COMPETITIVE ENERGY CARRIERS FOR TRANSPORTATION: A COMPARISON BETWEEN ELECTRICITY AND HYDROGEN

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Summary

Hydrogen has been presented in the recent past as an ideal solution to many constraints related to the global energy problem both from a social and an environmental point of view. The potential role of hydrogen has been confused, and probably even today it is still partially confused, with the wider range of opportunities related to fuel cell technologies and to CO_2 sequestration techniques, that both have their own significance in the power generation sector independently of an hydrogen based energy economy.
This paper proposes a critical analysis of the possible roles that hydrogen may have in the future as an energy carrier. The discussion is based on the status of current and mature technologies, on forecasts about upcoming opportunities for hydrogen production, management and use, and on general environmental, social and economical considerations. The attention is focused on the transportation sector, where recent scientific studies have proposed well-to-wheel primary energy consumption comparisons between several scenarios, in the long term, for vehicle propulsion, based on the analysis of the whole global life cycle and the overall induced environmental impact. For zero-local-emissions urban transportation, these studies indicate that both battery operated fully electric vehicles and hybrid vehicles have the potential to offer greater differential advantages from a global point of view, than hydrogen operated fuel-cell vehicles.

1. Introduction

In recent years hydrogen has often been presented as a unique solution for all environmental energy-related problems: the idea of a "hydrogen society" has been sometimes proposed as a viable alternative to the current energy economy based on fossil fuels and their derivatives (1-8). The public opinion has often been confused by demagogical, misleading and scientifically ill-posed information. The emphasis of mass-media on fascinating scoops, regardless of their scientific content, have amplified and boosted many hopes about hydrogen, creating a sort of accepted social consensus, based on an emotional behaviour rather than on rational and scientific analyses. Political decision makers, necessarily focused on public consensus, have found an easy strategy in empowering the funding opportunities toward hydrogen related researches and development, with the undesirable result of cutting on economical and human resources that could have been allocated to many other research themes and energy issues, at least as central as hydrogen.

2. General context

The economic interests behind this situation is quite complex and the growing number of skeptical scientists (9-16) are still overwhelmed by the greater impact of mass media over scientific journals. It is worth noting that the number of those who are progressively assuming a critical or at least skeptical position about hydrogen is increasing: for the sake of clarification, it must be mentioned that in all these positions there is no trace of obscurantism. Rather, the goal is to avoid the risk that unsustainable choices are made for the energy development of civil society. To this end, the awareness of the correct scientific assumptions that stem behind not only hydrogen but the entire energy problem, needs to be clarified and communicated to decision makers, politicians and common people.

Aware of the complexity of the global energy context, we present a critical analysis about the role that hydrogen might have in the future of energy. We give special attention to vehicle propulsion, and compare competitive alternatives from the point of view of feasibility and sustainability. Hydrogen production, storage, transportation and final use (for example to power a fuel-cell vehicle) are complex processes, involving a great consumption of primary energy (thermodynamic laws are inviolable) and require complex and expensive and innovative facilities. It is true that also electricity production, storage, transportation and final use are complex processes, but the whole electric system may be nowadays considered well experimented, quite safe and therefore easier and ready to manage (see also section 3). Moreover, on a well-to-wheel basis the use of electricity as energy carrier for urban vehicles requires less primary energy consumption than the use of hydrogen, thus giving an economical and environmental benefit to be considered while scouting for sustainable solutions in the transportation sector in the medium-long run.

3. Hydrogen and electricity as energy carriers: a comparison

Hydrogen is a very interesting element: when used as a fuel, it produces high-temperature flames. It is a light gas, ideal for rocket propulsion. Hydrogen combustion with air produces, as flue gas, almost only water vapour. It does not produce carbon monoxide, unburnt hydrocarbons, sulphur oxides, and thin dusts. When burnt in air, the only pollutants are nitrogen oxides that are produced in the same quantity (or slightly higher depending on the flame temperature) as in the combustion of methane. However, in addition to direct oxidation, hydrogen may be considered the preferential fuel for powering fuel cells, where it is oxidized indirectly through direct generation of electrical energy, although hydrogen is not the unique solution for powering fuel cells.

From the theoretical point of view hydrogen, once produced, can be used for traction, heating, domestic uses, and power generation by means of fuel cells, producing no (direct) local pollution.
It is very important, indeed, to avoid confusing the chances of hydrogen with those of fuel cells; the two represent different opportunities in the energy field, each with independent and different perspectives in current and future developments.
Though abundant in the Universe, free molecular hydrogen (H_2) is not directly available on our planet; no hydrogen wells may be found on Earth. To make it available for anthropogenic usage, we need to produce it by means of complex chemical or electrochemical processes, requiring high capital costs and high primary energy consumption. Two currently state-of-the-art production technologies are:
1. Water dissociation (electrolysis or thermo-scission: the opposite process of hydrogen combustion);
2. Thermo-chemical processes (such as steam reforming or partial oxidation of fossil hydrocarbons or coal).
With electrolysis, the electrical energy consumption is at least 20% more than the high heating value of the produced hydrogen.
With thermo-chemical process the energy stored in the produced hydrogen is definitely smaller that that of the fossil fuel used in the process: starting from natural gas me may obtain about 80% while starting with coal we stay close to 60%.
It is also important to remind that that both transportation and storage of H_2, due to its physical and chemical properties, gives rise to some problems and additional energy losses. Even when compressed at 800 bar or liquefied to -250°C, hydrogen has a heating value which is only about one third that of an equal volume of gasoline or diesel fuel.
Both compressed and liquid hydrogen represent quite complex and extreme conditions for the materials of the containing vessel. Moreover facilities and infrastructures for hydrogen distribution over medium and long distances, require specific technical constraints and involve additional energy consumption.
A critical problem about hydrogen distribution, related to social consensus, is that of safety and security measures (17). In this respect, a most interesting comparison would be with natural gas, gasoline, and diesel fuel which are normally considered and perceived by the social parties as safe fuels for vehicle propulsion. Despite the worldwide recognised strategic importance of safety and security analysis, the scientific literature still lacks an independent and complete comparative study about safety, security and environmental impact of the four mentioned energy carriers. One of the reasons is certainly due to the high complexity and the variety of phenomena and multiple considerations that need to be taken into account. It may be of interest to stress the need of research efforts toward these aspects, keeping as enlighting examples either the nuclear and the chemical field, which both routinely base their operating and accidental planning on safety analysis.
Hydrogen has a wider flammability range than methane (being the lower limit only slightly lower than that of methane) and it has a much smaller ignition energy; however it has the advantage to diffuse and spread in air faster as compared to methane, thus reducing, in open spaces, the chance of reaching flammability concentrations.
In spite of these peculiarities and uncertainties, hydrogen is being presented to the general public as a possible energy carrier, an alternative to electricity, which instead has been used widely and safely in industrialized countries for over 100 years.

Electricity, as an energy carrier, may be transported more easily, and losses are small and closed to 5% every 1000 km. It can be simply and efficiently converted into mechanical energy (and vice versa) and it can also be effectively stored in large quantities (as done every night in many countries including Italy) by using hydroelectric pumping systems to pump water from a lower to a higher elevation, with good overall efficiencies. Electricity may be considered reasonably safe and simple to regulate. It also has the added value of being the energy carrier directly produced by many power generation plants (solar, wind, and nuclear).

4. The possible roles for hydrogen

In this section, we discuss a few possible roles that hydrogen as an energy carrier may play in the future of the global energy economy. They refer to the following options:
1. Hydrogen usage for vehicle propulsion in highly polluted metropolitan areas, for reducing local pollution and improving air quality.
2. Hydrogen production by renewable energy sources, with special attention to those characterised by high uncertainties and intermittence (like sun and wind), for their valorisation. With this kind of sources, the production stage, possible only when the source is available, has to be separated from the usage stage, i.e., the time when the energy is requested. This so-called "contemporaneity constraint" leads to the need to store by some means the produced energy.
3. Hydrogen production by using nuclear power and/or coal used in base load power plants with CO_2 sequestering and confinement in order to reduce greenhouse gas emissions in the atmosphere.

Interestingly, the use of hydrogen by means of options 2 and 3, may allow the penetration in the transportation sector of some primary sources, such as renewables or coal and nuclear energy,. However, the same advantage would obtain by directly producing electricity according to options 2 and 3. It is also clear that CO_2 sequestration is equally viable while producing, by the same plants, electricity instead of hydrogen.
All the mentioned options (from 1 to 3) can obviously coexist in the future of the energy economy, but it is more rational to analyze their opportunities on a case by case basis, and then eventually consider the superposition of the effects.

4.1 Reduction of urban pollution from transportation, heating and domestic usage

The possible future usage of hydrogen as an energy carrier in urban centers regards mainly the transportation sector, but also the heating systems and the final domestic usage (18,19). Since sulphur content in fuels has been strongly reduced, vehicles play nowadays the most important role in urban pollution, as confirmed by a series of recent surveys and analyses (17,20). These studies are about vehicle pollution, but their conclusions may be applied with little modifications to the other fields. Data taken by a lot of interesting studies applied to Milan, Italy (17), but applicable also to other European and worldwide industrialized cities, show that pollution emissions from vehicles have about halved between 1990 and 2000 (only NO_x decreased with a lower trend). This has been mainly due (and the trend is continuing) to the evolution of internal combustion engines which progressively lead (and will go on leading) to greater

efficiencies and lower environmental impact. These effects are quite relevant globally and could suffice to overcome the increase in the number of circulating vehicles worldwide.
Contrary to the social perception, it has been demonstrated that, in recent years, air quality in large cities has improved, except for some pollutants not directly linked to vehicles emissions, like ozone and thin dust (such as PM_{10} and even the smaller $PM_{2.5}$).

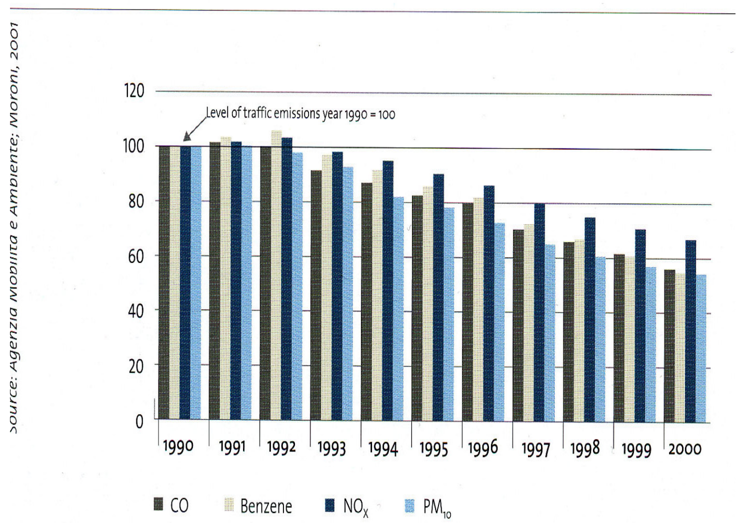

Figure 1. Data on vehicle emission of $C0_2$, benzene, NO_X and PM_{10} in Milan, Italy.

Ozone is a secondary pollutant, partially due to unburnt hydrocarbon (HC) and NO_x emissions, but strongly dependent on solar radiation.
Also thin powders, particularly the smallest $PM_{2.5}$, are mainly due to secondary phenomena, and are only partially related to engine emissions; rather they are strongly dependent on meteorological factors. This is the reason why, despite a general consistent pollutant reduction in the traffic emissions (see Fig. 1), there is no direct evidence of an equal improvement in urban air quality.
In the authors' opinion, to get the zero-emissions goal in the long term for polluted areas (with the least global impact), one of the most interesting solutions to be evaluated is the electric option, both for public and private transportation.
In the short period, the most promising solution probably relies on hybrid vehicles, powered by an internal combustion engine coupled with an electric motor-generator connected to electric batteries, which are capable of a limited autonomy of zero-emission *electric-only* mode of operation for use in urban centers. These vehicles allow high overall efficiencies because the thermal engine operates only at optimal conditions and the electric motor takes care of the accelerations and recovers part of the vehicle kinetic energy during deceleration. A first generation of these vehicles is already present in modern cities, particularly in Japan and the United States. They use traditional fuels, gasoline or diesel, and have total costs only slightly greater than traditional cars.
For vehicles that instead must be used only within urban centers, the most appropriate solution seems to be the fully electric propulsion supplied by batteries. New generation electric batteries (for example lithium-ion batteries which are lighter than traditional

lead batteries), mainly developed for electronic applications, offer significant improvements on electric vehicle performance, since they provide a 150 Wh/kg accumulation capacity instead of the traditional 50 Wh/kg.
In polluted areas, the usage of hydrogen in traditional internal combustion engines would not imply a large reduction in the local pollution because it would not remove NO_x emissions which are precursors for both ozone and PM_5.
The use of hydrogen cars with low temperature fuel cells, even if not currently available yet on the market, would bring the same local advantages obtained with fully electric cars operated on charged batteries. Hydrogen cars with fuel cells are in fact electric cars which, instead of the electric batteries on board, have a non-polluting electrochemical generator (the fuel cell) and a hydrogen tank. Both weight and volume of the tank and the fuel cell in an hydrogen vehicle are likely to exceed (21) weight and volume of the batteries in an electric only car. To contain weight and volume of the propulsion system, only a minimal storage battery to power auxiliaries can be mounted on board of a fuel cell car, and this results in lower performance because kinetic energy recovery during deceleration can be afforded.
Neither fully electric nor hydrogen cars allow competitive performances or competitive power/weight ratios, compared with traditional thermal engines. Instead, hybrid cars seem to permit reasonable compromises.
According to well-to-wheel studies (21-24), solutions involving hydrogen imply more primary energy consumptions, mainly fossil fuels, and consequently cause more CO_2 emissions when compared to electric car supplied with batteries.
By assuming current data for the electric car solution coherent with the already proven technology, and optimistic data for the hydrogen car solution, it is possible to compare the two solutions within two well-to-wheel reference scenarios (21-24):
- scenario A, assuming natural gas as the primary energy source used to produce electricity or hydrogen;
- scenario B, assuming a hypotetical fully renewable primary energy supply system, used to produce electricity and then hydrogen, by electrolysis.
In scenario A, it is possible to make the following considerations:
1. For the hydrogen cars a global efficiency of 25% is obtained from the following steps:
    a. Natural gas production, hydrogen production, hydrogen distribution and filling of the on-board hydrogen tank (overall off-board energy efficiency about 50%);
    b. On-board electrochemical conversion in the fuel cells, electromechanical conversion in the elctric motor (overall on-board energy efficiency about 50%);
2. For the electric car the resulting global efficiency is 30% and made up as follows:
    a. Electric energy production and distribution (energy efficiency about 45%);
    b. Charge/discharge of the on-board batteries, electromechanical conversion in the electric motor (energy efficiency about 70%);

In scenario B, the so called fully-renewable energy scenario, the situation seems even worse in term of primary energy consumption.
1. For fuel cells vehicles, starting from electric energy, the processes required for a hydrogen car lead to a global efficiency close to 25% and may be summarised as follows:
    a. Hydrogen production by electrolysis, hydrogen distribution and storage in the vehicle on-board tank (energy efficiency about 50%);

b. On-board electrochemical conversion in the fuel cells, electromechanical conversion in the elctric motor (overall on-board energy efficiency about 50%);

2. For the electric car, instead, the sequence of processes is simpler and leads to a 60% energy efficiency as follows:

a. Electric energy distribution (energy efficiency about 90%);

b. Charge/discharge of the on-board batteries, electromechanical conversion in the electric motor (energy efficiency about 70%).

In Scenario B, the fuel cell vehicles efficiency lead to a much greater primary energy consumption (more than double) than the electric vehicles (21).

It is noteworthy that also electric vehicles development needs high investments to expand the electricity distribution network and to empower facilities for fast battery recharging or to develop and spread proper infrastructures for battery replacements (considered as a valid option for refilling the car), but most of the know-how is already available and well known.

Finally we may consider that by using the existing electric power system and distribution network, the diffusion of electric vehicles in urban centres can take place gradually, beginning immediately. Of course, the infrastructures will result in higher costs with respect to the current system based on internal combustion engines, and can be sustained by the social community in view of the local environmental benefit that the new system can produce. In any case, these costs will be lower for the diffusion of electric cars than required to develop a system based on fuel-cell hydrogen cars.

Batteries recharging can be done during the empty hours with a positive effect of levelling the load diagram and according to these perspectives the opportunity of reaching a greater level of electric power penetration in the energy economy need to be properly considered.

As a final note it is interesting to underline that since the prices of traditional fuels derived by oil are progressively increasing and the environmental, social and geopolitical evaluations of the external costs caused by fossil fuel consumption are going to be included in the standard costing accounting, the electric options may be considered in the medium term (globally) more and more convenient and a greater penetration of this option strongly favored (9,21-26).

4.2 Energy valorisation from intermittent renewable sources

Temporary sorage of the energy produced from an intermittent source (available only on an unpredictable basis) may represent an interesting opportunity for overcoming some uncertainties related to renewable energy sources such as solar and wind energy (partially also fluent water energy). The possibility of temporarily storing the produced energy, allows a decoupling between the time when the source is available but not required and vice versa, increasing the potential related to renewable sources and their penetration in the market. A concrete way to realize this opportunity is again represented by electric power generation system: electricity can be virtually accumulated by the flexibility and the current capacity of the complex and well-distributed electric network. In case this is not enough, the hydroelectric pumping system may give an interesting support in storing water and consuming low cost electric energy, by pumping water in the hydroelectric basins during the night hours.

A higher penetration of the usage of renewable sources would lead to the following interesting advantages in the general energy policy:

1. A reduction in the consumptions and therefore in the imports of primary fossil sources (especially when the country is poor of prime resources like Italy);
2. A reduction in the global emissions of CO_2 in atmosphere.

To obtain these advantages, the supply chain including hydrogen production has been considered, but it may be justified only in the rare cases where reaching far field locations with the electric network is difficult and antieconomic to set up. In these cases the energy yield of the conversion chain (elecricity-hydrogen-electricity) will be low and globally high costing. The advantages of renewables may be indeed obtained with greater yield and lower costs, by using the electricity storage opportunities already available with well known technologies. Most industrialized countries with well working distribution networks and hydroelectric resources have already taken benefit from accumulating energy with pumping systems for more than thirty years (with overall cycle efficiencies well over 75%).

Obviously the potentiality of these renewable sources, though in great improvement, will remains low and marginal as compared with the overall needs, especially for the requirements of the highly industrialized countries.

As a final note, it is worth mentioning that electro-thermal applications, which are very common in countries with high electric penetration (Japan, France, Sweden), should be considered for the local environmental benefits they may yield in urban centers. Heat pump systems are more expensive than traditional gas boilers, but they are reversible and can be used also as air conditioners, and they are zero-local-emissions systems.

4.3 Hydrogen production by nuclear power

Currently, the political and social situation, and the concern about global environmental changes, seem to indicate that nuclear power plants, which today cover 17% of the electric energy production wordlwide, are going to have in the near future an interesting chance to grow, leading to a significant reduction in global CO_2 emissions.

Hydrogen may be produced by means of nuclear power with two different approaches:

1. by electrolysis using the electric power produced in conventional fission reactors,
2. by the process of water thermal-scission in high temperature reactors (27), a technology that however is nowadays not yet well studied.

Anyhow, the proposal of using nuclear power for hydrogen production does not seem nowadays a strategic issue, given our conclusion that a scenario of strong hydrogen penetration has no foreseeable advantages, in view of the fact, already showed, that in urban centers, for short distances, the fully electric and the hybrid vehicles seem to lead greater advantages than hydrogen fuel-cell vehicles.

4.4 Hydrogen production starting from coal with CO_2 sequestering and confinement

Clean coal technologies are opening a second era for coal usage in the energy sector. The low cost of this fossil fuel compared to oil and gas, and the proven availability with a more homogeneous distribution over the Planet, push policy maker and the general public to reconsider the coal option also for electric energy production in order to better

equilibrate the electric mix from fossil fuels, reducing costs and dependency from the middle east countries.
It is also possible to produce hydrogen by using coal plant with various thermo-chemical processes (gasification and shift). By using these processes it is possible to sequester the CO_2 produced and then to confine it for reducing greenhouse emission in the atmosphere. The technical and economical feasibility of the sequestration and confinement processes are still under evaluation. Hydrogen produced in these plants can be used on site for high efficiency electricity production. Moreover, it could be used for the production of synthetic fuels (like Fischer-Tropsch), dimethylethyl and methanol either from coal, heavy oil or natural gas.

5. Conclusion

A strong and monolithic focus of research activities around hydrogen technologies would be absolutely detrimental to the scientific community (28,29). Energy is often badly used and there are a lot of opportunities to improve energy management, control and administration and efficiency usage. Focusing on a single alternative, strongly pushing researches and investments as well as totally neglecting some other options belong to the set of emotional behaviours that need to be contrasted by the scientific community.
Innovation in both vehicle engines and power plants efficiency, improvement of pumping systems for effectively storing electric energy at night, development of bio-fuels and liquid synthetic fuels from coal and heavy hydrocarbons represent very interesting research themes (as well as many others) that ought to be considered in the energy scenario and require proper allocation of human and economical resources.
In particular, for the short distance and urban center transportation sector, the development of electric and hybrid cars requires research to improve the performance of electric batteries and kinetic energy recovery systems during deceleration and braking.
Energy is a complex sector where there is no optimal nor unique solution for all the problems, a mix of different alternatives must be considered and studied, the public opinion must be adequately informed and prepared, and politicians must be open to and rely on suggestions coming from the scientific and technological world.
The energy sector and its impact on environmental and social development represents a challenge for human intellectual capability. In addition to the development of appropriate technological solutions, it demands a deontological and ethical consciousness in evaluating and comparing sustainable solutions for the future of mankind.

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