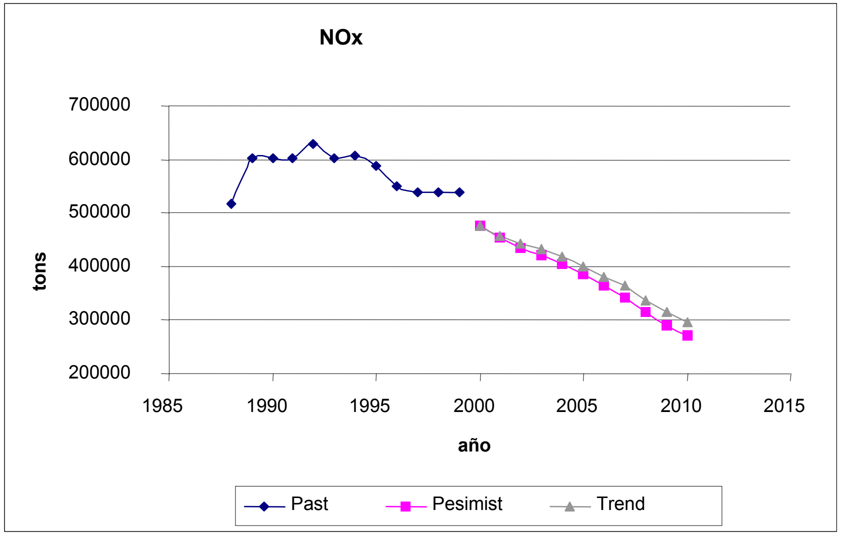

CO
tons
3000000
2500000
2000000
1500000
1000000
500000
0
1985
1990
1995
2000
2005
2010
2015
año
Past
Pesimist
Trend

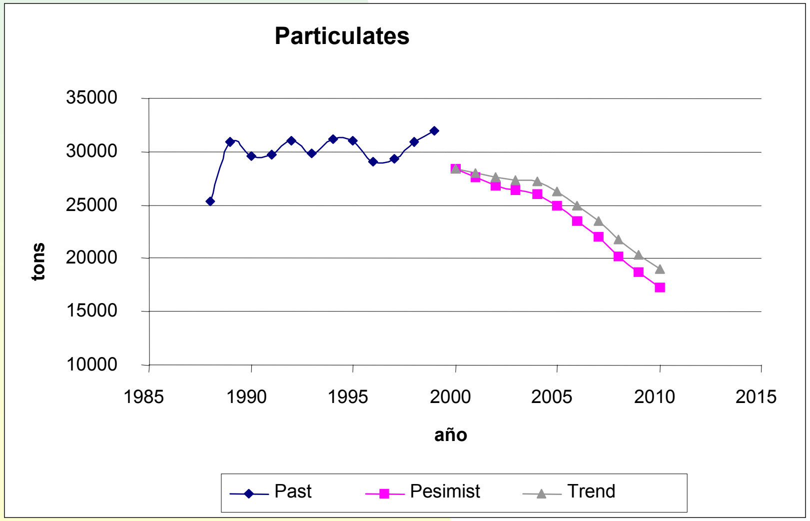

Factor de emisión de CO (g/km)
60
50
40
30
20
10
0
1970
1975
1980
1985
1990
1995
2000
Año

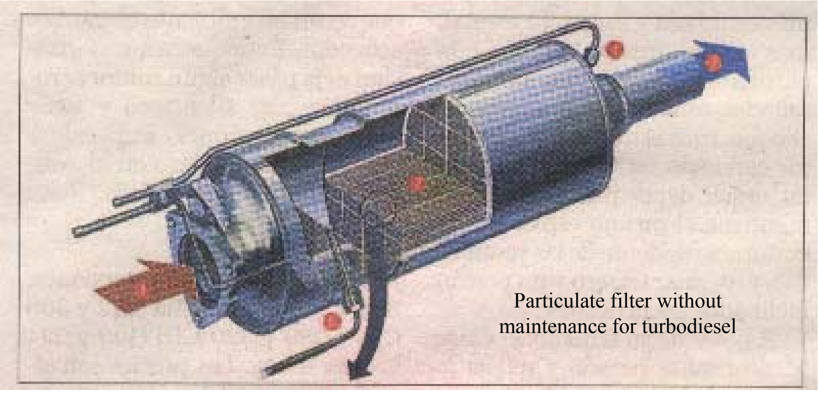

Factor de emisión de hidrocarburos (g/km)
8
7
6
5
4
3
2
1
0
1970
1975
1980
1985
1990
1995
2000
Año

# LOCAL EMISSIONS









Particulate filter without maintenance for turbodiesel

# Life cycle analysis of catalysts and vehicles

A **car exhaust catalyst** performs admirably in terms of environmental impacts if it´s regarded only in its usage phase; the releases of CO, VOC and $NO_x$ has fallen dramatically since catalytic exhausts were made mandatory in the EU (1993); because this technology requires unleaded fuel, this also put an end to lead pollution from this source.

If the entire life-cycle is considered, production of every 3- way catalyst requires 5 g of Pt and 15 g of Pd, and for every gram of these metals, 300 kg of ore is mined; the market leader in precious metals is in the Siberian industrial town of Norilsk, one of the world´s largest polluter complexes (the $SO_2$ emissions are estimated at 2,8 Mt/yr, about as much as Germany´s entire releases; a permanent blanket of $SO_2$, NOx, CO, phenol and chlorine covers the area, the town itself is devoid of trees and more than 4000 $km^2$ of forests are affected; finally, the average life expectancy of the male inhabitants of the town is only 49 years).

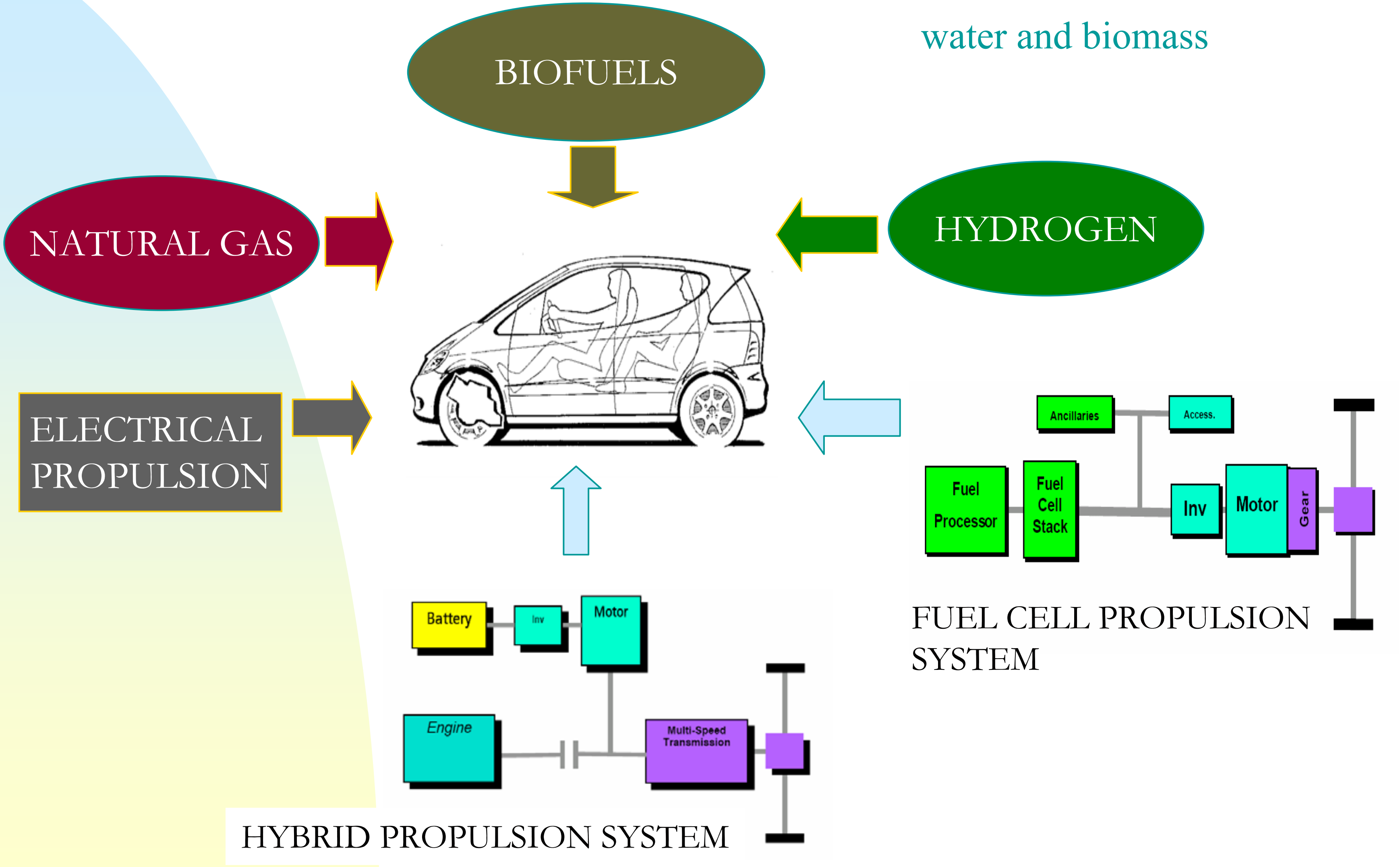
On the other hand, the efficiency of a car engine is strongly related to its compression ratio, and after the introduction of electronic injection systems in the 1980s values of 1:9,5 became normal with octane 98 leaded petrol; for proper functioning, however, car exhaust catalysts require octane 95 unleaded petrol and the compression had to be reduced to 1:8 (which caused fuel consumption to rise).

Hence, a choice was made between using less fuel per km but emitting a higher percentage of exhaust products (i.e. engine without catalyst) and a higher level of fuel consumption but `cleaner´ exhaust gases (i.e. with catalyst); the latter option was chosen, though this choice is not obvious as the consumption of fossil fuels and the related emissions of $CO_2$ are higher.

| Engine without catalyst | | Car exhaust catalyst | |
|---|---|---|---|
| Life use (yr·km) | 100000 | Life use (yr·km) | 100000 |
| | | Precious metals (g) | 20 |
| Fuel consumption (l/km) | 5 | Fuel consumption (l/km) | 6 |
| Carbon dioxide (g/l) | | Carbon dioxide (g/l) | |
| Exhaust pollutants (g/l) | | Exhaust pollutants (g/l) | 0 |
| $SO_2$ CO VOC NOx HAPs | | | |

LCA forces to view the entire system life-cycle, ensuring that important environmental problems are not overlooked;
example shows the importance of its two main functions: determining environmental impacts and comparing different products.

# Alternative technologies



water and biomass

BIOFUELS

NATURAL GAS

HYDROGEN

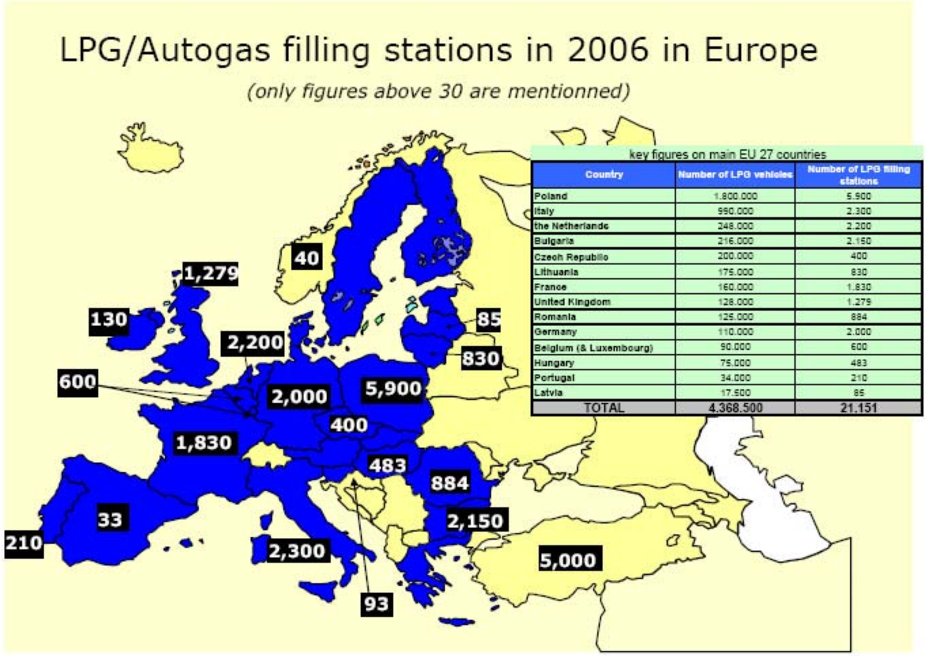
ELECTRICAL PROPULSION

FUEL CELL PROPULSION SYSTEM

HYBRID PROPULSION SYSTEM

## Filling stations with natural gas

(in countries painted brown natural gas is not available)



LPG/Autogas filling stations in 2006 in Europe

*(only figures above 30 are mentionned)*

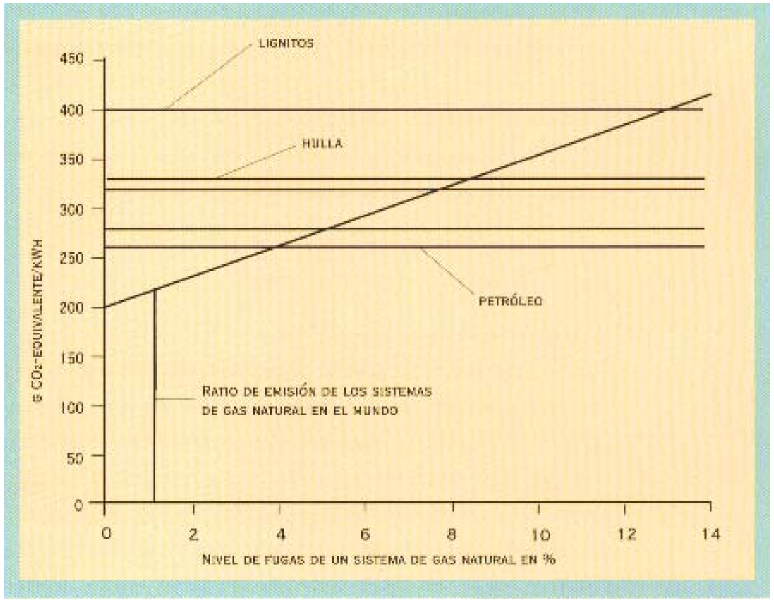
key figures on main EU 27 countries

| Country | Number of LPG vehicles | Number of LPG filling stations |
|---|---|---|
| Poland | 1.800.000 | 5.900 |
| Italy | 990.000 | 2.300 |
| the Netherlands | 248.000 | 2.200 |
| Bulgaria | 216.000 | 2.150 |
| Czech Republic | 200.000 | 400 |
| Lithuania | 175.000 | 830 |
| France | 160.000 | 1.830 |
| United Kingdom | 128.000 | 1.279 |
| Romania | 125.000 | 884 |
| Germany | 110.000 | 2.000 |
| Belgium (& Luxembourg) | 90.000 | 600 |
| Hungary | 75.000 | 483 |
| Portugal | 34.000 | 210 |
| Latvia | 17.500 | 85 |
| TOTAL | 4.368.500 | 21.151 |

**TABLA 6.** EFECTOS MEDIOAMBIENTALES DE LAS CENTRALES TÉRMICAS

| TIPO DE CENTRAL | TÉRMICA DE CARBÓN | TÉRMICA DE FUEL-OIL | TÉRMICA DE GAS NATURAL | CICLO COMBINADO DE GAS NATURAL |
|---|---|---|---|---|
| POTENCIA (MW) | 1.000 | 1.000 | 1.000 | 1.000 |
| CONSUMO: | | | | |
| COMBUSTIBLE (GAS: $m^3$s/año, OTROS t/año) | $2.2\ 10^{6}$ | $1.4\ 10^{6}$ | $1,6\ 10^{9}$ | $1,1\ 10^{9}$ |
| PIEDRA CALIZA (t/año) | 59.000 | 133.000 | – | – |
| EMISIONES | | | | |
| DIÓXIDO DE AZUFRE (t/año) | 8.750 | 6.580 | DESPRECIABLE | DESPRECIABLE |
| ÓXIDO DE NITRÓGENO (t/año) | 4.360 | 3.300 | 3.190 | 1.980 |
| PARTÍCULAS SÓLIDAS (t/año) | 1.090 | 830 | 77 | 53 |
| DIÓXIDO DE CARBONO (t/año) | 5.400.000 | 4.390.000 | 3.090.000 | 2.100.000 |
| RESIDUOS SÓLIDOS | | | | |
| CENIZAS (t/año) | 330.000 | 5.200 | – | – |
| YESO (t/año) | 101.000 | 229.000 | – | – |
| ELECTRICIDAD (GWh) | 6.000 | 6.000 | 6.000 | 6.000 |

Nivel de fugas de equilibrio para el metano



# Change from `conventional gasoline fueled´ to `electrical vehicles´

Aspects to take into account include:

1) Modifications in energy production

   We need information of electricity mix, e.g. in USA the average is 54% coal, 1% fueloil, 15% natural gas, 18% nuclear and 12% renewable (hydro, solar, wind, etc)

   Thus, substitution of ICE for electrical engines means lower dependence of oil imports vs greater mining of coal resources, uranium, etc.

2) Environmental impacts of energy use

   Studies based in the model “GREET 1.5 - Transportation Fuel Cycle” show that the use of electrical instead of conventional vehicles would reduce emissions per km traveled in a 25% for $CO_2$ and 80% for VOCs and CO, while increases 60% of $NO_x$ and 240% $SO_2$ .

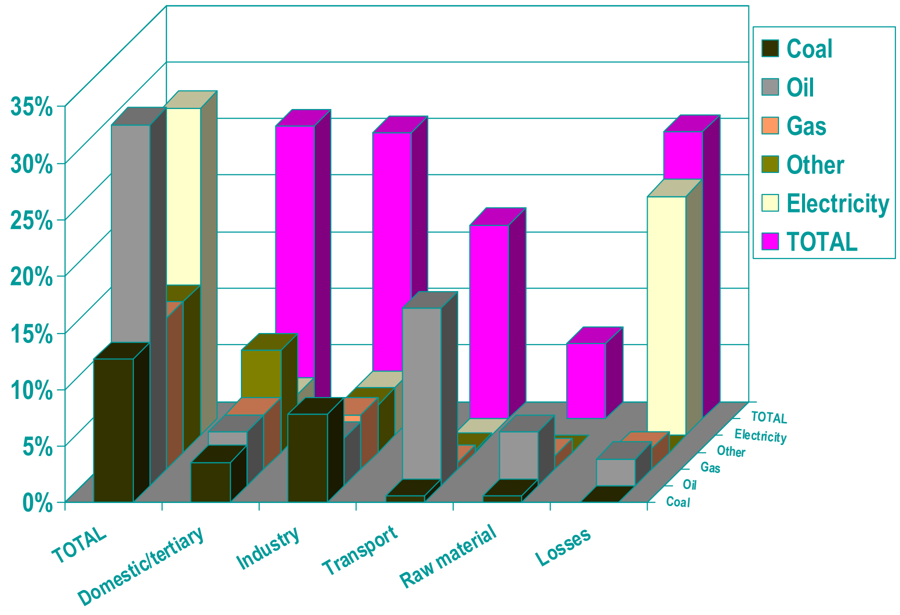
Global consumption of energy by source and sector, EJ/yr (1990) (also showed are the increases to 1998)

| | Coal | Oil | Gas | Nuclear | Hydro | Biomass | Electricity | Heat | Total |
|---|---|---|---|---|---|---|---|---|---|
| Primary | 91 (+1%) | 128 (+18%) | 71 (+13%) | 19 (+42%) | 21 (-57%) | 55 (-20%) | - | - | **385 (+5% )** |
| Final | 36 | 106 | 41 | - | - | 53 | 35 | 8 | **279** |
| - industry | 25 | 15 | 22 | - | - | 3 | 17 | 4 | **86** |
| - transport | 1 | 59 | 0 | - | - | 0 | 1 | 0 | **61** |
| - other | 10 | 18 | 18 | - | - | 50 | 17 | 4 | **117** |
| - raw material | 0 | 14 | 1 | - | - | 0 | - | - | **15** |

## Primary to secondary energy efficiencies:

| | Cumulative |
|---|---|
| ▪ oil to fuel (90%) | 90% |
| ▪ fuels to power (40%) | 36% |
| ▪ transmission and distribution (90%) | 32% |
| ▪ mechanical conversion of the electricity (40%) | 13% |
| ICE vehicles (11%) | 10% |

**Losses (energy industry): Oil refining (7%), Gas transmision (10%), Electricity conversión (69%) and transmision (4%)**



# Hybrid vehicles

- Combined fuel-electrical mechanics can reduce consumption and $CO_2$ emissions by 40%, by using the electricity stored in batteries during start-up or stop-and-go, specially in cities, and the combined driving in roads, which reduce the power of the fuel engine and recover the energy of braking

## EL APROVECHAMIENTO DE LA ENERGÍA

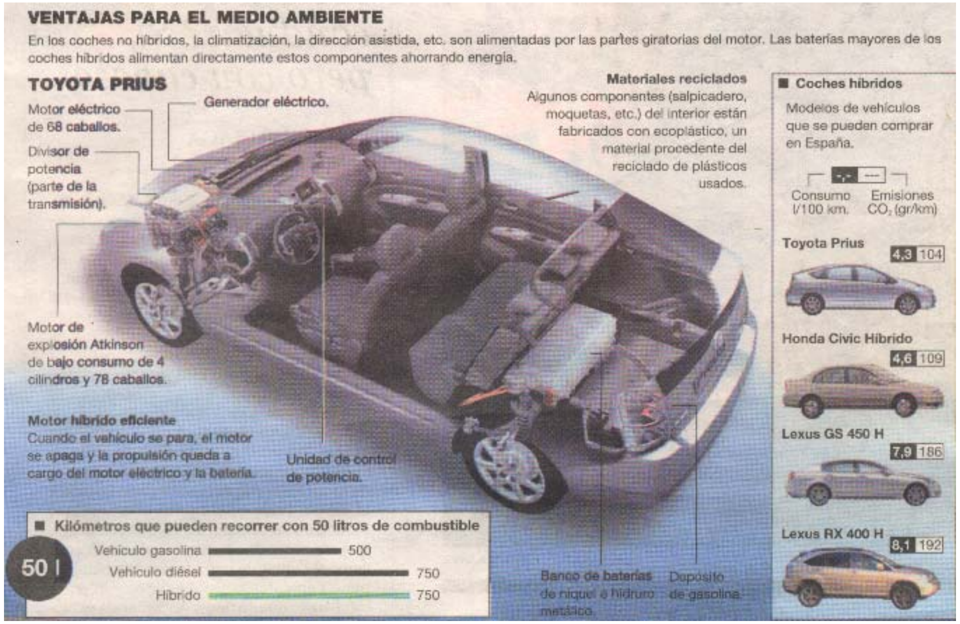
**Encendido**
Se produce con el motor **eléctrico y con la energía almacenada en la batería.**

**Conducción normal**
El sistema de gestión controla el motor de gasolina y el eléctrico para obtener un nivel óptimo de eficiencia. La batería se va recargando durante la marcha.

**Aceleración total**
La energía la suministra tanto el motor eléctrico como el motor de explosión. La salida de energía se eleva al máximo para dotar al vehículo de una aceleración muy potente.

**Deceleración**
El motor eléctrico funciona como un generador durante la deceleración y el frenado. La energía regenerada se usa para recargar la batería.

**Parado**
Al frenar hasta detener el vehículo, el motor de gasolina se apaga y el eléctrico conduce el vehículo hasta una frenada suave. El sistema evita el derroche para ahorrar gasolina y parar la emisión de $CO_2$.



## VENTAJAS PARA EL MEDIO AMBIENTE

En los coches no híbridos, la climatización, la dirección asistida, etc. son alimentadas por las partes giratorias del motor. Las baterías mayores de los coches híbridos alimentan directamente estos componentes ahorrando energía.

### TOYOTA PRIUS

**Materiales reciclados**
Algunos componentes (salpicadero, moquetas, etc.) del interior están fabricados con ecoplástico, un material procedente del reciclado de plásticos usados.

**Motor híbrido eficiente**
Cuando el vehículo se para, el motor se apaga y la propulsión queda a cargo del motor eléctrico y la batería.

**Kilómetros que pueden recorrer con 50 litros de combustible**

| | |
|---|---|
| Vehículo gasolina | 500 |
| Vehículo diésel | 750 |
| Híbrido | 750 |

**Coches híbridos**
Modelos de vehículos que se pueden comprar en España.

| | Consumo l/100 km. | Emisiones $CO_2$ (gr/km) |
|---|---|---|
| Toyota Prius | 4,3 | 104 |
| Honda Civic Híbrido | 4,6 | 109 |
| Lexus GS 450 H | 7,9 | 186 |
| Lexus RX 400 H | 8,1 | 192 |

# Thermoeconomy of the fuel cells

It´s derived from the two principles: conservation and degradation of the energy

- energy balance matrix of the n streams in m equipments: $\mathbf{A_{mxn}\cdot H_{nx1}= 0_{mx1}}$
- exergy cost to produce one stream: $\mathbf{A_{mxn}\cdot B^{*}_{nx1}= 0_{mx1}}$ $\quad \boldsymbol{\alpha_{(n-m)xn}\cdot B^{*}_{nx1}= \omega_{nx1}}$

- Ideal cells depend on electrochemical reactions of fuels and oxygen at low (PA&PEFC) or high temperatures (MC&SOFC):

$H_2 + \frac{1}{2} O_2 \rightarrow H_2O(l)$ $\quad E= E^o + RT/2f\cdot \ln P_{H2}P_{O2}^{1/2}/P_{H2O}$ $\quad (E^o=1,23V)$ $\quad \eta=\Delta G^o/\Delta H^o=0,83$

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ $\quad E= E^o + RT/8f\cdot \ln P_{CH4}P_{O2}^{2}/P_{H2O}^{2}P_{CO2}$

- Losses include polarization by activation, resistance and concentration: $V=\eta_e\cdot E$ (Tafel), which are function of the system characteristics and current density ($A/cm^2$), and must be optimized (e.g. size vs efficiency of the cell for stationary or mobile applications)

$\eta_t = 0,83/1,23\cdot V$ for a hydrogen fuel cell at standard conditions (1 atm and 25ºC)

- The utilization ratio refers to reagents entering the cells which react electrochemically, while change in gas composition along the process contribute to reduce cell voltages

$U_f= H_{2,consumed}/H_{2,input}$

# Fuel cells vs. efficiency limitations of traditional power cycles

- Hydrogen from high-temperature reaction of coal with steam, for use in a fuel cell:
  - $C(0)+2H_2O(\text{steam 2 at, -57,8})= CO_2(-94{,}1) +2H_2(0)$ net change: **+21,5 kcal**
  - $2\ H_2\ (0) + O_2\ (0) = 2\ H_2O\ (\text{gas 2 at, -57,8})$ net change: **-115,6 kcal**
- Coal combustion:
  - $C\ (0) + O_2\ (0) = CO_2\ (-94{,}1)$ net change: **-94,1 kcal**
- Both options have the same net mass and energy balance, but suppose the steam-power cycle is 40% efficient (a generous estimate), and the fuel cell 80% efficient; another 0,23 mole of carbon must be burned to supply the 21,5 kcal for the endothermic coal-steam reaction, so the bottom line for the fuel cell system is: 115,6·0,80/1,23= **75,2 kcal** of electricity per mole of carbon - twice as much as for the traditional power cycle (94,1·0,40= **37,6 kcal**).

Back-of-an-envelope comparison (numbers in parenthesis are the heats of formation, kcal/mole at 25ºC)

# The hydrogen economy

The so-called `hydrogen economy´ is a long-term project that can be defined as an effort to change the current energy system to one which attempts to combine the cleanliness of $H_2$ as an energy carrier with the efficiency of fuel cells (FCs) as devices to transform energy into electricity and heat; as energy carrier, hydrogen must be obtained from other energy sources, in processes that, at least in the long term, avoid or minimize $CO_2$ emissions.

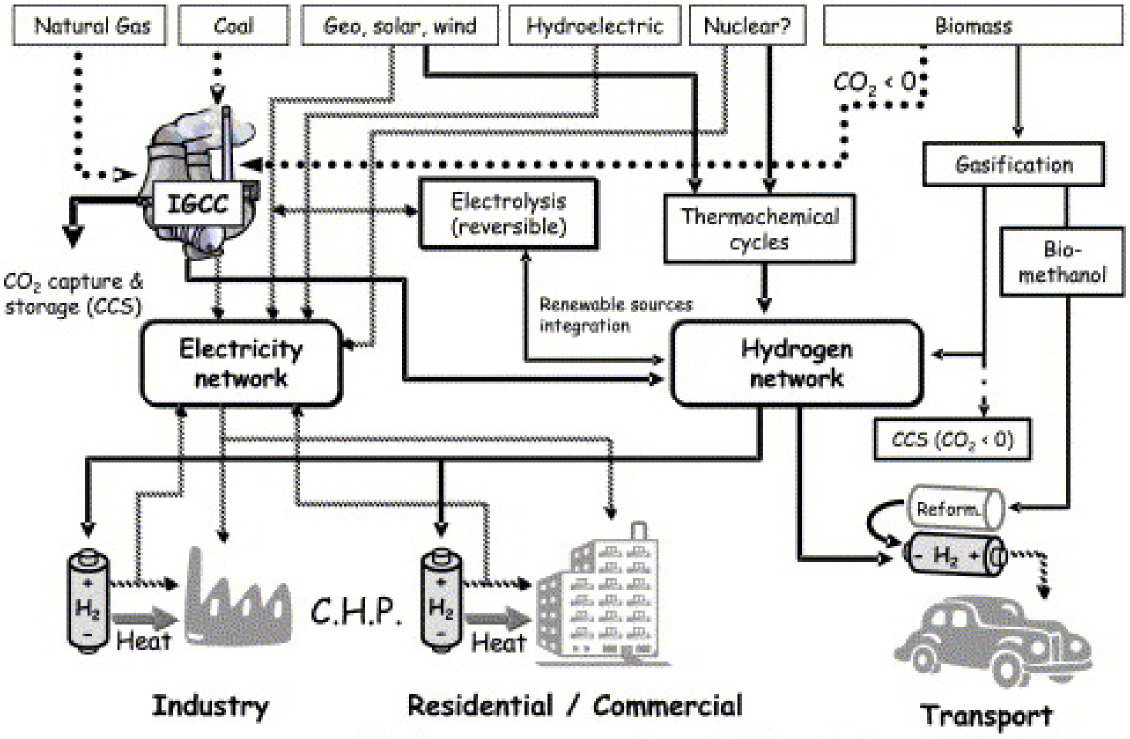
The main advantage of hydrogen as a fuel is the absence of $CO_2$ emissions, as well as other pollutants (e.g. thermal NOx if employed in low temperature FCs). This is especially important for the transport sector, which is responsible for 18% consumption of primary energy worldwide; apart from the economic and political interests involved in the substitution of oil-derived fuels, vehicles are highly dispersed $CO_2$ emission sources to install $CO_2$ capture and storage (CCS) systems. The two alternatives currently under consideration are hydrogen (and its derivative bio-methanol) and bio-fuels (bio-ethanol and bio-diesel).

Additionally hydrogen can be expected to allow the integration of some renewable energy sources, of an intermittent character, in the current energy system; thus, we can envisage a photovoltaic solar panel (or a windmill) linked to a reversible FC, which uses part of the electricity to produce $H_2$ during the day (or in windy conditions), and consumes $H_2$ during the night (or in absence of wind) to produce electricity.

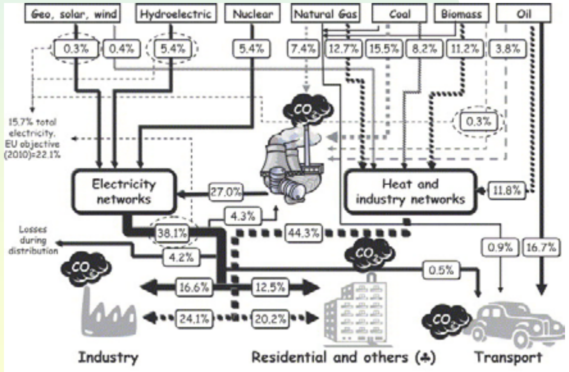
However, hydrogen is not an energy source but a carrier and consequently it will be as clean as the method employed in production; moreover, today its transport and storage is expensive and difficult due to its low energy density on a volume basis: gasoline density is 0.7 kg/l whilst $H_2$ density is 0.03, 0.06 and 0.07 kg/l at 350 atm, 700 atm and liquefied (at 20 K); as it is highly inflammable, $H_2$ is a dangerous gas in confined spaces, although it is safe in the open since it diffuses quickly into the atmosphere.

If all these difficulties for transition (taking into account the issues of hydrogen production, distribution, storage and use) are overcome, the energy supply and transformation systems will be managed as indicated in this expectative for the hydrogen society in a future, where renewables are intensified and fuel cells-hydrogen binomial is employed to achieve higher efficiencies:

**Year 20XX: Hydrogen Economy**



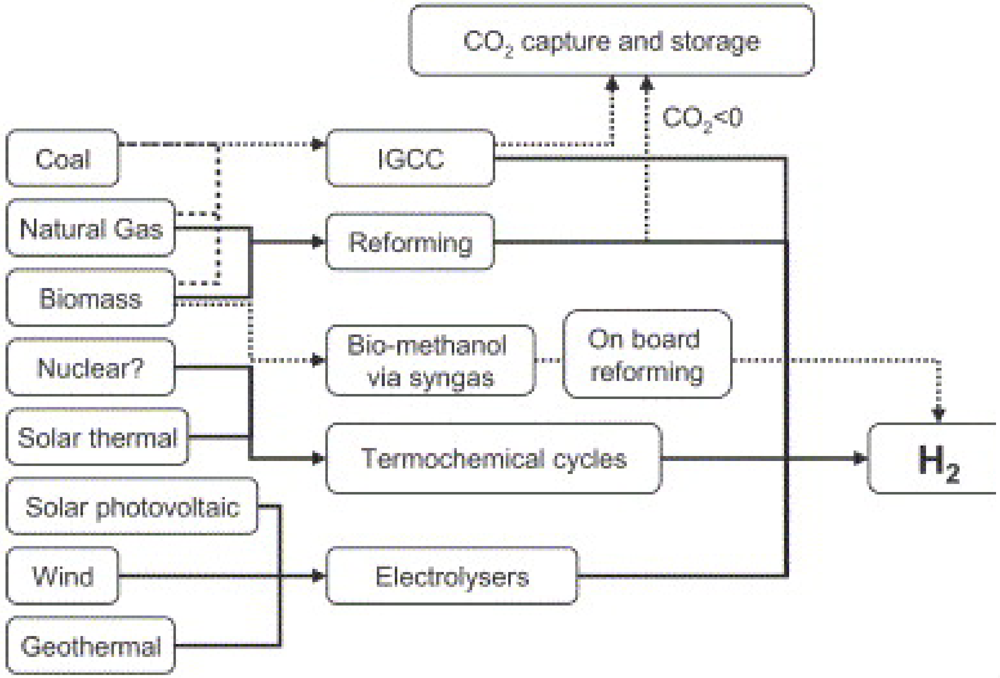
Worldwide primary energy (year 2050): >25 Gtoe



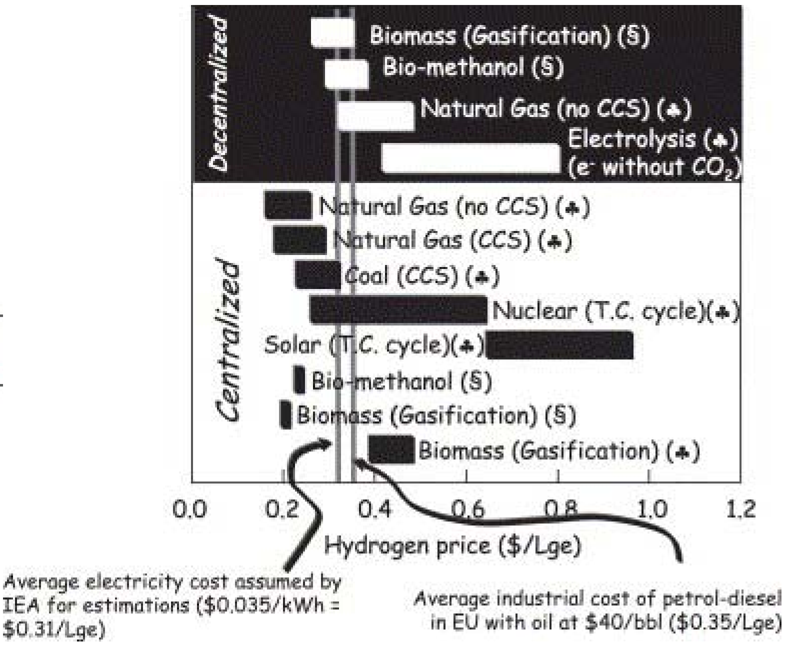
Two energy distribution networks will be operating: the electric network(s) and the hydrogen network(s), constituted by a multiplicity of interconnected production sources, with a lower capacity but more flexible than the current production sources (beyond the classical concept of a centralized distribution system).

# Energy sources mix and $H_2$ production processes in a hydrogen society

$H_2$ sources → production → transport → storage → use



Cost estimations in the future production of $H_2$



The equivalence in liters of gasoline is considered in terms of absolute energy content without taking into account the higher efficiency of the systems in which $H_2$ would be used (FCs); thus when comparing the prices of $H_2$ and gasoline *per kilometer* we should multiply the former by an approximate factor of 3/5.

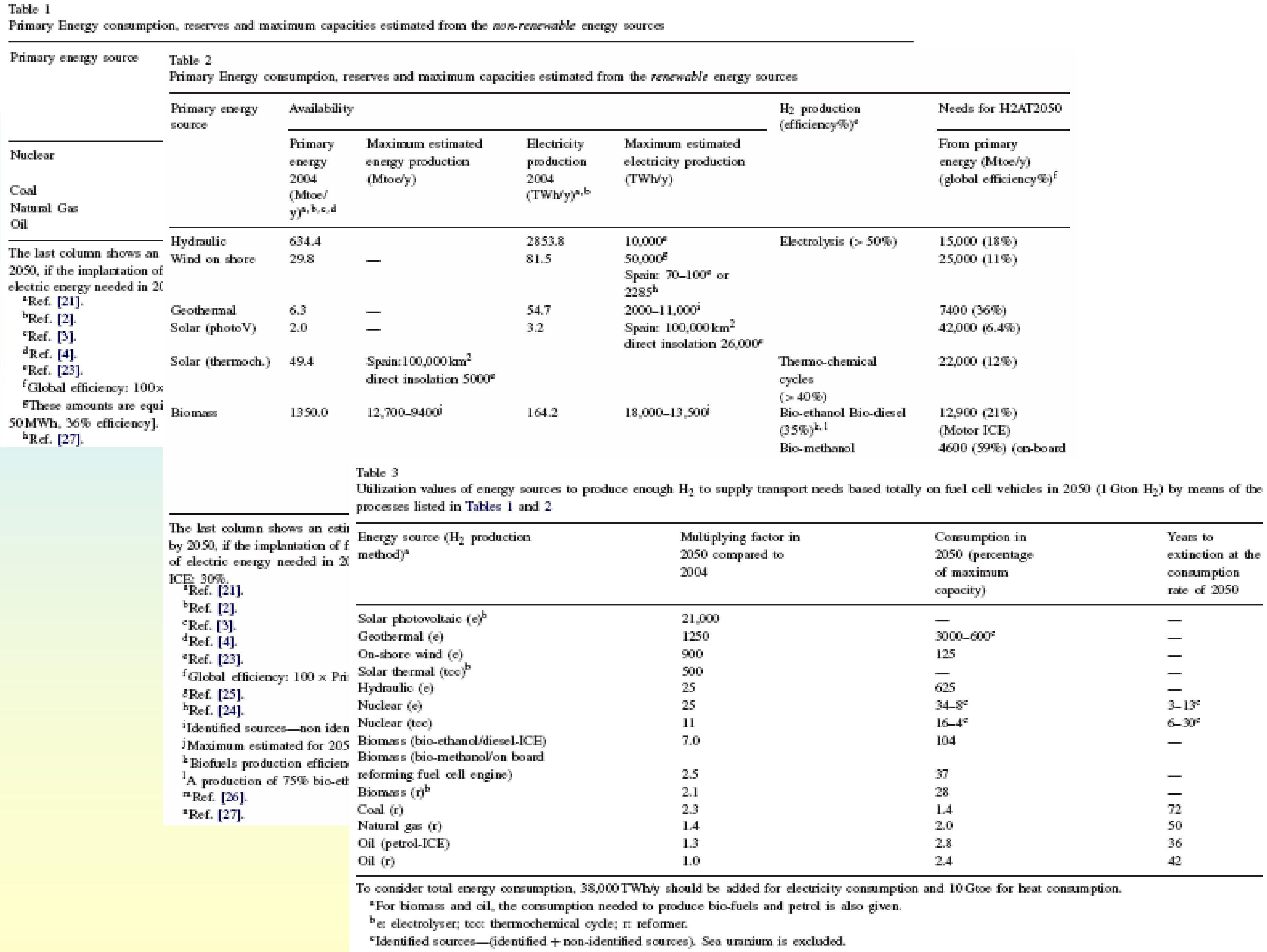


Table 1
Primary Energy consumption, reserves and maximum capacities estimated from the *non-renewable* energy sources

| Primary energy source |
|---|
| Nuclear |
| Coal |
| Natural Gas |
| Oil |

The last column shows an
2050, if the implantation of
electric energy needed in 2

[a]Ref. [21].
[b]Ref. [2].
[c]Ref. [3].
[d]Ref. [4].
[e]Ref. [23].
[f]Global efficiency: 100×
[g]These amounts are equi
50 MWh, 36% efficiency].
[h]Ref. [27].

Table 2
Primary Energy consumption, reserves and maximum capacities estimated from the *renewable* energy sources

| Primary energy source | Availability | | | | $H_2$ production (efficiency%)[e] | Needs for H2AT2050 |
|---|---|---|---|---|---|---|
| | Primary energy 2004 (Mtoe/y)[a, b, c, d] | Maximum estimated energy production (Mtoe/y) | Electricity production 2004 (TWh/y)[a, b] | Maximum estimated electricity production (TWh/y) | | From primary energy (Mtoe/y) (global efficiency%)[f] |
| Hydraulic | 634.4 | | 2853.8 | 10,000[e] | Electrolysis (> 50%) | 15,000 (18%) |
| Wind on shore | 29.8 | — | 81.5 | 50,000[g]<br>Spain: 70–100[e] or 2285[h] | | 25,000 (11%) |
| Geothermal | 6.3 | — | 54.7 | 2000–11,000[i] | | 7400 (36%) |
| Solar (photoV) | 2.0 | — | 3.2 | Spain: 100,000 km$^2$ direct insolation 26,000[e] | | 42,000 (6.4%) |
| Solar (thermoch.) | 49.4 | Spain:100,000 km$^2$ direct insolation 5000[e] | | | Thermo-chemical cycles (> 40%) | 22,000 (12%) |
| Biomass | 1350.0 | 12,700–9400[j] | 164.2 | 18,000–13,500[j] | Bio-ethanol Bio-diesel (35%)[k, l]<br>Bio-methanol | 12,900 (21%) (Motor ICE)<br>4600 (59%) (on-board |

The last column shows an esti
by 2050, if the implantation of f
of electric energy needed in 2
ICE: 30%.

[a]Ref. [21].
[b]Ref. [2].
[c]Ref. [3].
[d]Ref. [4].
[e]Ref. [23].
[f]Global efficiency: 100 × Pri
[g]Ref. [25].
[h]Ref. [24].
[i]Identified sources—non iden
[j]Maximum estimated for 205
[k]Biofuels production efficien
[l]A production of 75% bio-eth
[m]Ref. [26].
[n]Ref. [27].

Table 3
Utilization values of energy sources to produce enough $H_2$ to supply transport needs based totally on fuel cell vehicles in 2050 (1 Gton $H_2$) by means of the processes listed in Tables 1 and 2

| Energy source ($H_2$ production method)[a] | Multiplying factor in 2050 compared to 2004 | Consumption in 2050 (percentage of maximum capacity) | Years to extinction at the consumption rate of 2050 |
|---|---|---|---|
| Solar photovoltaic (e)[b] | 21,000 | — | — |
| Geothermal (e) | 1250 | 3000–600[c] | — |
| On-shore wind (e) | 900 | 125 | — |
| Solar thermal (tcc)[b] | 500 | — | — |
| Hydraulic (e) | 25 | 625 | — |
| Nuclear (e) | 25 | 34–8[c] | 3–13[c] |
| Nuclear (tcc) | 11 | 16–4[c] | 6–30[c] |
| Biomass (bio-ethanol/diesel-ICE) | 7.0 | 104 | — |
| Biomass (bio-methanol/on board reforming fuel cell engine) | 2.5 | 37 | — |
| Biomass (r)[b] | 2.1 | 28 | — |
| Coal (r) | 2.3 | 1.4 | 72 |
| Natural gas (r) | 1.4 | 2.0 | 50 |
| Oil (petrol-ICE) | 1.3 | 2.8 | 36 |
| Oil (r) | 1.0 | 2.4 | 42 |

To consider total energy consumption, 38,000 TWh/y should be added for electricity consumption and 10 Gtoe for heat consumption.

[a]For biomass and oil, the consumption needed to produce bio-fuels and petrol is also given.
[b]e: electrolyser; tcc: thermochemical cycle; r: reformer.
[c]Identified sources—(identified + non-identified sources). Sea uranium is excluded.

# Hydrogen storage and distribution network

Hydrogen produced in large centralized plants will be distributed to final consumption points by means of pipes. Alternatively, the hydrogen will be supplied *in situ* in small plants of decentralized production (production and refuelling stations).

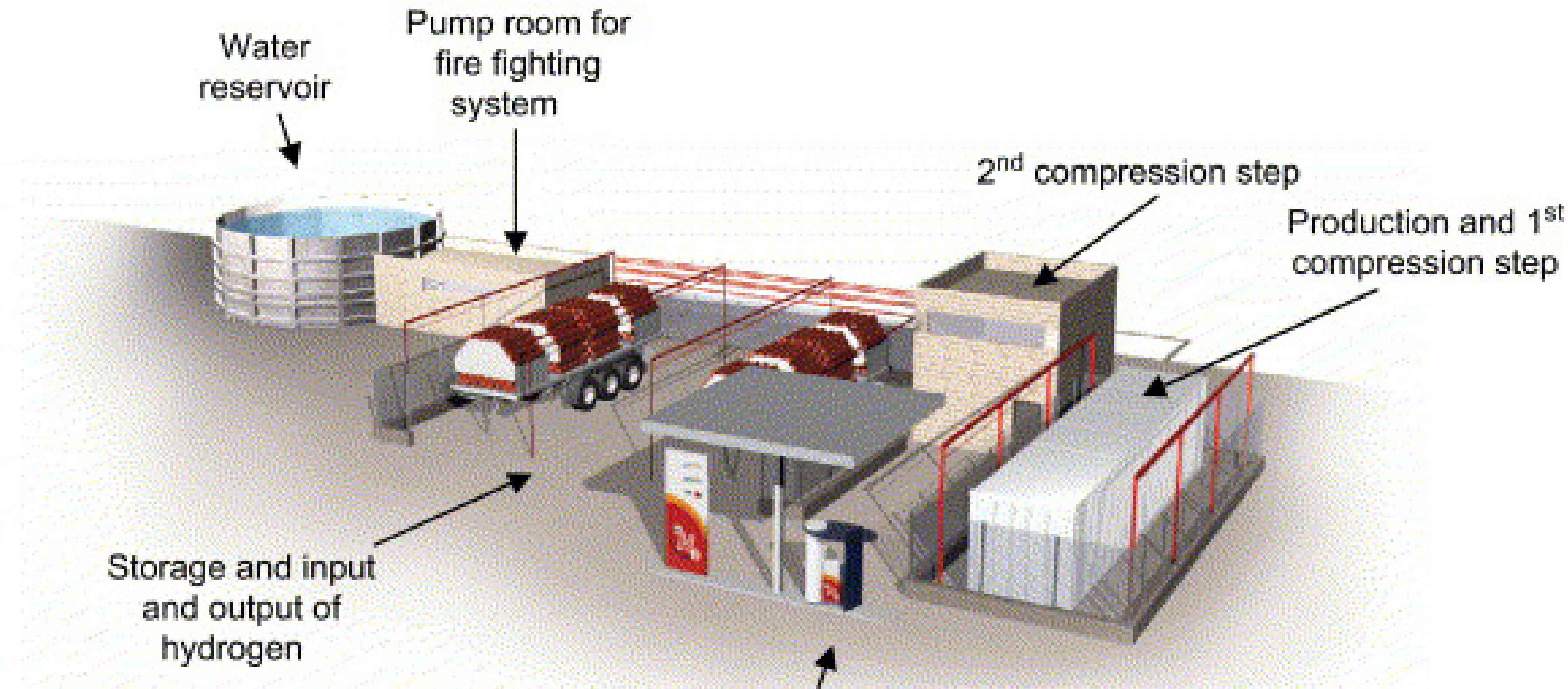
Most of the supply will be provided by a network of refuelling stations in which hydrogen will be supplied by a piping system connected to large scale production plants which use a mix of the primary energies most suited to each region. However, in order to supply the hydrogen to areas far from the general network it will be necessary to build refuelling stations able to generate hydrogen *in situ*, by means of electrolysers fed by renewable energies (such as photovoltaic solar panels or windmills) or biomass reformers.

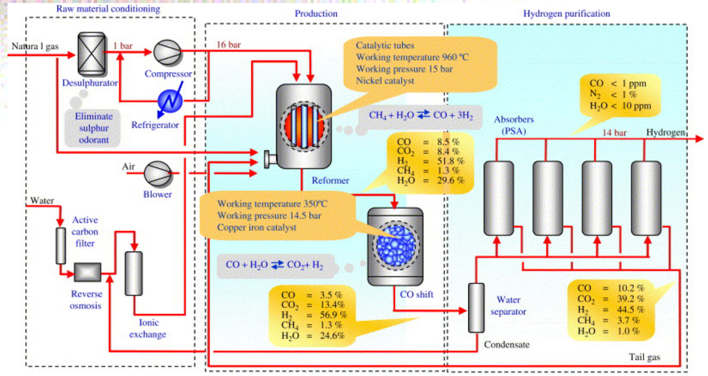
To store large quantities of hydrogen over long periods of time the best option is subterranean deposit, where $H_2$ is compressed and injected into natural gas fields and aquifers, cavities in saline formations, and depleted mines (the storage costs will vary depending on the type of geological formation, but they can be expected to be low).
For smaller scale storage at production points, similar systems to those employed in vehicles could be applied (pressure tanks, liquid hydrogen tanks, hydrides, etc.).

Centralized hydrogen production in thermal cogeneration power plants with CCS and scaled up reformers and electrolysers will lead to the creation of a distribution grid for transferring hydrogen to the consumption points (refuelling stations and residential CHP systems).

Today there are more than 16000 km of pipelines around the world that supply $H_2$ to refineries and chemical plants, with a diameter of 25–30 cm and operating at 10–20 atm, although they could operate at pressures of up to 100 atm. Considering that hydrogen pipes must be produced with non-porous materials such as steel, their cost for a given diameter is around twice that of pipes used for natural gas. Moreover, as the volumetric density of hydrogen is a fourth that of natural gas the cost of a $H_2$ pipe is about six times higher than that of a natural gas pipe, and we also need to include the cost of the refuelling stations (in a decentralized network, the cost of distribution would be avoided, but the global production cost of $H_2$ would be much higher).
If we assume that the creation of a centralized network could take as long as 60 years, the annual cost would be about 80 billion dollars (this is only 8% of worldwide armament expenditure in 2004).

# Fig. General layout of the hydrogen refuelling plant in Madrid





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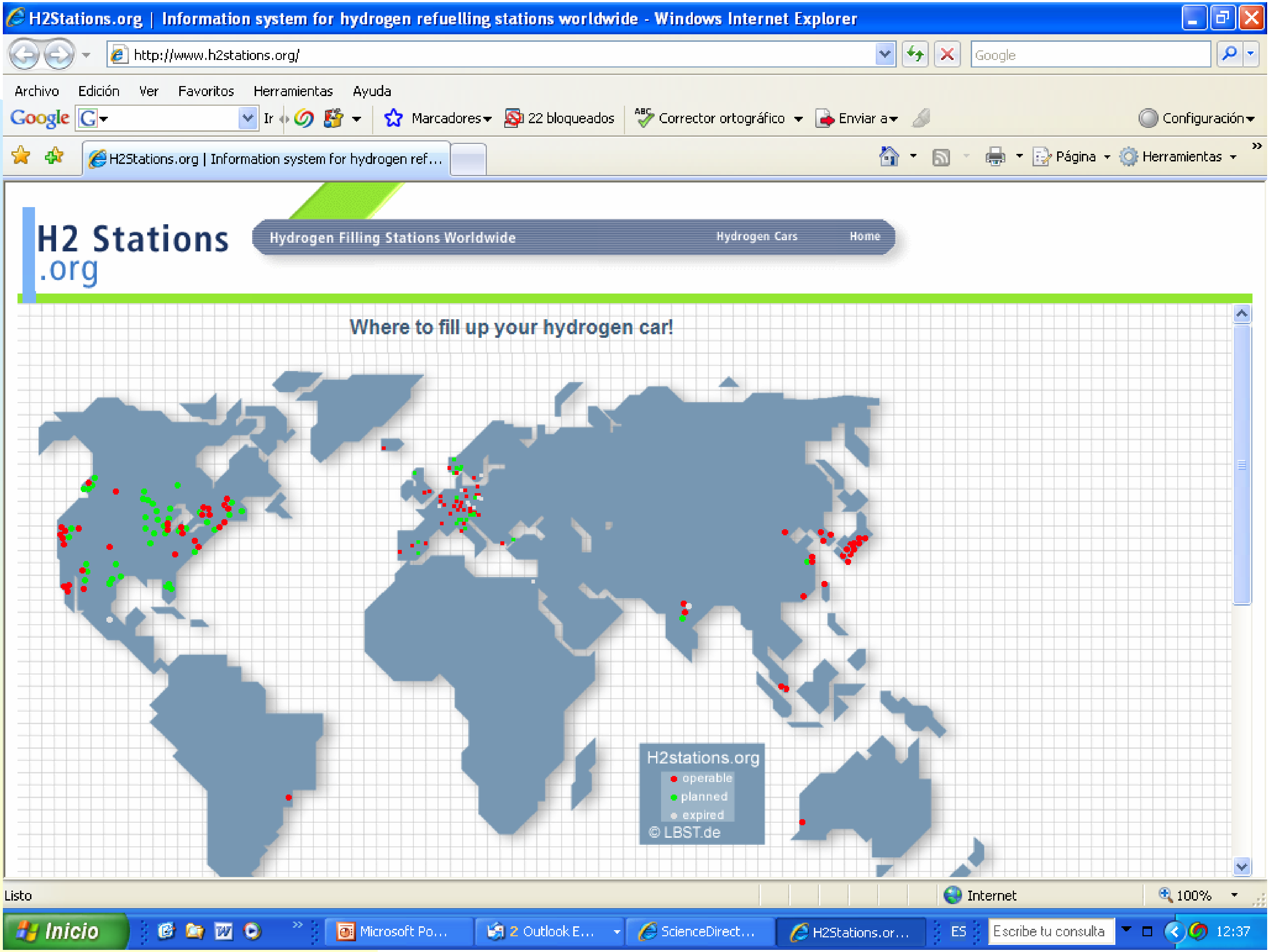
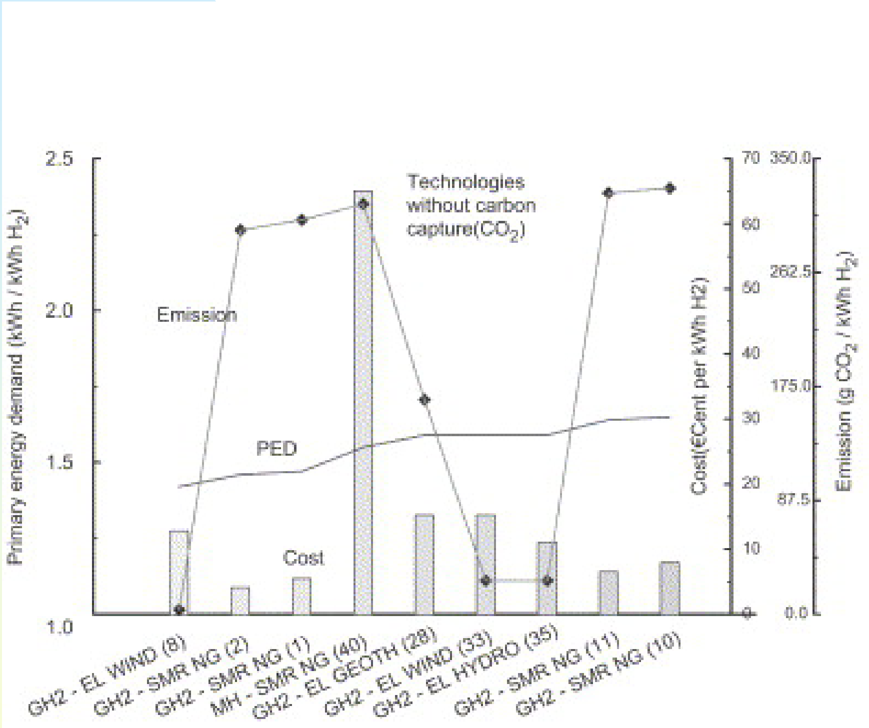
Production process diagram

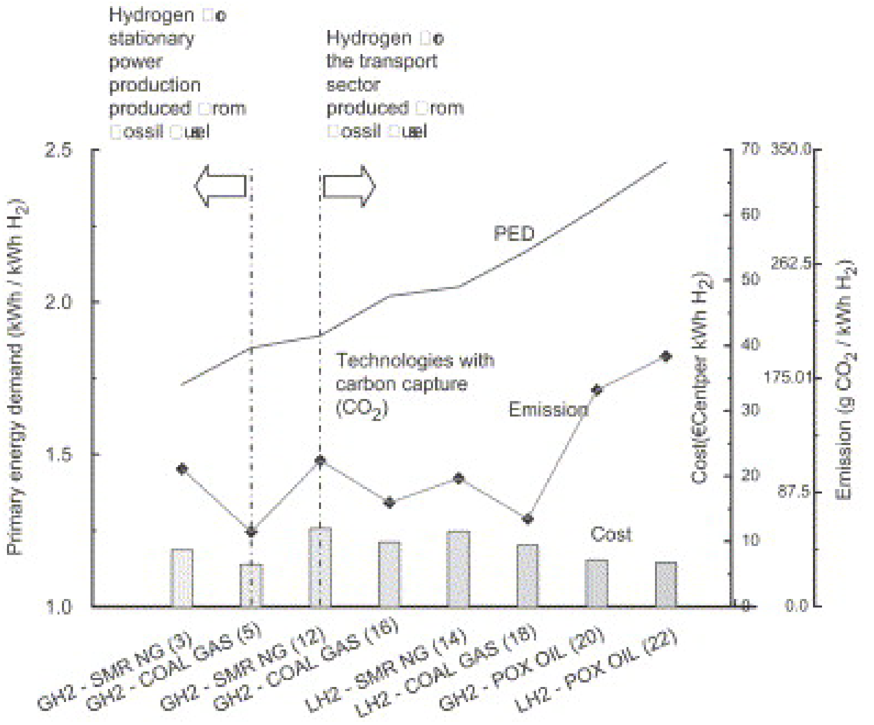


Where to fill up your hydrogen car!

# Energy supply system in a well-to-storage approach (excluding end-use) as resulting from HySociety pathways assessment, expressed in terms of cost, emission and primary energy demand (PED)

The left picture shows the nine most efficient hydrogen chains; the right pictures shows eight pathways from fossil fuels including CCS (ranked according to PED):





This well-to-storage loss can only be overcome if the end-use is more efficient than nowadays energy services. Since fuel cells are envisaged to give an overall well-to-use gain, high expectation of their efficiencies are roused, or it must be that local pollution and/or cost may make up for the additional conversion losses.

A clear message can be drawn: no chain presents itself as an obvious winner on all criteria: the best pathway in terms of efficiency never coincides with the best choice in terms of cost and emissions (this aspect may become quite decisive when it comes to a large-scale transition to hydrogen in Europe).

# Features of hydrogen pathway for fossil fuels with carbon capture as referred to in Fig.

| Pathway | Supply chain characteristics |
|---|---|
| GH2-SMR NG | Gaseous hydrogen from natural gas via centralized steam reforming. Carbon capture. Pipeline transport. 5 MPa bar buffer pressure. |
| GH2-COAL GAS | Compressed gaseous hydrogen via centralized gasification of hard coal. Carbon capture. Pipeline transport. 50 bar buffer pressure. Compression. Storage. Refuelling on-site. On-board storage at 70 MPa. |
| LH2-SMR NG | Liquid hydrogen from natural gas via steam reforming. Carbon capture. Central liquefaction. Transport in cryogenic tank by truck. Refuelling. Cryogenic on-board storage. |
| LH2-COAL GAS | Liquid hydrogen from natural gas via reforming. Carbon capture. Central liquefaction. Transport in cryogenic tank by truck. Refuelling. Cryogenic onboard storage. |
| GH2-POX OIL | Compressed gaseous hydrogen produced via partial oxidation of residual oil at refinery. Carbon capture. Pipeline transport. Compression. Storage. Refuelling on-site. On-board storage at 70 MPa. |
| LH2-POX OIL | Liquid hydrogen supplied via compressed gaseous hydrogen via partial oxidation of residue oil at refinery. Carbon capture. Centralized liquefaction. Transport in cryogenic tank by truck. Refuelling. On-board storage. |

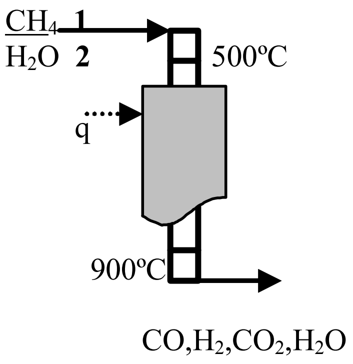
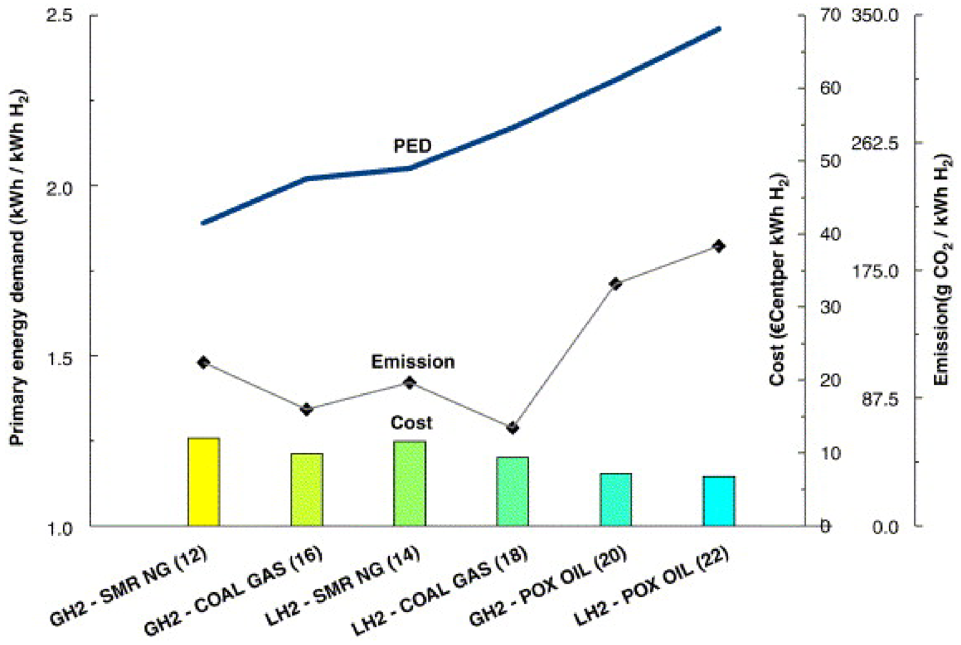


Fig. Pathways for hydrogen supply for the transport sector produced from fossil fuels with carbon capture by technology/export conditions (HySociety analyses).

Here the primary energy index, the cost and the emission are shown versus technologies (and state of hydrogen delivery).



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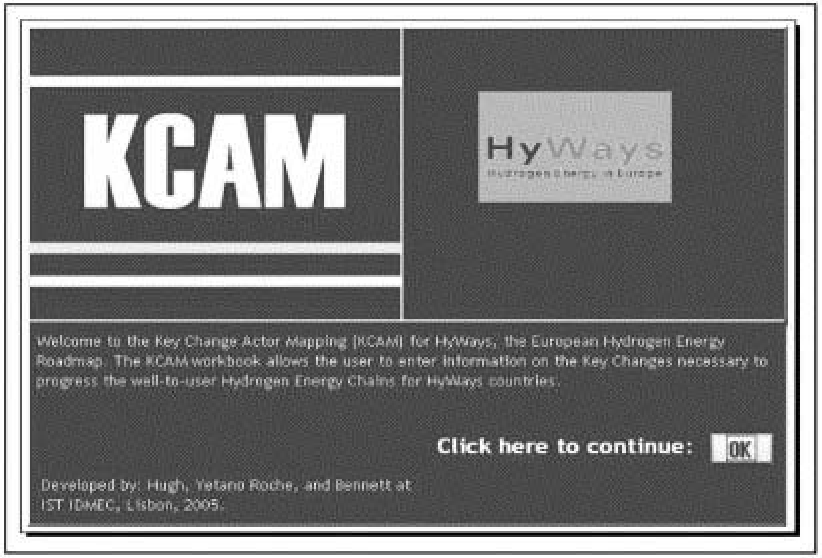
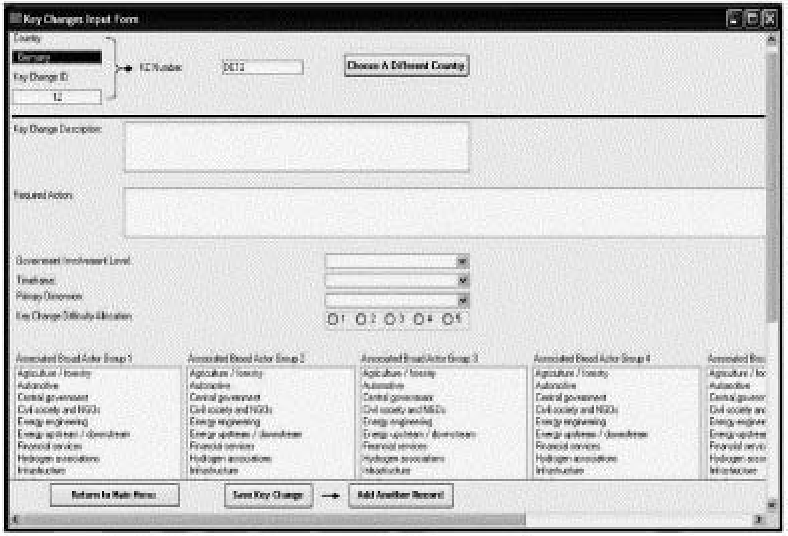
# Hydrogen supply chain structure by components with example chain component choices

| **Supply chain component structure** | **Example chain component choice** |
|---|---|
| Feedstock | Natural gas |
| **$H_2$** production method | Centralized steam methane reforming |
| Carbon capture and storage (CCS) | Yes |
| First conversion | No |
| **$H_2$** transport | Pipeline |
| Local **$H_2$** distribution system | Compressed **$H_2$** fuelling station |
| End use application | Fuel cell vehicle |



Welcome to the Key Change Actor Mapping (KCAM) for HyWays, the European Hydrogen Energy Roadmap. The KCAM workbook allows the user to enter information on the Key Changes necessary to progress the well-to-user Hydrogen Energy Chains for HyWays countries.

Developed by: Hugh, Yetano Roche, and Bennett at
IST IDMEC, Lisbon, 2005.



Hydrogen will also be able to supply a fraction of the energy requirements in residential and industrial sector, by means of solid oxide fuel cells (SOFC) which operate at high temperature with high efficiency (to cogenerate electricity and heat).

Small capacity units of 4-300 kW will be employed to supply energy to family residences and apartment blocks; medium capacity systems (<10 MW) will be able to provide electricity in residential, service and industrial areas. They are able to operate on different fuels ranging from methane to $H_2$, including $CO/H_2$ mixtures, which makes them an ideal system for the transition from natural gas to $H_2$.

The balance between the use of $H_2$ and electricity from the conventional network will be established by the law of supply and demand in the different sectors; the integration of cogeneration FCs in the electric network will permit the sale of energy excess; where the system is not integrated (i.e. single residences) small excesses of electricity generated in situations of low energy demand could be stored by lead-acid conventional batteries for use in situations of high demand.

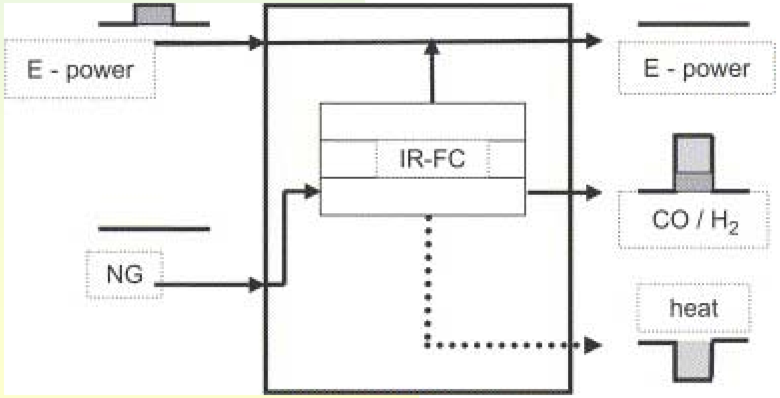
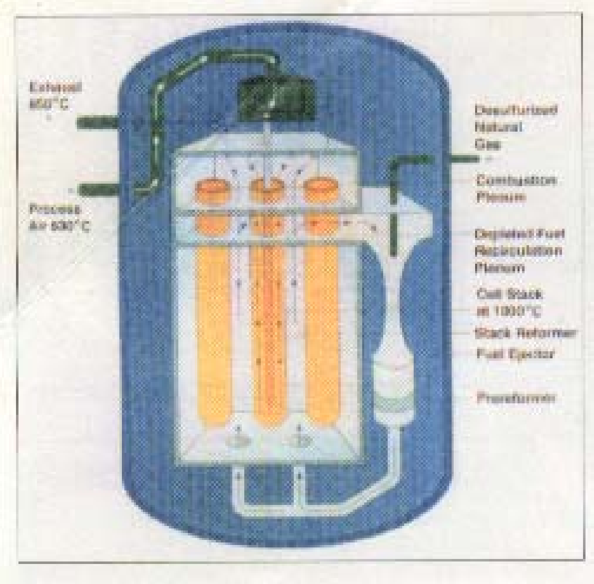
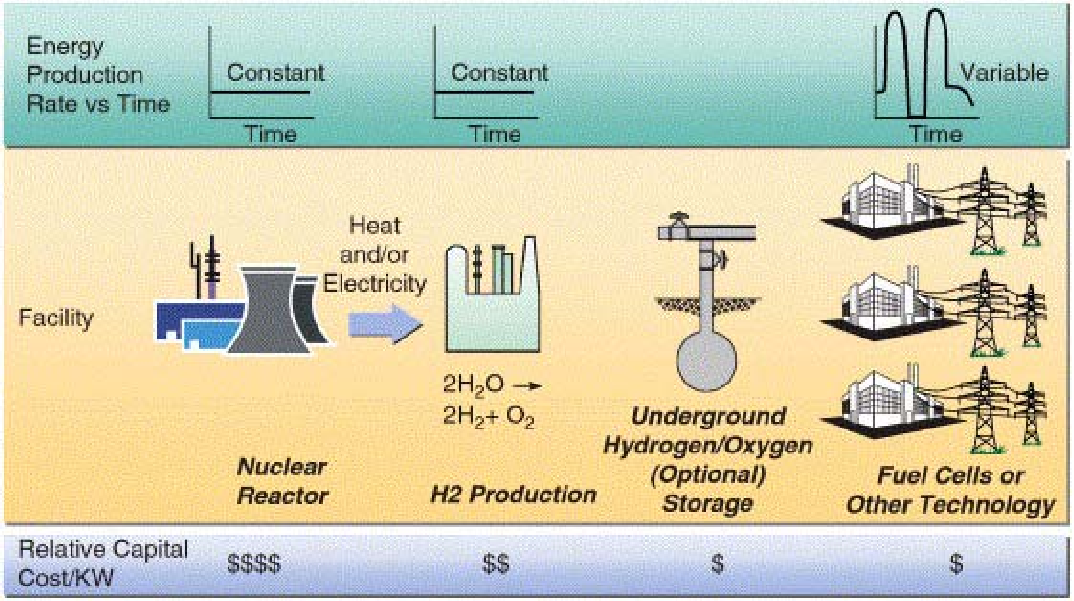


Fig. Energy hub using the flexible coproduction of hydrogen and power of an internal reforming fuel cell to compensate fluctuating supply of renewable



# Fig. Hydrogen intermediate and peak electrical system (HIPES) using nuclear hydrogen



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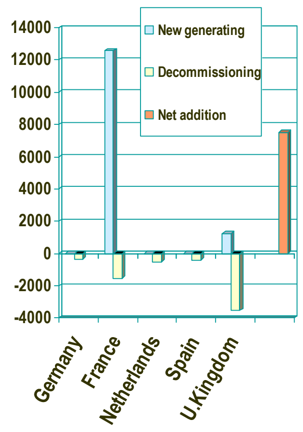
The present energy ratio for nuclear electricity is satisfactory, with a range from 10.2 to 16.5 for electrical output compared with thermal inputs, dominated by the enrichment of uranium accounting for 62% of the $24.2\ g_{CO2}/kWh$ life cycle emissions. Emissions from mining and milling are under 5%, but energy ratios for nuclear power is very sensitive to U ore grades: for concentrations below 100–200 ppm $CO_2$ emissions exceed those from an equivalent natural gas power station.

Breeder (fast) reactors could potentially extend the U reserves and the use of fertile Th resources to produce fissile material; but the only commercial reactor built -France's Superphenix- was shut down in 1998 after numerous problems.

## Major problems facing the nuclear sector

- Lack of public confidence that even Western nuclear technology can permanently guarantee safety.
- Fears about the ability to guarantee safe long term storage of high-level waste.
- Perception that the full cost of the nuclear cycle is greater than suggested (operation, decommissioning and waste handling).
- Key issues: operational safety (sp.loss of coolant), disposal of nuclear wastes (inc. decommissioning), risks as. with a plutonium economy, and the effects of low-level radiations.

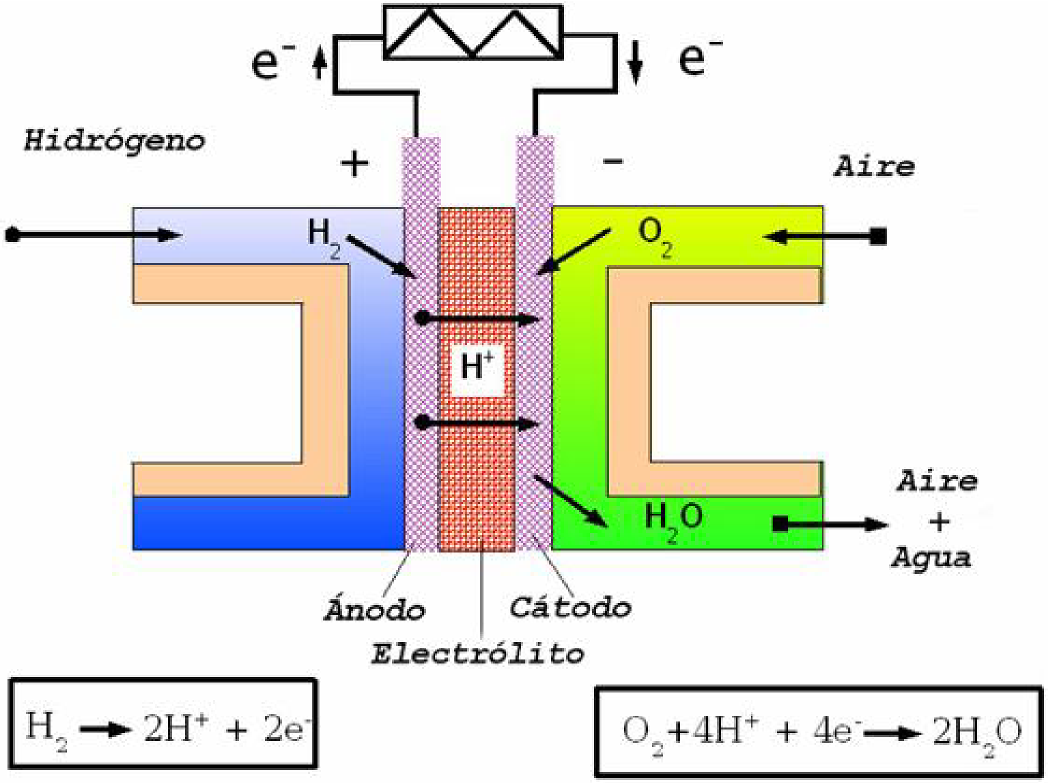
Nuclear power new capacities (MW) (1990-2005)



# Storage in vehicles and Fuel Cells (FCs)

In the hydrogen society, the main use of this fuel will be to feed the solid polymer electrolyte (or proton exchange membrane) fuel cells (PEMFC), which is a low temperature cell with high power densities, as most promising technology for onboard vehicles (road, marine and aerial); the price of vehicles based on fuel cells will need to decrease substantially, and so technological improvements in the FCs and storage systems will be required.

$H_2$ sources → production → transport → storage → use



http://weblogs.madrimasd.org/energiasalternativas/archive/2007/03/23/62133.aspx

# Technical specifications of the Honda FCX

Source: Honda 2006http://world.honda.com/news/2006/4060925FCXConcept/

Number of Passengers: 4

Motor: Max. Output: 95kW (129PS)
Max. Torque: 256N•m (26.1kg•m)
Type: AC synchronous motor (Honda mfg.)

Fuel Cell Stack: Type: PEFC (proton exchange membrane fuel cell, Honda mfg.)
Output: 100kW

Fuel: Type: Compressed hydrogen
Storage: High-pressure hydrogen tank (350atm)
Tank Capacity: 171 l

Dimensions: (L×W×H) 4,760×1,865×1,445mm
Max. Speed: 160km/h
Energy Storage: Lithium-ion battery
Vehicle Range: 570km

The current cost of FC vehicles is about \$2000/kW (a standard car will need a fuel cell stack of ~100 kW). Future previsions indicate that cost could be reduced to \$100/kW, although further reduction to \$50/kW will be needed to make them completely competitive.

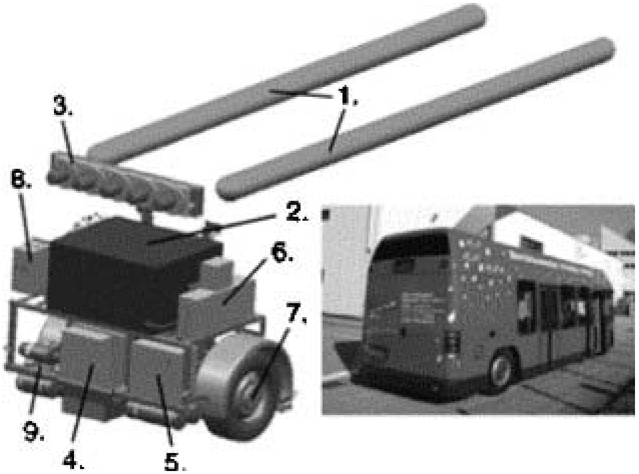
**Such a reduction cannot be achieved with the current technology, so new FC concepts are required; now PEMFC use conducting Nafion membranes as electrolytes, which operate at low temperature (80 °C); as consequence, the amount of Pt needed as catalysts in electrodes for the electrochemical conversion of $H_2$ and $O_2$ into water needs to be high (1.4 g/kW); two ways to reduce this amount would be either to increase reaction temperature over 100°C, which would imply the development of new membranes, or to resort to more active catalysts, e.g. platinum alloys with cobalt or chromium supported on electrodes with a higher surface area; the high temperatures FCs would additionally allow the bio-methanol reforming system to be integrated more easily in the vehicle.**

An exponential increase in the use of $H_2$ can be expected for transport in market niches where the engine and storage tank price is not critical (i.e. buses, trucks and planes).

The **hydrogen internal combustion engine** (ICE-$H_2$) is similar to the classic four-cylinder petrol engine except for some adjustments to the air mixture and other mechanical features; in the initial popularization step, it will permit the creation of a network of $H_2$ refuelling stations and become a bridge to FC vehicles.

During this transition some hybrid concepts will be put on the market to optimize the energetic efficiency of the vehicle (ICE/electric engine with a Li-ion battery and a computer to decide which motor should be activated in a given situation).

- To reach significant market share, barriers are technical performance, cost and social system in which technology is embedded:
  - City buses have been proposed as a `niche´ e.g. they are easier to design, can be developed as public demonstration projects, and the energy system is centrally refueled with hydrogen (comp.); in addition, they are used in populated areas where benefit of zero tail-pipe emissions is greater.
  - E.g. a bus route 9 km long, with 100 return trips a day (657000 km/yr), to compare CNG and diesel with prototype fuel cell buses (with hydrogen from decentralized steam reforming of natural gas), considering the local pollutants NOx, PM and noise, only in the use phase (tank-to-wheel).
  - Also considered is the potential to reduce `well to wheel´ GHG´s which depends on factors such as the hydrogen supply systems and the fuel and engine technologies of vehicle alternatives.



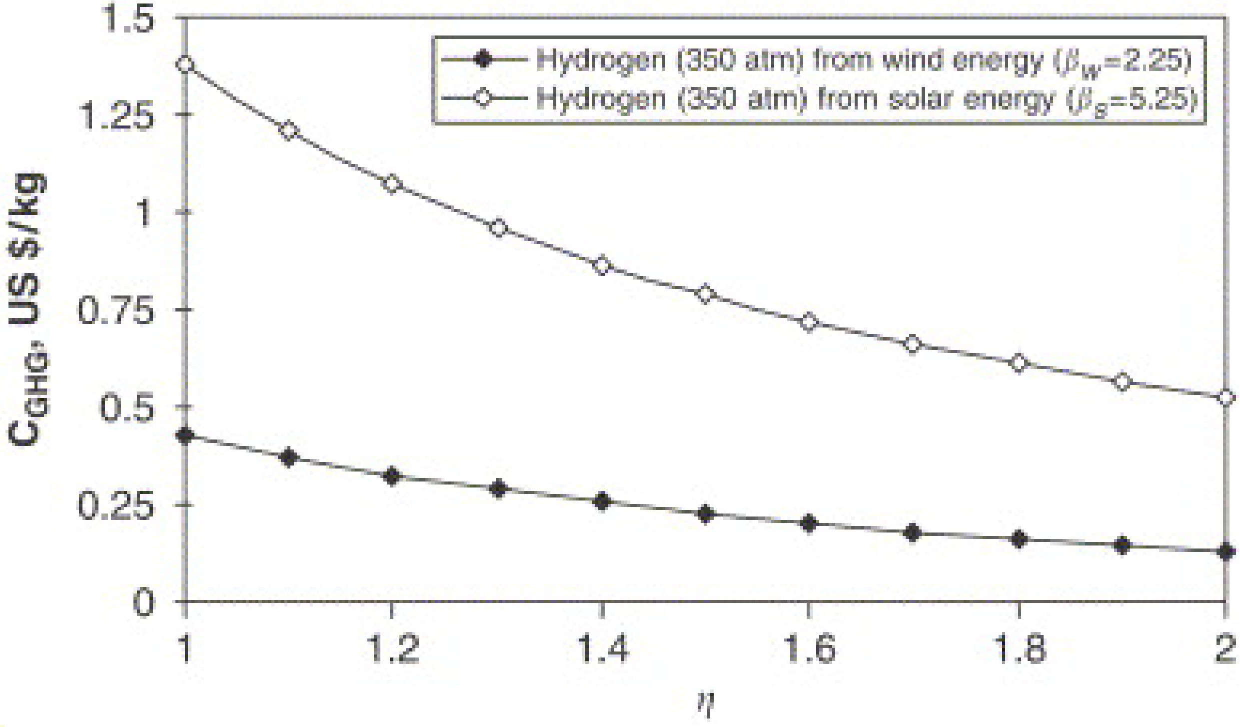
The propulsion system located in the rear of the bus

| Buses | Relative capital and fuel costs (Eur/km) | PM (mg/km) | $NO_x$ (g/km) | Local costs Eur/km | $CO_2$,eq | | Relative environmental costs (Eur/km) |
|---|---|---|---|---|---|---|---|
| | | choice | choice | | g/km | Eur/km | |
| Diesel | 0 | 28 | 2.10 | 0,059 | 1255 | 0,204 | 0,12 |
| CNG | | 17 | 2.10 | 0,041 | 1509 | 0,246 | |
| Fuel cell | 2,8 | 0 | 0,02 | 0 | 896 | 0,146 | 0 |

M.Karlström; Local environmental benefits of fuel cell buses – a case study (Sweden); J.Clean.Prod. 13 (2005) 679-85

Fig. The cost of GHG emissions reduction (per kg) as a result of hydrogen substitution for gasoline as a function of the ratio in efficiencies $\eta$ of internal combustion (gasoline powered) and fuel cell (hydrogen powered) vehicles.

**Introducing "renewable" hydrogen for fuel cell vehicles instead of gasoline can lead to an economically effective reduction of GHG emissions only if the efficiency of the fuel cell vehicle is more than two times higher than that of an internal combustion vehicle.**



**International Journal of Hydrogen Energy**
Volume 32, Issue 8, June 2007, Pages 927-931

Greenhouse gas emissions reduction by use of wind and solar energies for hydrogen and electricity production: Economic factors

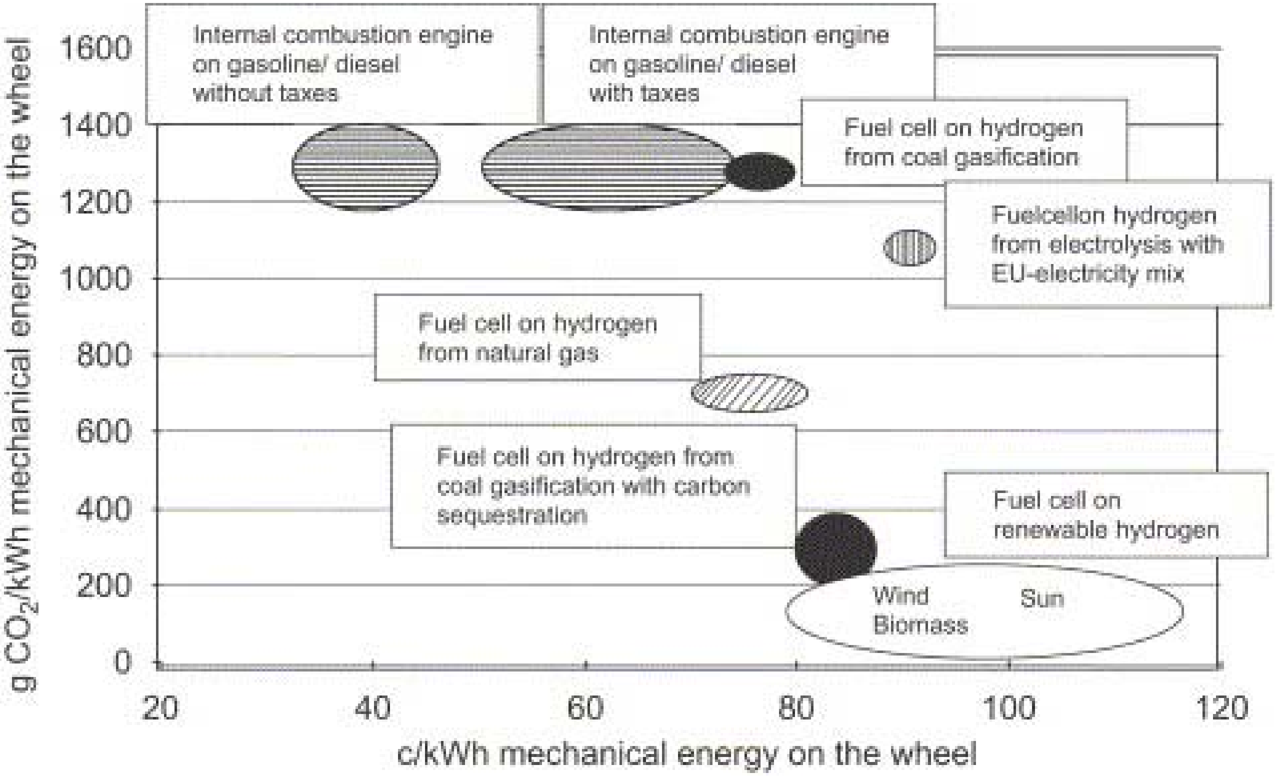
# Well-to-wheel analyses expressed in primary energy demand and emissions for several natural gas pathways, a gasoline pathway for reference, two hydrogen pathways with other energy sources than natural gas, and three hydrogen pathways including carbon capture

| | **E wheel (kWh)** | **Eff. (dimensionless)** | **E tank (kWh)** | **PED (kWh/kWh)** | **E primary (kWh)** | **Emission index (g/kWh fuel)** | **Emission (g/kWh wheel)** | **Emission (relative)** |
|---|---|---|---|---|---|---|---|---|
| *existing cars (2004)* | | | | | | | | |
| FC ($GH_2$ from NG) | 1 | 0.36 | 2.8 | 1.64 | **4.6** | 324 | 900 | **1** |
| ICE ($LH_2$ from NG) | 1 | 0.2 | 5.0 | 2.15 | **10.8** | 310 | 1550 | **1.7** |
| ICE (CNG) | 1 | 0.182 | 5.5 | 1.2 | **6.6** | 240 | 1320 | **1.5** |
| ICE (gasoline) | 1 | 0.182 | 5.5 | 1.15 | **6.3** | 291 | 1600 | **1.8** |
| FC ($GH_2$ from EL-wind) | 1 | 0.36 | 2.8 | 1.59 | **4.4** | 26 | 70 | **0.1** |
| FC ($GH_2$ from EL-EU mix) | 1 | 0.36 | 2.8 | 3.67 | **10.2** | 485 | 1350 | **1.5** |
| *Hybrid version (2010)* | | | | | | | | |
| FC ($GH_2$ from NG) HEV | 1 | 0.49 | 2.0 | 1.65 | **3.4** | 324 | 660 | **1.0** |
| ICE ($GH_2$) HEV | 1 | 0.35 | 2.9 | 1.65 | **4.7** | 324 | 930 | **1.4** |
| ICE NG-HEV | 1 | 0.318 | 3.1 | 1.2 | **3.8** | 240 | 750 | **1.1** |
| ICE (gasoline) HEV | 1 | 0.286 | 3.5 | 1.15 | **4.0** | 291 | 1020 | **1.5** |
| *carbon sequestration included* | | | | | | | | |
| FC ($GH_2$ from NG) HEV | 1 | 0.49 | 2.0 | 1.88 | **3.8** | 111 | 230 | **0.3** |
| FC ($GH_2$ from coal) HEV | 1 | 0.49 | 2.0 | 1.99 | **4.1** | 70 | 140 | **0.2** |
| ICE ($GH_2$ from NG) HEV | 1 | 0.35 | 2.9 | 1.88 | **5.4** | 111 | 320 | **0.5** |

the emission of a natural gas hybrid vehicle seemingly comes close to the emission of a hybrid fuel cell vehicle, whereas the impact of CCS is large on the emissions

# Comparison of several fuel pathways (well-to-wheel) regarding emission ($g_{CO2}$/kWh) and costs (c/kWh).

For the fossil fuels 2002 prices have been assumed with a crude oil price of 26 $/boe.



International Journal of Hydrogen Energy
Volume 32, Issues 10-11, July-August 2007, Pages 1324-1331

# Storage in vehicles

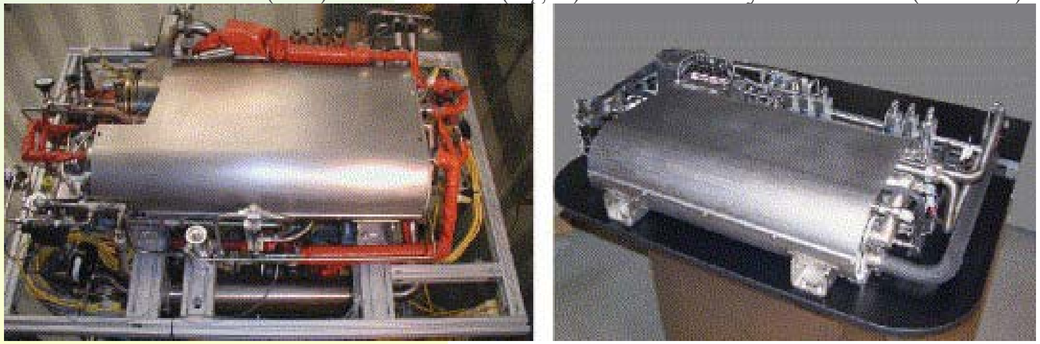
Secure and cheap $H_2$ storage systems will be needed in vehicles; it does not seem likely that the cost of compressing and liquefying hydrogen can be decreased to the level required for massive use, so other more predictable solutions include the development of solid deposits, e.g. rechargeable hydrides ($AlH_3$, $NH_4BH_4$, etc.) operating at pressures and temperatures of formation/decomposition between 1–10 atm and 25–100 °C.

An alternative option which can coexist with direct storage is onboard reforming of bio-methanol to produce the hydrogen that feeds the FC. Bio-methanol synthesized from biomass can be easily stored onboard, thus avoiding the high cost of hydrogen deposits.

While onboard $H_2$ storage and infrastructure still remain challenges, the `onboard fuel processors´ offer a promising solution to produce hydrogen for the fuel cell on the vehicle using conventional fuels such as gasoline or biofuels such as ethanol.

This technology could facilitate the early introduction of fuel cell vehicles while providing the potential to power them using various readily-available fuels.

Pictures of FPS 2.5 (left) and FPS 3A (right) on laboratory test stands (80 $dm^3$)



Onboard fuel processor for PEM fuel cell vehicles
**International Journal of Hydrogen Energy**
Volume 32, Issues 10-11
July-August 2007, Pages 1437-1442

Dual fuel vehicles -with hydrogen and gasoline feeding- are also being designed as transition from petrol to hydrogen, while the new refueling infrastructure is fully developed.

# Solid materials

## Due to the uncertainty about whether pressurized and liquid hydrogen tanks can be made at lower cost, the future seems to lie in storage in solid materials.

These systems require less energy to store $H_2$ in similar amounts to gaseous or liquid, at a lower volume and pressures; however their weight is considerably higher (50 L/200 kg for solids vs. 100 L/50 kg for $H_2$ compressed and liquid).

Rechargeable metallic hydrides, including their alloys, seem to be in a better starting position for winning the storage race, with an estimated value of 8 wt% (DOE objective: 6 wt% for a 400 km autonomy) at 10–60 atm.

Porous carbon was at one time considered an interesting material for $H_2$ adsorption; however, the failed expectations of nanotubes, whose initial results of 30–60 wt% stored hydrogen are now considered to have been an experimental error, has to some extent undermined research on these materials.

Other porous materials such as zeolites or (metal organic frameworks), MOF, with really high values of surface area are still in need of further development; they are capable of storing considerable amounts of $H_2$ at cryogenic temperatures but their adsorption capacities at ambient temperature are still quite low.

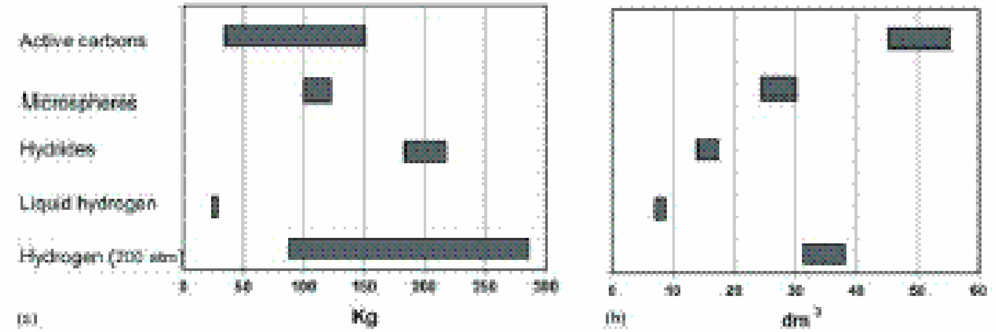


**Figure 1.** Weight (a) and volume (b) needed to store 4 kg of $H_2$ for different means

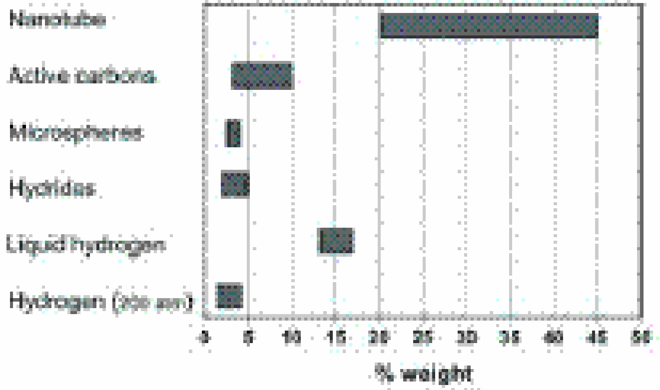


**Figure 2.** Percentage by weight of stored hydrogen for different

According to the technical target set by the US Department of Energy (DOE), the hydrogen stored in an on-board hydrogen storage system should be no less than 6% of the system weight by 2010 and no less than 9% by 2015. The corresponding costs should be no more than \$4/kWh and \$2/kWh, respectively.

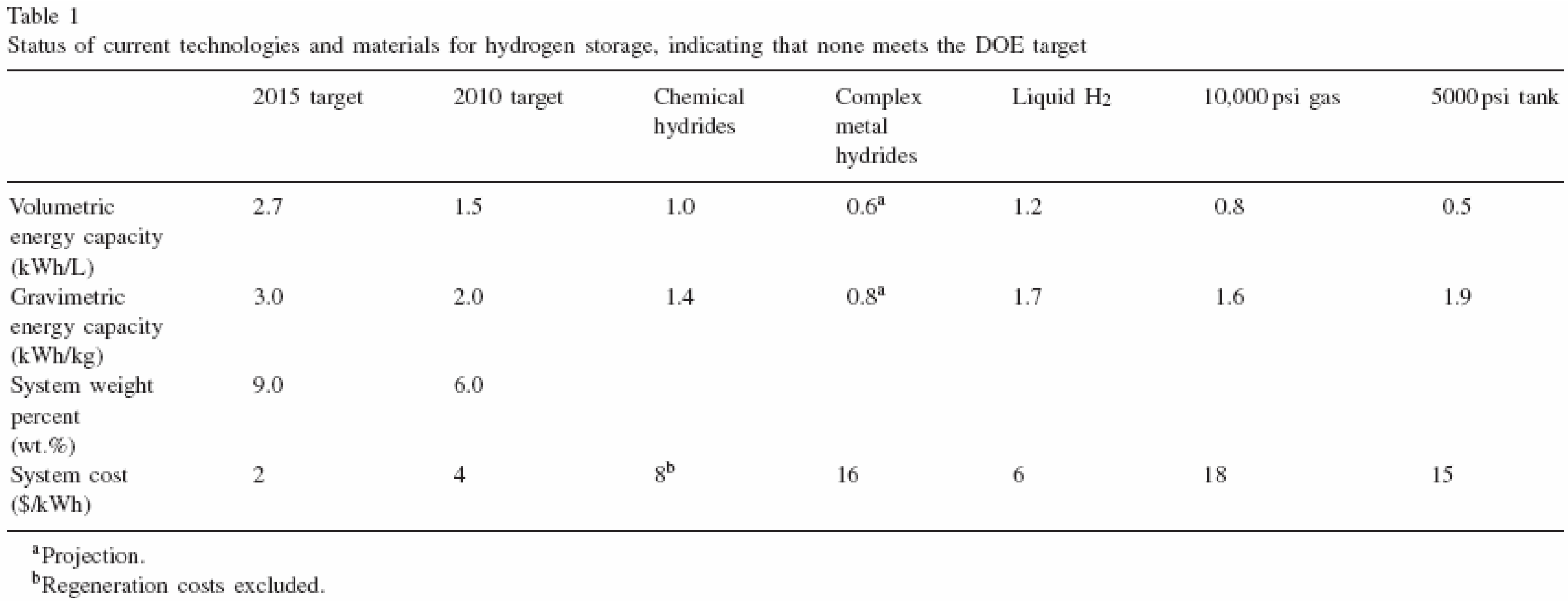


Table 1
Status of current technologies and materials for hydrogen storage, indicating that none meets the DOE target

| | 2015 target | 2010 target | Chemical hydrides | Complex metal hydrides | Liquid $H_2$ | 10,000 psi gas | 5000 psi tank |
|---|---|---|---|---|---|---|---|
| Volumetric energy capacity (kWh/L) | 2.7 | 1.5 | 1.0 | 0.6[a] | 1.2 | 0.8 | 0.5 |
| Gravimetric energy capacity (kWh/kg) | 3.0 | 2.0 | 1.4 | 0.8[a] | 1.7 | 1.6 | 1.9 |
| System weight percent (wt.%) | 9.0 | 6.0 | | | | | |
| System cost (\$/kWh) | 2 | 4 | 8[b] | 16 | 6 | 18 | 15 |

[a] Projection.
[b] Regeneration costs excluded.

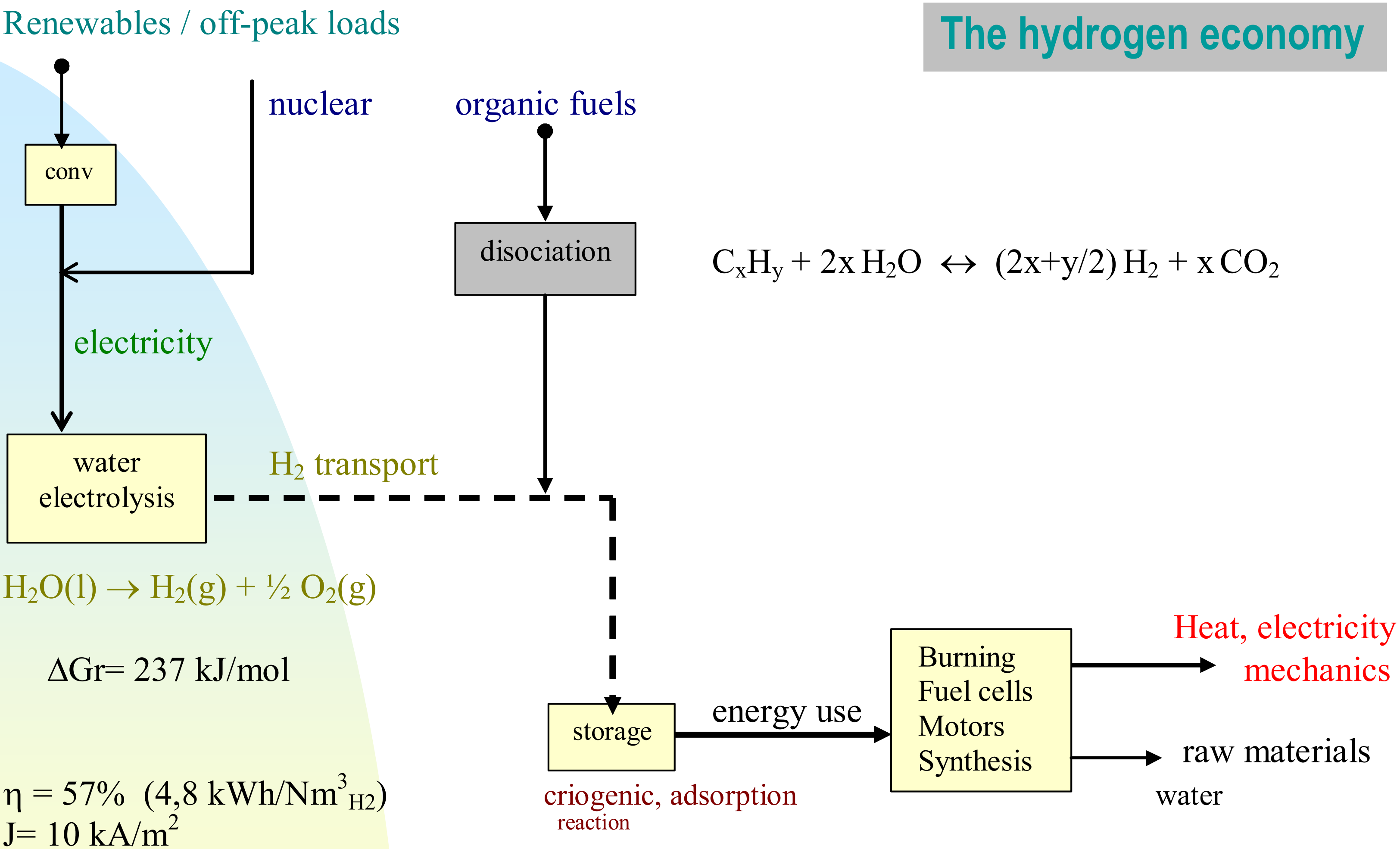
The hydrogen storage capability based on the techniques developed to date appears insufficient to meet the target, as illustrated in Table 1. It seems that high pressure tanks, cryogenic liquid cylinders, and conventional hydride materials have almost reached their limitations in capacity and it is unlikely that these approaches will make further significant progress toward DOE targets.

In 2003, US-DOE held a Hydrogen-Storage “Think Tank” meeting, which involved four Nobel Laureates and seven elite scientists. A “Grand Challenge” recommendation was made to solicit DOE single investigator projects for “Novel Materials and Concepts”. The DOE’s commitment has started many new projects in the last two years, which are generally divided into four areas:

- **Exploring new materials that have ultra large adsorption area**
- **Incorporating highly active sites into adsorption areas**
- **Introducing new adsorption/desorption mechanisms**
- **Seeking high hydrogen-content compounds**

Research frontier on new materials and concepts for hydrogen storage
International Journal of Hydrogen Energy 32 (2007) 224 – 228

# The hydrogen economy



Renewables / off-peak loads

nuclear

organic fuels

conv

disociation

$C_xH_y + 2x\,H_2O \leftrightarrow (2x+y/2)\,H_2 + x\,CO_2$

electricity

water electrolysis

$H_2$ transport

storage

criogenic, adsorption

reaction

energy use

Burning
Fuel cells
Motors
Synthesis

Heat, electricity
mechanics

raw materials

water

$H_2O(l) \rightarrow H_2(g) + \frac{1}{2}\,O_2(g)$

$\Delta Gr = 237$ kJ/mol

$\eta = 57\%$ (4,8 kWh/$Nm^3{}_{H2}$)
J= 10 kA/$m^2$
EDF/GDF (France)

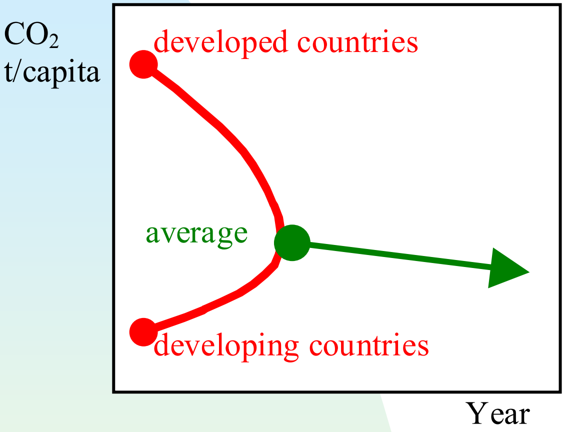
$\eta = 66\%$ (4,3 kWh/$Nm^3{}_{H2}$)
J= 2 kA/$m^2$
CONVENTIONAL

$H_2(g) + air \rightarrow H_2O + q + e$

$\mathbf{3H_2 + CO_2 \rightarrow CH_3OH + H_2O}$

$CaCO_3 \leftrightarrow CaO + CO_2$

It is necessary to change from a `fossilized´ to a `solar´ economy, to learn again walking smoothly on Earth and satisfy our needs in a way more free, intelligent and flexible, for not disappearing of the history face before the Sun ceases to bring its benefic contribution to other forms of life more modest



Two main restrictions for developing the new renewable energies (wind, solar, etc.) :

- **Competing and risks**, with current short-time accountability and investment practices (i.e. ecological economy is nedded).
- **Intensity**, due to dilution and space-time variability; i.e. the key issues are energy storage: with accumulators (batteries, heat), superconductor (bobbins, transmission), hydrogen and fuel cells.

Estimate the NPV of 1 million € invested in a 1 MW wind turbine 15 years from now, and compare it to buying bonds with a 6% interest rate.

- The annual average electricity production is 2.1 GWh, the maintenance costs are 20000 € and the electricity is sold at 0,04 €/kWh.

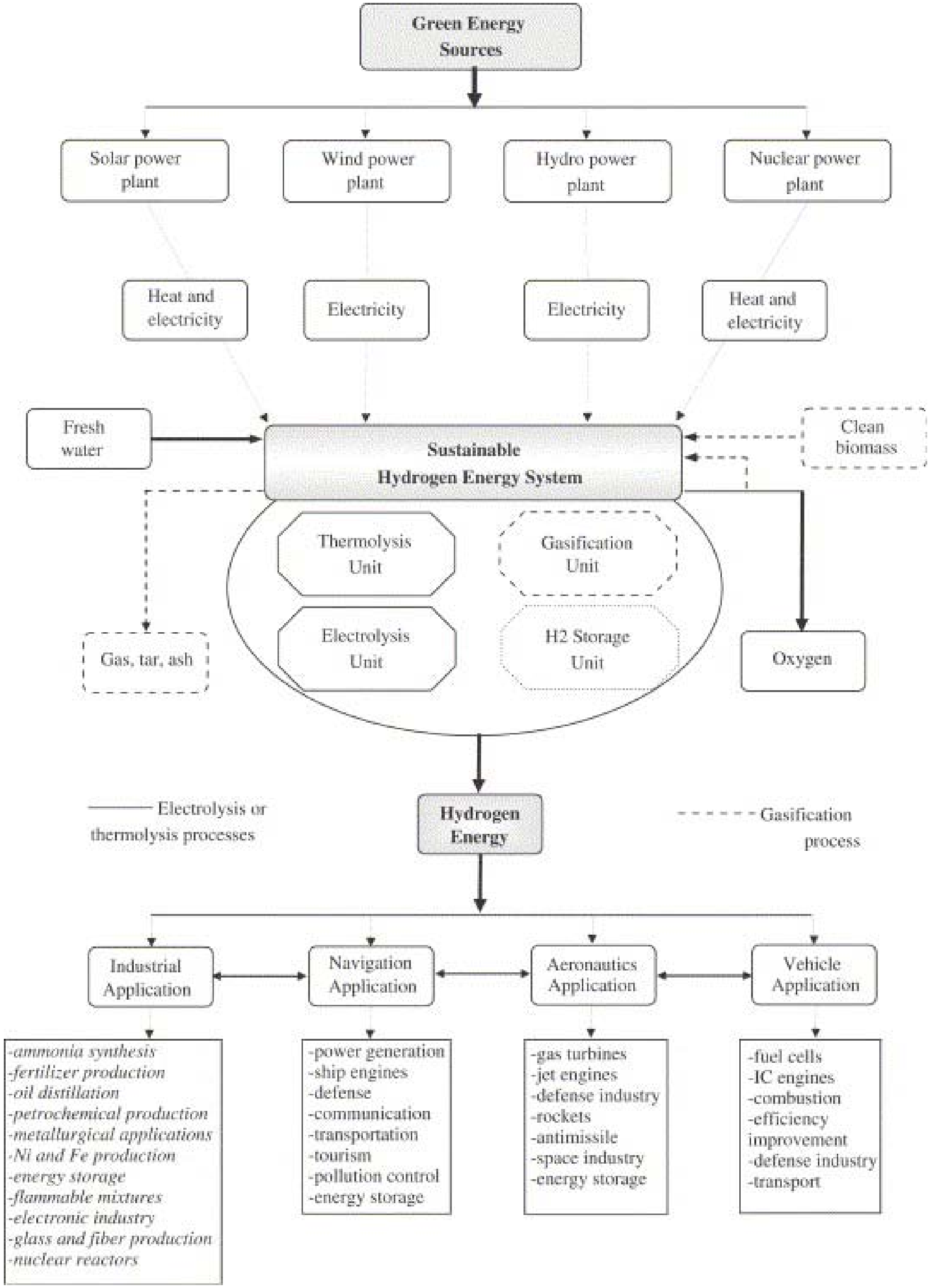
$$NPV_1 = -1000000 + (2{,}1\cdot10^6\cdot0{,}04 - 20000)\cdot\{(1+i)^t-1\}/\{i\cdot(1+i)^t\} = -378000\ €$$

- What will be the NPV if energy becomes scarce or external costs are taken into account, thus the price of this green electricity rises to 0,08 €/kWh ?

$$NPV_2 = -1000000 + (2{,}1\cdot10^6\cdot0{,}08 - 20000)\cdot\{(1+i)^t-1\}/\{i\cdot(1+i)^t\} = +437000\ €$$

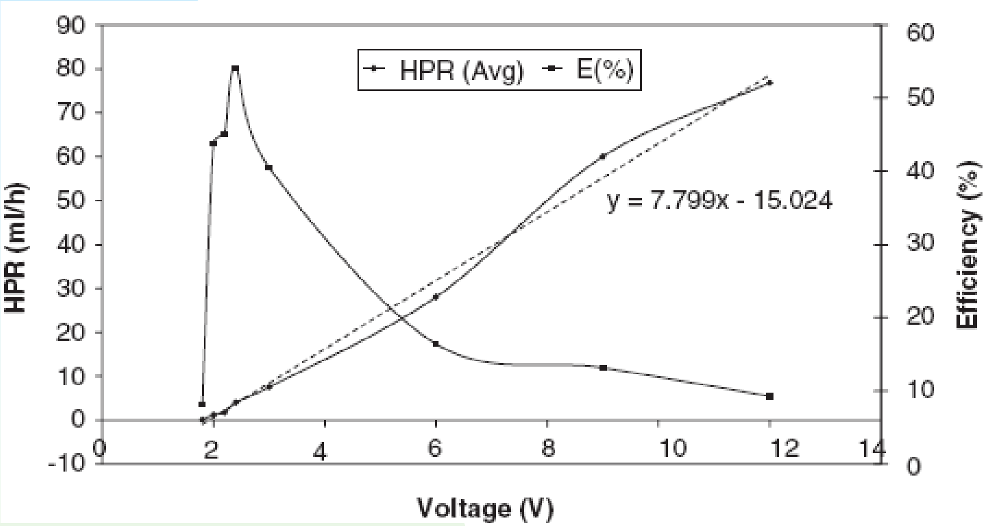
# Fig. Environmentally benign green energy based hydrogen energy system.

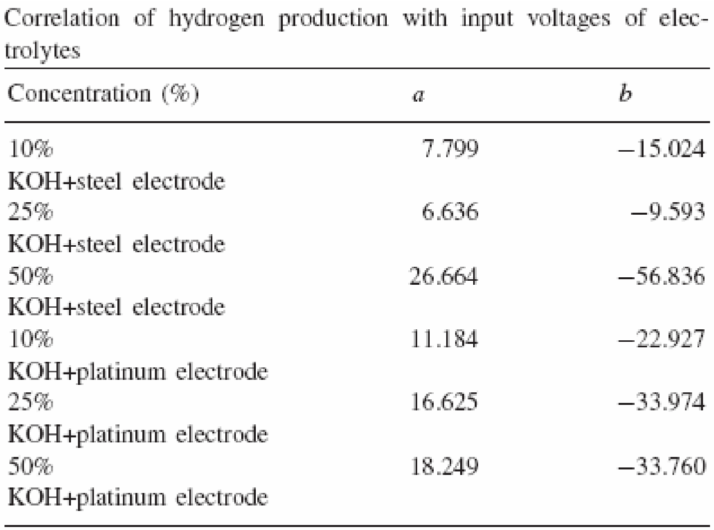
Intermitent RE and base-load electricity sources



# In these types of technologies, an efficient electrolyzer system would be the key factor:

Effect of voltage on Efficiency and Hydrogen Production Rate with 10% KOH electrolyte with steel electrode.





Correlation of hydrogen production with input voltages of electrolytes

| Concentration (%) | *a* | *b* |
|---|---|---|
| 10%<br>KOH+steel electrode | 7.799 | −15.024 |
| 25%<br>KOH+steel electrode | 6.636 | −9.593 |
| 50%<br>KOH+steel electrode | 26.664 | −56.836 |
| 10%<br>KOH+platinum electrode | 11.184 | −22.927 |
| 25%<br>KOH+platinum electrode | 16.625 | −33.974 |
| 50%<br>KOH+platinum electrode | 18.249 | −33.760 |

$$\mathbf{HPR} = b + a\cdot\mathbf{V}$$

From the experimental results and sensitivity analysis, it can be concluded that:

(i) As compared to theoretically required 1.23V, the optimum input voltage to get the highest efficiency was between 2.0 and 2.4V for varying concentrations of the electrolysis.

(ii) As the voltage increases, the efficiency decreases considerably.

Hence, it may be concluded that to achieve the best efficiency, an optimum voltage should be obtained, which would be depending upon the concentration of electrolyte, type of electrode and distance between the electrodes.

Optimization of electrolytic input power for the production of hydrogen
International Journal of Hydrogen Energy 31 (2006) 2329 – 2336

# Modeling and simulation of the production of hydrogen using hydroelectricity:

The total cost of production would be shown by

$$C_{TP} = \frac{C_I + C_{INV} + C_{OM}}{P_H}.$$

total consumption of electricity is

$$C_T = E_E + E_A + E_C = 1.24\,E_E.$$

cost of electricity for the production of electrolytic hydrogen is $C_{EE}=P_H C_T T_{EI}$ $C_I=C_{EE}$

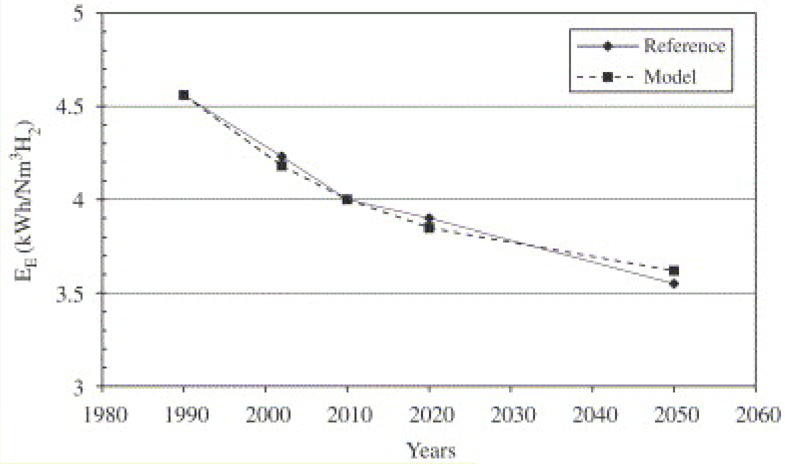


Fig. Energy efficiency

$$E_E=k_0 e^{-t/T}+k_1$$

$T_{EI}$ : industrial electricity tariff, \$/kWh

The cost of installing the electrolyser $C_{IE}=C_{EL}P$

in which power of the plant is obtained from $P=P_H C_T/DI$

$DI$ : annual availability (8328 h/year)

$$C_{EL} = 1499.74P^{-0.2167}, \quad R^2 = 0.987.$$

with the capital recovery factor

$$F = \frac{d(1+d)^n}{(1+d)^n - 1}$$

and the investment cost

$$C_{INV}=F \cdot C_{IE}$$
$$C_{OM}=\mathrm{OM} \cdot C_{INV}$$

International Journal of Hydrogen Energy
Volume 32, Issue 9, June 2007, Pages 1219-1224

# Estimates of the price of hydrogen as a medium for wind and solar sources

International Journal of Hydrogen Energy
Volume 32, Issue 12, August 2007, Pages 1605-1610

doi:10.1016/j.ijhydene.2007.04.037

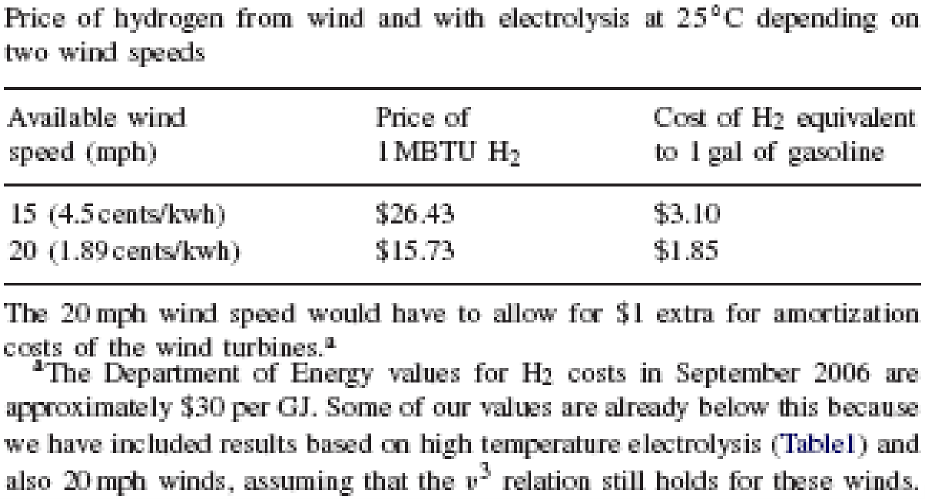
$$\text{Cost } (\$/\text{GJ}_{H2}) = 2.29 \cdot E \cdot c + 3$$

*E:* cell potential of the electrolysis: a normal figure in a modern commercial plant working at room temperature and at a current density = 100 mA·cm$^{-2}$ is 1.6 V (this involves the use of electro-catalytically favorable electrode coatings and associated conversion efficiency)

*c:* electricity cost available *to large-scale manufacturers* in cents per kwh

the second term is an aggregate of the amortization costs of building the plant, together with insurance, maintenance, and cost of employees to operate it

to these figures are added the costs of transfer of gas $H_2$ more than 1000 miles (rated at $1.66); finally, the figure obtained is multiplied by 1.25 ( 25% profit)

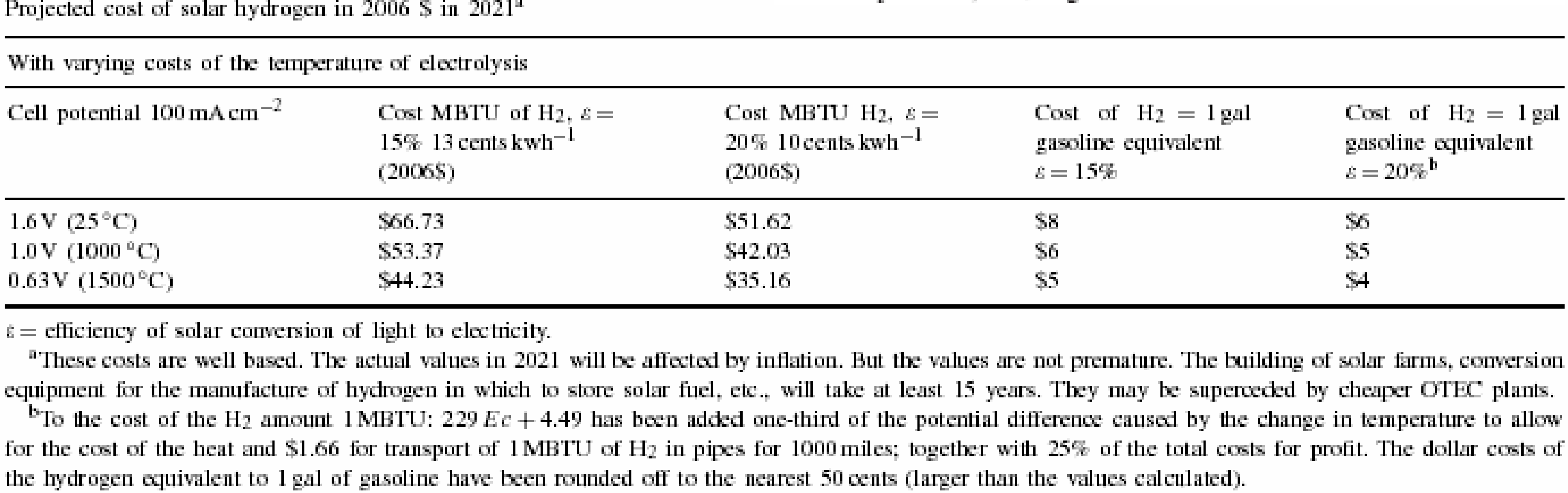


Price of hydrogen from wind and with electrolysis at 25 °C depending on two wind speeds

| Available wind speed (mph) | Price of 1 MBTU $H_2$ | Cost of $H_2$ equivalent to 1 gal of gasoline |
|---|---|---|
| 15 (4.5 cents/kwh) | $26.43 | $3.10 |
| 20 (1.89 cents/kwh) | $15.73 | $1.85 |

The 20 mph wind speed would have to allow for $1 extra for amortization costs of the wind turbines.[a]

[a] The Department of Energy values for $H_2$ costs in September 2006 are approximately $30 per GJ. Some of our values are already below this because we have included results based on high temperature electrolysis (Table1) and also 20 mph winds, assuming that the $v^3$ relation still holds for these winds.



Projected cost of solar hydrogen in 2006 $ in 2021[a]

| With varying costs of the temperature of electrolysis | | | | |
|---|---|---|---|---|
| Cell potential 100 mA cm$^{-2}$ | Cost MBTU of $H_2$, $\varepsilon =$ 15% 13 cents kwh$^{-1}$ (2006$) | Cost MBTU $H_2$, $\varepsilon =$ 20% 10 cents kwh$^{-1}$ (2006$) | Cost of $H_2$ = 1 gal gasoline equivalent $\varepsilon = 15\%$ | Cost of $H_2$ = 1 gal gasoline equivalent $\varepsilon = 20\%$[b] |
| 1.6 V (25 °C) | $66.73 | $51.62 | $8 | $6 |
| 1.0 V (1000 °C) | $53.37 | $42.03 | $6 | $5 |
| 0.63 V (1500 °C) | $44.23 | $35.16 | $5 | $4 |

$\varepsilon =$ efficiency of solar conversion of light to electricity.

[a] These costs are well based. The actual values in 2021 will be affected by inflation. But the values are not premature. The building of solar farms, conversion equipment for the manufacture of hydrogen in which to store solar fuel, etc., will take at least 15 years. They may be superceded by cheaper OTEC plants.

[b] To the cost of the $H_2$ amount 1 MBTU: $229\,Ec + 4.49$ has been added one-third of the potential difference caused by the change in temperature to allow for the cost of the heat and $1.66 for transport of 1 MBTU of $H_2$ in pipes for 1000 miles; together with 25% of the total costs for profit. The dollar costs of the hydrogen equivalent to 1 gal of gasoline have been rounded off to the nearest 50 cents (larger than the values calculated).

At 80 m above ground level, class 3 winds and higher (6.9 m/s average wind speed) occur on 12.2 million km$^2$ of the inhabited continents; assuming an spacing of one 2.0-MW turbine per km$^2$ and an average capacity factor (annual electricity of 30% of rated full-power output), the global potential wind energy can be calculated as 230 EJ primary electricity.

Energy analyses of the wind turbines based on detailed life-cycle analysis (ISO14040–14043) give an electrical energy output to primary energy input energy ratio of around 30; this value is derived via consideration of all material and energy inputs over a 20 year turbine life time for a typical on-shore location (turbine installation requirements are strongly linked to energy inputs and turbine electrical power output varies relative to the cube of wind speed).

Remote locations, intermittent supply, and large technical energy potential compared with electrical demand eventually necessitate conversion and storage of wind energy, and transmission to load centers, thus providing an opportunity for hydrogen.

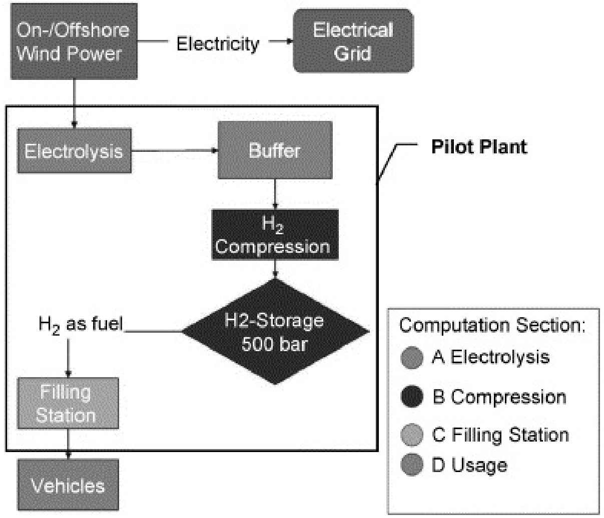
Electrolysizer units operate at 65–80% efficiency, with greater efficiencies promised; if, on average, we assume that only half the wind-generated electricity finishes up as hydrogen after electrolysis and transmission, energy ratios will be halved (additional reductions in this ratio will occur should the hydrogen be converted either thermally or chemically to electricity for end-uses); both this halving of delivered energy, the substantial investments needed for electrolizers, compressors and transmission pipes, and for some hydrogen storage at both points of production and end-use, will lead to further cost increases for hydrogen.

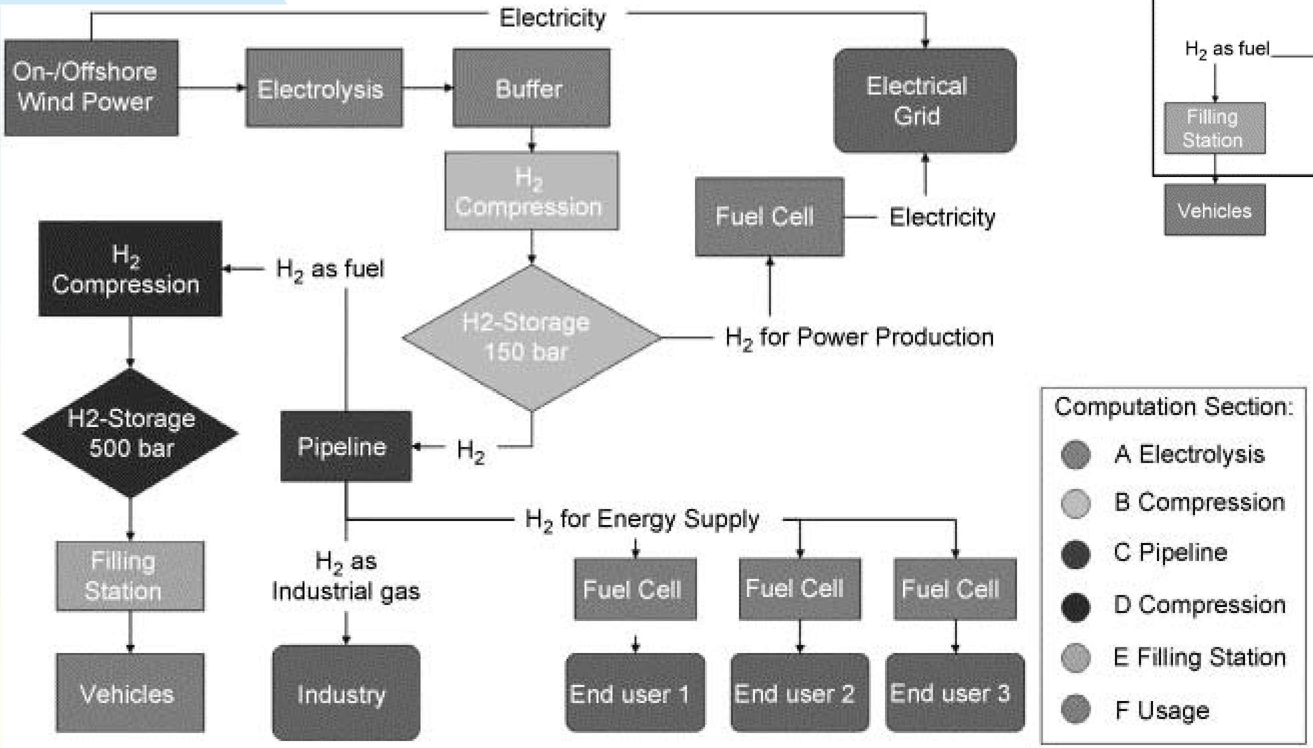
For gasoline, average energy ratio is 6–10

International Journal of Hydrogen Energy
Volume 32, Issue 12, August 2007, Pages 1616-1624
doi:10.1016/j.ijhydene.2006.12.008

# wind-hydrogen vehicle fuel production

pilot plant (right) and large scale installation (below)



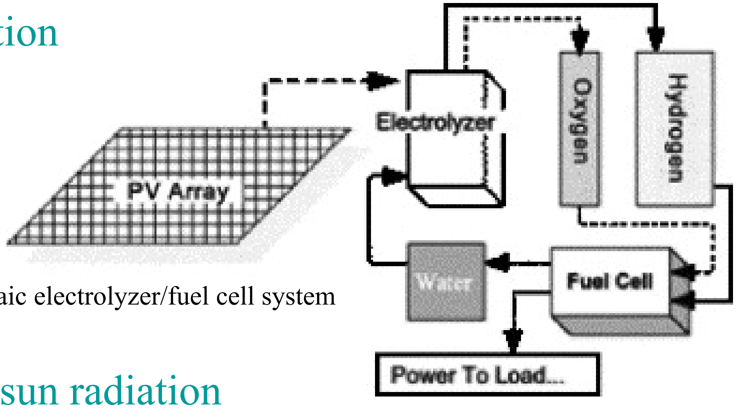


International Journal of Hydrogen Energy
Volume 32, Issues 10-11, July-August 2007, Pages 1492-1499

# Hydrogen-solar

Consist in the coupling of hydrogen sources and solar energy by using different process routes:

- **electrolysis**, with photovoltaic cells for electricity generation (yield 25-30%)



Regenerative photovoltaic electrolyzer/fuel cell system

- **photolytic**, through chemical or biological processes and sun radiation

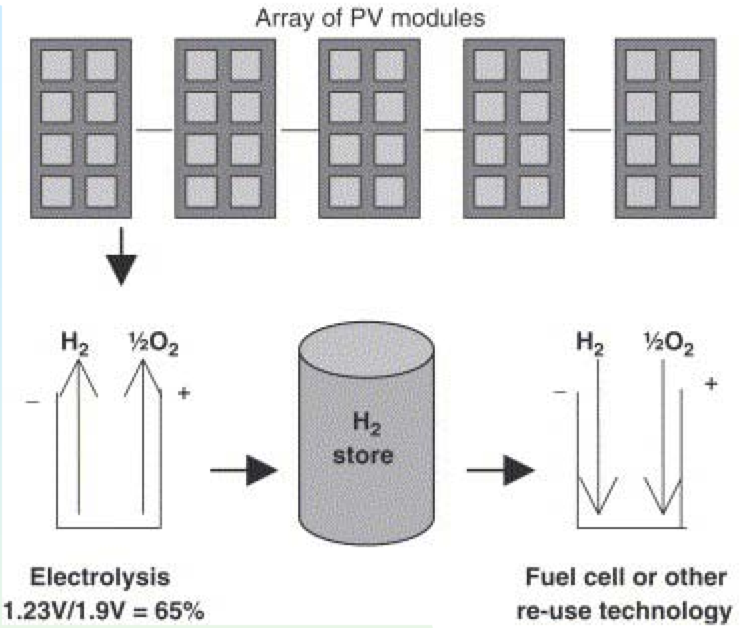
**photo-electrolysis** uses semiconductor catalysts in contact with water which by solar light activation produce the rupture of water molecules into $H_2$ and $O_2$ (this option will depend on the future development of new photocatalysts in terms of efficiency and stability).

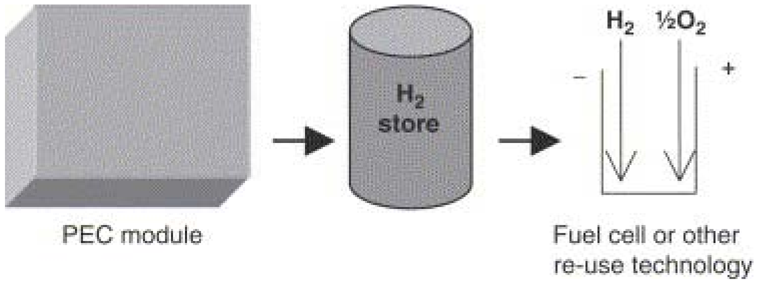
**bio-reactors** from photosynthetic processes with variety of plants (e.g. cyanobacteria and green algae can produce hydrogen from solar light, water and hydrogenase as enzyme) is a technology currently under research and development, with estimated solar to hydrogen conversion efficiencies of around 27% under ideal conditions.

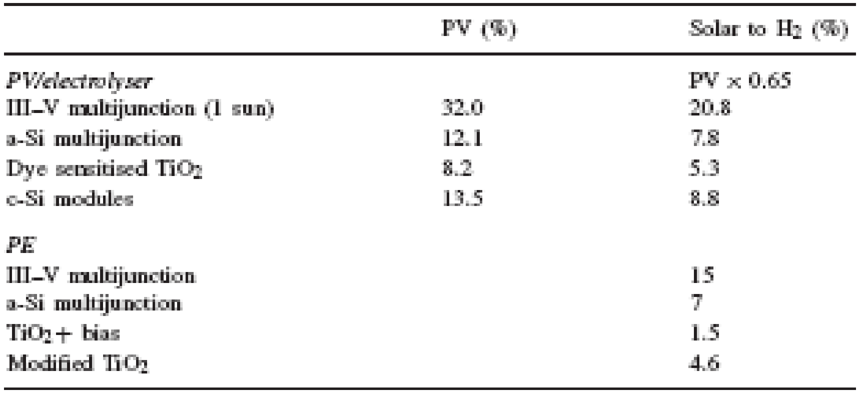
- **thermal processes**, by high temperature solar concentrators (40%)

$$H_2O \rightarrow H_2 + \frac{1}{2} O_2$$

# Comparison of PV/electrolyser and photoelectrolytic technologies in solar to hydrogen energy







| | PV (%) | Solar to $H_2$ (%) |
|---|---|---|
| *PV/electrolyser* | | PV × 0.65 |
| III–V multijunction (1 sun) | 32.0 | 20.8 |
| a-Si multijunction | 12.1 | 7.8 |
| Dye sensitised $TiO_2$ | 8.2 | 5.3 |
| c-Si modules | 13.5 | 8.8 |
| *PE* | | |
| III–V multijunction | | 15 |
| a-Si multijunction | | 7 |
| $TiO_2$ + bias | | 1.5 |
| Modified $TiO_2$ | | 4.6 |

At present PV/electrolysis, as compared to direct photoelectrolysis, is the more appropriate technology with higher efficiency for a 'solar to hydrogen' storage system. This is because of the greater maturity of the former and because the latter has significant challenges to overcome in terms of achieving sufficient PE photovoltage to split water at a high efficiency whilst also being stable. Nonetheless, these problems are likely to be solved in the future and given the greater simplicity, potential robustness and elegance of PE systems, they may overtake PV/electrolysis at some stage. However, whether this can become economically viable will depend on many other factors.

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# Thermochemical cycles

The high energy consumption of electrolyzers makes it necessary to find sources other than electricity for the production of hydrogen, such as nuclear or solar thermal power.

The direct thermal splitting of water is technically challenging, since it occurs at a very high temperature (~2500ºC); the use of two parallel thermal cycles in which hydrogen and oxygen are produced separately, allows $H_2$ to be obtained at a considerably lower temperature (<1000ºC), and the use of heat generated directly by \`solar´ or \`nuclear´ energy sources makes for a more globally efficient conversion process than that obtained by an electrolyser (almost two times).

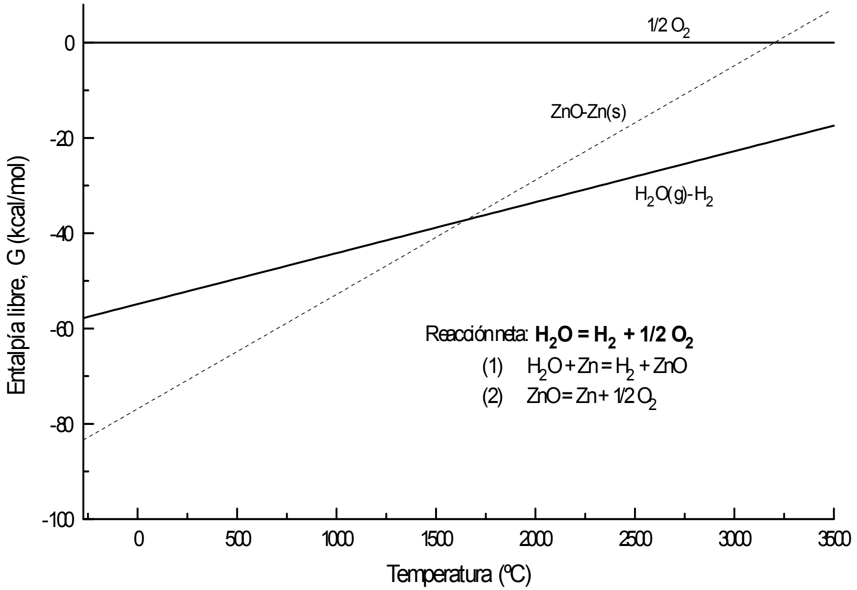
$$H_2O \rightarrow H_2 + ½\,O_2$$

(1) $H_2O + Zn \rightarrow ZnO + H_2$

(2) $ZnO \rightarrow Zn + ½\,O_2$

| Substance | ΔGfº | ΔHfº | ΔSfº=(ΔHfº-ΔGfº)/Tº |
|---|---|---|---|
| $H_2O$(g) | -54,6 | -57,8 | -10,7 |
| $H_2$, $O_2$ (g) | 0 | 0 | 0 |
| ZnO(s) | -76,1 | -83,2 | -23,8 |
| Zn (s) | 0 | 0 | 0 |

| Reactions for water decomposition to hydrogen and oxygen | | | |
|---|---|---|---|
| **the common difference** | **half of the reaction** | **ΔG(T)= ΔH -T·ΔS** | **T** |
| **$H_2O$-$H_2$ = ½ $O_2$** | **$H_2O$(g)-$H_2$** | **-57,8+0,0107(t+273)** | **5000ºC** |
| **$H_2O$-$H_2$ = ZnO-Zn** | **ZnO-Zn(s)** | **-83,2+0,0238(t+273)** | **3000ºC** |
| **ZnO-Zn = ½ $O_2$** | **½ $O_2$** | **0** | |

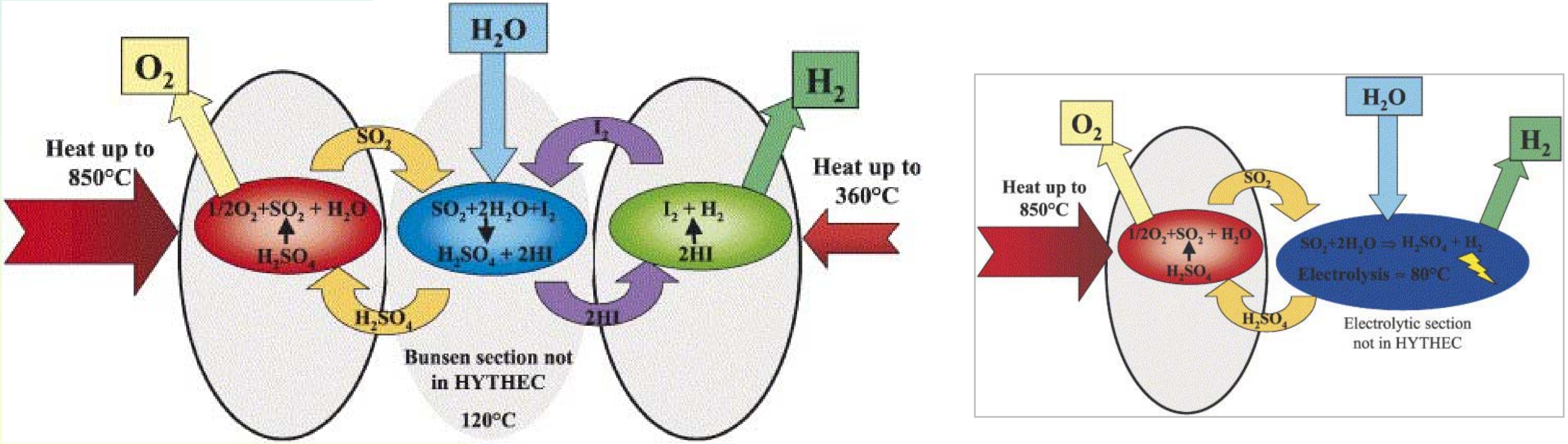


Many cycles are currently under study, the most popular being the S–I cycle (sulphur–iodine) which is based on the following reactions:

$I_2 + SO_2 + 2H_2O \rightarrow H_2SO_4 + 2HI$ (common reaction at 120 ◦C; afterwards the two products are separated)
$H_2SO_4 \rightarrow SO_2 + H_2O + 1/2O_2$ (at 850 ◦C; the $O_2$ is separated and the $SO_2$ is recycled)
$2HI \rightarrow I_2 + H_2$ (at 450 ◦C; the $H_2$ is separated and the $I_2$ is recycled)

The technological barriers include the cost, the development of economic and appropriate materials for the experimental conditions (separation membranes and heat exchangers) and an increase in thermal efficiency of over 50%.

The sulphur–iodine (S–I) and hybrid-sulfur (WH) cycles

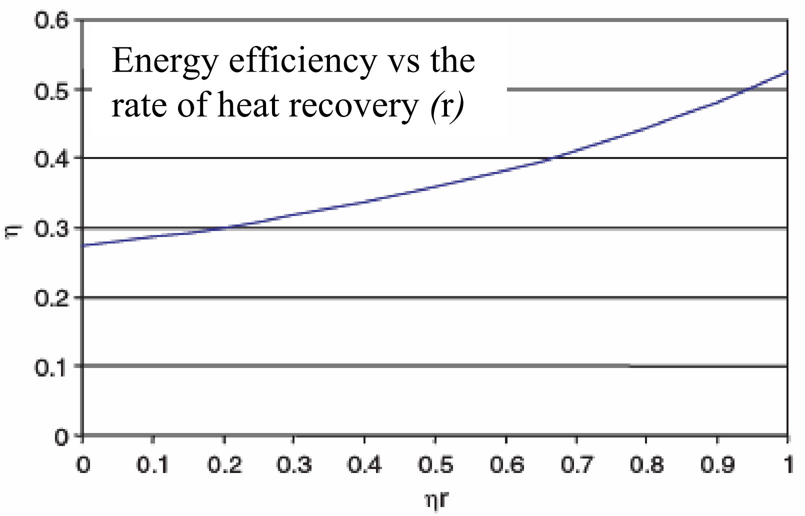


HYTHEC: An EC funded search for a long term massive hydrogen production route using solar and nuclear technologies

International Journal of Hydrogen Energy
Volume 32, Issues 10-11, July-August 2007, Pages 1516-1529

# The UT-3 cycle:

1. $CaO + Br_2 \rightarrow CaBr_2 + \frac{1}{2}O_2$ $\Delta G^0(800K) = -40.9\ \text{kJ mol}^{-1}$
2. $CaBr_2 + H_2O \rightarrow CaO + 2HBr$ $\Delta G^0(1000K) = +104.0\ \text{kJ mol}^{-1}$
3. $Fe_3O_4 + 8HBr \rightarrow 3FeBr_2 + 4H_2O + Br_2$ $\Delta G^0(500K) = -119.9\ \text{kJ mol}^{-1}$
4. $3FeBr_2 + 4H_2O \rightarrow Fe_3O_4 + 6HBr + H_2$ $\Delta G^0(900K) = +117.5\ \text{kJ mol}^{-1}$



The studies carried out on the UT3 cycle have demonstrated that even if this cycle has a pretty good efficiency, the technology that has to be considered could be very difficult to implement and the amount of research and development to obtain a viable industrial process would be very high. In addition, the use of highly toxic reactants will lead to consider very high level of safety that could increase very sensibly the cost of an industrial plant. That is why it is interesting to consider other cycles using no more than 3 reactions (to limit the complexity of the process) involving less toxic reactants (than bromine)

Technological and chemical assessment of various thermochemical cycles: From the UT3 cycle up to the two steps iron oxide cycle International J. of Hydrogen Energy 31 (2006) 2063 – 2075

# The $Fe_3O_4/Fe_2O_3$ cycle

(a) $2Fe_3O_4 + H_2O \rightarrow 3Fe_2O_3 + H_2$ $\Delta G^0(500K) = +25.2\ \text{kJ mol}^{-1}$

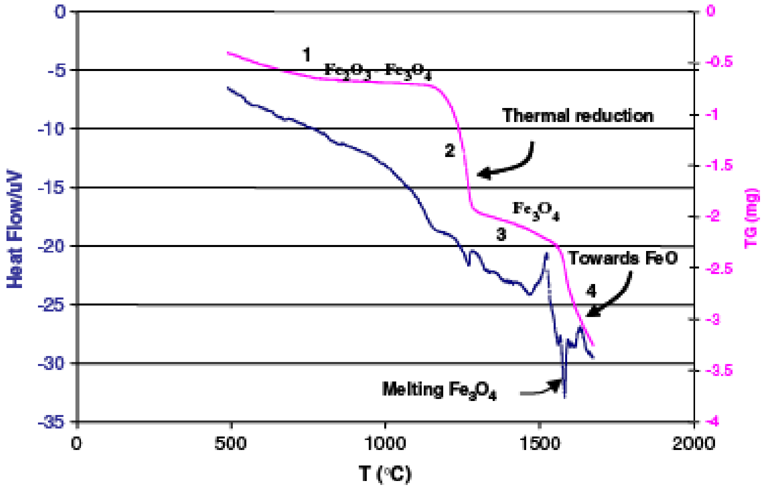
(b) $3Fe_2O_3 \rightarrow 2Fe_3O_4 + \frac{1}{2} O_2$ $\Delta G^0(1500K) = +49.9\ \text{kJ mol}^{-1}$

Studies have confirmed the feasibility of thermally reducing magnetite ($Fe_3O_4$) to wustite (FeO) in a solar furnace heated to 2090 K:

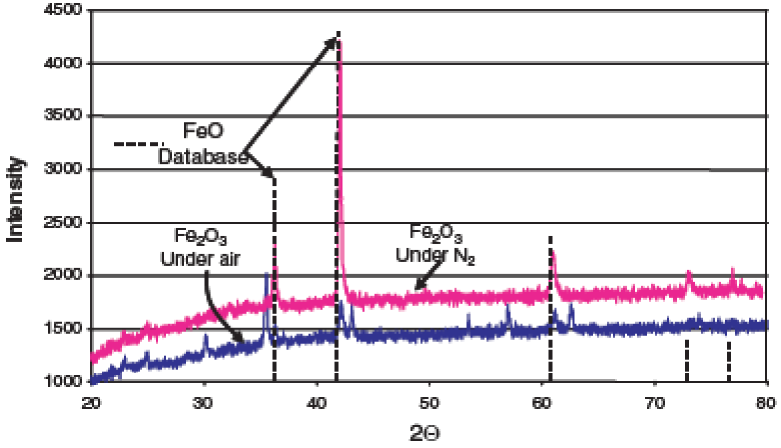
$$\mathbf{Fe_3O_4 \rightarrow 3FeO + \frac{1}{2} O_2}$$

This transition is highly advantageous, as the water reduction produces a greater amount of hydrogen per mole of iron:

$$\mathbf{3FeO + H_2O \rightarrow Fe_3O_4 + H_2}$$



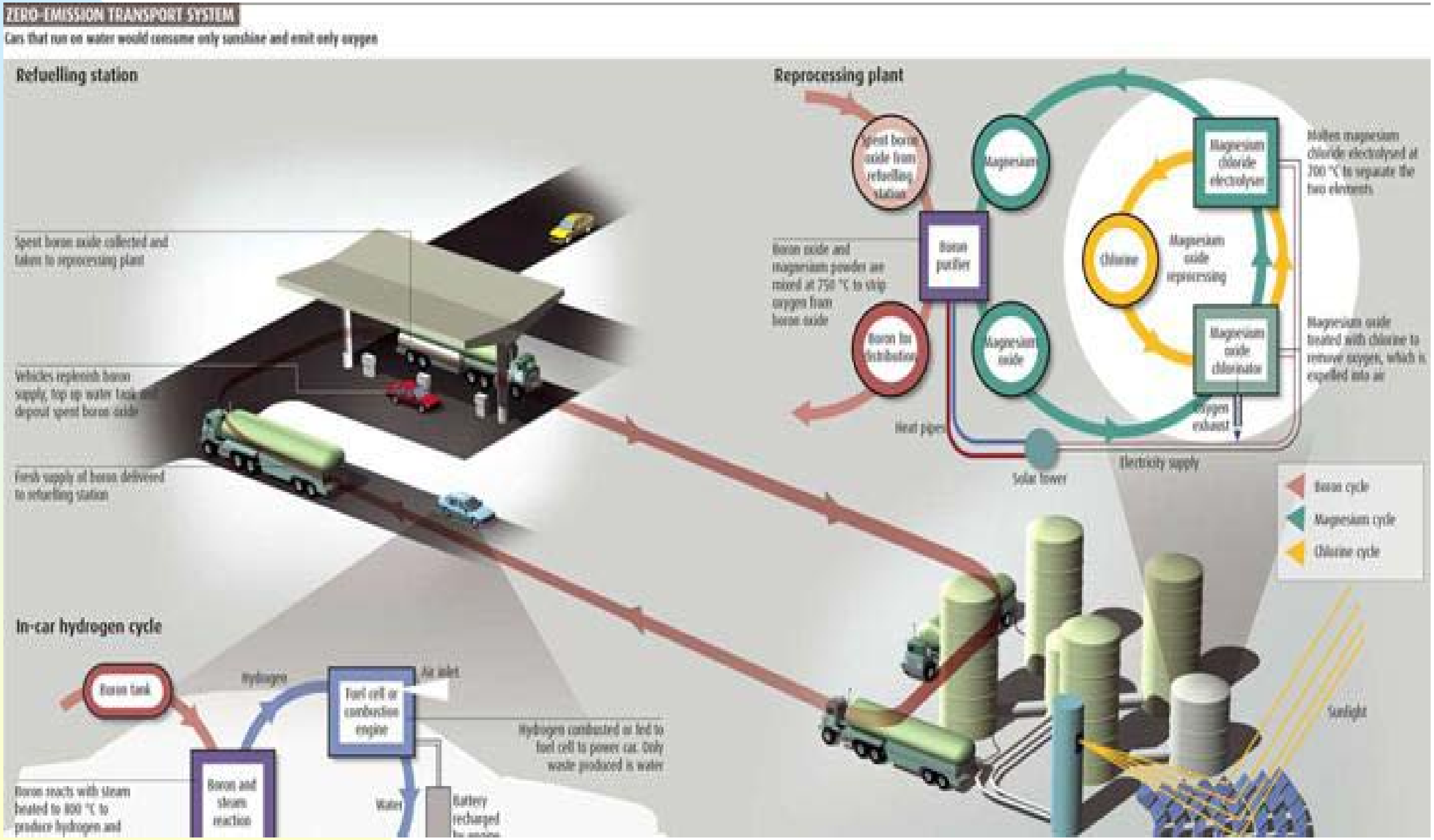
An experiment carried out in a solar reactor having a maximal flow of 1600 $Wcm^{-2}$ has demonstrated the possibility of reducing a few grams of $Fe_2O_3$ up to the pure wustite compound in 2 min (under an $N_2$ flow). In the case of a treatment under air, the result shows a mixture of $Fe_3O_4$ and FeO (fig. shows the XRD analysis performed in the both cases).



Despite the poor efficiency and unfavorable operating conditions, this cycle is attractive because it uses abundant, inexpensive, low-toxicity oxides, for which considerable industrial and scientific experience is available. Furthermore, low efficiency in this case could be offset with a solar coupling. Finally, it permits to store energy in the $Fe_3O_4$ or FeO compounds; since the experimental studies (either DTG or solar) show possible to reduce the $Fe_2O_3$ into FeO, it seems interesting to recommend the cycle involving the wustite.

$$2B(s) + 3H_2O \Longleftrightarrow B_2O_3(s) + 3H_2 \; -433 \text{ kJ}$$

Regeneration of boron (1273 kJ)



http://weblogs.madrimasd.org/energiasalternativas/archive/2007/06/01/66881.aspx

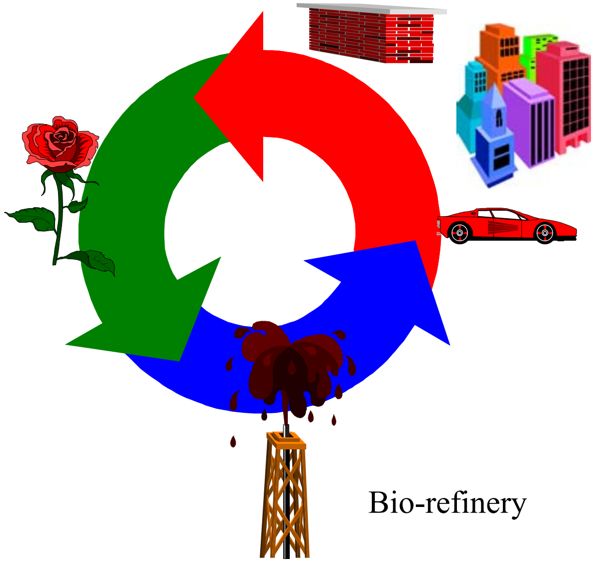
# Biomass

## sugar cane, starch and oil plants. wood, energy plantation, residues

- Advantages:
  - Clean combustion
  - energy security (fuel diversity)
  - development of rural areas
  - restoration of degraded lands

- Problems:
  - Diversion of agricultural land
  - Enhanced use of fertilizers
  - Large water requirements

FITOMASS – BIOFUEL – $CO_2$ CYCLE



1st generation bio-fuels for transport are produced from polysaccharids by hydrolisis and fermentation (ethanol), and from vegetal oils by transesterification (diesel); the UE target is to replace 10% of carburetants with biofuels by 2020.

Current gasoline deposits incorporate ETBE (máx.5%) and can use mixes with max. 10% ethanol, while new flexible fuel vehicles permit max. 85% bioethanol; all diesel vehicles made in the last decade can use 100% biodiesel.

**Biomass** can be employed as a clean form of energy mainly through the three conversion processes:

## **1.** Transformation to bio-fuels (bio-ethanol and bio-diesel) that are directly burnt in the ICE.

Spain is the leader in bio-ethanol production in Europe, while Germany and France are the biggest producers of bio-diesel. Biomass to generate bio-fuels will receive a better response with the massive implantation of short-rotation crops of lignocellulosic varieties, with low inputs and high productivity, which do not compete with food since they can be implanted in any land (including forests). Moreover their own lignin can be used as fuel in the cellulose transformation process, thus eliminating the use of fossil fuels; to achieve this, however, it will be necessary to optimize and reduce the cost of the cellulose-to-bio-ethanol process.

## **2.** Transformation to bio-methanol through syngas ($CO+H_2$) produced in biomass gasification

Liquid bio-methanol is stored in vehicles provided with a reformer in which the fuel reacts with water to produce $H_2$ that is fed to the FC engine. The bio-methanol option has the advantage of not requiring the storage of $H_2$, would allow the use of the existing liquid fuel distribution network, and largely increases energetic efficiency compared with bio-fuels. Thus, an ideal autothermal process would produce hydrogen with a 104% of the energy existing in the reacted methanol; a deposit with 33 kg of methanol and 14 kg of water (54 L) is sufficient to produce 5 kg of $H_2$ (reformer efficiency: 87%) which is enough to drive the FC car 400 km.

## **3.** Direct transformation of biomass to $H_2$

This option is employed in centralized reforming systems or in $H_2$-electricity cogeneration systems (i.e. IGCC). The gasification or reforming process produces a mixture of $H_2$ and $CO_x$; the CO is further reacted with water to produce $CO_2$ and more $H_2$ (water gas shift reaction). The use of hydrogen as fuel is slightly more efficient if the storage cost is not included, and would allow the combination of the large reforming plants with CCS systems, which would lead to negative net $CO_2$ emissions (or the removal of a part of $CO_2$ from the atmosphere).

| | **Gasoline** | **Ethanol** from corn or wheat | **Ethanol** from sugar cane | **Gasoil** | **Biodiesel** vegetal oil | **Diesel** Fischer-Tropsch |
|---|---|---|---|---|---|---|
| Equivalents | 1 l. | 1,53 l. | | 0,88 l. | 0,9 l. | 0,96 l. |
| Prodn costs | 0,35-0,38 $ | 0,43-0,82 $ | 0,34 $ | 0,35-0,42 $ | 0,70-0,73 $ | 0,68 $ |
| Land prodn | Refinery | 3000 l/ha | 5900 l/ha | Refinery | 1200 l/ha | 3300 l/ha |
| $CO_2$ emission | 196 g/km | 87-209 g/km | 25 g/km | 164 g/km | 78-87 g/km | 10-20 g/km |

Una conductora reposta bioetanol en Örnsköldsvik. A la izquierda, un autobús ecológico de Estocolmo.

Reference price of **bioethanol** for ETBE could be estimated in a similar amount than methanol for MTBE (0,12 €/l), plus hydrocarbon taxes (0,371 €/l for unleaded gasoline), i.e. about 0,49 € /l.

To produce 1 l. alcohol we require about 3 kg of cereal or 10 kg of beetroot, at guarantee prices of 0,12 and 0,02 €/kg, respectively.

Variable costs are established in 0,102 €/l and depreciation of the installation capacity in 1,8 M€/yr (for a distillery of 40 Ml/yr).

Total costs:

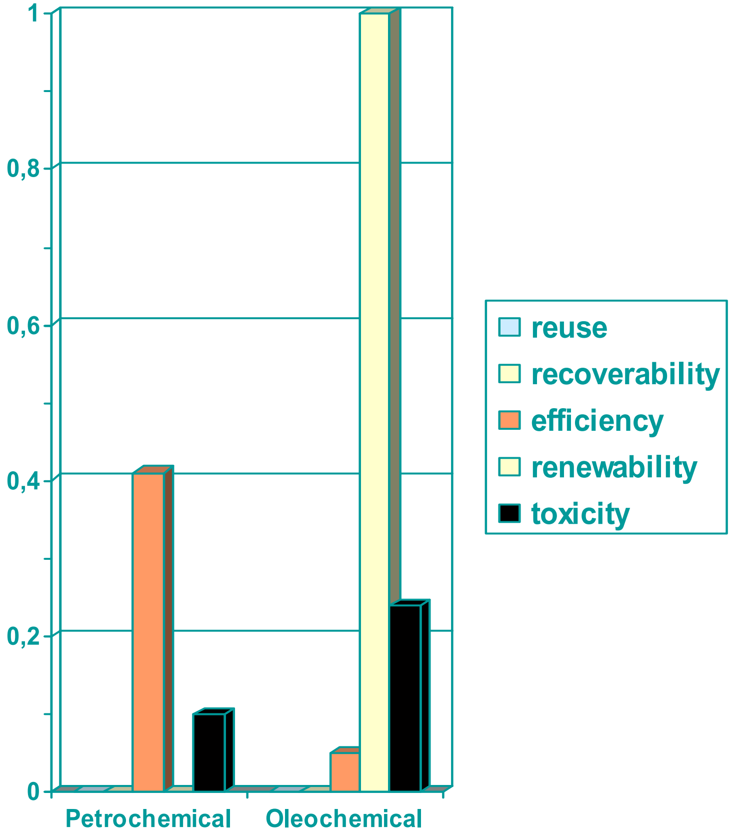
$$C_t = \mathrm{Rm}(\mathrm{kg/l})\cdot P_{\mathrm{Rm}}(€/\mathrm{kg}) + 0{,}102\ (€/\mathrm{l}) + 1{,}8\ \mathrm{M€/yr}/(40\ \mathrm{Ml/yr})$$

$$C_t\ (\text{cereal}) = 0{,}507$$
$$C_t\ (\text{beetroot}) = 0{,}347 < P_{ref}$$

# E.g. five indicators based in exergy ratios

- **the reuse**: input of used materials / total
  - virgin resources (0) residual materials (1)
- **recoverability** of product after its 1st use:
  usable fraction / total content of product
  - Industrial ecology concerns on reuse of the materials:
    - fuels for energy that ends in emissions (0)
    - products designed for recycling (DFR)
    or disassembly (DFD), durable goods (1)
- **the efficiency** on products:
  resource inputs / useful outputs (0 - 1)
- **renewablity** of virgin resources:
  consumption / production of ecosystem
  - fossil fuels or mineral ores (0)
  - consumption rate = ecosystem (1)
- **the toxicity** of emissions:
  deterioration rate / emission rate
  - waste factors (0 - 1)

**Scores of petrochemical and oleochemical alcohols on the five sustainability indicators**

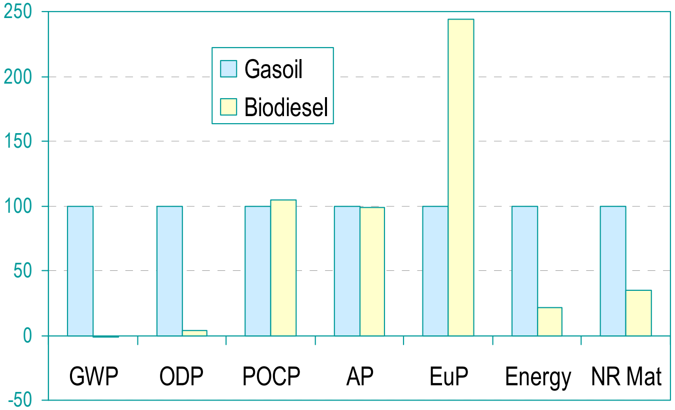


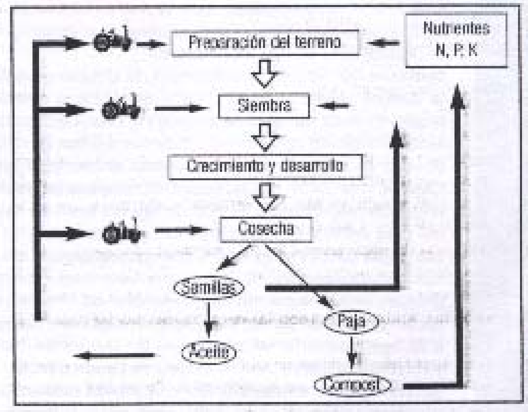
# LCA: gasoil vs biodiesel

- Raw material: hempseed (*Cannabis sativa L.*) Productivity potential: 12 $t_{biomass}$, 2 $t_{seeds}$ and 0,7 $t_{oil}$ /ha (with agricultural advantages for soils, adaptability of cultures, low watering and pesticide requirements)

  Functional unit: impacts of fuel consumption of one MW truck (payload 18 t) in an urban route of 50 km, which represents 44,8 l of gasoil or 47,0 l of biodiesel (byproducts: 5,3 kg glycerin, 95 kg proteins and 600 kg of grass)

| Impact | Units | Gasoil | Biodiesel |
|---|---|---|---|
| GWP | kg $CO_2$ | 139 | -2,3 |
| ODP | kg CFC | $158 \cdot 10^{-6}$ | $5{,}9 \cdot 10^{-6}$ |
| POCP | kg $C_2H_4$ | 0,35 | 0,37 |
| AP | kg $SO_2$ | 1,92 | 1,89 |
| EuP | kg $PO_4^{3-}$ | 0,32 | 0,78 |
| Energy | MJ | 2136 | 458 |
| NRMat | $10^{-12}$ kg | 0,88 | 0,31 |



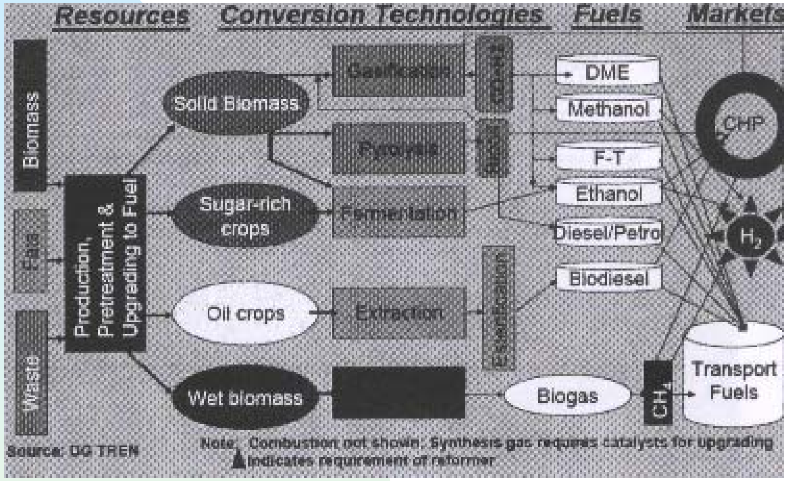


- LC stages:
  - **Cultivation and production of seed**: has the main effect in the impact categories of eutrophication (EuP), consumption (energy) and depletion of non renewable resources (NR Mat), but its capability to fix $CO_2$ has a positive effect on the global warming potential balance of the system (GWP: -2,3 $kg_{CO2,eq.}$); use of synthetic fertilizers cause emissions of 1 $kg_{SO2,\ eq}$ and 3,5 $kg_{PO4,eq}$ /ha.
  - **Extraction and fabrication of biodiesel**: is responsible of contribution to ozone depletion potential (ODP)
  - **Use of fuel in in the vehicle**: shows the major impacts (GWP, acidification AP and photochemicals POCP)

- Improvements:
  - Integral benefit of biomass (with a redistribution of the environmental loads according to byproduct values)
  - Use of organic residues like fertilizers (to reduce EuP, AP and waste management from farming activities)
  - Improve productivity of cultures, agro-ecological practices, and consumption distances of less than 50 km

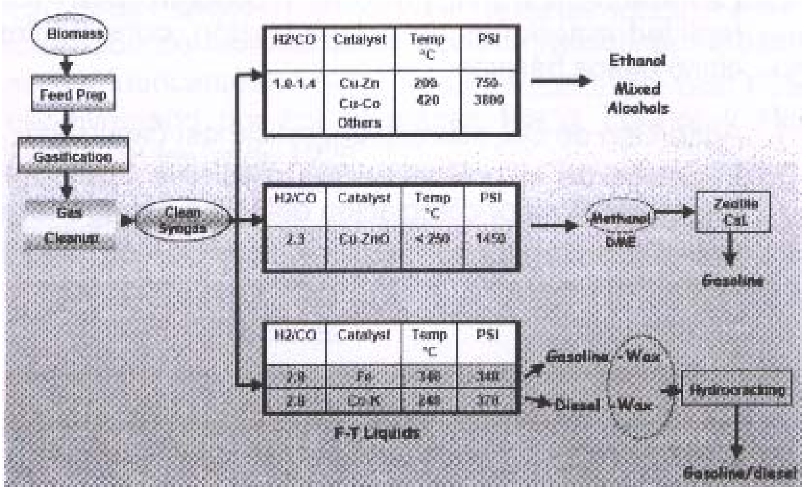
# 2nd generation bio-fuels

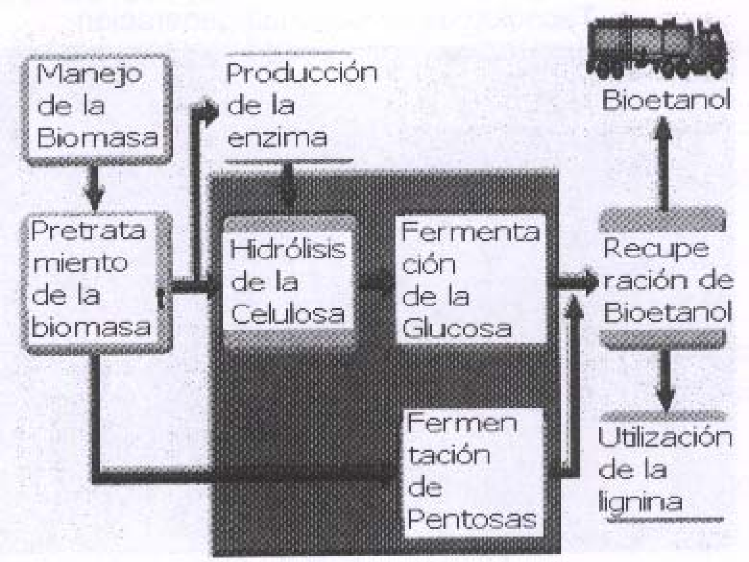
- They are fuels which are produced from lignocellulosic crops by wet or thermal processes, including ethanol via hydrolisis, syn-diesel, methanol, eters and bio-hydrogen for transport

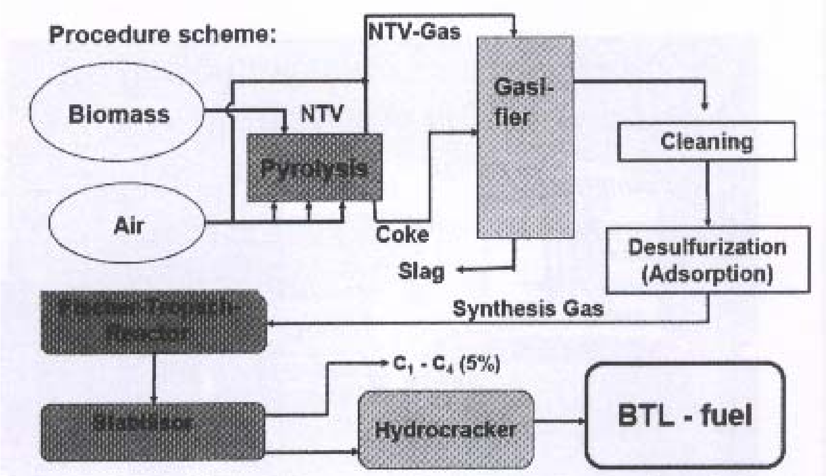


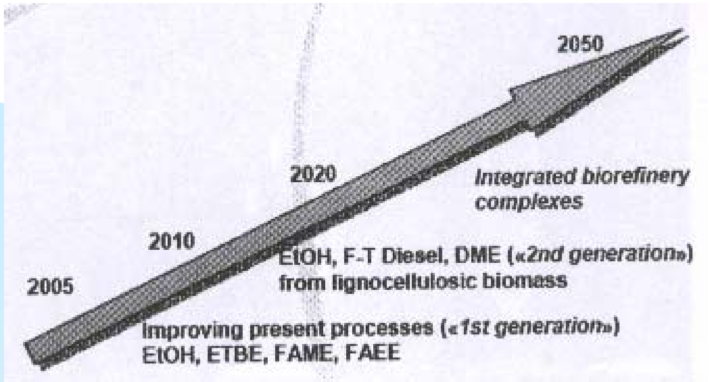
Source: DG TREN

Note: Combustion not shown. Synthesis gas requires catalysts for upgrading
▲ Indicates requirement of reformer





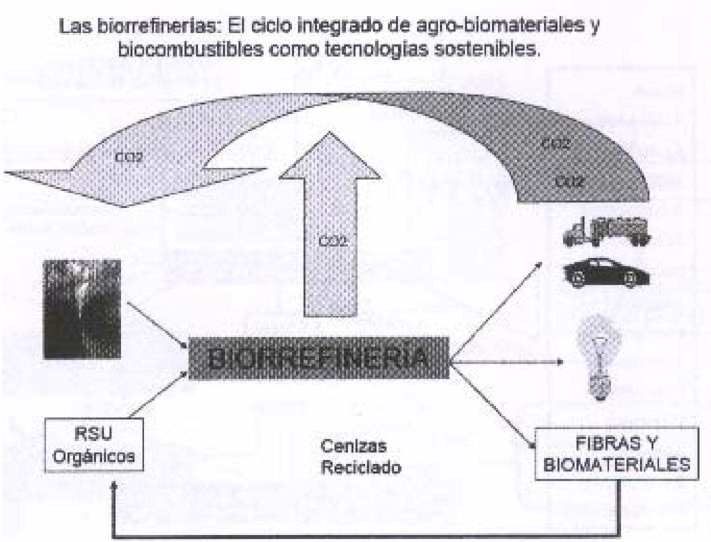




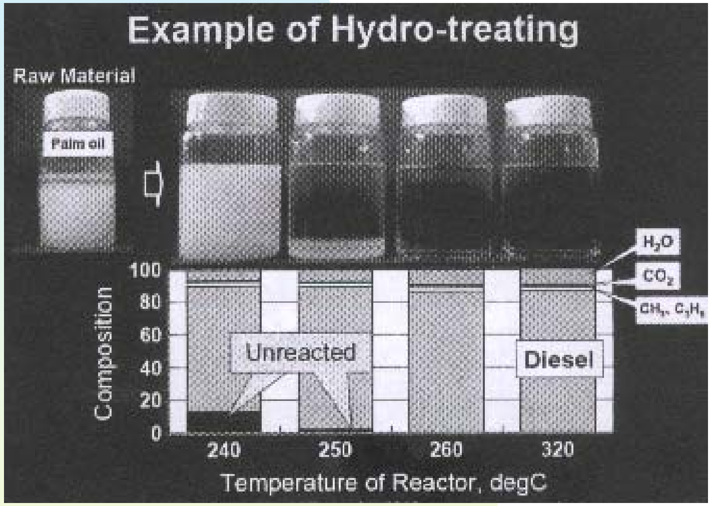
*Integrated biorefinery complexes*

EtOH, F-T Diesel, DME («*2nd generation*») from lignocellulosic biomass

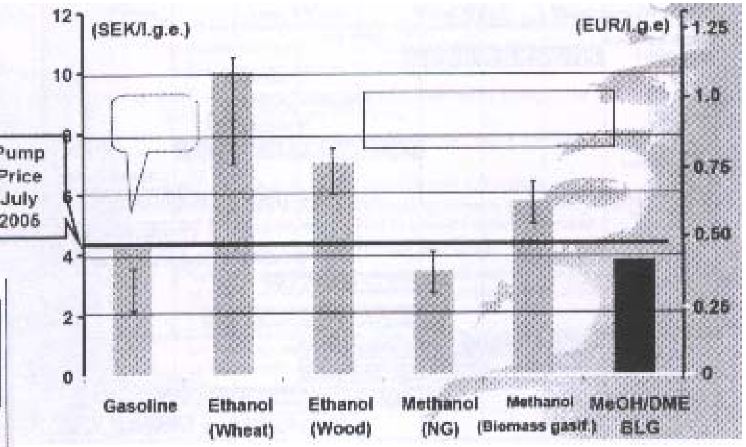
Improving present processes («*1st generation*»)
EtOH, ETBE, FAME, FAEE

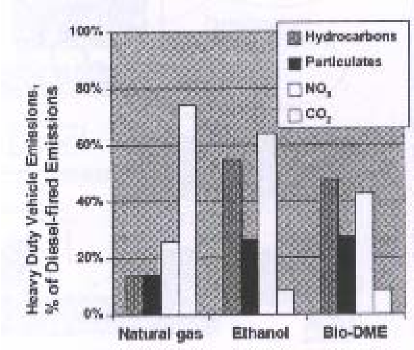


Las biorrefinerías: El ciclo integrado de agro-biomateriales y biocombustibles como tecnologías sostenibles.

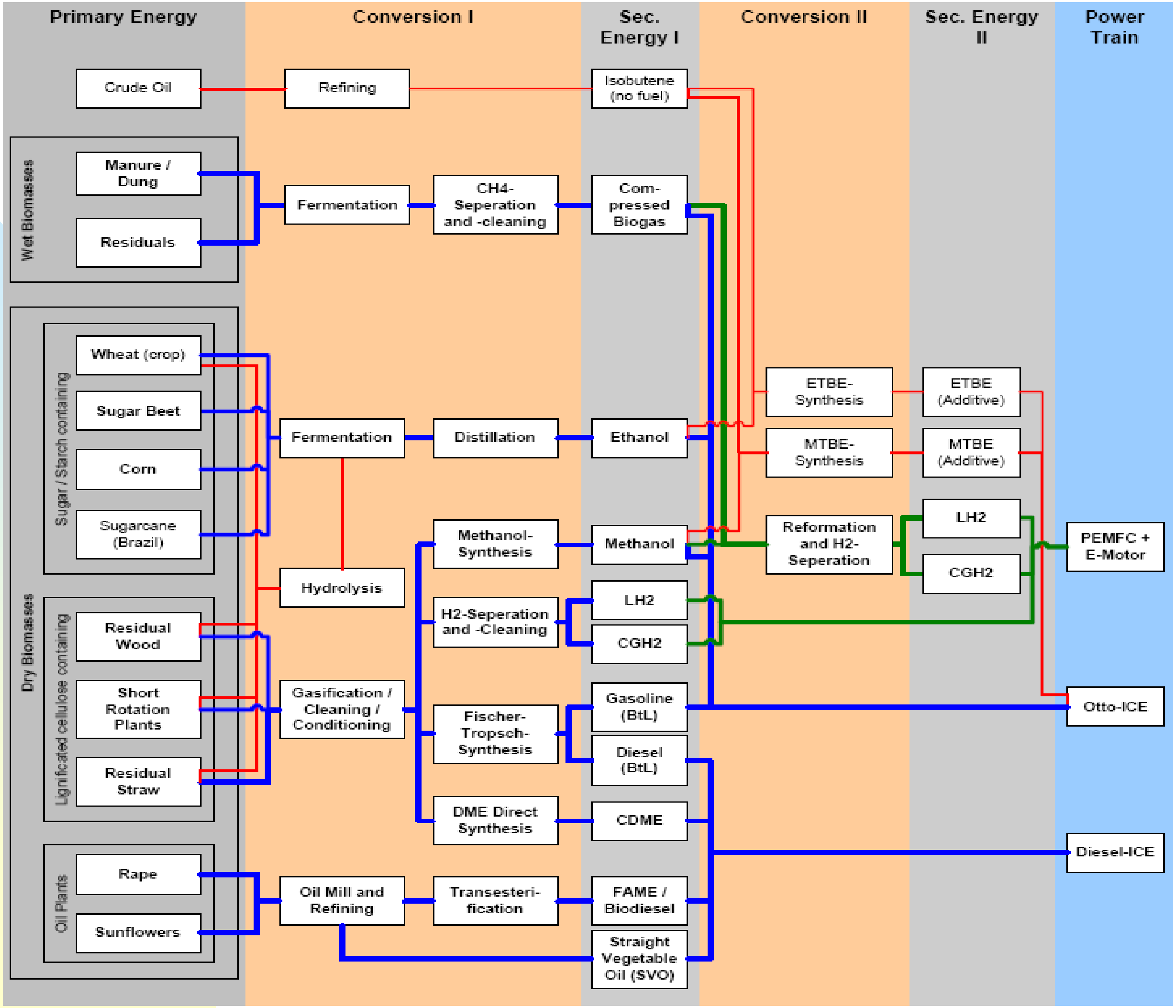


Example of Hydro-treating





# Biofuel pathways



Primary Energy

Crude Oil

Wet Biomasses
- Manure / Dung
- Residuals

Dry Biomasses

Sugar / Starch containing
- Wheat (crop)
- Sugar Beet
- Corn
- Sugarcane (Brazil)

Lignificated cellulose containing
- Residual Wood
- Short Rotation Plants
- Residual Straw

Oil Plants
- Rape
- Sunflowers

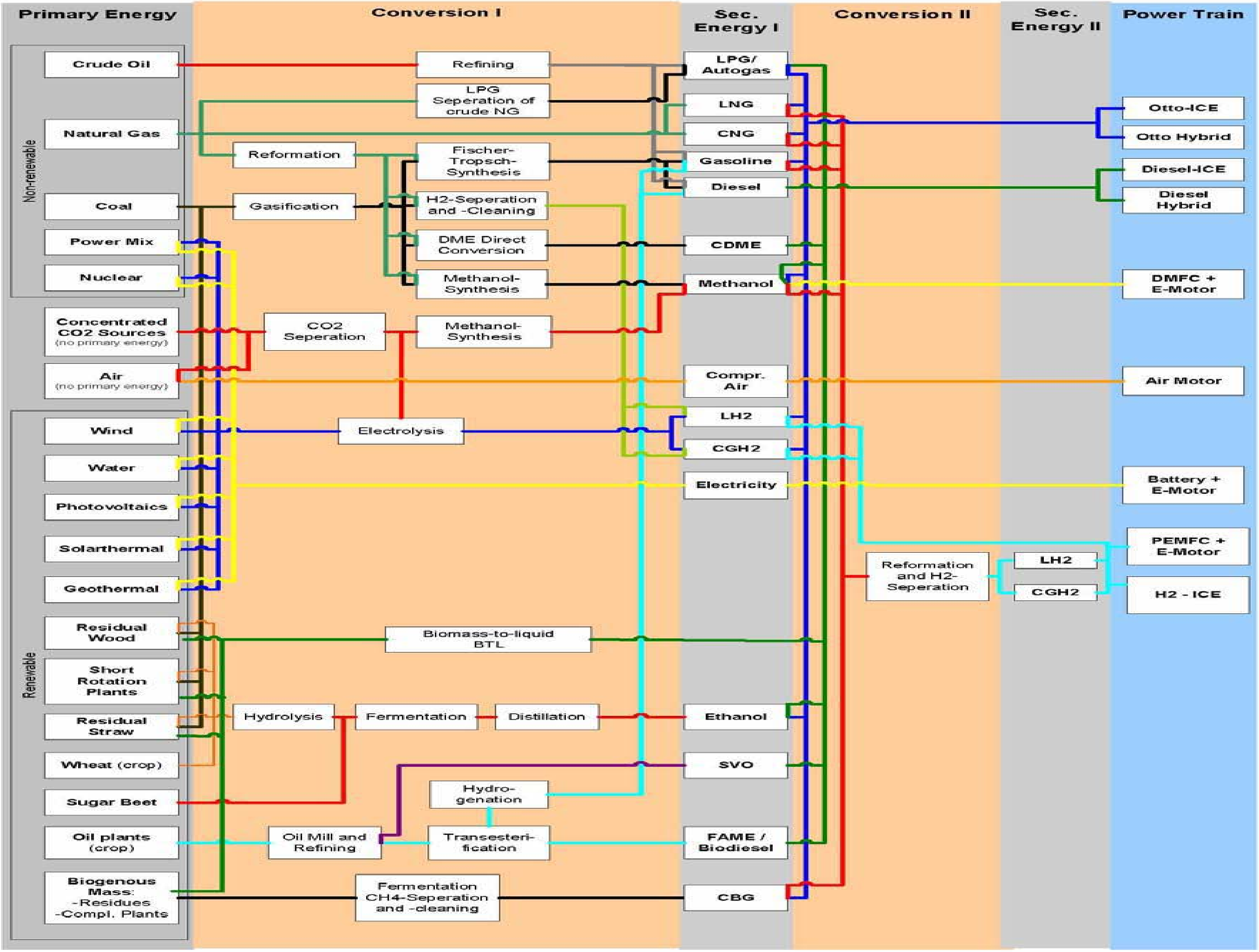
Conversion I
- Refining
- Fermentation
- CH4-Seperation and -cleaning
- Fermentation
- Distillation
- Hydrolysis
- Methanol-Synthesis
- H2-Seperation and -Cleaning
- Gasification / Cleaning / Conditioning
- Fischer-Tropsch-Synthesis
- DME Direct Synthesis
- Oil Mill and Refining
- Transesterification

Sec. Energy I
- Isobutene (no fuel)
- Compressed Biogas
- Ethanol
- Methanol
- LH2
- CGH2
- Gasoline (BtL)
- Diesel (BtL)
- CDME
- FAME / Biodiesel
- Straight Vegetable Oil (SVO)

Conversion II
- ETBE-Synthesis
- MTBE-Synthesis
- Reformation and H2-Seperation

Sec. Energy II
- ETBE (Additive)
- MTBE (Additive)
- LH2
- CGH2

Power Train
- PEMFC + E-Motor
- Otto-ICE
- Diesel-ICE


Primary Energy
Conversion I
Sec. Energy I
Conversion II
Sec. Energy II
Power Train
Non-renewable
Crude Oil
Natural Gas
Coal
Power Mix
Nuclear
Concentrated CO2 Sources (no primary energy)
Air (no primary energy)
Renewable
Wind
Water
Photovoltaics
Solarthermal
Geothermal
Residual Wood
Short Rotation Plants
Residual Straw
Wheat (crop)
Sugar Beet
Oil plants (crop)
Biogenous Mass: -Residues -Compl. Plants
Refining
LPG Seperation of crude NG
Reformation
Fischer-Tropsch-Synthesis
Gasification
H2-Seperation and -Cleaning
DME Direct Conversion
Methanol-Synthesis
CO2 Seperation
Methanol-Synthesis
Electrolysis
Biomass-to-liquid BTL
Hydrolysis
Fermentation
Distillation
Hydro-genation
Oil Mill and Refining
Transesteri-fication
Fermentation CH4-Seperation and -cleaning
LPG/ Autogas
LNG
CNG
Gasoline
Diesel
CDME
Methanol
Compr. Air
LH2
CGH2
Electricity
Ethanol
SVO
FAME / Biodiesel
CBG
Reformation and H2-Seperation
LH2
CGH2
Otto-ICE
Otto Hybrid
Diesel-ICE
Diesel Hybrid
DMFC + E-Motor
Air Motor
Battery + E-Motor
PEMFC + E-Motor
H2 - ICE

# Aviation transport

- It´s by far the less ecological transport mean (e.g. two transoceanic travelers only contribute more to global warming than one average car during a year), though airlines represent a 3% of greenhouse emissions nowadays
  - But jet-fuel demand (kerosene) is expected to continue rising; presently, there is no substitute for this fuel and with world-wide passenger increase of 135% the outlook is for robust growth
  - New aircraft are 20% more efficient than the average for the existing stock; increasing size of planes, better occupancy rates and improved jet turbine technology will continue to cut the energy input per passenger-km; but overall intensity gains vs GDP will, however, be lower than for any other sectors (GHGs are expected to duplicate by 2030, and they are more damaging at high altitudes)
  - Jet motors used in large aircrafts contribute also with significant emissions of NOx, particulates and noise

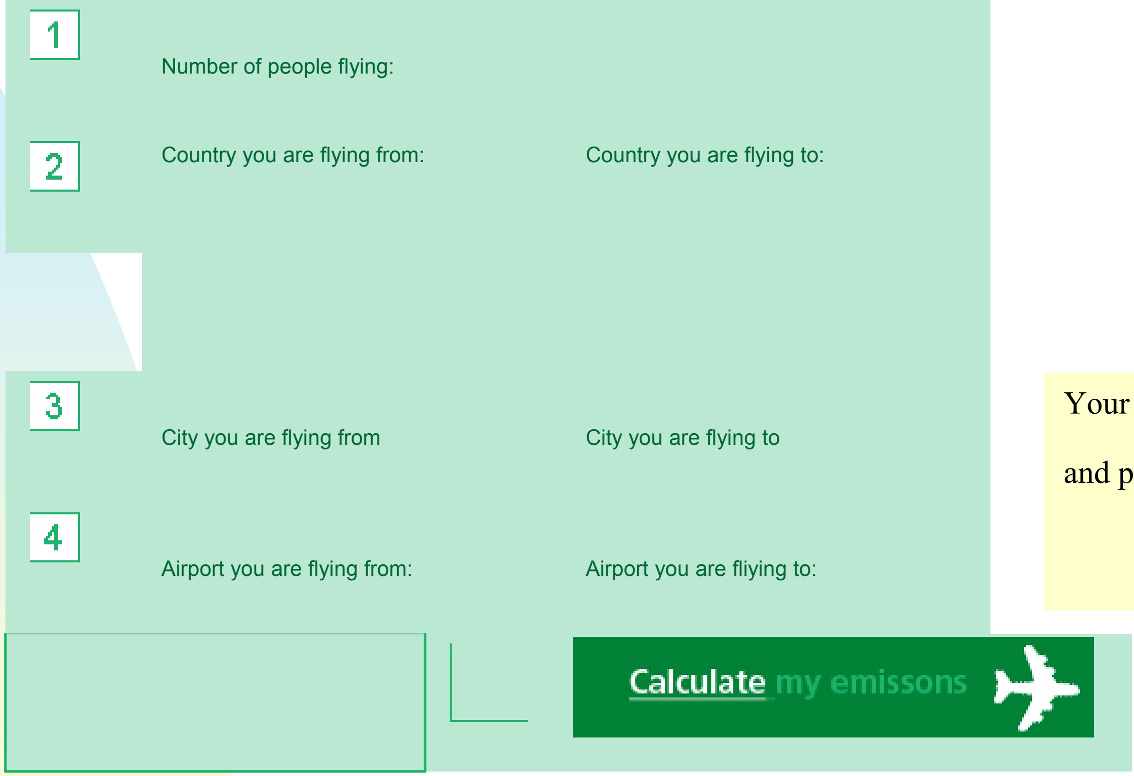
- Because such increases would ruin one quarter of foreseen 8% reduction of GHGs (P.Kyoto), the EU studies to include the international air transport in carbon tax and trading schemes, which would lead to a moderate increase of the tickets costs (about 9 € per course)
    - Difficulties to reduce own impacts lead companies to calculate their flight emissions and invest in other sustainable projects worldwide like `future forests´ or `atmosfair´, intending to avoid the environmental taxes on flights

- Other activities to limit emissions should include the air traffic management and elimination of legal obstacles to impose jet-fuels; transportation systems -road, rail, aviation and ships- would be also improved by better integration (inter-connection)

http://europa.eu.int/comm/environment/climat/aviation_en.htm

# Voluntary $CO_2$ compensations

Customers can calculate their flights´ carbon dioxide emissions and neutralize them investing in projects for renewable energy; the company in charge of administering payment transactions is CarbonNeutral Company.



1 Number of people flying:

2 Country you are flying from: Country you are flying to:

3 City you are flying from City you are flying to

4 Airport you are flying from: Airport you are fliying to:

Your flight will cover **2060 Km**

and produce **0.3 tonnes** of $CO_2$

**cost - € 4.14**

The amount paid by passengers is invested in projects outside Europe, where $CO_2$ reductions are less expensive; it is of no consecuence for the $CO_2$ emissions where the reduction takes place.

http://www.carbonneutral.com/cncalculators/flightcalculatorSAS.asp

# ENFICA-FC "Environmentally Friendly Inter City Aircraft powered by Fuel Cells"

- The main objective of the **ENFICA-FC** project is to **develop and validate the use of a fuel cell based power system for propulsion of more/all electric aircrafts:**

  Hydrogen and fuel cell power technologies have now reached the point where they can exploited to initiate a new era of propulsion systems for **light aircraft** and **small commuter aircraft**. In addition, these technologies can also be developed for the future replacement of on-board electrical systems in larger 'more-electric' or 'all-electric' aircraft.

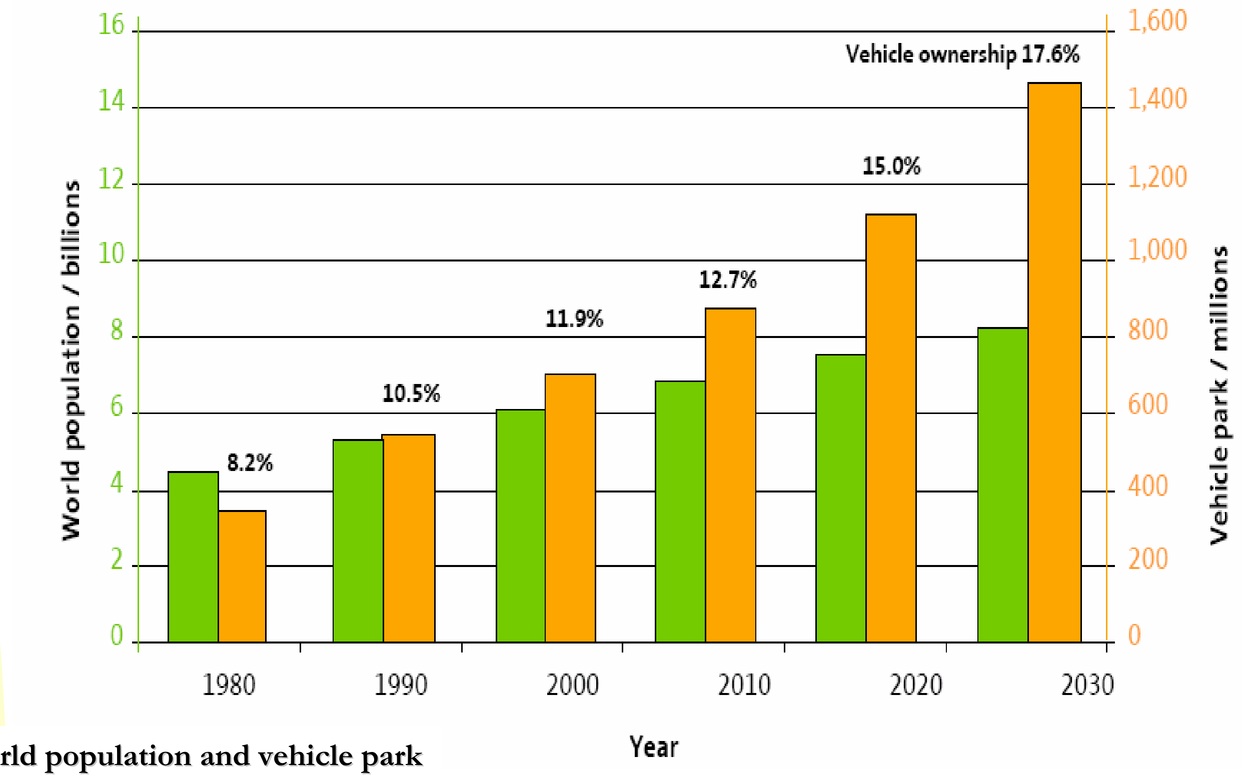
  The primary advantages of deploying these technologies are **low noise and low emissions** – features which are particularly important for commuter airplanes that usually takeoff and land from urban areas.

# Zephyr Unmanned Aerial Vehicle

the ultra-light aircraft is solar-electric powered, autonomous and is designed to fly at altitudes in excess of 50,000 feet, above normal commercial air-lanes and most weather; the combination of solar panels on the upper wing surface and rechargeable batteries allows Zephyr to be flown for durations of many weeks and even months

# Sustainable mobility

- Sustainable mobility plans constitute an adequate system approach in the cities, where it´s consumed 40% of the energy demand and one main contributor is the private transport with a very low efficiency and other impacts like casualties and reduction of public spaces
  - This is enhanced by a territory model of dispersion of population and economic activity, caused by house prices and lifestyles, without adequate infrastructure to approach sustainability like collective transport, intermodality, the use of `shared vehicles´, dissuasive `parkings´, restrictions of `traffic´, public information, translate costs to infrastructure users, driving behavior, cycling and walking, etc

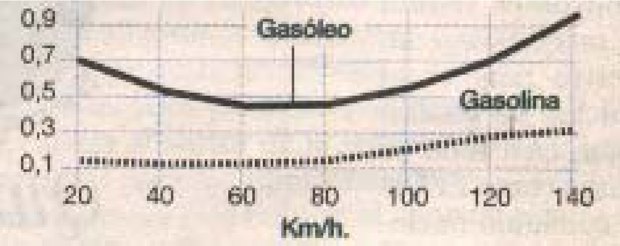


Evolution estimates for world population and vehicle park

# Don´t be fuelish !

**Driving behavior** affects performance in transport concerning safety, environment and economies. Good practices have demonstrated a potential decrease in fuel consumption of about 20%, with the corresponding reductions in GHGs, other noxious emissions and savings of 250€ each 20000 km

e.g. long motor developments, gearshift to 1500 rpm in diesel or 2000 rpm in the gasoline vehicles, don´t misuse accelerator, 1st gear for start the movement of the wheels only, reduction of noise, etc



Emission index of private cars in g /100 km

( the minimum is reached at about 80 km/h, and increases exponentially after this point)

One delivering company which operates in the same city for several years has experienced growing the location and modifying its number of vehicles, trip distances and exhaust emissions controls as indicated in the table.

Calculate the absolute and relative emissions of VOCs during this frame of time.

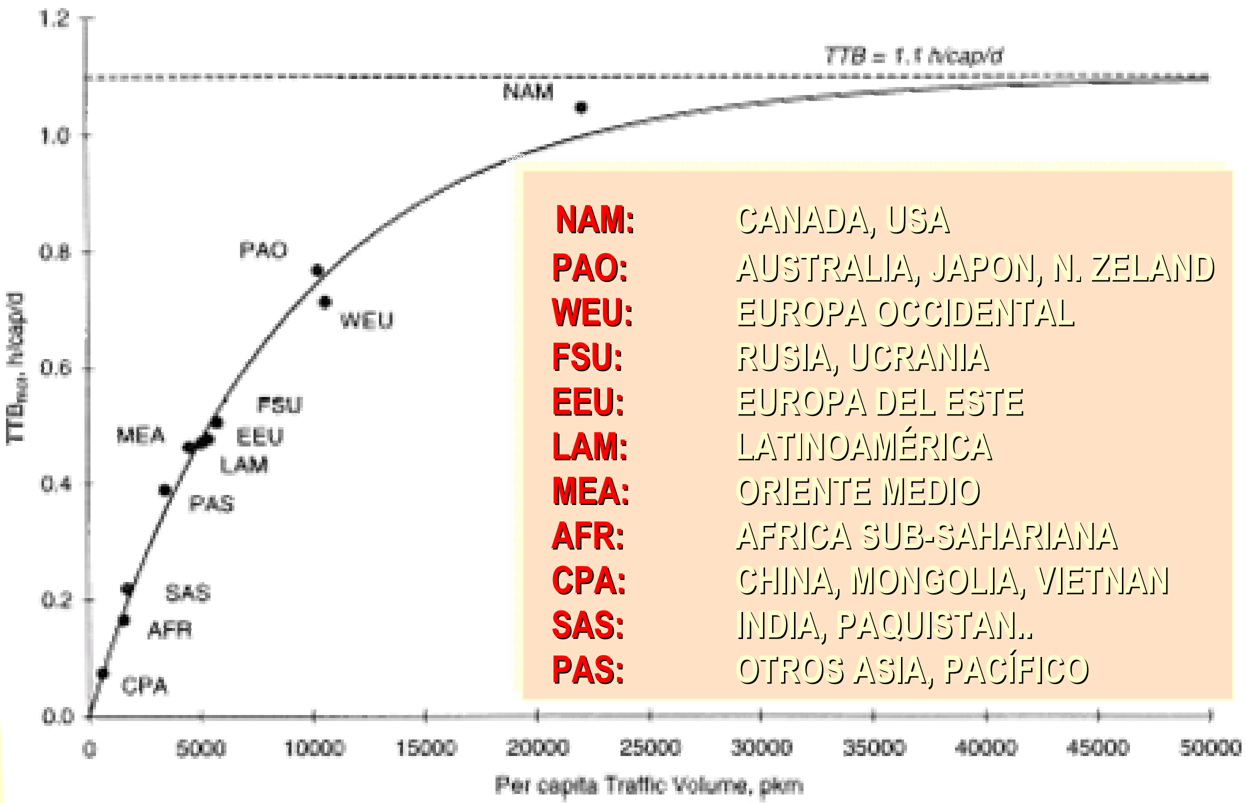
| Years | vehicles | Run-trips (km/yr) | Emissions ($g_{VOC}$/km) | Total ($Kg_{VOC}$ /yr) | Total urban emissions ($Tg_{VOC}$/yr) |
|---|---|---|---|---|---|
| 1980 | 100 | 20000 | 0,30 | 600,0 | 1,4 |
| 1990 | 150 | 25000 | 0,15 | 526,5 | 2,6 |
| 2000 | 200 | 30000 | 0,02 | 120,0 | 4,3 |

Some trends like working or daily life patterns are compensated by the growing of leisure mobility or methods of production based in just-in-time delivery of components.

Promoting rail and waterway for medium distance transports is a key target vs road or air congestion, by better integration and debottlenecking of transeuropean networks.

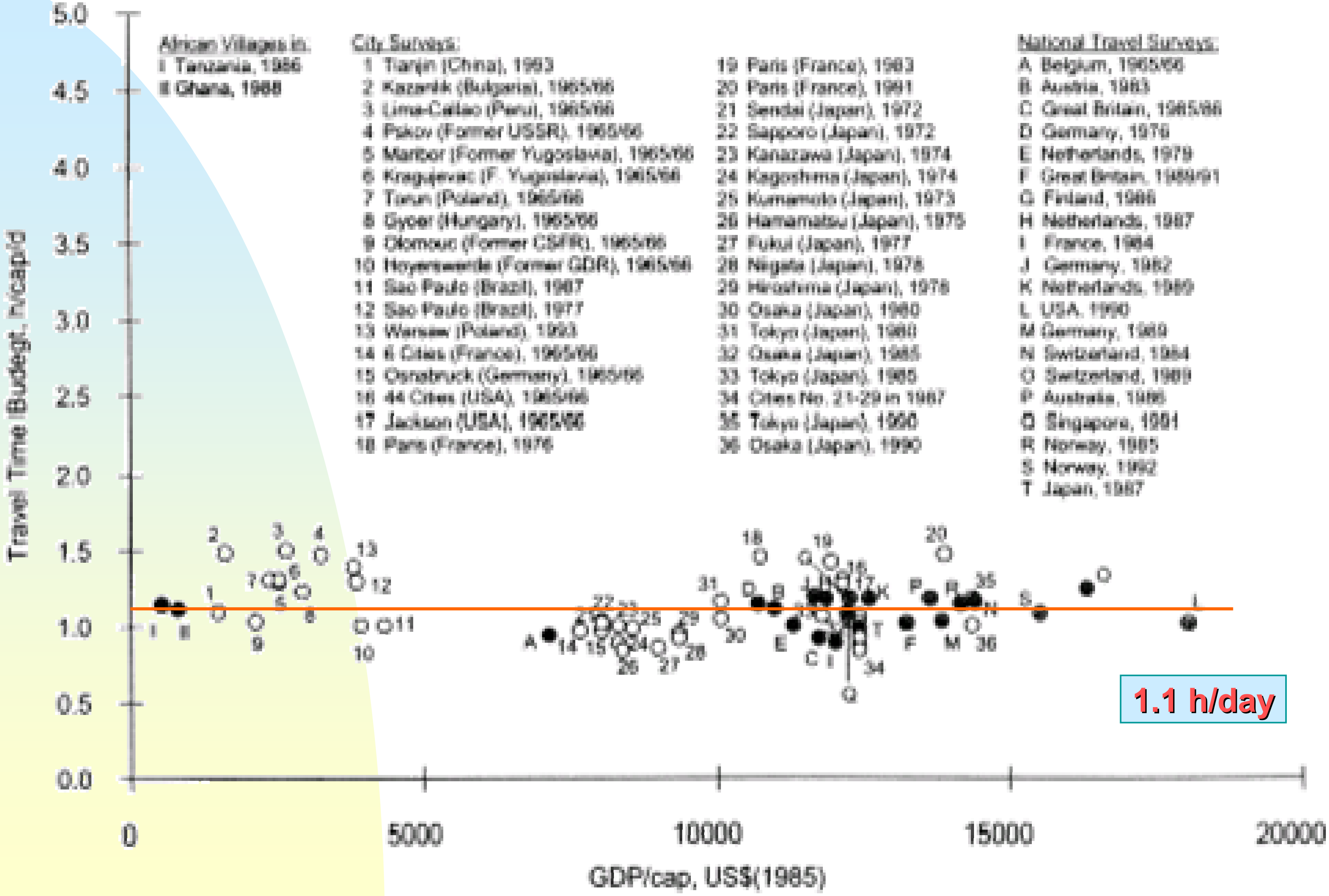
The UE transport policy for 2010 (http://europa.eu/scadplus/leg/es/s13000.htm)

## Daily time average spent in motorized transport means vs traffic volume



| | |
|---|---|
| **NAM:** | CANADA, USA |
| **PAO:** | AUSTRALIA, JAPON, N. ZELAND |
| **WEU:** | EUROPA OCCIDENTAL |
| **FSU:** | RUSIA, UCRANIA |
| **EEU:** | EUROPA DEL ESTE |
| **LAM:** | LATINOAMÉRICA |
| **MEA:** | ORIENTE MEDIO |
| **AFR:** | AFRICA SUB-SAHARIANA |
| **CPA:** | CHINA, MONGOLIA, VIETNAN |
| **SAS:** | INDIA, PAQUISTAN.. |
| **PAS:** | OTROS ASIA, PACÍFICO |

# Daily time average for mobility in 36 cities and 20 national surveys

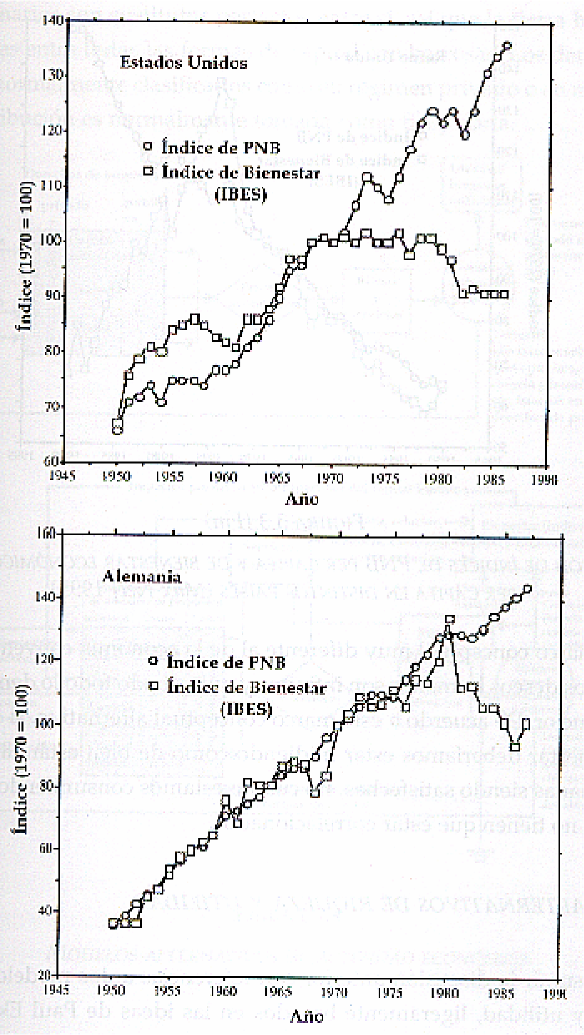


- One evidence is that none single-dimension parameter (as the GDP sum) is an adequate measure of the social welfare
- There are other like the sustainable economical welfare index (IBES) that is based in production and use,

by adjusting the sustainability of this consumption,
the negative impacts on the natural capital,
the distribution along income groups
and other reasonable settings;

though not a perfect measure of welfare yet (the end)
and assuming still correlated with consumption (the way)

| **Needs** (or true desires) | **Wants** (or with we resign) |
|---|---|
| **pride** | **a luxury car** |
| **serenity** | **drugs** |
| **health** | **medicaments** |
| **human joy** | **GDP** |
| **permanent prosperity** | **unsustainable growth** |

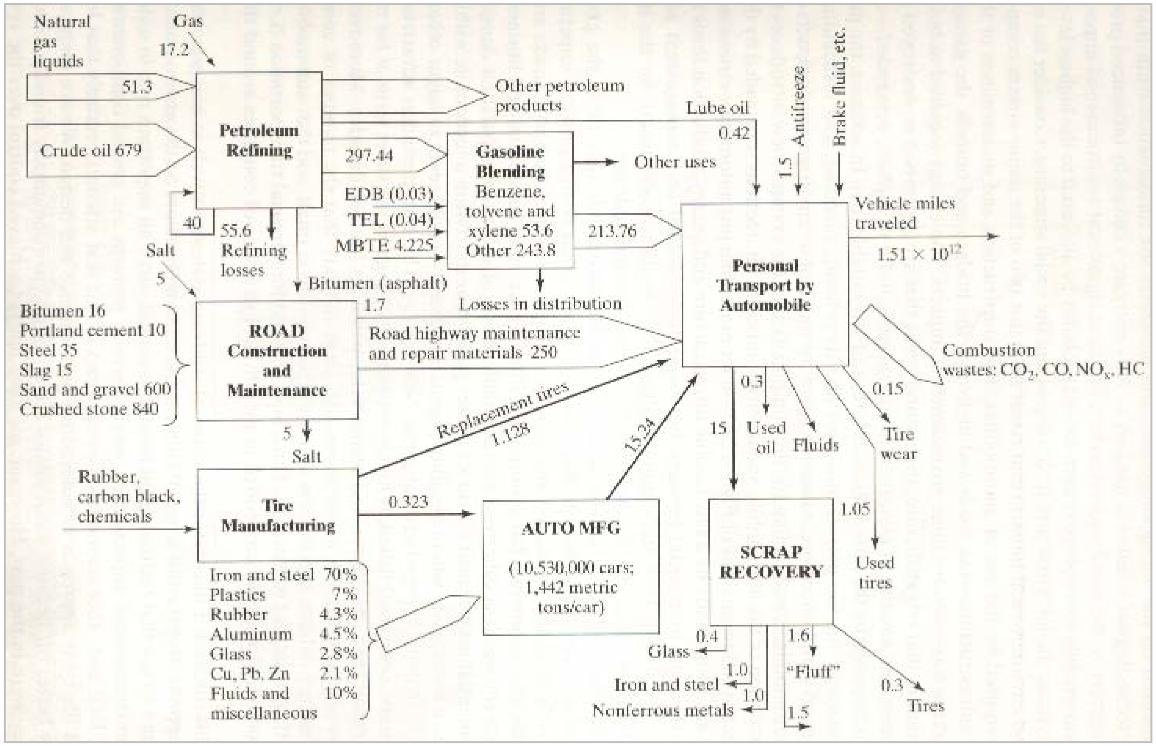


# The future of automotive technological systems ?

Includes the lower level of mechanical and manufacturing subsystems (technologically rich); and vehicle´s use, with its technical (improvements engines and exhaust controls) and cultural dimensions (where the failures are evident, by the continuous growing of the automotive park, the traveled distances, the speed limits and high energy consumption).

One simple overview shows which attention is being paid in the wrong subsystem, and that technical solutions are not enough, as the most significant effects are in the higher system level: the physical framework required for the use of vehicles and the social structures; the former implicate big impacts due to the building of transport routes and refineries; on the other hand, a fundamental final consequence is the geographical dispersion of population, as the use of private transport favors diffuse densities which are unsustainable

All this indicates the importance of system approaches, as well as their components, to appreciate the whole factors associated with environment, though even we have improved vehicle efficiencies, we haven´t reached yet a control over the systems which link the technology, society and environment.



Mass flows for the automotive technological system in USA (1998)