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Comparative Economic Competitiveness Assessment of Hydrogen as a Fuel in the Transport Sector in Algeria

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Worldwide, the increase in the vehicle park size has lead to a number of issues related more particularly to greenhouse gases emissions and fuel security. Improvement in engine efficiency, alternative vehicle and fuel options have been proposed to address these issues. The suitability of an alternative fuel depends on its performance, cost and availability. By its versatility in use and its renewability, hydrogen, as an alternative fuel, offers the best potential for reducing greenhouse gases emission, improving engine efficiency and ensuring fuel security. The present study objective is the analysis of the alternative fuels economic competitiveness. Based on the techno-economic factors, a comparative assessment of the economical competitiveness of hydrogen powered vehicles with a gasoline powered vehicle is then carried out. The technique of hydrogen production considered is that of a PV-electrolysis one. Results show that improvement in production techniques will lead to a more competitive hydrogen powered technology.

1. Introduction

Dominated since the late nineteenth century by oil based fuels and internal combustion engines, the transport system is actually facing many challenges. Indeed as the demand for fuels is steadily increasing, concern about the depleting energy sources is increasing. Moreover, the use of oil based fuels in engine vehicles is responsible for environment degradation as a result of pollutants emission. To then effectively address these challenges, steps have to be taken not only to introduce low emission and high efficiency technologies but also to move away from the oil based fuels by introducing cleaner alternative fuels.
Presently, there are various competing vehicle technologies and alternative fuels (Johnston et al., 2005). Among all the alternative fuels under consideration, hydrogen and more particularly, renewable hydrogen as a fuel is the best contender as it is carbon free and permits sustainability. Hydrogen is also a versatile fuel as it can be used in fuel cell vehicle or in internal combustion vehicle as sole fuel or mixed with other fuels such gasoline or natural gas. However many hurdles must be overcome before an effective penetration of hydrogen as alternative fuel in the transport sector could be possible. These hurdles are related mainly to the implementation of the hydrogen-dedicated infrastructure, the consumers' acceptance, and the availability and the competiveness of hydrogen as a fuel with other fuels.
There are various pathways for producing hydrogen for fueling vehicles (Balat, 2008). Each path is characterized by its location choice and its production method. For the location choice, three options could be considered. The first option is the centralized option where hydrogen is produced at large units; then dispatched to refueling stations. The second option is the decentralized option where hydrogen is produced at smaller size units, at refueling stations. Finally the last case is the option where hydrogen is produced on board, i.e, on the vehicle. For the hydrogen production method, different options are possible concerning the feedstocks, the energy used for the production and the processes (Boudries and Dizene, 2010). But it is only with renewable energy and renewable feedstock that hydrogen can be clean and sustainable (Miltner et al., 2009). The availability of cost effective and technological sound hydrogen vehicles is necessary to insure the hydrogen penetration in the transport sector. The two major vehicle options are hydrogen internal combustion engine vehicles and fuel cell vehicles. Hybrid vehicles and hydrogen-oil based fuel vehicles are also considered but mainly as a transition technology towards a full hydrogen vehicle.

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Basic techno-economic, prototyping and test activities are being carried out on hydrogen fuelled vehicles (Sisiopiku et al., 2006). The main factors taken into account in these investigations are cost, efficiency, performance and pollutants emission. Hydrogen fuel cell vehicles (HFCV) are taking advantage of the tremendous advances in fuel cell technology. Hydrogen in the fuel cell is converted into electricity in a clean and very high efficient way. However HFCV not only suffer from the high fuel cell cost but require also hydrogen of excessively high purity. Significant improvements in fuel cell reliability, durability and cost reduction are then necessary to give HFCV the edge.
Less expensive and using hydrogen of only industrial purity, hydrogen internal combustion engine vehicles (HICV) offer a number of very interesting advantages such as the capacity of running on mixed fuel. The use of hydrogen-oil based fuel mixture as a fuel for internal combustion engine vehicles offers numerous advantages. It is a bridging technology that takes advantage of the already existing technology and it permits the achievement of higher efficiency and lower pollution emission. Extensive work has been carried out on hydrogen-gasoline mixture fuel (HGICV). Results have indicated that addition of hydrogen to gasoline introduces an improvement of 30 % to 40 % in fuel consumption (Yuksel and Ceviz, 2003).
Though interest in development of HICV is still high, more focus is actually on HFCV development (Bhaskar et al., 2013). However, it is hard to predict which technology will prevail in the long run. Several studies have been carried out and results have not given any clear indication (Sopena et al., 2010).
Besides the development of safety standards (Amyotte and Rigas,2013), a prerequisite for widespread adoption of hydrogen as a fuel is its availability at a price that is competitive with the oil-based fuels. This means that not only the technologies of production and the infrastructure of distribution have to be efficient but the hydrogen powered vehicle and hydrogen as a fuel must be economically competitive. Concerning safety standards, tools for risk evaluation and analysis are necessary to determine hazardous situations and establish effective mitigation actions (Pastorino, et al. 2011).
In the present work, study is focused on the economic assessment. The scope is the determination of the economic competiveness of hydrogen as a fuel with gasoline. The technique of hydrogen production considered is that of a PV-electrolysis one. Taking into account the techno-economic factors, a comparative assessment of the economic competitiveness of hydrogen powered vehicles with a gasoline powered internal combustion engine vehicle (GICV) is carried out. Three types of hydrogen powered vehicles are considered: the purely hydrogen fuel powered vehicle (HICV), the hydrogen-gasoline mixture fuel powered vehicle (HGICV) and the hydrogen fuel cell powered vehicle (HFCV). The cost of fuel for a hydrogen powered vehicle to cover 100 km is compared to the cost of gasoline for a GICV to cover the same distance.
For Algeria, the introduction of hydrogen into the transport sector opens many opportunities. First it permits the exploitation of the huge solar energy potential. Then it alloys the country to meet the surging needs particularly in the transport sector (Boudries et al. 2000) and to contribute in the development of the isolated area of the South. It also addresses the problem of pollution and this could contribute to stopping desertification and promoting arid land development.

2. Assessment of hydrogen fuel competitiveness

The case of hydrogen produced using a PV electrolysis system is considered. This system not only insures sustainability but is also based on a technology that is simple, modular and technically mature.
The cost of hydrogen includes the cost of production and the cost of distribution. The focus of the present work is on the production cost and its effect on the viability and competitiveness of hydrogen as a fuel in the transport sector. Strategies for economic viable infrastructure distribution are underway (Agnolucci et al., 2013). In the present study, a rough estimate of the distribution cost has been found to be around 15 % of the overall hydrogen cost.

2.1 Hydrogen production assessment

The PV-electrolyzer system under consideration includes the PV unit for electricity generation and the electrolysis unit for hydrogen generation. Details of this system are reported earlier (Boudries and Dizene, 2008). The main components of the PV unit are the silicon PV modules for energy solar collection and conversion into electricity, the tracking system for the sun north/south tracking and the power conditioning system for shaping and conditioning the PV power output. The electrolysis unit main component is the electrolyzer cell rack. Besides that, the electrolysis system comprises auxiliary components such as the control component, the water supply and treatment component and the gas separation component.

2.2 Cost estimation of hydrogen production

Previous studies have shown that the capital costs depend on the size production and on the technology maturity (Harmon, 2000). The hydrogen production cost C could be divided into the cost C_e of the electricity production system, i.e., the PV unit and the cost C_{elec} of the electrolysis unit (Boudries and Dizene, 2012):

$$C = C_e + C_{elec} \tag{1}$$

2.2.1 Cost of PV electricity generation

The electricity generation system cost includes the PV capital cost C_{mod}, the cost of the balance of system (BOS) C_{BOS} and the operational and maintenance costs and related costs C_{OM}. Moreover, a capital cost Cpc has been added for the power related to the BOS. It should be noted that the BOS includes all the part of the PV system except the PV modules. In the present work, the cost of the tracking system is assumed to be 10 % of the PV system cost and a value of 40 $/m^2 is taken for the cost of the BOS (Boudries & Dizene, 2012). The PV capital cost is varied from the value of 1 $/Wp to the value predicted by the learning curve. The efficiency of the PV modules η_{mod} and that of the BOS η_{BOS} are taken to be 0.12 and 0.89 respectively. The cost of the electricity generation is estimated using the following relation (Ogden, 1993):

$$C_e = \frac{K\left(C_{mod} + C_{bos} + C_{pc} I_p \eta_{mod} \eta_{bos}\right) + C_{OM}}{31.536 \eta_e \eta_{mod} H_{mod} \eta_T} \tag{2}$$

η_T includes the meteorological effect on the PV module characteristics. Ip, equal to 1 kW/m^2, represents the solar irradiance at the standard test conditions. η_e is the electrolyzer efficiency. K is a factor related to economic parameters such as the discount rate, the taxes, the insurances, the indirect cost and the PV system lifetime. K has been estimated to be 0.096 when using 30 y for the PV lifetime. The number 31.536 is related to the year base time and to the expression of costs in $/GJ.

2.2.2 Cost of electrolysis

In the model used in the present work, the electrolyzer system cost can be divided into two parts (Bilgen, 2004). In the first part pertaining to the electrolyzer cell, the costs are function of the electrolyzer capital cost C_{em}; but with a fraction f_1 of the equipment independent of the electrolyzer operating and rated current densities i and i_r. The second part is pertained to the associated costs, i.e., installation, start up, etc. that are function of a fraction f_2 of the electrolyzer capital cost. The parameters f_1 and f_2, and the current densities i and i_r depend on the technology. The electrolyzer technology under consideration here is that of the unipolar type. Its characteristics could be found in the literature (Bilgen, 2004). The current densities i and i_r are taken to be 134 and 268 mA/cm^2 respectively. The costs of the electrolyzer unit can be expressed as (Bilgen, 2004):

$$C_{elec} = \frac{K_{el}}{31.536 \eta_r CF} C_{em} \left[f_1 + (1-f_1)\frac{i_r}{i} + \frac{f_2}{2}\left(1 + \frac{i_r}{i}\right) \right] \tag{3}$$

η_r is the electrolyzer efficiency at rated current and CF is the electrolyzer capacity utilization factor. K_{el} is a factor related to the operation and maintenance cost and to economic parameters such as the discount rate, taxes, insurances and electrolyzer system lifetime. With an electrolyzer lifetime of 20 years, a value of 0.128 is found for K_{el}. The efficiency at the operating voltage is taken to be 0.84 and the electrolysis system unit capital cost is 170 $/kW.

2.3 Determination of hydrogen fuel competitiveness

In the present study, to determine the economic competitiveness of hydrogen as an energy vector, a comparison of hydrogen, as a fuel, has been carried out with the commonly used conventional fuel, namely gasoline. The properties of these two fuels are reported in Table 1.

Table 1 : comparison of hydrogen fuel to gasoline

	LHV (kWh/kg)	HHV (kWh/kg)	T_f* (°C)	E_{mi}** (mJ)	Toxicity	Emission CO_2 (kg/l)
Gasoline	12.36	13.14	2307	0.7	high	2.3
Hydrogen	33.31	39.33	2207	0.02	low	-

*T_f flame temperature, ** E_{mi}: minimum ignition energy

Gasoline price posted at the Naftal gas stations in Algiers is about $ 0.32/l. Naftal is the Algerian vehicle fuel retailer. Both the fuels energy content and the engines efficiencies are taken into account in the comparison. For this purpose, the case of a motor vehicle with gasoline internal combustion (GICV) is taken as example. The competitiveness is determined from the ratio of the cost of hydrogen fuel for a hydrogen powered vehicle to cover a distance of 100 km to the cost of gasoline for a GICV to cover the same distance. A relative cost lower than unity is an indication of the good competitiveness of hydrogen as a fuel. The hydrogen energy E_H needed by the hydrogen powered vehicles to run 100 km is given by (Podgorny, 1984):

$$E_H = \frac{E_O}{1+\eta_m} + M_S e_s \quad (4)$$

E_o represents the gasoline energy needed by the GICV to cover a distance of 100 km. It is assumed that the GICV has a fuel consumption of 8 l/100 km. E_o is determined from this value and from the gasoline energy density given in Table 1. η_m is the reduced consumption of the hydrogen powered vehicles relative to the GICV. η_m depends on the nature of the hydrogen powered vehicle. Three different types of hydrogen powered vehicles have been considered. The first type is that of a HICV type. Previous studies have shown that this type of vehicle consumes about 35 % less energy than a gasoline engine. The second type is that of a HGICV type. The fuel considered here has a composition of 45 % hydrogen and 55 % gasoline. Studies undertaken on this vehicle type have reported a power consumption reduction of about 30 % compared to a GICV. The third type is a HFCV with a PEM fuel cell. HFCV are known for their high efficiency. The reduction in fuel consumption could be higher than 100 % .
Concerning the cost of hydrogen necessary to run the hydrogen powered vehicles, it is taken as the product of the hydrogen consumed quantity and the production cost determined as outlined above.

3. Results and discussion

In this study, it has been found that the cost of hydrogen production for a PV-electrolyzer system is dominated by the cost of the electricity production. In the actual state of PV technology, it is more than 75 %. Reduction in the cost of electricity production is then the key to lowering the hydrogen production cost using a PV-electrolyzer system. In this paper, the cost of fuel refers to the cost of the fuel quantity necessary to cover a distance of 100 km. The competitiveness of the hydrogen powered vehicles fuels as function of the PV efficiency for different PV capital costs is reported for each vehicle type under consideration in Figure 1, Figure 2 and Figure 3.

Table 2: Characterization of vehicles under consideration

Vehicle	Engine	Fuel	Fuel intensity (MJ/100 km)
GICV	Internal Combustion	Gasoline	263.35
HICV	Internal combustion	Hydrogen	195.08
GHICV	Internal combustion	Hydrogen & gasoline	202.58
HFCV	Fuel cell	Hydrogen	131.68

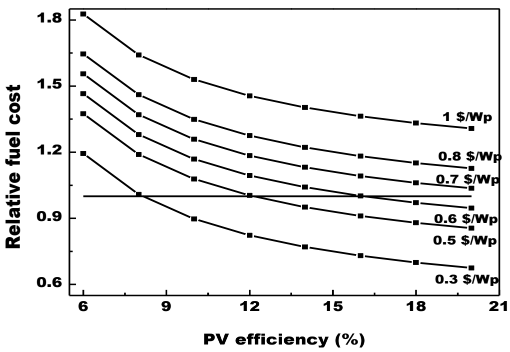

Figure 1: Relative fuel cost of a HFCV

The cost of CO_2 emitted by the fuel burned during the distance covered by the vehicles is not considered. The results show that an increase in PV module efficiency leads to a drop in fuel costs and so an increase in their competitiveness. These results show also that, if this is accompanied by a drop in the PV capital cost, this leads to an even better competitiveness. This situation is possible under the double effect of advances in technology and improvement in quality manufacturing.
At the present state of technology, Figure 1 indicates that the prospect for hydrogen as a fuel for a HFCV to be competitive is good. The results indicate that hydrogen as a fuel for a HFCV is competitive starting at a PV capital cost of 0.5 $/Wp. If the cost of the CO_2 is taken into account, the competiveness starts with a PV capital cost as high as 0.8 $/Wp for the same PV efficiency. However, Figure 2 indicates that the prospect for the GHICV to be competitive is not as good. This fuel starts being competitive at a PV efficiency of about 12 % but unfortunately for a PV capital cost as low as 0.3 $/Wp. The situation improves when the cost of CO_2 is taken into account. It could be more competitive at more realistic, i.e., higher PV capital cost, but for much higher PV efficiencies. As it can be seen from Figure 3, the prospect for hydrogen, as a fuel for a HICV, to be competitive is low at the present stage of technology and quality of manufacturing. The results indicate though that a progress in PV technology and quality manufacturing is necessary and will lead indubitably to the competiveness of this fuel.
For an inter-comparison of the competitiveness of the fuels used in the hydrogen powered vehicles under consideration, the relative costs of the fuels as function of the PV efficiency are reported in Figure 4.

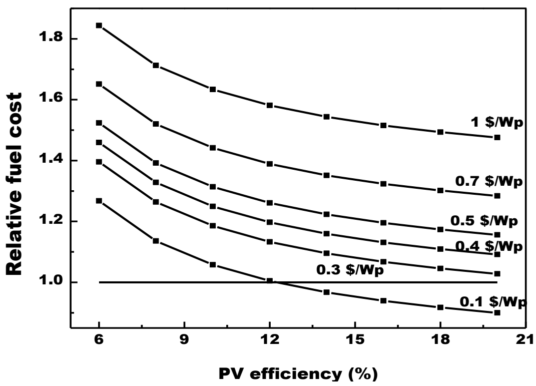

Figure 2: Relative fuel cost of a HGICV

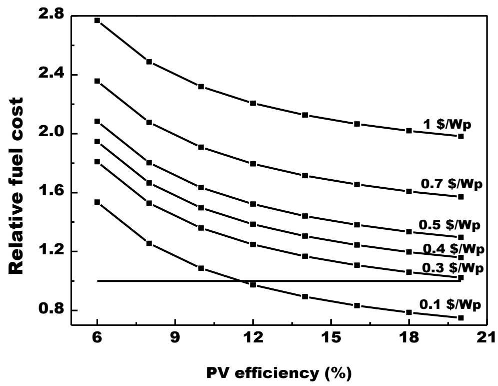

Figure 3: Relative fuel cost of a HICV

This figure clearly shows that the fuel for HFCV is the most competitive and its competitiveness is reinforced with advances in technology. The cost of hydrogen fuel used to power HFCV is all the time 52 % lower than the cost of hydrogen fuel used to power HICV. For PV efficiency of 12 % and capital cost of 1 $/Wp. Figure 4 shows that the GHICV fuel cost is 39.6 % lower than the HICV fuel cost but 8.60 % higher than the HFCV fuel cost. Now if a 0.3 $/Wp PV capital cost is considered, it can be noticed from the same figure that the two reported values become about 30 % and about 17 % respectively. In the case where the cost of CO_2 is taken into account and the PV efficiency is 12 %, the above mentioned values are respectively 10 % and about 38 % when the PV capital cost is 1 $/Wp and about 0.4 % and 52 % when the PV capital cost is 0.3 $/Wp.

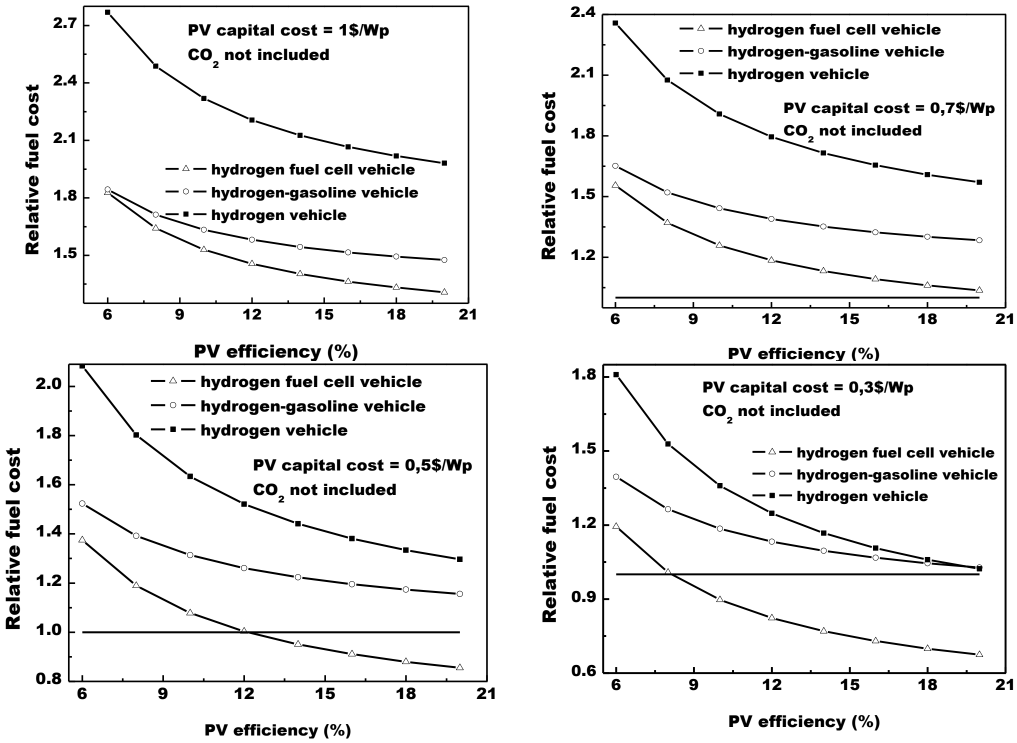

Figure 4: Comparison of the relative fuel costs of hydrogen powered vehicles for different PV efficiencies and for different PV capital costs

In this work, only fuel costs have been considered. However the total mobility cost requires an analysis of the effect of the vehicle capital cost as well as the power train maturity on the overall competitiveness of the vehicle. In this case, the competitiveness of the HFCV erodes as the vehicle capital cost, despite recent drops, remains extremely high. Moreover advances in vehicle fuel cell technology are necessary. On the other hand, GHICV becomes an interesting option as it benefits from the conventional internal combustion technology and its cost is much lower than that of a HFCV.

4. Conclusion

The present results show that the overwhelming part of the cost of hydrogen production using a PV electrolysis system is due to PV electricity generation. In the present work, the competitiveness of the hydrogen based fuel with gasoline fuel has been addressed. The case of hydrogen produced by water electrolysis using a PV system to generate the electricity needed for the electrolysis. Three types of hydrogen powered vehicles have been considered, namely the HICV, the HFCV and the HGICV. For the HGICV, the fuel is supposed to be a mixture of 45 % hydrogen and 55 % gasoline. From the results, it is hard to state that the hydrogen based fuels used for hydrogen powered vehicles are actually competitive with gasoline for GICV. However, as technologies mature, the PV capital cost is going to go down and the PV module efficiency up, leading to a better competitiveness of the hydrogen based fuels. A comparison between the three hydrogen based fuels vehicle has shown that the fuel for the HFCV is by large the most competitive. Hydrogen gasoline mixture as a fuel for HGICV is a very interesting case. However, as the technology mature hydrogen as a sole fuel will be more competitive than the hydrogen gasoline mixture fuel. The hydrogen gasoline mixture is then a very interesting fuel only as a transition fuel towards a full hydrogen fuel.

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