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"Solar Hydrogen - Why, Potential, When?"

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These are preliminary lecture notes, intended only for distribution to participants.

SOLAR HYDROGEN - WHY, POTENTIAL, WHEN ?

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ABSTRACT

Hydrogen is a carbonfree fuel which oxidizes to water as combustion product. The generated water becomes, together with renewable primary energy for splitting it, a source of clean and abundant energy in a carbon-free, natural cycle.

Hydrogen is a fuel which can be transported over long distances and stored so that solar energy can be transported from energy rich countries over long distances in ships to Europe, stored and used in gaseous or liquid form in industry, households, power stations, motor cars and aviation propulsion and steel fabrication.

Solar energy as primary energy is discussed, a special form of it, the cheapest and by now largely available hydropower, is stressed.

Techniques of hydrogen production, vectorization and end use is discussed as well as safety aspects, costs and strategy for its implementation.

The Euro-Québec Hydro-Hydrogen Pilot Project is shortly described including its latest realisation of seven demonstration projects on the use of hydrogen in the fields of public transport, aviation propulsion, steel fabrication and storage.

KEYWORDS

Solar energy; hydrogen; economics of solar hydrogen.

WHY HYDROGEN?

Hydrogen is a carbon-free fuel which oxidizes to water as combustion product. The generated water becomes, together with renewable primary energy for splitting it, a source of clean and abundant energy in a carbon-free, natural cycle.

The hydrogen technology is ecologically benign, entailing little or no local pollution.

Hydrogen can be transported and stored in gaseous and liquid form and used as fuel in industry, households, power stations, motor car and aviation.

The intermittence and the geographical distribution of solar energy require means of storing and transporting it to the user's place. An almost ideal means of doing this is to split water with this primary energy source in order to obtain hydrogen.

The characteristics of hydrogen assign to it a role which is complementary to that of electricity. But unlike electricity, hydrogen is a fuel which can, with by now established techniques, be transported over long distances and stored so that solar energy can be transported from energy rich countries over long distances in ships to Europe, stored underground or in containers and used in the different forms.

Hydrogen can thus open up clean and abundant renewable energy sources distributed all over the World and give countries of the Third World the opportunity to export energy to the developed countries. It leads by that virtue to more independence from the actual fossil fuel exporting countries and contributed thus to the economic cooperation of nations and the "North-South Compensation".

The transport of hydrogen entails no tanker oil spills (1989: Approx. 3 Mio To oil went into the oceans from tanker wrecks (13), tanker cleaning, pipeline and drilling platform leaks).

Hydrogen from hydropower is relatively cheap and in some cases already competitive (steel fabrication with Brazilian hydro/hydrogen).

Hydrogen allows smooths transition from the existing energy systems to clean and renewable energy systems since hydrogen energy systems need virtually no basic engineering breakthrough; all components of such systems exist, they need continuous, gradual development; large pilot/demonstration projects can today be built and run.

PRIMARY ENERGY

Hydrogen being a secondary energy - an energy vector - it has to be generated with primary energy i.e. direct or indirect solar energy such as hydropower and wind energy if the overall system is to be clean and renewable.

The most convenient process for the generation of hydrogen is electrolysis which requires electricity as primary energy.

Direct Solar Energy Conversion

The most developed technologies for helioelectricity generation are photovoltaic, thermal and wind conversion. All these technologies are today sufficiently developed and field-tested so that the erection and operation of pilot/demonstration plants in the 1-100 MW range can be undertaken.

A 100 MW el photovoltaic power plant, situated in an equatorial country with global yearly insolation of say 2300 kWh/m^2, y and 7.5% global efficiency of conversion from solar radiation into hydrogen would have a collector surface of about 1 km^2, covering some 3 km^2 land surface and would produce yearly $0.5 \cdot 10^9$ m^3 of hydrogen. New technologies like multi-band solar cells, capable of utilizing photons in a number of adjacent frequency bands and bringing the theoretical efficiencies up to 25% or 45% would reduce costs, material and land requirements proportionally.

Indirect Solar Energy Conversion Hydropower

Natural hydropower and hydropower of already existing dams are amongst the cleanest and most promising renewable energy sources. 23% of the solar energy falling on the earth operates the hydrological cycle, i.e. evaporation of water, precipitation and storage in water and ice.

Some characteristics of hydropower are given heareafter:

- 23% of the solar energy falling on the earth, i.e. $\sim 350 \cdot 10^6$ TWh/y, operates the hydrological cycle, i.e. evaporation of water, precipitation and storage in water and ice;
- the World's topological and technically exploitable estimated hydroenergy potential is $\sim 20 \cdot 10^3$ TWh/y, i.e. 0.0057% of the hydrological cycle energy;
- the yearly average utilization factor of hydroenergy is ~ 65% (in 1986, Worldwide installed 380 GW generated 2200 TWh electricity);
- today's hydropower electricity generation of about 2200 TWh/y represents ~ 21% of the World's electricity generation;
- the table gives the World's estimated hydropower potential and its approximate distribution:

. Asia (without UDSSR)	:	$5.3 \cdot 10^3$ TWh/y
. South America	:	$3.8 \cdot 10^3$ TWh/y
. Africa	:	$3.1 \cdot 10^3$ TWh/y
. North America	:	$3.1 \cdot 10^3$ TWh/y
. Ex UDSSR	:	$2.2 \cdot 10^3$ TWh/y
. Greenland	:	$1.5 \cdot 10^3$ TWh/y
. Europe	:	$1.4 \cdot 10^3$ TWh/y

(for comparison, Europe's (EC) electricity consumption (1984) was $1.3 \cdot 10^3$ TWh/y).

ENVIRONMENTAL ASPECTS

The combustion of hydrogen does not produce CO_2, CO, SO_2 VOC and particles, but entails emission of water vapour and NOx.

Water vapour emissions from airplanes may be harmful since they generate - depending on the cruising altitude and latitude - ice clouds with ensuing greenhouse effects and ozone depletion. The problem is of great importance and actually under investigation.

The formation of NOx is a function of flame temperature and - duration. Considering the wide flammability range of hydrogen its combustion can be influenced by the design of the engine so that the NOx emission can be reduced.

The worldwide water evaporation from the oceans and rivers is $\sim 5 \cdot 10^{14}$ m^3 per year. If mankind's today's total energy consumption of sustained 11 TW would be effectuated by hydrogen, the ensuing yearly water evaporation would be some $2.5 \cdot 10^{10}$ m^3 i.e. about 1/20000 of the natural evaporation. Once hydrogen will be massively used, local considerations are obligatory like it is the case for today's wet cooling towers.

END USE

Hydrogen is a carbonfree fuel with excellent combustion properties. This makes it a clean, universal fuel for use in industry, households, power stations, road vehicles and aviation.

The specific properties of hydrogen induce new end use techniques, like:

Fuel Cells

The key element of an efficient electricity generation will be the fuel cell for which hydrogen is the best fuel. Being devices which transform chemical energy directly into electrical energy its generation is not subjected to Carnot cycle limitations, is done silently without moving parts and with high efficiencies. Efficiencies of future fuel cells like molten carbonate cells operating at 600-800°C, with total energy efficiencies of 60-80% with waste heat at 600°C, make the fuel cell concept a potential candidate for use in power stations, road and space vehicles. Progress in catalyst and electrode technology and cost reductions have to be made, however, before fuel cells can competively be considered for general use.

Hydrogen is an excellent fuel for fuel cells, its more or less cold combustion will reduce the NOx emissions even down to zero.

Catalytic Burners

Hydrogen, having lower ignition energy than for instance natural gas, burns smokeless when in contact with a suitable catalytic surface at low temperatures between 20 and 400°C. This would be a preferred technology for generating low temperature heat in residential space heaters, cooking devices and industrial dryers and heaters.

Catalytic combustion has the advantage of high safety, very high efficiencies of up to 99% and negligible emissions of nitrogen oxides.

Super/Hypersonic Aviation

Jet engines at super/hypersonic speeds are advantageously - if not necessarily - powered with liquid hydrogen (LH_2) for mainly two reasons, its almost 3 fold gravimetric heating value compared with kerosene and its capacity of cooling parts (turbine inlet rim, wing leading edges, passenger cabine) of the plane exposed to outside stagnation temperatures of 1300°C at Mach 6, cryogenic storage temperature being at -252°C. Moreover, cooling of the wing skin induces laminar flow and therewith considerably reduces drag by up to, theoretically, 30% ("laminar flow control").

Water vapour emissions, however, are likely to form more or less long lasting ice clouds which enhance the greenhouse effect. The problem is of extreme importance and is seriously to be investigated not only in view of hydrogen - the combustion of hydrogen sets 2.5 times more water vapour free than that of kerosene - but also concerning kerosene combustion in general.

The elimination of CO, CO_2, SO_2 and VOC by using hydrogen not only is beneficial for the atmosphere, but reduces considerably airport ground pollution. For example, the NOx emis-

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sions resulting from the daily average 1259 landing/take-off cycles at Los Angeles International Airport are equivalent to the operation of about 1 Mio passenger cars.

Road Vehicle Propulsion

In Germany, for example, from the overall emissions, those resulting from road traffic are: 52% NOx, 70% CO and 49% VOC. The main problem of hydrogen utilization in vehicles is storage due to the low volumetric energy content of hydrogen of about one third of that of gasoline. From the three different storage technologies i.e. gaseous hydrogen in pressure vessels, cryogenic liquid hydrogen and hydrogen chemically bonded in metal and liquid hydrides (methylcycloexane), liquid hydrogen seems to be the most suitable solution.

The low ignition energy of hydrogen and its wide ignition range of hydrogen/air mixtures make gas turbines as well as piston engines well adaptable for hydrogen combustion. The ignition within a wide range of non-stoechiometric air/fuel mixture permits combustion with high amount of excess air and thus full and part load operation with low nitrogen oxides emission.

Since 1937, more than 30 vehicles with hydride storage have been built and operated in Europe by Daimler Benz, (more than 600.000 km), BMW and experimental trucks by Paul Scherrer Institute (Switzerland).

It should be emphasized that the building up the necessary infrastructure is at least as lengthy as the development of the technology itself.

Steel Fabrication

With ~2 kg CO_2 emissions per kg steel fabricated with carbon as reductant, the World's steel fabrication contributes 10-12% to the world's total anthropogenic CO_2 production and is therewith amongst the most intensive single CO_2 polluter.

Hydrogen is an excellent and clean reductant emitting water vapour instead of CO_2 and does not introduce extra impurities as coke does (sulphur in particular). If generated with relatively cheap and abundant hydropower, its application in steel fabrication is in some cases already competitive for instance Brazil which disposes of enormous resources of iron are in the vicinity of large hydropower installations.

The penetration of hydrogen into the steel industry would be favorized by the fact that steel fabrication is rather centralized, the power per steel fabrication plant being in the order of GW compared with, for instance, 100 kW per motor car, which eases the logistics of intervention of hydrogen in steel fabrication.

Safety

Each energy carrier has its specific dangers and risks. Compared with natural gas and liquid fuel hydrogen scores less well since it:
- is flammable within a wide range of hydrogen - air mixtures of between 4 and 75 Vol. % vs. methane between 5 and 15%;
- has a low ignition energy of up to 15 times lower than methane;

- is much more prone to leak; liquid hydrogen leakage rates are 50 times that of water;
- has high flame velocities of about 7 times that of methane and therewith reacts violently once it is inflamed.

Hydrogen is advantageous since:
- it has a high diffusivity of about 4 times larger air so that spills disperse rapidly to below flammability; there is higher probability of surviving an airplane crach - if one is not killed by the impact if the airplane - if it is fuelled with hydrogen rather than with kerosene;
- air flames are nearly invisible i.e. they release little heat by radiation implying both hazards in fire fighting because one does not feel the flame as well as advantages since fire fighters can work closer to the flame.

Experience from the use during decades of town gas containing 60 Vol. % hydrogen is available as well as from the operation of a 210 km long pipeline network operating with pure hydrogen at 25 bar in Germany since 1936, and by a 80 km hydrogen carrying pipeline in Houston, Texas. Considerable experience in liquid hydrogen storage and road/rail transportation has been gained in the course of space activities, in which no specific hydrogen fatality has been experienced.

Hydrogen is undoubtedly a hazardous material but there is general agreement that with proper use under adequate safety measures hydrogen will be no more hazardous than the fuels currently used.

On 18.12.1990 the BAM (German Federal Institut for Material Research) declared that liquid hydrogen would be not more dangerous than LNG and LPG and that it has no objection to the transport of liquid hydrogen in 2 G type ships (IMO rules).

COSTS

In the Euro-Québec Hydro-Hydrogen Pilot Project, for instance, the cost of liquid hydrogen, produced with hydropower at 2 $cents_{ECU}$/kWh, shipped to Europe and stored in the port of Hamburg are 14.8 $cents_{ECU}$/kWh at an annuity of 11.7%.

The specific product costs and their breakdown for the LH_2 vector are given in Figs. 1 and 2.

ECONOMICS

An adequate comparison of hydrogen costs with costs of the actual hydrocarbon energy has to take into account the external costs i.e. costs for pollution abatement/prevention and climate effects of fossil fuel burning. If the costs for pollution abatement originating from fossil energy use are evaluable only very approximatively and with great difficulties, the cost of the negative drawbacks on climate changes are clearly imponderable i.e. impossible to evaluate numerically.

The hydrogen cost of 15 $cents_{ECU}$/kWh are pictured in Fig. 3 together with the costs of taxed gasoline prices in Europe (average of the 12 EC countries, August 1990) of 8.5 $cents_{ECU}$/kWh which are made up of 3 $cents_{ECU}$/kWh for the crude oil itself, its transportation, refinement, manipulation and distribution and of 5.5 $cents_{ECU}$/kWh for taxes.

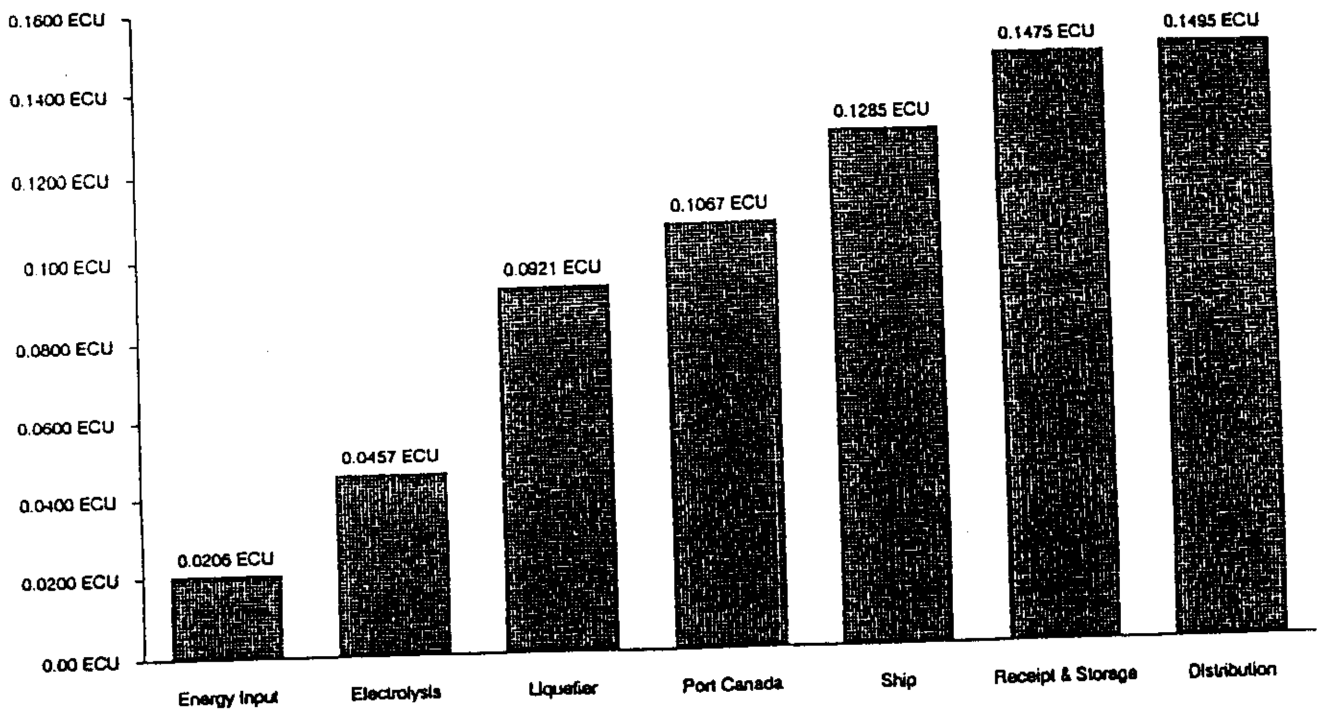

Fig. 1. Specific costs, ECU/kWh.

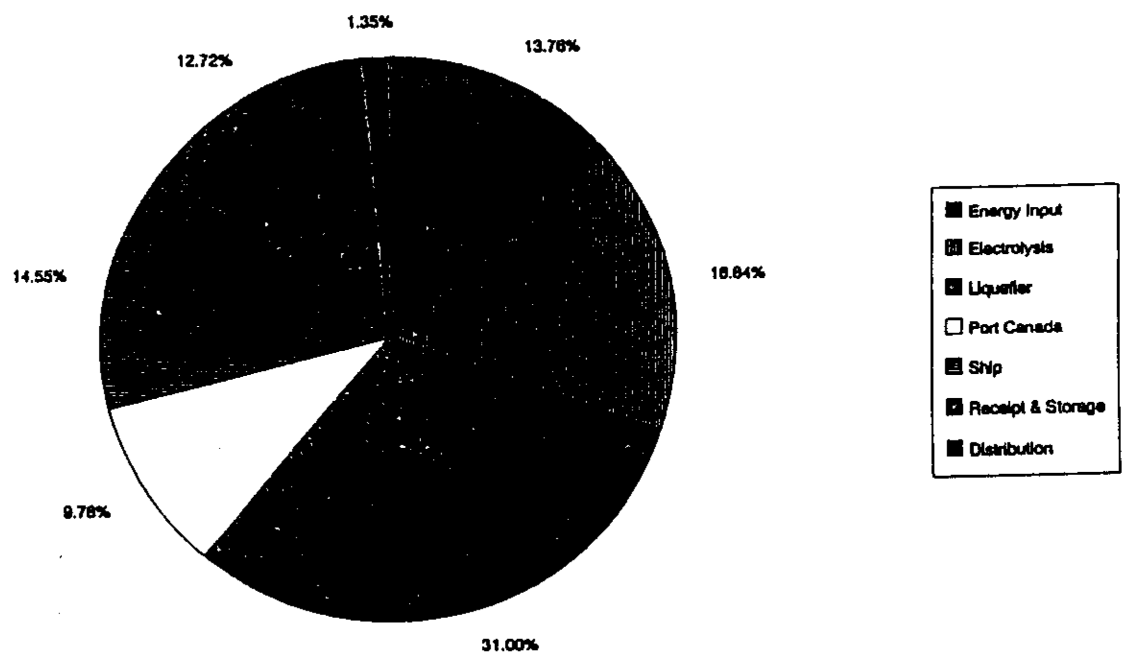

Fig. 2. Specific costs distribution.

With the above values and including the submerged costs of protection/repair of the damaged environment resulting from the use of fossil fuel (the value of 2.5 $cents_{ECU}$/kWh is the average from various literature sources), the "FUEL COST ICEBERG" would look as shown in Fig. 3.

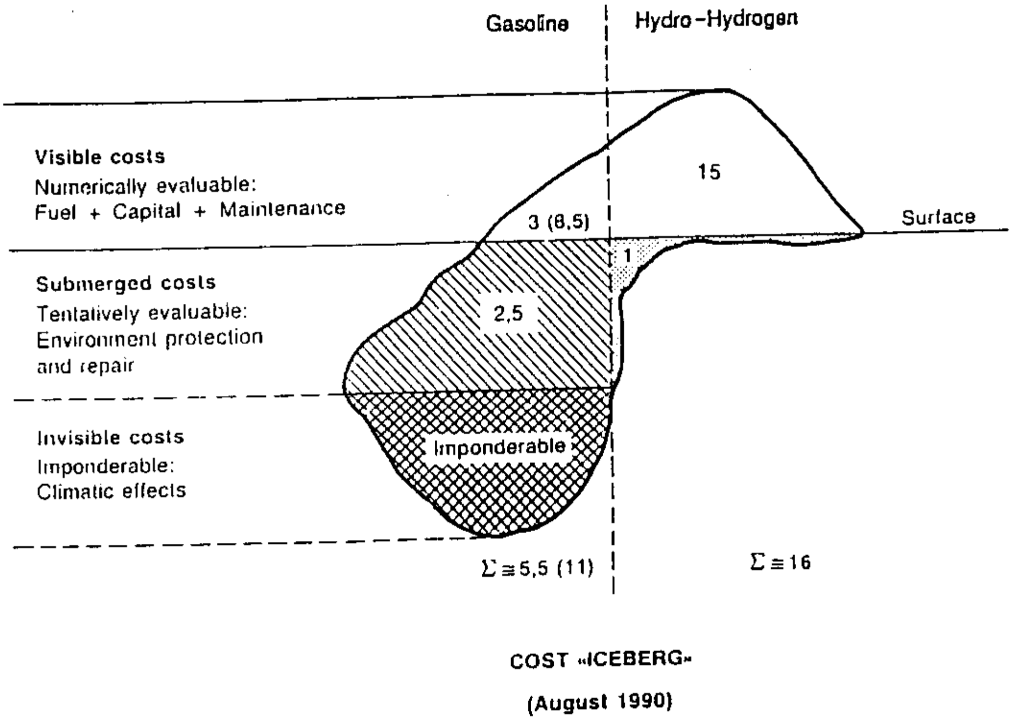

Fig. 3. Fuel cost comparison ($¢_{ECU}$/kWh; figures in ( ) are for taxed fuel).

With internalization of external costs, hydrogen energy would thus be about (1.45) 2.9 times higher than hydrocarbon energy costs, not taking into account the imponderable costs of climate effects.

WHEN?

Given the long lead times and the dynamics of the introduction of energy technologies, time is likely to become a precious raw material in view of the menacing deterioration of the environment.

Analysis of the molecular composition shows an increasing ratio of hydrogen to carbon molecule of the fossil fuels used worldwide since 1860, going from wood (H/C = 0.1) to coal (1), to oil (2) and finally - during the 90's - to methane (4). If that trend is to continue, extra hydrogen has to be provided from an external source i.e. water, see Fig. 4. This leads to the concept of water splitting using non-fossil fuels.

The analysis of the market penetration curve of new technologies, see Fig. 5, indicates that the conquest of the first 10% of the market is not very different from the one between 10 and 90%.

In the past it took about 100 years for a market penetration from 10 to 50%, which means that solar hydrogen should cover 10% of the energy market by the year 2000 if by the year 2100 it is assumed to cover 50% and if things would go at the same pace as in the past. Even if things move faster now solar hydrogen will not cover 10% of the market by the year 2000. Works on solar hydrogen should - by judiciously analyzing the penetration curve - have started before the beginning of the century in order to have 50% of mankind's energy consumption covered by solar hydrogen by the year 2100. The least to say is that it is not too early to start working on it now.

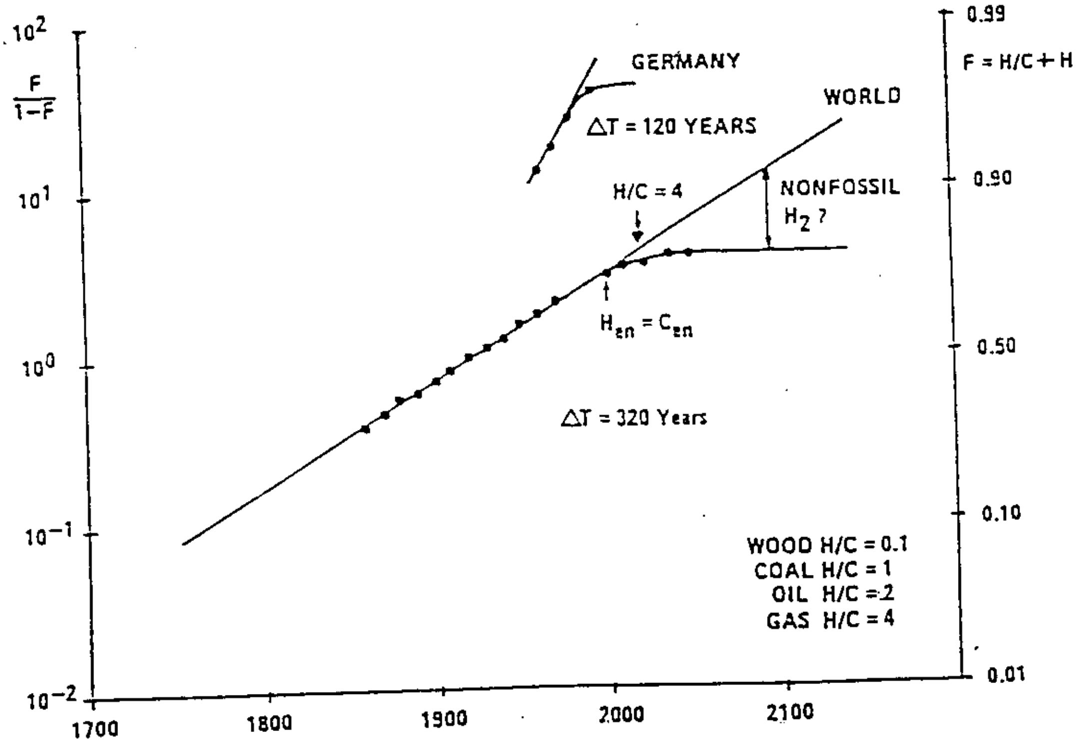

Fig. 4. Evolution of the hydrogen/carbon molecule ratio of the fossil fuels.

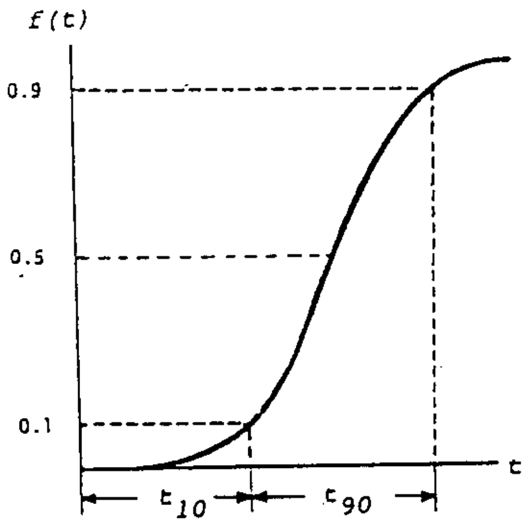

Fig. 5. Technology penetration.

STRATEGY FOR THE IMPLEMENTATION OF SOLAR HYDROGEN

The transition to the non-fossil energy era will take place the moment non-fossil energy becomes economically competitive, i.e. when the total costs including societal costs of fossil fuels, growing diseconomics of supply and environmental imperatives become greater than those for non-fossil energy.

Although it is not possible to predict neither the evolution of fossil fuel costs nor the moment the costs of fossil fuel pollution become internalized there are indications that the onset of a hydrogen technology within new clean and renewable energy supply systems will take place by 1995-2000, with pronounced deployment by 2020-2040.

A PRESENT REALIZATION OF THE TECHNOLOGY: THE EURO-QUEBEC HYDRO-HYDROGEN PILOT PROJECT

The concept of a hydrogen-based, clean, renewable energy system, conceived by the Joint Research Centre Ispra of the Commission of the European Communities, is currently investigated by European and Canadian Industries, coordinated by the JRC-Ispra of the Commission of the European Communities and the Government of Québec.

The 100 MW pilot project is to demonstrate the provision of clean and renewable primary energy in the form of already available hydroelectricity from Québec converted via electrolysis into hydrogen and shipped to Europe, where it is stored and used in different ways: electricity/heat cogeneration, vehicle and aviation propulsion, steel fabrication and hydrogen enrichment of natural gas for use in industry and households, see Fig. 6.

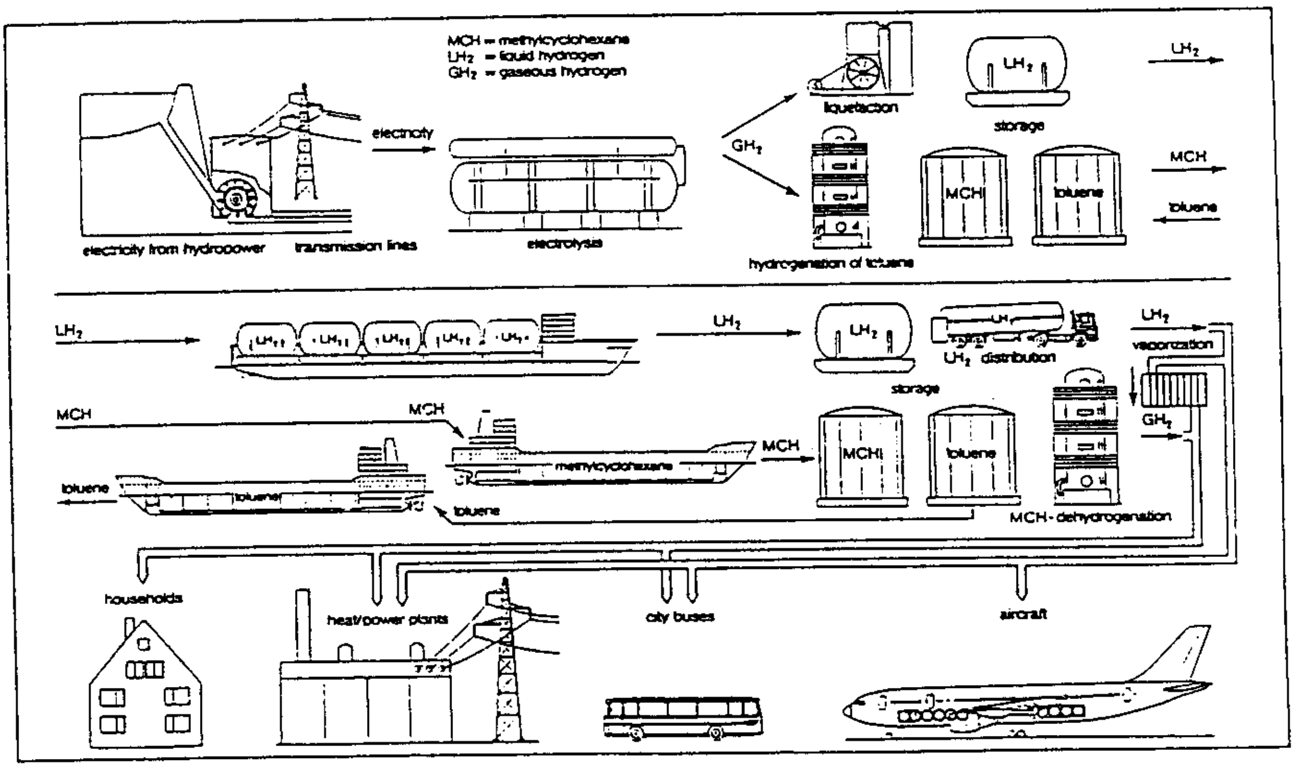

Fig. 6. The concept of the EQHHPP project.

Funds have been made available by the Commission of the European Communities in 1991 and by European industry as well as from the Government of Québec and from Canadian industry to undertake demonstration projects on the utilization of hydrogen in four fields where the use of hydrogen exhibits its attractiveness. In Europe, these projects are executed by industry on the basis of contracts following a tender action by the Commission with a cost sharing of at least 50% by the industrial partner:

- Vehicle propulsion: In Germany, for example, from the overall emissions those resulting from road traffic are: 52% NOx, 70% CO and 49% VOC.
  Public transport is predestinated for the introduction of clean and therewith expensive fuel since fuel costs are only a small fraction of the overall operating costs of buses. A typical bus operation costbreakdown shows that fuel costs are only 7.3% of the total operation costs.
  Four public transport buses of different concepts will be built and operated: internal combustion engine, fuel cell, Stirling engine.
- Aviation propulsion: The elimination of CO, CO_2, SO_2 and VOC by using hydrogen not only is beneficial for the atmosphere, but reduces considerably airport ground pollution. A problem to be solved, however, is the increased water vapour emission.
  An Airbus combustion chamber designed for minimum NOx emission will be built and operated.
- Steel fabrication: With ~ 2 kg CO_2 emissions per kg steel fabricated with carbon as reductant, the world's steel fabrication contributes over 10% to the world's total anthropogenic CO_2 production. Hydrogen as excellent and clean reductant has a large potential to reduce CO_2 emissions.
  A demonstration component including iron ore reduction with hydrogen by plasma arc process will be designed, built and tested.
- Advanced techniques of liquid hydrogen storage.
  Large scale model containers will be built and tested, including accident simulation and rupture tests.

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