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COMPARISON OF THE RENEWABLE TRANSPORTATION FUELS, LIQUID HYDROGEN AND METHANOL, WITH GASOLINE—ENERGETIC AND ECONOMIC ASPECTS

M. SPECHT,* F. STAISS,* A. BANDI* and T. WEIMER†
*Center for Solar Energy and Hydrogen Research, Hessbruehlstr. 21 C, D-70565, Stuttgart, Germany
†Institute of Technical Thermodynamics and Thermal Process Engineering, Stuttgart University, Pfaffenwaldring 9, D-70569, Stuttgart, Germany

Abstract—In this paper, the renewable energy vectors liquid hydrogen (LH_2) and methanol generated from atmospheric CO_2 are compared with the conventional crude oil–gasoline system. Both renewable concepts, liquid hydrogen and methanol, lead to a drastic CO_2 reduction compared to the fossil-based system. The comparison between the LH_2 and methanol vector for the transport sector shows nearly the same fuel cost and energy efficiency but strong infrastructure advantages for methanol. © 1998 International Association for Hydrogen Energy

INTRODUCTION

For the introduction of LH_2 as fuel in the transportation sector a new infrastructure has to be erected with new techniques for hydrogen transportation, distribution and storage. If hydrogen is stored as methanol which is liquid at ambient temperature, it can be utilized directly with minor changes of the existing infrastructure today. Methanol is specially favoured for road transportation in combustion engines as a low emission fuel today, and for future application in fuel cell-powered vehicles as an on-board hydrogen storage medium. Besides other chemical storage systems, such as methylcyclohexane and ammonia, methanol is an interesting option for hydrogen storage and long distance energy transportation.

For the comparison of the renewable energy vectors hydroelectric power → LH_2 and hydroelectric power → methanol the established crude oil → gasoline system is used as reference. For all three vectors the overall energy efficiency and the costs are analysed and discussed. The process design for renewable fuel generation (liquid hydrogen and methanol) is based on technologies available today to get reliable results.

DESCRIPTION OF VECTORS

The selection of the energy vectors was made according to a representative fuel supply in central European countries or Germany in particular. All relevant data for the cost calculations are given in Figs 1–3. The energetic data refers to the lower heating values (LHV) of the fuels.

The crude oil–gasoline vector

This vector comprises five elements: the crude oil production in one of the OPEC countries, the intercontinental tanker transportation, a refinery in Germany, the distribution of gasoline to the filling station and an intermediate passenger car (Fig. 1). The intercontinental crude oil transportation is realised with a conventional tanker. The travelling time for a round trip is 36 days for a distance of 17 600 km (Middle East—Germany—Middle East). The refinery represents the mix of refineries in Germany in 1990 for which data on the energy consumption and costs have been available. The distribution of gasoline is realised by a typical tank truck. The reference car shows an average fuel consumption of 8.2 liters gasoline per 100 km. The cost of gasoline which is 1.50 DM l^{-1} includes 0.98 DM mineral oil tax and 0.20 DM value added tax according to regulations applied in Germany.

The hydropower–liquid hydrogen vector

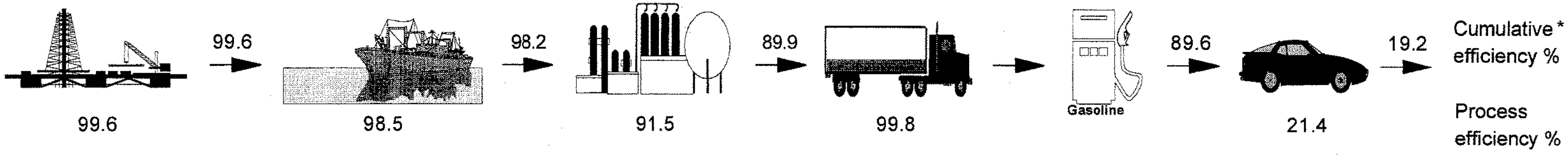
This vector was mainly taken from the feasibility study on the "Euro-Quebec Hydro-Hydrogen Pilot Project (EQHHPP)" published in 1991 [1]. Some modifications have been made in order to enable a consistent comparison of the energy vectors. A detailed description of production, transport and distribution of this vector is presented in Fig. 2. The intercontinental hydrogen transportation is realised with a specially designed LH_2 barge carrier with a capacity of 1036 t LH_2 and 15 round trips

Crude Oil - Gasoline Vector

OPEC Crude Oil
Crude oil price: 16.5 US$/barrel

Refinery Germany
Reference plant: mix West Germany 1990
Gasoline price refinery: 387 DM/t

Gasoline Car
Type: medium size passenger car
Engine: 85kW
Fuel: unleaded gasoline
Fuel consumption: 8.2 l/100 km
Annual km: 15,000
Fuel cost (incl. tax): 1.50 DM/l



Intercontinental Crude Oil Transport
Oil Tanker
Capacity: 250,000 tdw (tons dead weight)
Fuel: heavy fuel oil
Distance: 17,600 km
Travel time 36 days
Capital cost: 30,000 DM per day
Operating cost: 18,000 DM per day
Crude oil price Germany: 251 DM/t

Gasoline Distribution
Tank truck
Capacity: 35,000 l
Fuel consumption: 35 l Diesel/100 km
Distance: 200 km
Number of round trips: 500 per year
Investment/depreciation time:
Towing vehicle: 175,000 DM/6 years
Tank trailer: 175,000 DM/10 years
Total cost: 2.33 DM/km
Filling station commission: 0.025 DM/l
Gasoline price filling station: 0.33 DM/l
(untaxed)

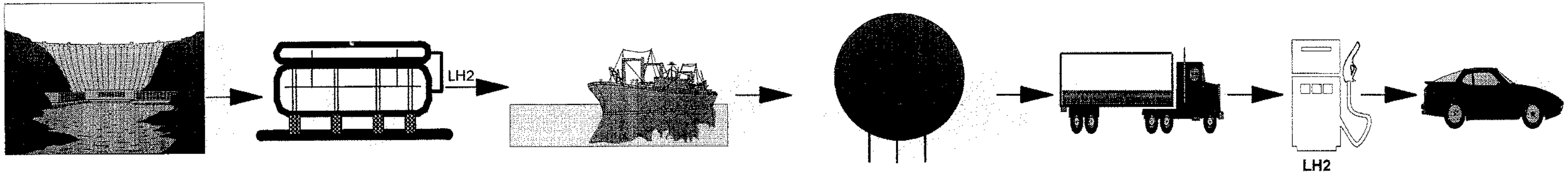
Fig. 1. Energetic efficiency and process data of the crude oil–gasoline vector.

Liquid Hydrogen Vector

Hydroelectric power station
Canada
Capacity: 100 MW_e
Full load hours: 8,300 h/a
Electricity cost: 0.05 DM/kWh_e

Intercontinental LH_2-Transport
LH_2-barge carrier
Fuel: heavy fuel oil
LH_2 tanks: vacuum isolated, mobile
Capacity (volume): 5 x 3,000 $m^3{}_{net}$
Capacity (mass): 1,036 t LH_2
Evaporation losses: 1.4 %
Distance: 11,500 km
Depreciation time: 15 years
Investment:
Barge carrier: 92 Mill DM
LH_2-tanks: 48 Mill DM

LH_2-Car
Type: medium size passenger car
Engine: 85 kW Otto
Fuel consumption: 2.2 kg LH_2/100 km
Tank volume: 130 l
Evaporation losses: 1.7 % per day
Filling losses: 5 %
Annual km: 15,000
Average efficiency: 17.8 %



LH_2 Production
Electrolysis:
Advanced alkaline elektrolysis
Energy consumption: 4.2 kW_e/Nm^3H_2
Depreciation time: 15 years
Investment: 1,400 DM/kW_e
Liquefaction:
Energy consumption: 11 kWh_e/kgH_2
Depreciation time: 15 years
Investment: 1,000 DM/kW_{LHV} H_2

LH_2 Distribution
LH_2 tank truck
Fuel: Diesel
LH_2 tank: Exchange containment, liquid nitrogen casing
Capacity: $37m^3LH_2$
Transfuse losses: 5%
Evaporation losses: 0.05% per day
Distance: 200 km
Number of round trips: 500 p. a.
Investment/depreciation time:
Towing vecicle: 175,000 DM/6 years
Tank trailer: 420,000 DM/20 years
Filling station commission: 0.14 DM/kg LH_2

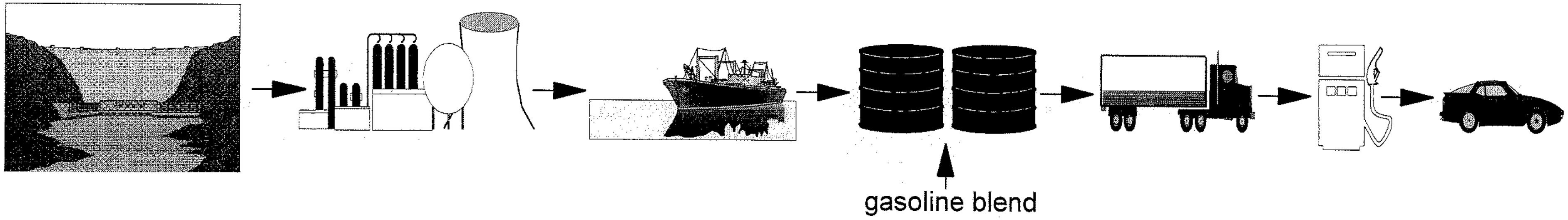
Fig. 2. Process data of the liquid hydrogen vector.

Methanol Vector

Hydroelectric power station Canada
Capacity: 100 MW_e
Full load hours: 8,300 h/a
Electricity cost: 0.05 DM/kWh_e

Intercontinental Methanol Transport
Product Carrier: Tanker
Capacity: 24,200 tdw
Fuel: heavy fuel oil
Distance: 11,500 km
Travel time: 23 days
Depreciation time: 15 years
Investment: 100 Mill DM
Operating Cost: 17,000 DM per day
Fuel Cost: 180 DM/t
Cost of blending Methanol and Gasoline (M85): 0.015 DM/l

M85-Car
Type: medium size passenger car
flexible fuel vehicle (M0-M85)
Engine: 85 kW Otto
Fuel consumption: 14 l M85/100 km
Annual km: 15,000
Average efficiency: 23.5%



Methanol production
Capacity: 170 t per day
Efficiency: 38.1 %
CO_2 absorber, air flow rate: 8,000 m^3/s
CO_2 absorption rate: 65 %
electrodialytic production: 425 t NaOH per day
Electrolysis: alkaline pressure electrolysis,
energy consumption: 4.2 kWh_e/Nm^3H_2
Depreciation time: 15 years
Investment:
CO_2 absorber/enrichment: 19 Mill DM
Electrodialysis: 26 Mill DM
Electrolysis: 88 Mill DM
Synthesis: 30 Mill DM

Fuel (M85)-Distribution
Tank truck,
parameters like gasoline distribution
Filling station commission: 0.02 DM/l

Fig. 3. Process data of the methanol vector.

per year. In Germany LH_2 is transferred to mobile LH_2 tanks which are distributed to filling stations by tank trucks. H_2 evaporation losses at the gas station during the refill of the car tank are fed to a natural gas pipeline (revenues, Fig. 5). The car is based on the reference vehicle for the gasoline vector but requires specific LH_2 equipment. Its average fuel consumption is considered to be 2.2 kg LH_2 per 100 km. Including energetic and material losses the car's efficiency will be 17.9%.

The hydropower–methanol vector

Generation of methanol. A new process has been designed for methanol generation from atmospheric CO_2 [2]. The recovery of higher quantities of CO_2 from the air requires new highly efficient technologies with a low specific energy consumption, due to the low concentration of CO_2 in the air. During the absorption process of CO_2 from the air, Na_2CO_3 is formed from the NaOH scrubbing solution (Fig. 4). The recovery of CO_2 from the carbonate solution produced in the absorption column occurs by acidifying the spent solution with sulphuric acid. For the regeneration of the caustic scrubbing liquid and the acid solution an electrodialytic process with bipolar membranes is used. The methanol production is carried out by a catalytic conversion of CO_2 and electrolytically generated hydrogen over a Cu/ZnO catalyst. All energy process data used in this study are based on experimental results and represent a technology available today with an overall efficiency of 38.1% related to the LHV of methanol. CO_2 can also be taken from high concentration sources, such as fossil-fired power plants, cement production, etc. If a carbon-based fuel is produced from atmospheric CO_2, the energy carrier will be CO_2-neutral due to the closed carbon cycle without any greenhouse gas emissions. Furthermore, the use of atmospheric CO_2 allows methanol synthesis at any location (with renewable energy resources) without the costs for CO_2 transport and storage.

Methanol vector description. For the methanol vector it was assumed that not pure methanol but a blend of 85% methanol and 15% gasoline will be used in cars. This is simply due to the fact that presently only flexible fuel cars are available, as no country with a dense grid of methanol filling stations will be available in the near future. But it is worth noting here that pure methanol cars have already been built and successfully operated in a number of large demonstration projects under commercial conditions, and pure methanol engines show higher efficiencies than gasoline engines. For a better comparison it was assumed that the same hydropower plant in Canada is applied to provide the primary energy input as for the LH_2 vector (Fig. 3). The hydrogen is again produced by an advanced electrolysis. The other components required for methanol production are CO_2 absorption, electrodialysis and methanol synthesis (total investment: 163 million DM). In a second step, methanol is transported from Canada to Germany with a conventional product tanker with a capacity of 24 000 t. For the transportation of the annual methanol produced only two to three round trips are required. Therefore the costs are calculated on presently applied freight rates. This is different to the EQHHPP-LH_2 vector where the size of the barge carrier was selected specially for this project and for continuous operation (15 round trips per year). In Germany, methanol is blended with gasoline to M85 (85 vol.% methanol, 15% gasoline) at a refinery. The cost and energy requirements for providing gasoline are taken from the results of the crude oil–gasoline vector described above. For transporting M85 from the refinery to the filling station, the same reference tank truck is used as for the gasoline vector. The car is again an intermediate passenger car that corresponds to flexible fuel cars produced by different automobile manufacturers, which usually show an increase in efficiency of 10% at M85 operation compared to pure gasoline operation. The cost of adapting the fuel system to M85 in a series production is moderate, in the order of 1000 DM.

COMPARISON OF ENERGY EFFICIENCIES

The crude oil–gasoline vector reaches an overall efficiency for the first four vector elements of almost 90%. This excellent value is due to the marginal energy requirements for crude oil production (0.4%) and the high efficiency of tanker transportation (1.5%), as the fuel consumption of the engines is only 3600 t heavy oil for a round trip, when 250 000 t crude oil is transported. Only the refinery requires a higher energy equivalent (about 8.5%) to convert crude oil into products. The distribution of gasoline is again very efficient as the tank truck requires only 70 l diesel for one round trip but transports 35 000 l gasoline. The only crucial element of the gasoline vector is the car with an average efficiency of only 21.4%. Thus, the energy efficiency of the entire gasoline vector reaches 19.2%.

It is obvious that the production efficiency of the renewable energy carriers LH_2 and methanol is lower than gasoline production efficiency, due to the conversion of the primary energy hydroelectric power to a completely different energy carrier. The overall efficiency of the LH_2 production is 57.7% related to the hydroelectricity input and the LHV of hydrogen (Fig. 5). The transport capacity of the barge carrier is 1036 t LH_2, but it consumes 800 t heavy fuel oil during a round trip which is roughly one fourth of the consumption of the crude oil tanker and its transport capacity is 250 000 tons of crude oil. The average efficiency of LH_2 distribution is primarily determined by the losses occurring when filling the mobile tanks. Five per cent of LH_2 evaporates and has to be liquefied again. The efficiency of the LH_2 car is determined by: filling losses, evaporation losses and the efficiency of the car in motion which has the same efficiency as the gasoline car (21.4%). The car's annual average efficiency was calculated to 17.9% assuming a mileage of 15 000 km and 52 tank refills per year. The total efficiency of the entire LH_2 vector related to the overall primary energy input is 8.7%.

As shown in Fig. 6, the efficiency of the methanol

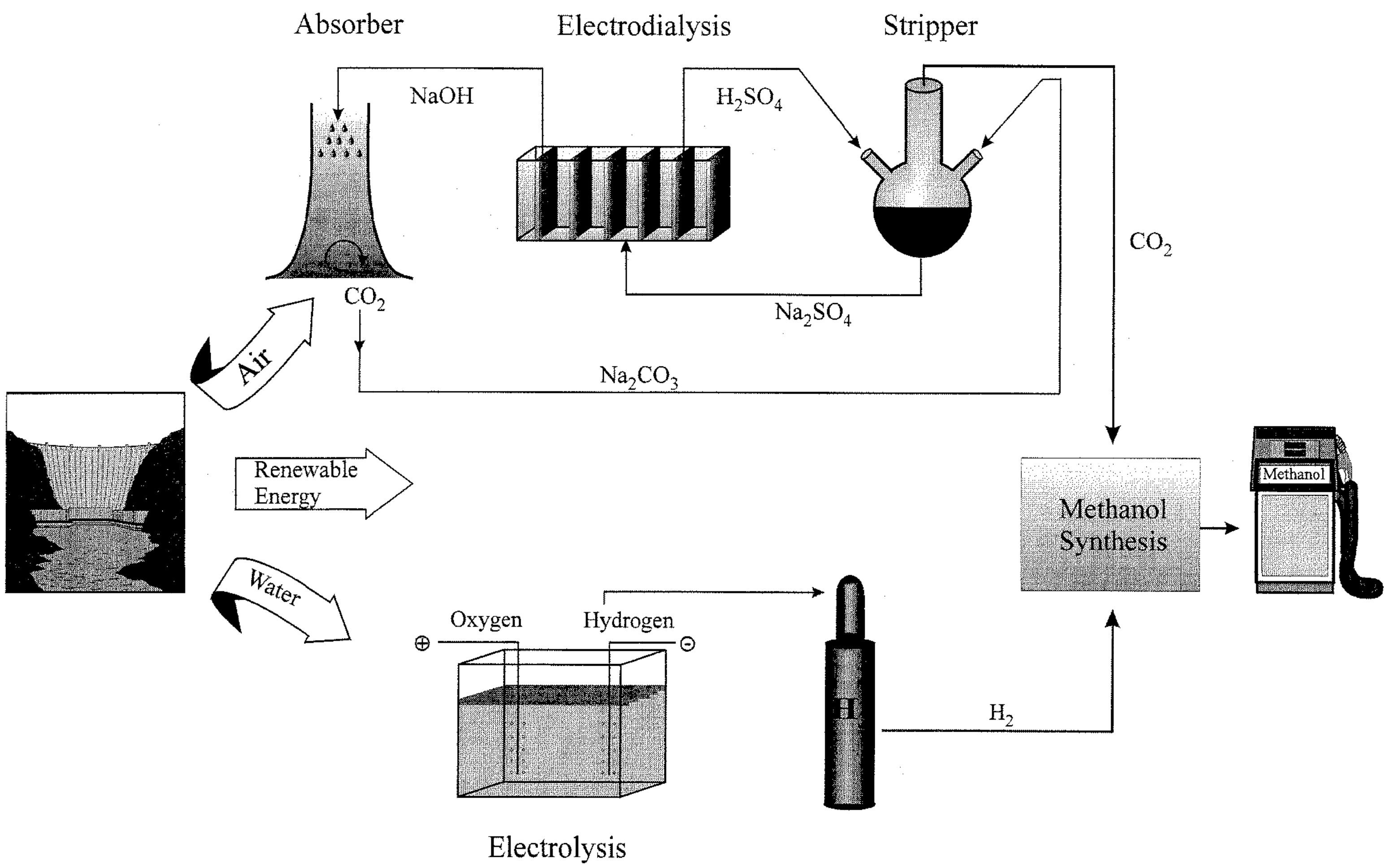


Fig. 4. Schematic process flow sheet of methanol generation from atmospheric carbon dioxide.

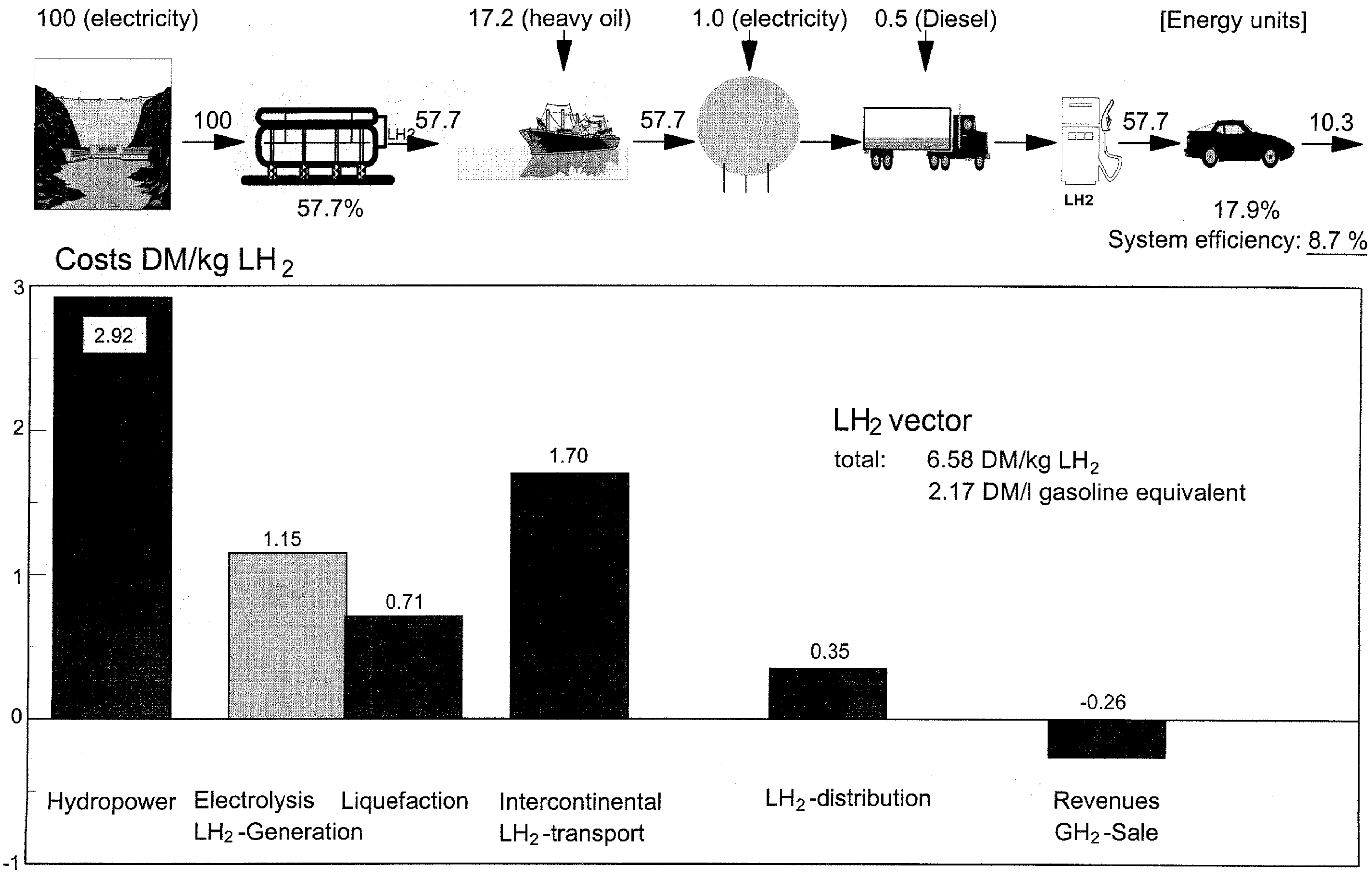


Fig. 5. Energetic efficiency of the liquid hydrogen vector and LH_2 cost calculation.

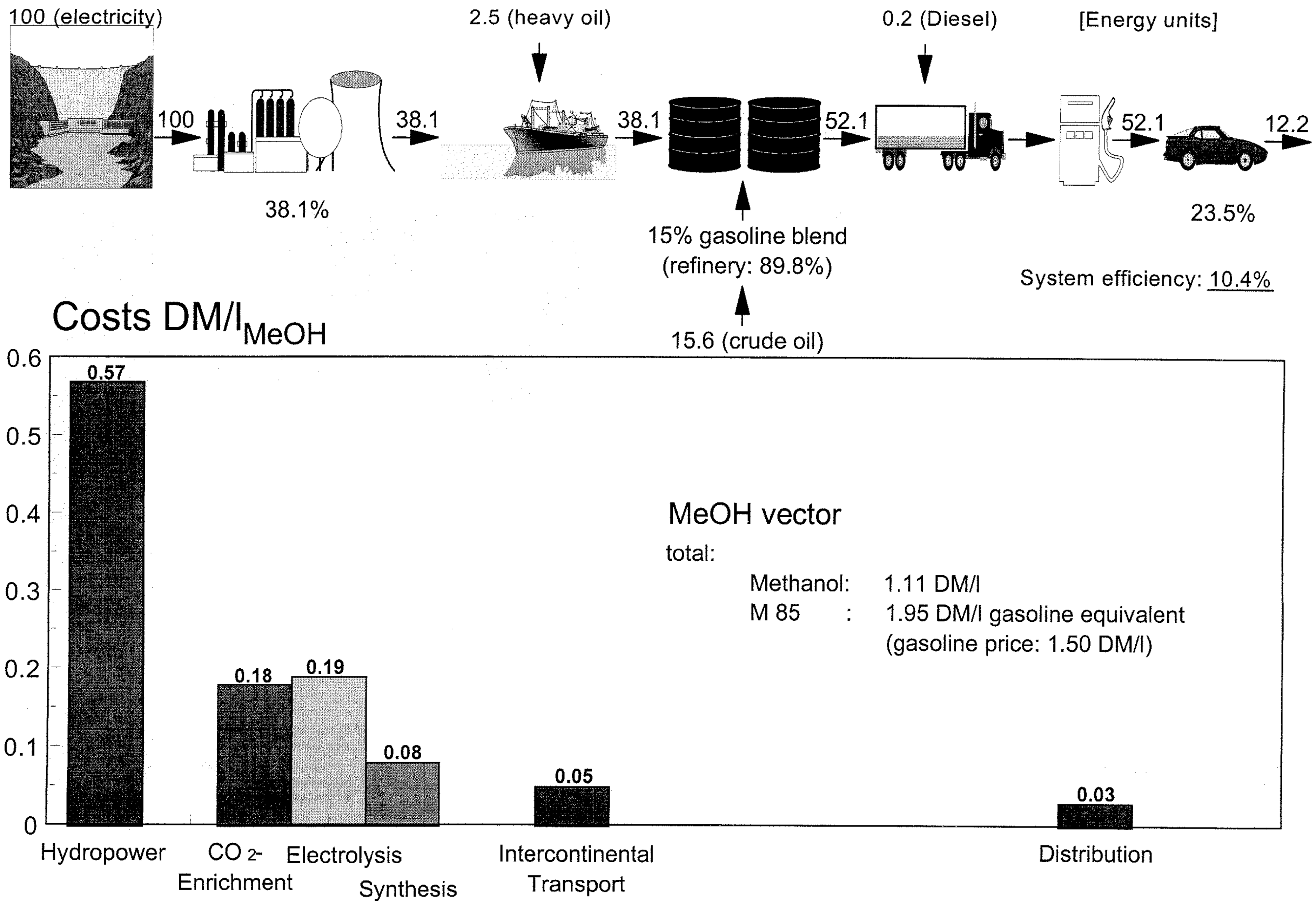


Fig. 6. Energetic efficiency of the methanol vector and methanol cost calculation.

vector strongly depends on the production process which amounts to 38.1%. The efficiency of methanol transportation is much higher compared to LH_2, as the capacity of the tanker is higher and no evaporation and filling losses occur. As methanol is then blended with gasoline to M85, efficiencies of distribution and of the methanol car (23.5%) are related to M85. Because M85 consists of 15% gasoline and the efficiency of gasoline production is rather high (89.9%, Fig. 1), this positively influences the overall efficiency of the M85 vector, which will be 10.4%. For a pure methanol vector the efficiency of fuel production and distribution would be a little lower. But on the other hand the efficiency of a pure methanol car could be in the range of 25%. The overall efficiency of the pure methanol (M100) vector therefore would be in the order of 9.3%.

COMPARISON OF COSTS

The costs are mainly determined by the energy input and the capital cost of the production plants. For both renewable energy vectors it was assumed that hydroelectricity is available at 0.05 DM kWh^{-1} and 8300 h y^{-1}. Capital costs are calculated on a real interest rate of 8% and depreciation periods (usually 15 years) correspond to about 50% of the expected technical lifetime of the plants (see Figs 5 and 6). These parameters have been selected according to practical standards in the energy industry. On these assumptions it follows that LH_2 provided to the consumer costs 6.58 DM kg^{-1} (untaxed) which corresponds to 2.17 DM l^{-1} gasoline equivalent. This value is calculated for an annual base taking into account evaporation losses that occur even when the car is not in use. As Fig. 5 shows, about 25% of the LH_2 cost is determined by the overseas transportation, which could be considerably reduced if transportation capacities increase in the future.

The cost of producing and providing methanol to the consumer can be calculated as 1.11 DM l^{-1} methanol (untaxed) which is 2.30 DM related to the energy content of one liter of gasoline. Taking into account the 10% higher operation efficiency of M85 cars compared to gasoline cars, the value has to be reduced correspondingly to 2.08 DM l^{-1} gasoline equivalent. Assuming gasoline costs of 1.50 DM l^{-1} for blending, the price of M85 is 1.95 DM l^{-1} gasoline equivalent.

CONCLUSIONS

Comparing the untaxed gasoline equivalent costs of LH_2 (2.17 DM) with that of the methanol in the M85 vector (2.08 DM) or the resulting cost of M85 (1.95 DM), in the frame of calculation precision the costs are almost equal. The higher costs of the renewable fuels, liquid hydrogen and methanol, will become more comparable to the fossil fuel costs, if environment damage costs and CO_2 taxes are included in calculations in the future.

The investment and operation costs of the methanol synthesis, based on CO_2 and H_2, are equivalent to a conventional plant but without the steam reformer costs, which are more than 50% of the total investment. The costs for methanol production from CO_2 and the hydrogen generation costs are reliable but the CO_2 enrichment costs are somewhat uncertain due to the non-existence of such plants today. The CO_2 enrichment costs are only 16% while the energy costs are more than 50% of the overall methanol costs, therefore higher CO_2 enrichment costs would not lead to a drastically increased methanol price.

It is also worth noting that fuel costs represent only one aspect for the consumer. Of higher importance is the energy service cost, i.e. driving a distance of 100 km with a passenger car. To determine this cost one has to consider the investment of the car, the decrease in value, operation and maintenance costs, tax and insurance. Here the methanol has clear advantages compared to LH_2 as only minor modifications of the car have to be done while LH_2 cars require complex and costly equipment. Considering the advantage of the existing infrastructure for liquid fuels and the cost disadvantage for the liquid hydrogen powered car (minimum 20% additional car investment costs for the LH_2 equipment), the methanol vector shows a considerable advantage over the LH_2 vector, even if the fuel costs are almost equal.

The comparison of the LH_2 with the methanol vector shows an energetic advantage for the methanol concept. This is mainly due to the evaporation losses in the LH_2 concept and due to higher efficiency of the methanol car. Even if LH_2 evaporation losses could be reduced near to zero, this would not change the result in principle. The efficiency of the methanol vector was calculated to be 38.1%. With an advanced technology, the process efficiency can be improved to 44% [2]. A further efficiency improvement will be possible with high temperature processes for CO_2 enrichment and synthesis [3].

Efficiencies will be even higher if CO_2 is taken from concentrated emissions (e.g. fossil-fired power plants or cement production). Cost calculations based on these assumptions lead to 30% lower methanol prices compared to the atmospheric CO_2 path. Further cost reductions are feasible by using other carbon sources as feedstocks such as biomass or waste for synthesis gas production via gasification and subsequent methanol generation. Synfuels from renewable hydrogen and carbonaceous resources are the link to conventional fuels, which allows the continuous transition from fossil to renewable energy carriers.

For both concepts, LH_2 and methanol, an increase of the car efficiency is possible in the future. A pure methanol (M100) car with an internal combustion engine has an improved efficiency of 30% compared to a gasoline car. A further improvement can be achieved by fuel cell-powered cars. Thus, the overall energy efficiency of both renewable vectors will approach the crude oil vector efficiency.

The main advantage of the renewable concepts is related to the greenhouse gas emission reduction potential. Both renewable energy vectors, LH_2 and methanol, can contribute to a substantial reduction of CO_2 emissions in the transport sector.

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