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# Hydrogen - The Ecologically Ideal Energy Vector

Mircea Cârdu[1] and Malvina Baica[2]
*[1]HERBING S.R.L, Bucharest*
*[2]Department of Mathematical and Computer Sciences, The University of Wisconsin*
*[1]Romania*
*[2]USA*

## 1. Introduction

Strategic analysis of the energy sector of the global economy reveals two very important elements which have a substantial influence on the development process in this domain. These elements are:

The exhaustion of available conventional fuels (natural gas, coal, oil) in the near future. The time limit for this process is estimated to be a few decades for natural gas and oil, and about two centuries for coal. It is evident that, as these fuel reserves are depleted over time, their cost will continuously increase. There has been a tremendous increase in terrestrial atmospheric pollution, from noxious and greenhouse gases, emitted during the combustion process in conventional fuels by the energy industry (thermo power plants), as well as metallurgical, chemical, and construction materials, and from energy for aviation, naval, auto and railway transport. The continuous increase in the average temperature at the earth's surface, due to the greenhouse effect produced by $CO_2$ accumulation in the atmosphere, has an increasingly intense effect on terrestrial flora and fauna, as well as on climate change.

This apocalyptic scenario of mankind's future should mobilize the international community to take global measures to reduce atmospheric pollution, and to produce useful energy especially electrical energy from non-conventional sources (sun, wind, sea, waves, tide, and geothermal energy).

Although these sources have very little constancy (with a reduced energy density), and to place a value on them is both difficult and unsatisfactory, when viewed against mankind's permanently increasing demand for energy, these sources are well suited for the production of electrical and thermal energy. However, to produce the energy needed to propel all the means of transportation currently available, there is a need for an intermediate, non-polluting energy carrier from unconventional energy sources; one of the most promising of such energy carriers in this situation is Hydrogen.

Hydropower plants (HPPs), and very often nuclear power plants (NPPs), are only suited for production of electrical energy. Hydraulic energy cannot be directly used to power vehicles, and the use of nuclear energy is not feasible on a large scale in the near future, except for ships and submarines. Resources for hydraulic energy are limited, although regions with large energy consumption (Europe, North America) which are equipped to use hydraulic energy resources, the economical advantages are considerable high. As for the majority of

unconventional resources HPPs can produce only electrical energy consequently their contribution to energy for transportation is limited to the production (by electricity) of an intermediate energy carrier, which could be Hydrogen.
Hydraulic energy resources are limited, but as a result of natural water circulation on the planet, they are recyclable. Evidently, producing electrical energy in HPPs does not result in noxious or greenhouse gas emissions into the atmosphere. Thus, from this point of view, HPPs represent a very advantageous electrical energy source. However, HPP's can have a somewhat negative effect due to perturbation of the ecological equilibrium in the local ecosystems where they are located.
Nuclear energy is the future alternative to producing energy from conventional fuels; nuclear fuel reserves are estimated to last for two to three centuries. Moreover, there is also the possibility of recycling these primary nuclear fuels naturally existent by using them to reproduce nuclear reactors. In this way, natural nuclear fuel resources can be amplified. NPPs do not produce noxious or greenhouse gas emissions.
Considering the increasing global energy and fuel demand, and at the same time attempting to maintain a strict limit on atmospheric pollution, the use of primary energy resources such as coal and hydrocarbons should be continued on the condition, that these resources be recycled, in order to limit, as much as possible, the continuing degradation of our environment.
At the present time, many proposals exist for recycling carbon from conventional fuels, using a chemical process for the carbon dioxide ($CO_2$) resulting from their combustion. This process in turn requires a great deal of energy consumption, but it results in hydrocarbons, alcohol or methanol, high quality fuels.
$CO_2$ collection for recycling is a practical possibility at stationary energy installations, but for vehicles $CO_2$ collection and its storage are operations which involve enormous technical problems. For ecological reasons, and because $CO_2$ is the principal greenhouse gas, studies are being conducted which consider the possibility of storing huge quantities of this gas for later use.
Careful analysis of these two important problems, which have arisen because of the continuing, large-scale use of conventional fuels, will lead to the conclusion that Hydrogen is the ideal energy carrier of the future. Mainly, we refer to molecular Hydrogen, which is stable and can be easily used in practical applications. Further justification for this conclusion will follow.
Hydrogen is not a natural primary energy source, as is, for example, coal. Molecular Hydrogen is found in natural states in the cosmos only where it is free in a proportion of 70%, compared with the total interstellar matter. It occurs in extremely reduced quantities compared with the volume of the stars, including the Sun, where Hydrogen is 70% of their composition. The atmospheres of exterior planets of the solar system (Mars, Jupiter, Saturn Uranus Neptune, Pluto), have 90% hydrogen content; the remaining 10% is helium (He).
On Earth, Hydrogen can come from an inexhaustible source, water, but to obtain Hydrogen from water requires the use of another energy form (solar, electrical etc.) in a quantity of 20-80%, compared with the energy obtained from its use as a fuel. Thus, we consider its denomination as the energy vector, and not as an energy source. Since, by burning Hydrogen we obtain water vapor, it's recycling from water is achieved by an automatic integration of the water cycle in nature. Water vapors are not toxic, and from an ecological point of view, Hydrogen used as fuel represents an ideal energy carrier (Cârdu & Baica, 1999). This offers a real advantage for Hydrogen, if it is obtained from water using a technology where a primary nonpolluting energy source, such as solar, hydraulic or nuclear energy is utilized.

The characteristics of Hydrogen will be analyzed as a stable fuel; methods for production, storage, and transportation, as well as the technical systems employed in using it as fuel, will be examined.

## 2. Characteristics of hydrogen

In this section, the physical and thermodynamic characteristics of Hydrogen which determine its behavior as fuel, will be discussed. Table 1 (see –page 346) gives for comparison, the principal characteristics of Hydrogen and some hydrocarbons currently used, especially in transportation. In order to proceed systematically, these characteristics will be analyzed and grouped into two categories, advantageous and disadvantageous characteristics respectively, in all aspects of its use as fuel.

### 2.1 Advantages of hydrogen over other fuels

Water is produced by Hydrogen combustion, and as we know, water is not noxious. Because of the nitrogen content in the atmosphere, burning Hydrogen in the air can produce $NO_x$ which is a noxious gas, but for $NO_x$ content reduction, known and applied methods for any classical fuel combustion process can be used in power plants or thermic engines.

The reduced value of $NO_x$ content in gases resulting from combustion is due to the reduced air quantity for stoichiometric combustion, related to the resultant energy in Hydrogen, compared with other fuels. Thus, knowing the inferior heat power compared to the mass-unit of Hydrogen is 121 MJ/kg, and the air quantity needed for the stoichiometric combustion of a kg of Hydrogen is of 34.2 kg/kg, it follows that the specific air quantity needed in the combustion for each MJ of heat released is, in the case of Hydrogen about 280 g. Some other conventional fuels of superior quality (gasoline, methanol or methane gas), have a higher value of these characteristics, which is about 340 g. Given that Hydrogen has the smallest molecular mass compared with all other elements or chemical combinations, it is the best reactive fluid which can be utilized in a rocket propulsion system; the propulsive force of such a fluid is so much greater due to the fact that the molecular mass of the respective fluid is smaller. Thus, in this case we cannot say that Hydrogen can be used as fuel, but only as jet fluid. This problem will be analyzed in detail in another chapter, in which the problems of using Hydrogen as a fuel will be addressed. The diffusion velocity value in air of Hydrogen is greater than that of any other fuel. This represents an advantage for forming a homogeneous mixture with air, or Oxygen, in a very short time, with a positive effect on the burning quality (a more complete combustion process).

The domain between the two inflammation limits of Hydrogen is very large, especially in the poor mixture zone (very large value $\lambda > 2$ for the air excess). This characteristic represents an advantage, particularly when Hydrogen is used as fuel for thermic engines. Such engines can be more stable functioning in conditions with large air temperature variations; these conditions do not require a highly precise control of the feeding and ignition.

### 2.2 Disadvantages of hydrogen compared with other fuels

The density of Hydrogen, both in gaseous and liquid form, has very low value compared with all other gaseous or liquid fuels. This characteristic of Hydrogen represents a disadvantage compared with other fuels, especially when Hydrogen is used in transportation, since the volume and the mass of the fuel containers for the vehicles is by necessity very large, and the distance covered between two successive refueling is substantial. The high value of Hydrogen's heat power, relative to the mass unit, reduces this disadvantage to some extent. All these facts lead us to prefer the storage of Hydrogen in liquid form. This storage form in turn represents a disadvantage since it requires the containers to function at very high pressures and very low temperatures. High pressures require heavy containers and low temperatures demand special construction materials, since materials used today, especially steel, become fragile at these temperatures. Moreover, Hydrogen has the ability to diffuse easily through steel at normal temperatures, and so the mechanical characteristics of steel can suffer severe deterioration.

The storage and transportation of Hydrogen in a gaseous form (which can be implemented if it is used for stationary energy installations), also creates important problems because of its very reduced heat power values relative to its volume, as a consequence of its very low density value.

Solving this problem requires large diameter pipes for transportation, and large volume containers for storage. At the same time, to transport Hydrogen using these pipes, and to store it in these containers requires high power compressors.

The characteristics of Hydrogen for ignition energy and burning velocity are advantageous from one point of view, and disadvantageous for other reasons. Thus, fast ignition and burning processes are considered advantages as far as combustion is concerned, especially for engines with compression ignition. On the other hand, fast ignition and high burning velocity can provoke untimely burning initiatives and high pressure gradients inside cylinders, resulting in very high mechanical stress.

The above mentioned advantage can thus be very useful, using Hydrogen as combustion initiator when some conventional fuels (hydrocarbons) mixed with Hydrogen are used.

## 3. Production, storage and transportation of hydrogen

### 3.1 Hydrogen production

It has been stated that Hydrogen is not a fuel which can be found naturally on earth, as can the classic fuels (coal, hydrocarbons, and biomass). Hydrogen can be obtained from the chemical combinations in which it exists, just as hydrocarbons or especially, water. It becomes an energy vector, thus it still can be used in its turn as fuel, since its combination with Oxygen is exothermic (combustion), and its final product is water (non-pollutant). Evidently, by extracting Hydrogen from hydrocarbons result in carbon byproducts, typically carbon monoxide (CO) and/or carbon dioxide ($CO_2$). These byproducts generate pollution; they are noxious and they belong to the category of greenhouse gases. On the other hand, the Hydrogen extraction process involves energy consumption, usually of thermic nature, and its production also requires conventional fuel consumption. This process results in noxious gas emissions in the atmosphere. Thus, Hydrogen produced by this method does not solve either of the problems mentioned in the first section of this paper.

Another way to extract Hydrogen, this time from water, is the gasification of coal or other organic substances. The gasification process involves the consumption of these fuels, in addition to Hydrogen, some pollutant gases, primarily $CO_2$, are also produced. Consequently, this method of producing Hydrogen, on the basis of carbon (C) or hydrocarbons will not be examined here.

Hydrogen often appears as a secondary product in oil processing, and to use it as fuel also presents an interesting possibility (Peltier, 2007).

In the respective technological processes, Hydrogen appears as a mixture, especially with CO, but also with some other gases, such as $CO_2$, $CH_4$, $N_2$ and water vapors. In these occurrences it is very important to separate Hydrogen from the gas mixture. This separation by membranes is a very frequently used industrial method. Thus, for example, in refineries, Hydrogen results in the production of toluene transformation in benzene at the catalytic isomerism and in the processing of heavy fractions, in order to obtain lighter hydrocarbons. Hydrogen is separated from the gas mixture issuing from these processes with the help of membranes.

The ammonium synthesis process (starting from methane), also results in a very high proportion (about 60%) of Hydrogen in the gas mixture formed. Hydrogen separation can also be realized in this case by using two modules with membranes installed in the cascade.

In the countries with a developed chemical industry, Hydrogen production is very important as a secondary product. Germany is a significant example; the German chemical industry annually produces about 10 billion $m^3$ of Hydrogen. Hydrogen also results as a secondary product in the heavy water fabrication process, if some special technologies are applied (Peculea, 1995).

Electrolysis is the principal procedure for obtaining Hydrogen from water using electrical energy. If this energy were produced in its turn in power plants using nonpolluting primary energy (hydraulic, nuclear, solar, wind), the problem of obtaining fuel for transportation, could be solved without polluting the atmosphere. The primary energy forms mentioned above (hydraulic, nuclear, etc.) are practically inexhaustible, offering a solution to the exhaustion of global energy resources, and the degradation of the ecological equilibrium, as noted in the first chapter.

The process of producing Hydrogen, using nuclear energy, was also approached in the study *Vision 2020,* produced by the NEI (Nuclear Energy Institute) of the USA. In *Vision 2020* it is shown that sea water desalination and hydrogen production, using the nuclear energy installations, could be as important in the 21$^{st}$ century as electrification was in the 20$^{th}$ century.

The problem of introducing Hydrogen as a fuel on a large scale in contemporary society is not at all simple from the technical and economic point of view.

First, it is evident that using an energy reactor as the primary-source energy circuit continuously, to the final energy utilizer, inevitably results in an energy loss, mainly because of the energy vector production process. Thus, in Hydrogen production by electrolysis, the specific electrical energy consumption is about 4-5 kWh/$m^3$N. Expressed in international units, this specific consumption is about 14,400-18,000 kJ/$m^3$N. The inferior heat power of Hydrogen is 10,880 kJ/ $m^3$N. This means that the electrical energy efficiency to transform Hydrogen in a fuel is $\varepsilon_p$ = 0.6-0.75. In other words, in this process, just for the production process of Hydrogen, about 25-40% of the electrical energy will be lost. This in its turn is produced from a primary energy source with an efficiency $\eta < 1$, depending to its mode of production.

We have to mention that using CNE (NPPs) as energy source to produce Hydrogen by electrolysis presents as disadvantage a risk of radioactive pollution. This thing is more evident now, after what happened at the NPP Fukushima-Japan, as a result of the devastating earth-quake of March 11, 2011.

These considerations of losing up to 40% of the electrical energy when the efficiency is <1 regarding energy source and materials, related to obtaining and preparing water for electrolysis, adapting installations to electrolysis, and determining a price for Hydrogen (compared to the caloric energy unit produced by combustion) cause the use of Hydrogen to cost more than the price of the hydrocarbons as fuels, respectively. It is agreed that solar energy is a satisfactory choice among the primary non pollutant energy sources for producing Hydrogen by electrolysis. Because of its nature (cyclical variable and variable intensity) solar energy must be accumulated under a special form (Hydrogen storage).

Radiolysis is a physical phenomenon which can be used to decompose water into its component elements. This decomposition is produced in homogeneous nuclear reactors (NR), under the influence of radiation and nuclear particles, which appear as a result of fission in the nuclear fuel. This modality for the production of Hydrogen is of great interest, especially since the process of radiolysis can be organized at relatively reduced values of the NR temperature; thereby increasing security in its operation. However, obtaining Hydrogen by radiolysis is disadvantageous from the point of view of energy efficiency. At a value of about $10^{13}cm^{-2}s^{-1}$ for the neutron flux (normal for a homogeneous NR), the value of this efficiency is only 6%. An increase in efficiency could be gained by increasing the value of the neutron flux in RN.

In thermonuclear fusion it is possible to obtain, for example, neutron flux of ($10^{15}$-$10^{16}$) $cm^{-2}s^{-1}$.

There have been some proposals for using photosynthesis (directly or as a model), to produce Hydrogen. It is known that in green plants and algae (especially blue algae), photosynthesis, under the influence of solar radiation, produces a decomposition process of the water molecule into O (emitted in the atmosphere), and Hydrogen, followed by a secondary cycle to recombine Hydrogen and $CO_2$, thereby obtaining carbon hydroxide, which is needed as plant food.

With this natural process as a model, Professor Jean Marie Lehn, of Strasbourg University, in France invented an industrial system to produce Hydrogen using this method. He proposed the replacement of chloroplasts in the plant cell with a chemical substance based on ruthenium (Ru). This metal (group VIII b in the periodic element table), is capable of absorbing part of the solar radiation. This energy is used to obtain Hydrogen from water, with the help of a solution containing rhodium (Rh), which takes the role of the natural enzyme contained in the plants, and is named Hydrogenise. Research continues in this domain. Also, it is studied the possibility of producing Hydrogen biologically (by fermentation) where is no need for the solar light.

### 3.2 Storage and transportation of Hydrogen

Hydrogen storage also presents special technical difficulties; these problems result from theoretical considerations, but they are confirmed by NASA’s operation staff, which is experienced in storing and handling Hydrogen in liquid form for the Saturn and Centaur rockets.

The simplest way to store Hydrogen is at a high pressure, or at atmospheric pressure, if this is performed when Hydrogen is in a gaseous state. However, given the very low density value of Hydrogen, this method of storage is of no practical value, especially for vehicles, where the volume and weight of fuel transportation reservoirs are especially important. Thus, for an automobile with reduced capacity, about 14 kg of Hydrogen (the equivalent of 40 kg of gasoline), would be necessary and would require 18 gas cylinders with Hydrogen, at a 150 bars pressure. Since such a gas cylinder weighs about 70 kg, the total weight of the fuel storage system would be about 1200 kg greater than the weight of the car.

Up to the present, this problem was solved for rockets, as we have shown, by storing Hydrogen in a liquid state (at -253°C) in very well-insulated thermic reservoirs (cryogenic reservoirs). Since the density of Hydrogen in a liquid state is much greater than Hydrogen in a gaseous state, the reservoirs have a lower volume and weight, so that Hydrogen storage in a liquid state becomes feasible. This approach is possible in large vehicles, such as trucks and buses. The disadvantage of this storage system is that a cryogenic reservoir is complicated and expensive; it requires a high energy consumption to perform Hydrogen liquefaction; the feeding system is complicated and there is a significant loss during feeding and storage.

The transportation of Hydrogen does not involve more difficulties than for other flammable gaseous liquids however. One example is the actual transportation of gaseous Hydrogen using a pipeline some hundred km long, which existed in Germany for more than 60 years.

One storage method with great future possibilities uses metallic hydrides as the Hydrogen impregnating mass. It is known that some metals dissolve large quantities of Hydrogen at high temperatures. Thus, in inter crystalline interstices of iron (Fe), a volume of Hydrogen can be inserted which is 19 times greater that the volume of Fe, and this characteristic has the value 875 in palladium (Pd). The metals' capacity to react with Hydrogen decreases from left to right in the serial arrangement of the Mendeleev Periodic Table. The elements of the group III b (Sc, Y La, Ac), are most reactive in this situation, and those of group IX b (Co, Rb, It) to X b (Ni, Rd, Pt) are less reactive. A remarkable exception to this rule is Pd of the group X b.

Some economic considerations (the price of some metals), influenced the choice of the metals for Hydrogen storage in the form of hydrides to be made, requiring more than the above rule. Thus, some experiments are presently being performed on two types of alloys, Fe-Ti and

Mg - Ni. These are less expensive alloys, and their Hydrogen absorption capability compared well with the base material mass (the alloy used). Very often a mixture of both alloys is used. Since Hydrogen inclusion in a metal (or an alloy) is exothermic, and Hydrogen liberation is an endothermic reaction, these two processes can be used in air conditioning for homes, industrial spaces, and some vehicles.

Lately, there is more and more research to store Hydrogen using some absorptions of type LiBH4-MgH2 together with Ru under the non particle form as catalyst.

## 4. Hydrogen as fuel

The possibilities for using Hydrogen as a fuel depend on its characteristics, analyzed in Chapter 2, and their advantages or disadvantages compared with other fuels used in transportation or energy. The most important advantage of Hydrogen is, as we have shown, that Hydrogen combustion results almost exclusively in water vapors which are not noxious; they do not contribute to atmospheric pollution, nor do they have a negative influence on animals and plants. From this point of view, Hydrogen is an ideal fuel. Hydrogen combustion can be used in all types of engines or thermo power plants which presently use known conventional fuels. To a great extent, Hydrogen can be used as fuel for engines and installations in their existing form, without important modifications, and with minimum adjustments.

A practical use of any Hydrogen storage system, described in the previous chapter, includes a modality with characteristics corresponding to the technical domain in which Hydrogen is used as a fuel. In addition to thermo power engines and installations currently used, Hydrogen is very well suited for use in an energy system category which will be employed more and more in the future--namely fuel cells (Apollo Space Program…, 2009). As we know, fuel cells (FC), generate electrical energy directly as a result of the electrochemical reaction of a hydrocarbon (methane gas or methanol) or of Hydrogen. Depending on the FC type, and the temperature at which the electrochemical reaction is produced, efficiencies of 40% to 70% can be obtained for the electrical energy produced. For the case of electrochemical reaction high values for efficiency can be obtained for high power FC (2-3 MW) in the existence of high temperature values (800-1000°C).

### 4.1 Motor vehicles

Extensive research is presently being undertaken, especially for ecological reasons, to find alternatives to conventional fuels (gasoline, diesel fuel, methanol), which can be used for ground transportation vehicles, whose numbers are continuously increasing. This research is concentrated on two solutions: replacing thermic engines with pistons with electrical motors fed from accumulator batteries, and total or partial replacement of conventional fuels with Hydrogen. Among these types of engines, those with sparking ignitions are best suited to function with Hydrogen. Transforming actual engines for this purpose requires minimal adaptation.

Engines with compression ignitions are less suited to function with Hydrogen. It has been proven that the best storage for Hydrogen, in use with trucks and cars, is in its liquid form, in cryogenic reservoirs. .Injecting liquid Hydrogen into the cylinders is very difficult, since its boiling temperature is very low. Engines with sparking ignitions, operating with Hydrogen have an effective efficiency of about 35%, greater than engines using conventional fuels. Maximum efficiency using Hydrogen can be obtained for high values of excess air ($\lambda > 2$), compared with $\lambda \approx 1{\cdot}1$ in conventional engines. Engines operating with Hydrogen are more economical than gasoline using an inferior load, but by using Hydrogen there is a reduction of the engine's maximum power. Therefore, when the load increases, gasoline participation also increases; thus, for a load more than 85% of maximum, the engine is fed exclusively with gasoline. Using the mixture Hydrogen – gasoline, gasoline savings of 70-75% were obtained. For this reason, the start and function of duel fuel engines, using Hydrogen, is presently being investigated.

These characteristics of the dual fuel engine could be expected to elicit large-scale application to urban transportation. Investigations are also being made into the use of fuel cells (FC) fed with Hydrogen in automotive traction systems. These are able to produce electricity continuously, which is very advantageous for traction systems.

### 4.2 Aviation

The rationale for using Hydrogen in airplanes equipped with turbo reactor motors is based on the fact that for equal volumes of gasoline, Hydrogen is ten times lighter; but the heating power of Hydrogen, related to the weight unit, is about three times less than that of gasoline. Allowing for the weight of Hydrogen, the volume and thus the dimensions of a plane using Hydrogen would be greater, but the weight would be smaller than planes using conventional fuels. For this reason, the take-off distance for Hydrogen-operated airplanes could be reduced by 50%.

Only minor modifications are required to adapt a turbo-reactor motor to function with Hydrogen. The high energy value in Hydrogen vaporization constitutes an advantage for the cooling structure of high-flight velocity airplanes, where the aerodynamic heating phenomenon is very important. Thus, flying the Concorde at 18,000m, and a velocity characterized by Mach number M = 2, the wing temperature rises to 90°C. For, M = 3, this

temperature reaches 250°C. For this reason, experts consider that high-speed airplanes (M > 5), will require the use of H as fuel. Certainly, as in automobile engines, there is the possibility of using dual fuels for turbo reactor motors.
Research in this direction led to some interesting results in the area of environmental protection. Adding Hydrogen to the gasoline mass flow (5-6) %, and injecting gasoline for the remaining 95% in the combustion chamber, resulted in a four-fold reduction in atmospheric CO and CH emissions. An addition of 12% Hydrogen reduced these noxious gas emissions by a factor of more than 20. All of these elements, which make the use of Hydrogen as fuel for the turbo reactor airplanes very attractive, have resulted in considerable research.

### 4.3 Space technology

Space technology represents the only domain which presently employs Hydrogen on an industrial scale to propel Saturn and Centaur rockets, used by NASA, by utilizing the reaction force of the motors' rocket, resulting from Hydrogen combustion in its contact with oxygen, both of these components being stored in a liquid state (cryogenic reservoirs).
The opportunity to use Hydrogen as rocket fuel first resulted from good specific traction characteristics (reaction force), realized by using this apparatus. Additionally, it emits almost no atmospheric pollution.
The decision to use Hydrogen as fuel was planned as far back as the ballistic $V_2$ rocket, used by Germany in the Second World War. In this case, by using methyl alcohol as fuel for the $V_2$ Rocket, the flue gas evacuation velocity from the jet nozzle was of 2100 m/s, and the operating radius was (theoretically) about 550 km, and practically about 300 km. In order to increase the operation radius by the 1500 km, necessary to reach the United States, it would be absolutely necessary to use Hydrogen as fuel, since, as a result of hydrogen-oxygen reaction, it would obtain a propulsion gas velocity of about 3100 m/s (with $O_2$ liquid carburant). In space technology it is of great interest to use Hydrogen not only as a fuel but also as a rocket propulsion fluid.
This approach is justified by the fact that the reaction gas exit velocity is inversely proportional to the molecular weight of the corresponding gas; and among all gases, Hydrogen has the smallest molecular weight, as shown in Chapter 1. However, the reaction force in the gas jet propulsion motor is directly proportional to the respective gas evacuation velocity from the jet nozzle.
However, as has been shown, in addition to its dependence on the gas molecular weight, this velocity also depends on the absolute temperature value of the gas at the entrance of the set nozzle. In fact, it is directly proportional to this temperature. Thus, for a value of the corresponding temperature at $T_0$ = 1773 K ($t_0$ = 1500°C), the maximum velocity of Hydrogen at the exit from a considered reaction jet, having an exit infinite size section, is 6700 m/s. In order to heat Hydrogen at a high temperature, a heat source contained in a much reduced mass at the rocket board is needed.
Returning to the velocity problem at the exit from the TNR jet nozzle: Using Hydrogen as the reactive fluid, we note that if atomic hydrogen were used, the velocity would be double that of molecular hydrogen. Thus, practically, the limited value of the exit section area of the jet nozzle, would reach values of this velocity for about 10,000 m/s using atomic Hydrogen, compared with about 5000 m/s using molecular Hydrogen. However, it is known that the dissociation of molecular Hydrogen in atomic Hydrogen is very difficult to achieve at very

high temperatures. Thus, the dissociation degree, expressed by the Hydrogen molecule in Hydrogen atoms, compared with the total Hydrogen molecular number, is 1%, for 1900 K, and it increases with the temperature up to 82%, for 4000 K. On the other hand, atomic Hydrogen is very unstable, having a very strong tendency to return to its molecular Hydrogen form.

### 4.4 Energy

A very large field of Hydrogen utilization in energy is represented by gas turbine installations (GTI); this can be achieved either by Hydrogen with air, or oxygen combustion.
Obviously, the principal advantage of using Hydrogen in GTI is of an ecological nature. In Hydrogen combustion with oxygen, water appears as a combustion product and it is not a pollutant. In Hydrogen combustion with air, nitrogen oxides could appear as pollutant products. For this reason, measures must be taken to reduce the content of nitrogen oxides in the flue gases; these measures could include temperature reduction in the combustion chamber (CC), which is already very high. Therefore, during Hydrogen combustion with air (under stichiometric conditions) the maximum combustion temperature is 2503 K (see Table 1). The temperature reduction in CC, up to the desired value, can be achieved by introducing supplementary air, or by water injection. In the case of Hydrogen combustion with oxygen, it is appropriate to consider the Total Water Injection System – TWI (Cârdu&Baica, 2002). In this system the working fluid in the turbine could be a unique gas steam, which after its expansion could be condensed, with complete water recuperation, as in a steam turbine. Of course, such power plants can be technically and economically justified only when Hydrogen is available as a secondary product, resulting from a technological process of the chemical industry, for example. Thus, it is completely illogical to consider producing Hydrogen for energy purposes using a conventional energy primary source (caloric, hydraulic, solar etc.), when this respective primary source can be directly used to produce electrical energy with a greater total efficiency. However, producers of electrical energy are advised to operate with a constant load, as with nuclear power plants (NPPs). It is possible that Hydrogen produced by electrolysis could be profitable when energy demand in the respective power system is reduced. Hydrogen produced in this manner constitutes a not pollutant fuel reservoir, which can be used in a GTI, when electrical demand is greater in that energy system.
Hydrogen can also be an energy accumulator, very important for some electrical energy producers (electrolyze), which, by their nature have widely fluctuating energy demands, as in the case of electricity from the solar or wind energy.
In addition to the ecological advantages of using Hydrogen for GTI in energetics, there are technical elements which justify the assertion for thermo dynamic advantage, however this subject is not the goal of this paper.
In the USA, the Los Alamos National Laboratory is studying an interesting integrated system which produces (not pollutant) Hydrogen from coal in generating thermal and electrical energy (Lackner & Ziock, 2000). The electrical energy is produced using Hydrogen in a high temperature solid oxide fuel cell (HTSOFC). Hydrogen is produced from coal and steam using a conventional gasification process. As a result of this process, ashes are obtained simultaneously with Hydrogen, $CO_2$. From the mixture of Hydrogen and $CO_2$, $CO_2$ is held back by a chemical process, where it combines with CaO to result in a solid form; $CaCO_3$. In its turn, $CaCO_3$ is calcined with the help of the heat which results from the

process which takes place in the HTSOFC. As a result of $CaCO_3$ calcination, CO (which is recyclable), and $CO_2$ are produced. $CO_2$, in its turn, can be naturally recycled by its combination with magnesium silicate (serpentine), from which results magnesium carbonate, silica (quartz), and water. This is an exothermic reaction and the resultant heat can be also used. This gasification process can be carried out without the contribution of air, and consequently $NO_x$ does not appear. In using coal with sulphur (S) content, a necessary quantity of CaO or $CaCO_3$ is used to retain this sulphur. In this way we eliminate the possibility of sumptuous oxides emission.

## 5. Conclusions

The previous chapters have demonstrated the following:

**5.1.** Hydrogen is a gas with physical and chemical properties recommended for use as fuel for thermodynamic engines and plants; it has many advantages over conventional fuels such as coal and hydrocarbons). A very important ecological advantage is that Hydrogen combustion does not produce $CO_2$ or $SO_2$, noxious gases or greenhouse gas ($CO_2$). In its combustion with air, it can produce nitrogen oxides ($NO_x$) which are noxious gases and greenhouse gases, but the actual technological level ensures minimal $NO_x$ content in the flue gases. Hydrogen combustion produces water vapors almost exclusively, and they are not noxious.

Hydrogen also has disadvantages compared with other fuels, and some of the most important are those concerning technical difficulties regarding its storage.

**5.2.** Hydrogen is not found in a free state in nature. Thus we cannot speak of Hydrogen as a primary source, as are conventional fuels. To obtain Hydrogen from the substances in which it occurs, another form of energy must first be consumed. For this reason, Hydrogen is in fact an energy vector from its production source (most desirable without producing atmospheric pollution), to the point at which it is used as a fuel.

The progression of Hydrogen from product to tool, is exemplified by its production via electrolysis (using electricity produced by a nuclear power plant), and ending with Hydrogen used to perform rocket propulsion. By using the chemical energy of some fuels to produce Hydrogen (particularly thermal energy), this approach becomes rational if Hydrogen results as a secondary product, based on some technological processes of the chemical industry. Thus, from an ecological point of view, it is justifiable to produce Hydrogen by electrolysis (using electrical energy), by radiolysis (using nuclear particles of radiations energy), or by photosynthesis (using the solar radiation energy), and also by biological way (fermentation).

Moreover, Hydrogen storage can be achieved either in liquid form at a high pressure and extremely low temperature (about 20K), or in the form of metallic hybrids. Storage is one of the most difficult problems in the technology of using Hydrogen for energy.

**5.3.** Presently, there are still major technical and economical difficulties in using Hydrogen as fuel on large scale, but the increasing demand for protecting the environment will require ever greater use of Hydrogen as fuel. Hydrogen can be used as fuel in all areas presently using conventional fuels (coal and hydrocarbons): transportation, space technology (rockets) and for energy (thermo power plants). The existing experimental installations in all of these fields assure that, should there be an immediate, large-scale demand for Hydrogen as fuel, there will be a technical solution available. Moreover space technology has used Hydrogen for a long time as fuel for Saturn and Centaur rockets in the USA space program. Great importance is also attached to using Hydrogen as a fuel in automotive transportation in the USA.

| The characteristics | MU | The fuel | | | | | |
|---|---|---|---|---|---|---|---|
| | | Hydrogen | Gasoline | Diesel oil | Kerosene | Natural gas | Methanol |
| Chemical composition C/H/O | - | -<br>1.0<br>- | 0.85<br>0.15<br>- | 0.87<br>0.13<br>- | 0.853<br>0.147<br>- | 0.75<br>0.25<br>- | 0.375<br>0.125<br>0.500 |
| Density (gas/liquid) | $\frac{kg}{m^3}$ | 0.0899<br>70.8 | 4.88<br>700-755 | -<br>820-930 | -<br>800-850 | 0.717<br>415 | -<br>791 |
| Diffusion coefficient in air | m/s | $0.66 \cdot 10^{-6}$ | - | - | - | - | $0.186 \cdot 10^{-4}$ |
| Feature temperatures<br>- boiling start<br>- boiling finish<br>- of ignition<br>- of freezing<br>- maximum of combustion in air | K | <br>20.2<br>20.2<br>823-873<br>11<br>2503 | <br>313<br>453<br>773-793<br>213<br>- | <br>-<br>-<br>593-653<br>213<br>- | <br>423<br>523<br>708<br>213<br>2340 | <br>111·4<br>-<br>923-973<br>90.4<br>2316 | <br>337·7<br>-<br>741<br>175.2<br>2175 |
| Stoichiometric air quantity | kg/kg | 34.2 | 14.9 | 14.3-14.7 | 14.8 | 17.25 | 6.47 |
| Inflammability limits<br>- inferior<br>- superior | % vol. | <br>4<br>75 | <br>0.59<br>6 | <br>-<br>- | <br>-<br>- | <br>5.5<br>15 | <br>-<br>- |
| Vaporization energy (at 20°C) | kJ/kg | 451-476<br>(at 20.2K) | 292-314 | 18 | 208 | 5111 | 1105 |
| Ignition energy | kJ/kg*) | 20 | 250 | - | 250 | - | - |
| Inferior heat power (at 15°C; 760 mm Hg) | MJ/kg | 121 | 43.744 | 42.5 | 42.85 | 49.79 | 19.3 |
| Combustion speed | m/s | 2.7 | 0.4 | 0.4 | 0.4 | 0.36 | - |

*) 1 kg of fuel in stoichiometric mixture with air

Table 1. The main technical characteristics of the hydrogen in comparision with other fluid fuels (hydrocarbons)

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## 7. References


Cârdu, M., Baica, M., (1999), Regarding a new variant methodology to estimate globally the ecologic impact of thermo power plants, *Energy Conversion and Management (ECM)*, 40, pp. 1569-1575.

Cârdu, M., Baica, M., (2002), Gas turbine installation with total water injection in the combustion chamber, *Energy Conversion and Management (ECM)*, 43, pp. 2395-2404.

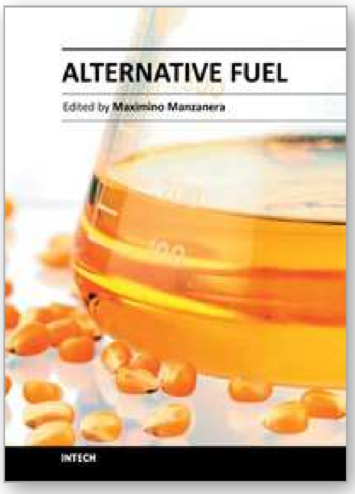
Jianfeng, M., et al. (2011), Enhanced hydrogen sorption properties in the LiBH4 – MgH2 system catalysed by Ru nanoparticles supported on multiwalled carbon nanotubes, *Journal of Alloys and Compounds*, Vol. 509, Issue 15, 14 April, pp. 5012-5016.

Lackner, K.S., Ziock, H.J., (2000), From low to no-emissions, *Modern Power System (MPS)*, March.

Peculea, M., (1995), The Romanian Technology for Heavy Water Separation, *Energetica Journal*, 43, No. 1, Serie A (in Romanian).

Peltier, R., (2007), Port Arthur II Integrated Hydrogen/Cogeneration Facility, Port Arthur, Texas, *Power*, Vol. 151, No. 9, September, pp. 2-4.

***Apollo Space Program Hydrogen Fuel Cell, (2009), *Spaceaholic. com.*, Retrieved 2009-09-21.

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Renewable energy sources such as biodiesel, bioethanol, biomethane, biomass from wastes or hydrogen are subject of great interest in the current energy scene. These fuels contribute to the reduction of prices and dependence on fossil fuels. In addition, energy sources such as these could partially replace the use of what is considered as the major factor responsible for global warming and the main source of local environmental pollution. For these reasons they are known as alternative fuels. There is an urgent need to find and optimise the use of alternative fuels to provide a net energy gain, to be economically competitive and to be producible in large quantities without compromising food resources.



**InTech Europe**
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

**InTech China**
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821