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THE HYDROGEN OPTION FOR ENERGY: A REVIEW OF TECHNICAL, ENVIRONMENTAL AND ECONOMIC ASPECTS

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Abstract—Hydrogen, within technical spheres, has not yet obtained, generally, sound validity as an integrating fuel. Apart from the cost of production, the main reason seems to be a safety problem. In the present article, the author tries to contribute to the "cause" of this excellent element, as a wholly non-polluting fuel and an acceptably reliable one. The article is divided into five parts. The first is concerned with CO_2 production by combustion throughout the planet, and its effect on the earth's temperature. The second part is a comparative technical and environmental outline of different kinds of fuel: methane, pit-coal, gasoline, hydrogen. Thirdly, some qualitative indices are defined: pollution, flammability, expansion or explosivity index. In the fourth part the stages of a solar-hydrogen cycle are presented. The final part treats the economic aspects, and offers a comparative survey of the above-mentioned fuels.

NOMENCLATURE

c_P	Specific heat at P = const. (kcal kg^{-1} °C^{-1})
i_{jk}	Pollution indices
i_{jT}	Flammability indices
i_{jv}	Expansion indices
i_G	Global indices
P_{ci}	Lower heat power of fuel (kcal kg^{-1})
T_c	Combustion temperature (°C)
$T_{crit.}$	Critical temperature (°C)
T_0	Conventional igniting temperature of fuel at standard conditions (°C)
U	Flame speed (ms^{-1})
v'''	Specific volume of gas or vapour at normal conditions (1 bar at 15°C) (m^3 kg^{-1})
v''	Specific volume of liquid at critical conditions (m^3 kg^{-1})
x_{jk}	Mass concentration of pollutants in the combustion fumes (kg kg^{-1} of fuel)

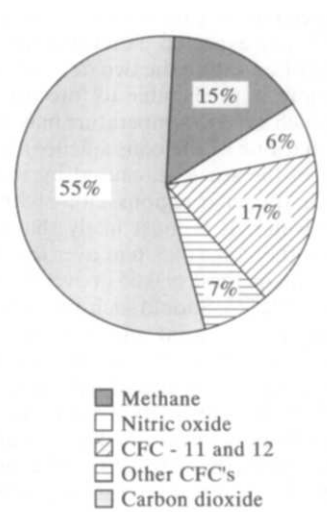

Fig. 1. A percentage contribution to the overall heating up of the earth's temperature by greenhouse gases.

INTRODUCTION

The employment of an ever-growing amount of fossil fuel and the intensive deforestation that is being carried out give rise to a sudden consequence, i.e. an increase of carbon dioxide concentration in the atmosphere. Recent research [1] estimates a CO_2 concentration in the atmosphere of 300 ppm (591 mg N m^{-3}) up to 380 ppm (748 mg N m^{-3}) referred to as the business-as-usual (BAU) IPCC scenario for the years 1985–2100.

Carbon dioxide causes an increase of the earth's average temperature as it offers no barrier to solar radiation, though it presents an opaque quality as regards the infrared radiation, thus catching the heat in areas that are close to the earth's surface (greenhouse effect). Other man-produced gases dispersed in the atmosphere such as nitric oxide, methane and chlorofluoridecarbide (CFC) are all contributors to the greenhouse effect.

Figure 1 points out for each gas the individual contribution to the overall rise of earth's temperature up to the present time [3]. It is rather difficult to quantify the extent of such warming: the rise in temperature over the

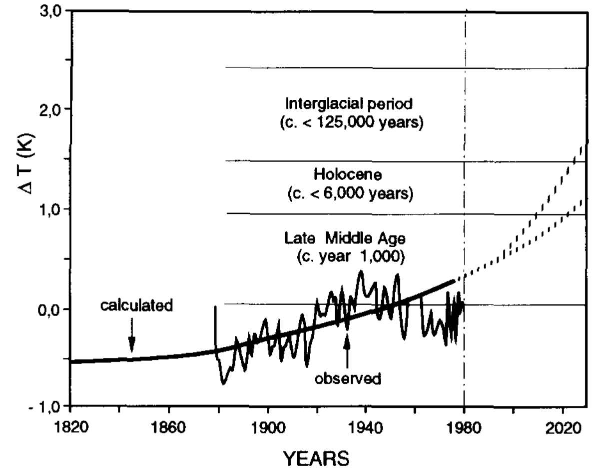

Fig. 2. Progress of the earth's average surface temperatue.

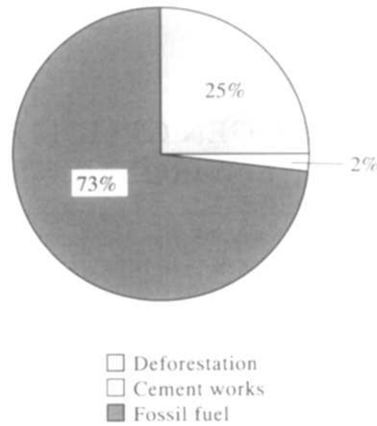

Fig. 3. Sources of carbon dioxide (%).

past 100 years due to the greenhouse effect has been assessed at about 0.3–0.6°C (BAU) [4].

Figure 2 shows the progress of temperature on the earth's surface, making allowances for the natural absorption of greenhouse gasses with a forecast up to the year 2030 [5]. The expected panorama for the years to come are comprised within the two dotted lines. It is even harder and more unpredictable to forecast the possible reaction that such a rise in temperature may trigger. There is no doubt that one of the consequences is represented by the rising of the sea level caused by thawing of the huge glaciers in the polar regions, along with the thermal expansion of water. It is most likely that the sea level will increase in the range of 5–6 m over the next 200–500 years, whereas an increase of 0.65 m over the next century is deemed probable [6]. Should such forecasts materialize, they will bring about social and economic damage on areas located along the world's coast lines, let alone the flooding of seaside towns and of extensive fertile areas. In order to limit the aftermath of such a grave problem, one of the solutions is the gradual and steady reduction of greenhouse gases, namely CO_2. The production of CO_2 is largely due to the combustion processes of fossil matter (gasoline, pit-coal, methane, etc.) as shown in Fig. 3 [3].

On the other hand, the world's demand for energy has always been on an increase due to the exponential growth of the world population and improvement in living conditions. According to the present trend, this will entail a constant rise in hydrocarbon consumption (Fig. 4) which brings about a further impoverishment of the environment in terms of the greenhouse effect. Thus, in order to exit this perverse spiral, it is imperative to take steps as soon as possible by substituting fossil fuel by other cleaner, non-conventional fuel.

Along this rationale, a comparison, from a range of viewpoints, between the major fossil fuel and hydrogen as a clean energy option is suggested in this paper.

An integral energetic cycle is particularly enhanced which, starting from solar energy, dissociates H_2O to produce H_2. In this way hydrogen becomes an accumulator of a renewable energy.

A COMPARATIVE TECHNICAL AND ENVIRONMENTAL OUTLINE OF DIFFERENT KINDS OF FUEL

General

A few polluting agents obnoxious to human health over a short time are produced during the combustion process of fossil fuel, apart from CO_2, which does not cause serious physiological damage, but grave problems at the climatic level.

Table 1 [7] shows the concentration of polluting matter originating from combustion at standard conditions*

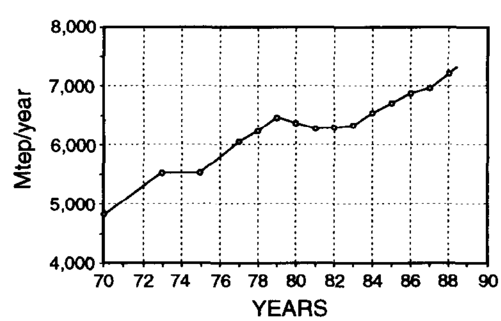

Fig. 4. Trend of hydrocarbon world consumption.

*Combustion carried out with 50% excess of air at 80% relative humidity.

Table 1. Specific quantities of polluting matter in combustion fumes

FUEL		CONTENTS OF POLLUTING MATTER IN FUMES (kg/kg of fuel)					
N	Formula	CO_2	SO_2	N_xO	DUST and UNBURNED MATTER	H_2O	$Pb(C_2H_5)_4$
a	C	1.893	0.012	0.008	0.1	0.633	0
b	CH_4	2.75	0.03	0.0075	0	2.154	0
c	C_8H_{17}	3.09	0.010	0.0115	0.85	1.254	0.001
d	H_2	0	0	0.016	0	7	0
		1	2	3	4	5	6

when burning a kilogram of pit-coal, methane, gasoline or hydrogen. The thermo-physical features of these kinds of fuel [8–10] which are of major concern are compared in Table 2.

Definition of quality indices

Based on the data laid out in Tables 1 and 2, we may set a few indices with a view to sketching a comparative model picture amongst the range of fuel mentioned in this article with reference to the following aspects: pollution, flammability and expansion.

Pollution indices. (Related to the polluting matter produced through standard reactions.)

$$i_{jk} = \left(1 - \frac{x_{jk}}{P_{ci}(c_p T_0)^{-1}}\right)_j,$$

where j shows the jth ($j = a \rightarrow d$) and k shows the kth pollutant ($k = 1 \rightarrow 6$). The term $P_{ci}/c_p T_0$ in the denominator is a dimensionless choice of the energetic contents of the fuel itself. For example, index i_{c6} shall be defined as follows:

$$i_{c6} = \left(1 - \frac{x_6}{P_{ci}(c_p T_0)^{-1}}\right)_c = 0.999.$$

We defined i^*_{c6} as the relative value of i_{c6} referred to the fuel maximum value. In this example, e.g. $i_{c6}/1 = 0.999/1 = 0.999$ (see Table 3).

Flammability indices. (In connection with the dangers offered by fuel when referred to their combustion temperature.)

Table 2. Thermo-physical properties of fuel

FUEL and MOLECULAR WEIGHT	SPECIFIC HEAT c_p	HEAT POWER P_{ci}	SPECIFIC VOLUME P_{ci}	FLASH POINT TEMPERATURE T_0	COMBUSTION TEMPERATURE T_c	FLAME SPEED U
PIT-COAL (°) C (12)	0.30	7620	$v''' = 0.8$ $v'' = 0.006$	609	2000	0.40
METHANE CH_4 (16)	0.531	11900	$v''' = 1.4$ $v'' = 0.0062$	632	1745	0.35
GASOLINE C_8H_{17} (113)	0.530	10400	$v''' = 0.236$ $v'' = 0.012$	550	3500	25
HYDROGEN H_2 (2)	3.408	25000	$v''' = 11.2$ $v'' = 0.0323$	571	2332	2.65

(°) The thermo-physical features of carbon as shown generally refer to CO.

$$i_{jT} = 1 - \left(\frac{T_c - T_0}{T_c}\right)_j.$$

Expansion indices. (Related to the increase in volume that fuel undergoes when changing from liquid or highly compressed state to a normal state.)

$$i_{jv} = 1 - \left(\frac{v''' - v''}{v'''}\right)_j.$$

Please note that all indices set in this way are less than unity: this value stands as the high quality of fuel.

The normalized values bear an asterisk and have been obtained from the ratio between the actual and the maximum value, i.e. $i^* = i/i_{max}$.

For comparison amongst the various kinds of fuel, a further elaboration of multiplication indices prior to normalization leads to the localization of the following global indices:

$$i^*_{G1} = \Pi\ i^*_{jk} \qquad \text{(with or without } H_2O\text{)}.$$

$$i^*_{G2} = \Pi\ i^*_{jv} i^*_{jT} i^*_{c6}$$

$$i^*_{G3} = \Pi\ i^*_{jk} \cdot \Pi\ i^*_{jv} i^*_{jT} i^*_{c6}$$

$$i^*_{G4} = \Pi\ i^*_{jk} i^*_{jT} \ (i^*_{jk} \text{ have no } H_2O).$$

When we have formulated these multiplication indices by referring to the same fuel we have taken into account two facts.

(1) We gave included steam in the six polluting combustion products, though it is not really one. This procedure penalizes hydrogen.

(2) Expansion also has a penalizing feature for H_2 when it is calculated, as we have warily done, by starting from the liquefied gas at $T_{crit.} = -240°C$. As a matter of fact, this condition may not be considered a correct use of hydrogen stocking [11].

The last-mentioned multiplication index includes these comments.

The numeric values of normalized indices defined above have been collected in Table 3, representing a

Table 3. Relative pollution safety indices of fuel

FUEL	i^*_{jk}	i^*_{jT}	i^*_{jv}	i^*_{c6}	i^*_{G1}	i^*_{G2}	i^*_{G3}	i^*_{G4}
C	0.9546 0.9997 0.9998 0.9976 0.9848 1	0.841	0.147	1	0.9374 0.9518 (No H_2O)	0.1236	0.1159 0.1176 (No H_2O)	0.8004
CH_4	0.9225 0.9991 0.9998 1 0.9392 1	1	0.088	1	0.8655 0.9215 (No H_2O)	0.0880	0.0762 0.0811 (No H_2O)	0.9215
C_8H_{17}	0.9000 0.9998 0.9997 0.9726 0.9595 1	0.434	1	0.9999	0.8395 0.8749 (No H_2O)	0.4339	0.3664 0.3796 (No H_2O)	0.3797
H_2	1 1 0.9987 1 0.4551 1	0.676	0.057	1	0.4545 0.9987 (No H_2O)	0.0385	0.0175 0.0384 (No H_2O)	0.6751

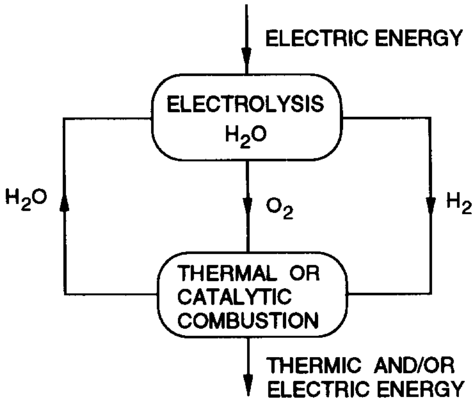

Fig. 5. The hydrogen cycle.

comparative outlook, in both technical and environmental terms, between hydrogen and fossil fuel.

SOLAR HYDROGEN

The idea of energy saving based on hydrogen, in other words a fuel cycle effected, through a total synthesis without carbon, was developed over the last 15 years (1975–1990), following the critical supplying of oil. Such an idea is more feasible if we take into account the technical and the environmental conclusions arrived at as shown in Table 3. The most widespread technique for the production of hydrogen is based on the following water scission reaction (electrolysis)

$$\text{Electric energy} + 2\ H_2O = 2\ H_2 + O_2.$$

The hydrogen produced by this method is usually recombined with O_2 inside suitable burners, where the original water is reconstituted by giving off a remarkable quantity of heat, in compliance with the following exothermic combustion reaction:

$$2\ H_2 + O_2 = 2H_2O + \text{Thermal energy}.$$

The overall process is shown in Fig. 5. If the electric energy input to the system comes from a solar source, we would be talking of solar hydrogen; by doing so we are making hypotheses on a renewable energetic cycle where a radiating energy is being accumulated by way of the hydrogen. Leaving the financial aspect aside for the time being (it will be tackled in the next paragraph) we want to underline a few outstanding aspects of the

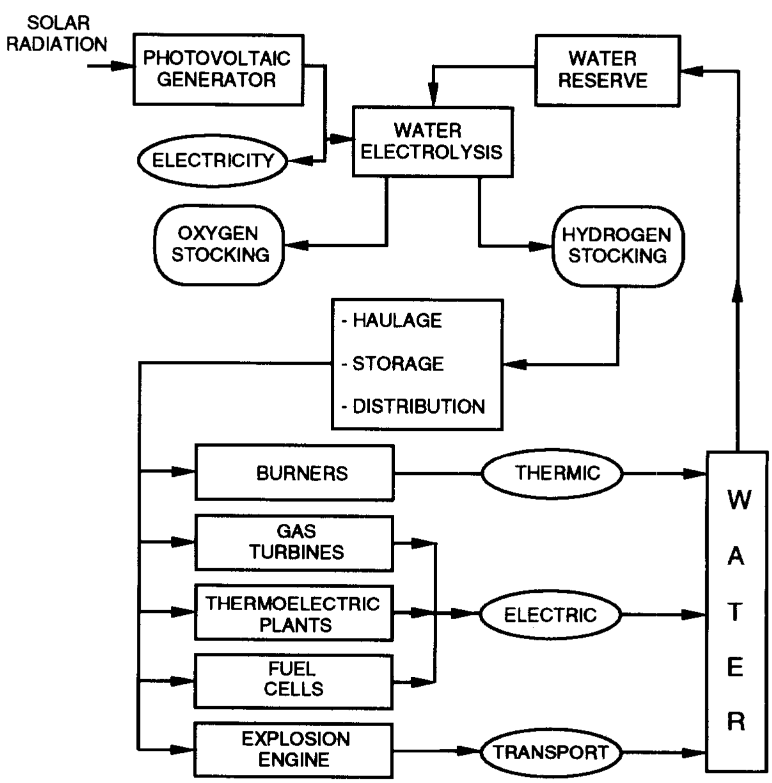

Fig. 6. Solar hydrogen energy diagram.

solar hydrogen. The major advantages offered by this energetic cycle may be basically summarized by two points.

(1) The power production system through a solar source (photovoltaic) would experience a remarkable development by relaunching alternative energy sources.

(2) Such an approach would eventually lead to a gradual replacement of fossil fuels along with their manifold applications, so that the environment would benefit by healing the damage due to the greenhouse effects and pollution in general.

There are, of course, a few practical problems that have to be solved in order to be able to use H_2 as a fuel. First is the accumulation and haulage of hydrogen; it is in fact an extremely light gas and easy to disperse. A second set of problems of no less importance, concerns safety when utilizing the gas, as it is highly flammable and risks originating explosive or detonating mixtures.

A possible diagram for an integral energy cycle based on solar hydrogen is represented in Fig. 6.

AN ECONOMIC COMPARATIVE SURVEY OF FUEL

To shape a thorough energy alternative it is necessary to draw a cost-effective comparison between the solar hydrogen and the various fossil fuels we have examined. This economic survey, although conceptually simple, turns out to be rather complicated when applied in practical terms, because of the intervening large number of technical and economic parameters.

As to the solar hydrogen, recent calculations [12] point out the cost for an energy unit of 195 US GJ^{-1}. This price is inclusive of both the cost for photovoltaic energy and electrolysis, and is more or less tenfold higher as compared with the conventional production of energy by using fossil fuel. In point of fact this discrepancy would appear less dramatic if social and environmental costs as a result of using fossil fuels are contemplated. Entering such costs into the budget, with an aim to drawing an economic comparison among the various energy solutions, introduced *de facto* a new criterion in the economic assessment that sums up in the concept of "real economy" [13]. It is a matter of shifting our attention after the production process by including in the cost survey its final use, along with the effects produced by such use.

The real cost for the energy unit is broken down into the following items: fuel price; damage on the environment ensuing from the use of fuel; and fuel use efficiency within the specific sector.

The environmental damage from each of the principal fossil fuels considered was evaluated in terms of dollars per gigajoule of usable energy production. Throughout the damage evaluations, both the short-term effects and the postponed effects were taken in account. Two separate degrees of dangerousness or harmfulness were attributed to each fuel: a degree g_s concerning the direct sanitary injury, and a degree g_p for the postponed general environmental damage.

The following four causes of damage were considered, and the respective levels of harmfulness *approximately* guessed:

atmospheric pollution

$(g_s = 1;\ g_p = 0.6)$;

water pollution $(g_s = 0.6;\ g_p = 0.8)$;

acid rainfall $(g_s = 0.4;\ g_p = 0.5)$;

greenhouse effect $(g_s = 0.2;\ g_p = 0.3)$.

It may be noted that the lower the level of degree the less is the damage-effect hypothesized. Based on this approach, the real cost of an energy unit was calculated for fossil fuel and for solar hydrogen [14]. The results, properly processed, are contrasted in Table 4 by emphasizing their use efficiency in the specific sectors of application.

CONCLUSION

The comparison of technical and ecological validity amongst the four types of fuel we have been discussing so far is reported in Table 3. If we leave out the steam-related index i^*_{jk} from the computation, it is undeniable that, in terms of chemical pollution due to combustion, hydrogen ranks first ($i_{G1}{}^* = 0.9987$). On the other hand, this may well be considered as non-polluting matter and can be recycled through condensation. Gasoline stands out as the most polluting fuel, and is further penalized by the production of tetraethyl lead.

Safety-wise (flammability and expansion), fossil fuels are generally better than hydrogen. Gasoline is the sole exception—it is at the bottom of the chart ($i^*_T = 0.434$) as regards flammability.

For what pertains to the overall aspect of technical and ecological effectiveness, the multiplication indices i_G reveal the clear-cut superiority of hydrogen when the following general criteria are taken into consideration.

(1) Hydrogen is endowed with a slow flame propagation against gasoline.

(2) Hydrogen expansion is lower for the conventional storing requirements of non-liquefied gases in their critical state, but it is compressed at 80–100 bar pressure.

(3) Water produced by combustion is subsequently recycled as shown in Fig. 6 which refers to the solar hydrogen energy cycle.

(4) Fossil fuels are heavier than hydrogen and give off a diffused radiance through a flame that is not quite steady when burning. In other words, the flame of hydrogen is steady and its radiation aims upwards.

Cost-wise, Table 4 shows the overall advantages of fossil fuels compared with hydrogen in terms of real savings. The extent of the difference, though, is minimal

Table 4. Fuel cost against the sectors where they are employed

FUEL	Utilization Area	Use Effectiveness	Final Cost ($/GJ) A	Estimated Damage ($/GJ) B	Real Cost ($/GJ) C=A+B
Pit-coal	Private	0.800	3.84	11.50	15.34
	Industry	0.800	2.20	11.50	13.70
	Electric	0.380	2.13	11.50	13.63
	Transport	-	-	-	-
Methane	Private	0.800	8.45	4.71	13.16
	Industry	0.800	5.09	4.71	9.80
	Electric	0.380	5.12	4.71	9.83
	Transport	-	-	-	-
Gasoline	Private	0.800	13.17	9.71	22.88
	Industry	0.800	7.83	9.71	17.54
	Electric	0.380	5.64	9.71	15.35
	Transport	0.250	10.34	9.71	20.05
Solar hydrogen	Private	0.80(1)	15(1)	0	15(1)
		1(2)	12(2)	0	12(2)
	Industry	0.80(1)	15(1)	0	15(1)
		1(2)	12(2)	0	12(2)
	Electric	0.38(1)	15(1)	0	15(1)
		0.70(3)	8.14(3)	0	8.14(3)
	Transport	0.33(4)	11.4(4)	0	11.4(4)
		0.70(5)	5.36(5)	0	5.36(5)

(1) Naked flame combustion; (2) Catalytic combustion; (3) Fuel cells;
(4) Liquid hydrogen (explosion engine); (5) Fuel cells (electric engine).

or even non-existent for some of the sectors where it is employed.

All such qualitative and quantitative considerations wholly justify the use of hydrogen for a future energy option, in that it solves pollution problems, especially where the greenhouse effect is concerned.

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