

**LBST ANALYSIS**

**YIELD OF BIOFUELS  
VERSUS  
HYDROGEN FROM PHOTOVOLTAICS AND WIND POWER**

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# Yield of Biofuels versus Hydrogen from Photovoltaics and Wind Power

## Scope

The area required for the production of renewable transportation fuels is an issue of intensive discussion. The present LBST Analysis compares the yield per hectare of land area of final fuel for different biomass derived fuels and hydrogen from photovoltaics and from wind power for the German situation. The results show significant differences between the various biofuels, and between biofuels and hydrogen derived from renewable power sources.

The fuels compared here are:

- Biodiesel (RME) produced from rapeseed
- Ethanol from wheat
- Ethanol from short rotation forestry
- Biomethane
- BTL – Biomass to Liquids
- Compressed Gaseous Hydrogen (CGH<sub>2</sub>) from short rotation forestry
- Liquid Hydrogen (LH<sub>2</sub>) from short rotation forestry)
- Compressed Gaseous Hydrogen (CGH<sub>2</sub>) from Photovoltaics (PV)
- Liquid Hydrogen (LH<sub>2</sub>) from Photovoltaics (PV)
- Compressed Gaseous Hydrogen (CGH<sub>2</sub>) from Wind Power
- Liquid Hydrogen (LH<sub>2</sub>) from Wind Power.

In a second step, the number of passenger cars supported by one hectare of land area is calculated from the fuel yields and taking into account the fuel consumption of the different drive train technologies. The differences are even more pronounced as for the fuels because hydrogen consuming fuel cell drive trains are significantly more efficient than diesel and otto engines.

## ***Data used for fuel yield calculations***

### **Biodiesel (RME)**

The rapeseed yield is assumed to be 3 to 4 tons per hectare per year at a water content of 10%. According to [KTBL 2006], an average rapeseed yield of 3.3 t per ha and year can be expected in Germany. About 0.4 tons biodiesel can be generated per ton of rapeseed.

### **Ethanol from wheat**

In [CONCAWE 2007] the average yield for winter wheat in the EU is indicated with 6.5 t per ha and year at a water content of 13%. The yield of wheat varieties adapted for ethanol production is 13.5% higher than the weighted average of the present mix of wheat types. As a result, the yield of wheat grain for ethanol production is about 7.6 t per ha and year at a water content of 16%. The lower heating value (LHV) of wheat is 17 MJ/kg of dry substance and the LHV of the ethanol is 26.8 MJ/kg. About 400 l ethanol can be generated per t of wheat grain [Senn 2003]. The water content of wheat grain typically ranges between 13 to 16%. Then about 0.59 MJ ethanol can be generated per MJ of wheat grain. [Kavalov 2004] indicates a slightly lower ethanol yield (7.42 GJ/t of wheat at a water content of 16% leading to about 0.52 MJ/MJ of wheat). As a result, per MJ of wheat grain 0.52 to 0.59 MJ ethanol are produced.

### **Ethanol from short rotation forestry**

For short rotation forestry (plantation of fast growing trees such as poplar and willow) the yield is assumed to be about 10 t of dry substance per ha and year<sup>1</sup>. The LHV of wood amounts to 18.5 MJ/kg.

Ethanol can be generated from lignocellulosic biomass via hydrolysis and fermentation. In [CONCAWE 2007] the ethanol yield has been assumed to be 0.32 to 0.36 MJ per MJ of wood chips from residual wood and from poplar.

### **BTL – Biomass to Liquids**

In [Hamenlinck 2004] the generation of synthetic diesel and gasoline via gasification and Fischer-Tropsch synthesis has been described. If a hydrocarbon chain growth probability of 0.85 is assumed, 139.1 MW liquid hydrocarbons and 33.3 MW excess electricity are generated from an input of 367 MW biomass. These assumptions also have been applied in [CONCAWE 2007]. For a hydrocarbon chain growth probability of 0.90 the BTL yield increases to about 154.8 MW leading to about 0.42 MJ per MJ

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<sup>1</sup> average yield per year (harvested at 3 to 5 years intervals)

of biomass. According to [Dena 2006], up to 0.43 MJ BTL can be generated per MJ of wood chips.

### Compressed Gaseous Hydrogen (CGH<sub>2</sub>) and Liquid Hydrogen (LH<sub>2</sub>) from short rotation forestry

Pure hydrogen (H<sub>2</sub>) can be generated from biomass via gasification. The main components of the plant are the gasifier with dust removal, the CO shift reactor and the pressure swing adsorption (PSA) plant. The tail gas from the PSA contains combustible gases which are used in a gas engine for electricity generation. About 0.50 MJ compressed gaseous hydrogen can be produced per MJ of wood chips in relatively small plants (10 MW<sub>th</sub> biomass input) based on the so-called “staged reforming” developed by the German company D.M.2. In case of liquid hydrogen, large plants (~370 MW<sub>th</sub> biomass input) based on the Battelle Columbus Laboratory (BCL) gasifier with a higher yield of pure hydrogen (0.68 MJ/MJ of biomass) are used. Including biomass storage losses and the electricity generation for the gasification and the H<sub>2</sub> liquefaction plant, about 0.41 MJ are generated per MJ of wood chips. It has been assumed that the electricity requirement for the gasification (0.082 MJ/MJ of hydrogen) and the hydrogen liquefaction (0.30 MJ/MJ of hydrogen) is generated by a biomass fuelled integrated gasification combined cycle (IGCC) power plant with an efficiency of 42.5%. The same assumptions have been made in [CONCAWE 2007].

### Biomethane

For energy crops used in biogas plants the yield is assumed to be 10 to 25 t of dry substance per ha and year. The lower limit has been derived from [Kopetz 2002], the upper limit has been derived from [Graf 2000]. The gross biogas yield amounts to about 450 Nm<sup>3</sup>/t of dry substance. The LHV of the biogas is assumed to be about 23.4 MJ/Nm<sup>3</sup> leading to 105 to 263 GJ biogas per ha and year. According to [KTBL 2006], a gross biogas yield of 133 to 199 GJ per ha and year can be expected in case of maize whole plant silage. In case of sudan grass silage, an average gross biogas yield of about 124 GJ per ha and year can be expected in Germany. The gross biogas yield indicated in [KTBL 2006] includes the storage losses (12% of the dry substance).

The heat and electricity supply of the fermenter and for biogas upgrading to a methane content of more than 98% is supplied by a biogas fuelled combined heat and power (CHP) plant. The net yield of compressed methane gas is 0.71 MJ per MJ of the gross biogas yield [LBST 2006].

## Compressed Gaseous Hydrogen (CGH<sub>2</sub>) and Liquid Hydrogen (LH<sub>2</sub>) from Photovoltaics (PV)

In case of photovoltaics (PV), it has been assumed that only one third of the area is covered by photovoltaic panels. This assumption has to be compared with the jointly agreed guidelines of the Naturschutzbund Deutschland (NABU) and the Unternehmensvereinigung Solarwirtschaft (UVS) where photovoltaic panels should not cover more than 50% of the land area [Peters 2006].

The electricity consumption for the generation of hydrogen via electrolysis amounts to about 1.54 MJ/MJ of hydrogen based on the LHV. The electricity requirement for hydrogen compressions amounts to about 0.06 MJ/MJ of compressed gaseous hydrogen (CGH<sub>2</sub>). As a result, the efficiency for CGH<sub>2</sub> generation amounts to about 62.5%. Including electricity transport and distribution to the filling station, the efficiency for CGH<sub>2</sub> supply amounts to about 60%. The same assumptions have been made in [CONCAWE 2007].

Analogous to [CONCAWE 2007] for LH<sub>2</sub> it has been assumed that the electricity consumption for hydrogen liquefaction amounts to about 0.30 MJ/MJ of LH<sub>2</sub>. Including electricity transport and distribution to the electrolysis and liquefaction plant, the efficiency for LH<sub>2</sub> supply amounts to about 54%.

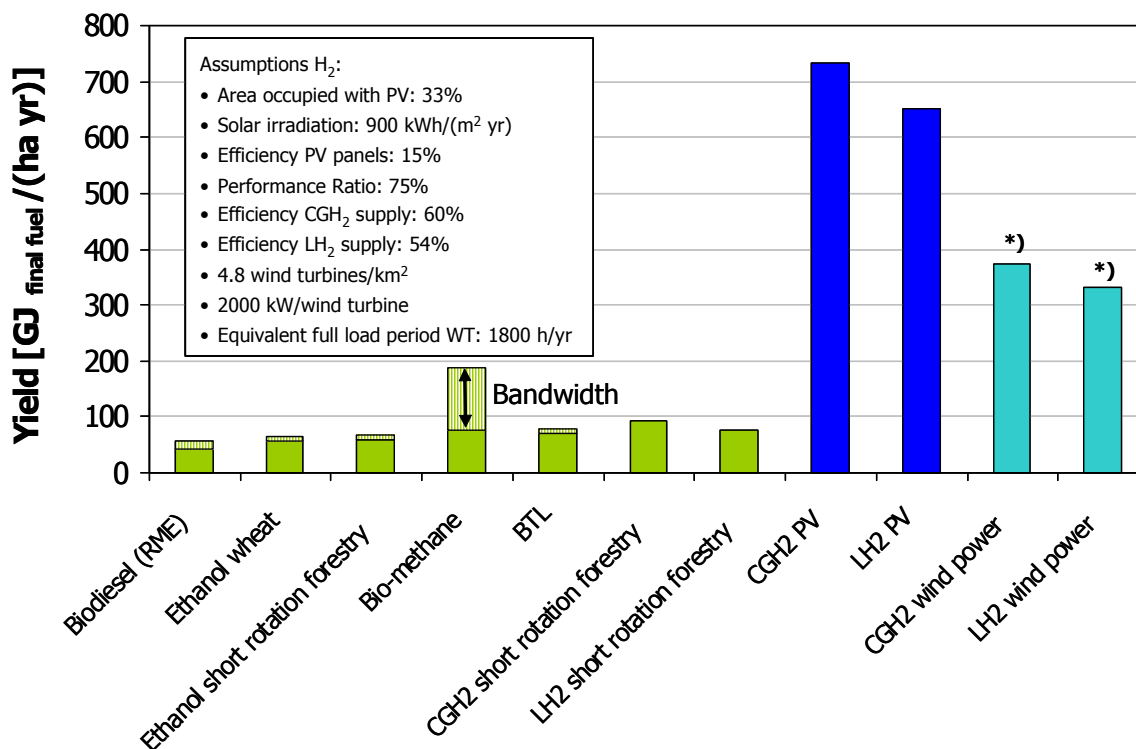
## Compressed Gaseous Hydrogen (CGH<sub>2</sub>) and Liquid Hydrogen (LH<sub>2</sub>) from Wind Power

For wind power it has been assumed that the distance between the wind turbines is 8 rotor diameters for the main wind direction and 4 diameters for the lateral wind direction. The rotor diameter of the 2 MW wind turbine is assumed to be 81 m.

## Results

Figure 1 shows the yield of final fuel per hectare per year for different transportation fuels.

Figure 1: Yield of final fuel per ha and year for different transportation fuels



**\*) more than 99% of the land area can still be used for other purposes e.g. agriculture**

Biodiesel (RME) gives the lowest yield of all renewable transportation fuels per ha and year whereas hydrogen from renewable electricity gives the highest yield. The yield for hydrogen from photovoltaic panels is higher than for the best biofuel (upper limit for compressed methane from biogas) even though it is assumed that only one third of the land area is covered by photovoltaic panels. The yield of compressed gaseous hydrogen (CGH<sub>2</sub>) from photovoltaics is approximately 5 to 15 times higher than that of biofuels. This does not even take into account that photovoltaics, and above all wind power plants, allow the farmland to be used for additional purposes or nature conservation assignments. Furthermore, photovoltaics in particular may also be installed on roofs and other building structures.

Assuming hydrogen to power fuel cell cars, the number of passenger cars supplied from one hectare of land shows an even higher advantage for electrolytic hydrogen produced by wind power or by photovoltaics compared to biofuels.

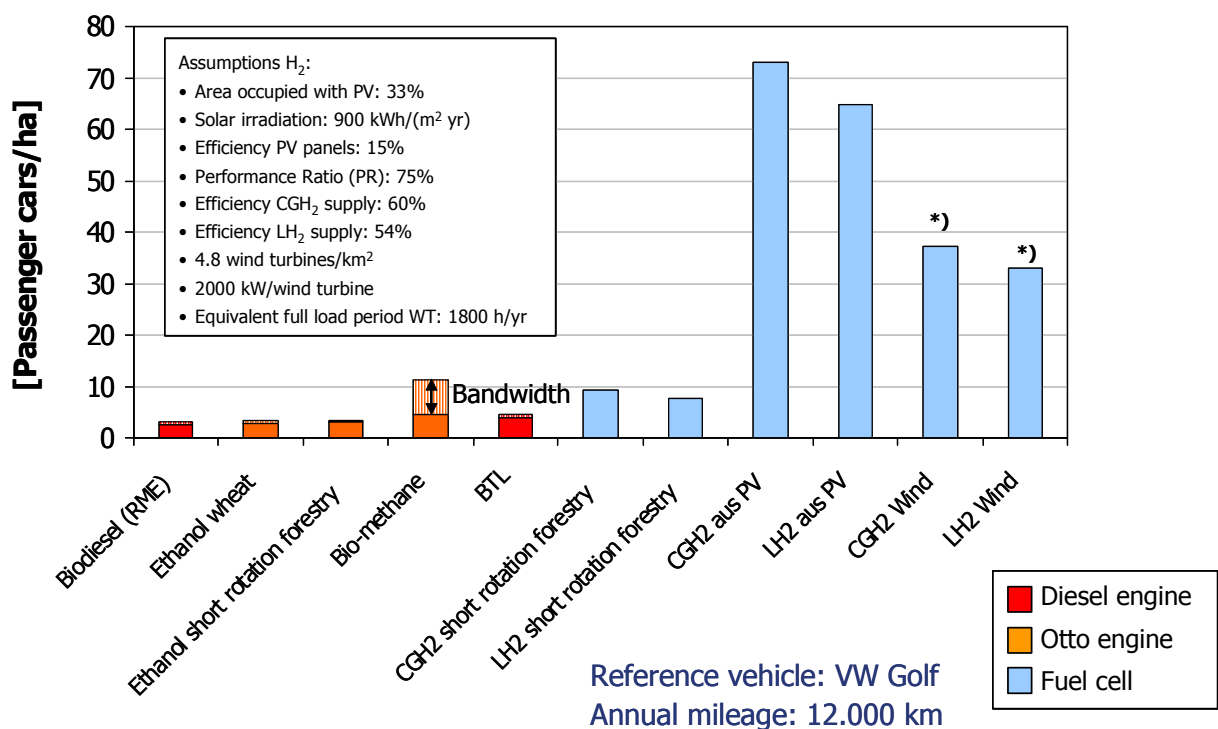
Table 1 shows the fuel consumption of various hybrid passenger cars. Figure 2 shows the number of cars which can be supplied per ha of land. Compressed natural gas (CNG) cars can also be operated with compressed methane gas from biogas.

**Table 1: Fuel consumption of various passenger cars (reference car: VW Golf) [CONCAWE 2007]**

	[MJ/km]	I GE/(100 km)
Diesel engine with diesel particle filter	1.456	4.5
CNG engine	1.394	4.4
Ethanol engine	1.630	5.1
H <sub>2</sub> fuel cell	0.837	2.6

GE: gasoline equivalent (LHV (gasoline): 32 MJ/l)

**Figure 2: Number of hybrid passenger cars which can be supplied from one hectare of land**



**\*) more than 99% of the land area can still be used for other purposes e.g. agriculture**

The number of passenger cars which can be supplied per hectare with compressed gaseous hydrogen (CGH<sub>2</sub>) from photovoltaics is about 10 to 30 times higher than the number of passenger vehicles fuelled with biofuels.

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