Energy Conversion and Management 89 (2015) 205–213

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# A technical and environmental comparison between hydrogen and some fossil fuels

Giovanni Nicoletti *, Natale Arcuri, Gerardo Nicoletti, Roberto Bruno

*Mechanical, Energetic and Management Engineering Department, University of Calabria, Arcavacata di Rende, CS 87036, Italy*

ARTICLE INFO

*Article history:*
Received 4 July 2014
Accepted 19 September 2014
Available online 15 October 2014

*Keywords:*
Fossil fuels
Hydrogen
Combustion
Environment pollution
Technical quality indexes
Environmental quality indexes

ABSTRACT

The exploitation of some fossil fuels such as oil, intended as gasoline or diesel fuel, natural gas and coal, currently satisfy the majority of the growing world energy demand, but they are destined to run out relatively quickly. Beyond this point, their combustion products are the main cause of some global problems such as the greenhouse effect, the hole in the ozone layer, acid rains and generalized environment pollution, so their impact is extremely harmful.

Therefore, it is clear that a solution to the energy problem can be obtained only through the use of renewable sources and by means of the exploitation of new low-polluting fuels.

In this scenario an important role might be played by hydrogen, which is able to define a new energy system that is more sustainable and cleaner than current systems.

For the comparison of the different fuels investigated in this paper, a methodology, which defines appropriate technical and environmental quality indexes, has been developed. These indexes are connected to the pollution produced by combustion reactions and to their intrinsic characteristics of flammability and expansiveness linked to the use of the considered fuels. An appropriate combination of these indexes, in the specific sector of utilization, allows to evaluate a global environmental index for the investigated fuels, highlighting that hydrogen reaches the highest score. In the final part of the paper, a new hydrogen energy economy that would lead to solving the serious environmental problems that damages all the ecosystems of the planet earth, is presented.



## 1. Introduction

In recent years, the problem of air pollution has reached limits of considerable dangerousness both human health and for the environment that surrounds them [1,2]. This situation is the direct consequence of the continuous and copious reversal in the atmosphere of combustion products provided by energy systems, which employ, especially, fossil fuels.

Unfortunately, these emission levels have been increasing proportionately according to industrial progress, pursued by different nations for a long time, together the relative population growth.

Three possible scenario trends of industrial development with a well-defined model of population growth are shown in Fig. 1. The latter concomitant factors are the main reasons for the energy requirement growth, and they lead to emissions of large quantities of pollutants, such as $SO_x$, $N_xO_y$, particulate, carbon monoxide and carbon dioxide, which create serious environmental problems and liveability.

In this context, hydrogen has a role of primary importance to solve these serious environmental problems [3–7]. If hydrogen is introduced into the actual energy system based on the exploitation of fossil fuels, it would allow for a reduction of the local environmental impact of fuels, whilst also reducing the global impact. If hydrogen production is carried out starting from renewable sources, the world impact will also be solved. However, molecular hydrogen is not available in nature, so it must be produced using energy.

Hydrogen can be stored both in liquid or gas form, and it could later be converted into thermal energy by its combustion. For this reason, hydrogen is an energy carrier. The advantages of using hydrogen in energy systems are numerous; the main reason is the ability to produce electricity and heat using fuel cells [11–13]. These devices are characterized by high efficiency and no pollutant emissions (water vapour). In this sense, it can be defined as a clean energy carrier.

Currently, despite different ways of producing hydrogen in a molecular form, it is more expensive than fossil fuels, but only if the costs concerning social and environmental impacts are excluded [14–16].

* Corresponding author. Tel.: +39 0984494610; fax: +39 0984494673.
*E-mail address:* giovanni.nicoletti@unical.it (G. Nicoletti).

http://dx.doi.org/10.1016/j.enconman.2014.09.057
0196-8904/

After a review of the several methods and strategies for hydrogen production, hypothesizing the most frequent uses in the various areas of intervention, this paper proposes suitable indicators to quantify the real advantages of hydrogen as new fuels with regard to the technical and environmental aspects.

A comparison between conventional energy systems, which exploit fossil fuels, and a sustainable hydrogen energy system is proposed defining appropriate technical and ecological quality indexes.

For this purpose, in the first part of the paper hypothesizing standard combustion, the effects concerning pollution, flammability and expansion properties of hydrogen and other fossil fuels (coal, methane and gasoline) have been investigated. In the second part of the paper, a new economic scenario based on hydrogen systems to solve environmental problems such as the greenhouse effect, acid rain, the hole in the ozone layer and widespread pollution, is evaluated.

*1.1. Environmental damage and security in production of heat*

The production of heat and electricity through the use of traditional fossil fuels (methane, coal and oil) and with an alternative source as hydrogen, gives rise to two types of problems.

The first, as already mentioned in the introduction, is associated with environmental damage, resulting in the emission of large amounts of pollutants during their combustion.

The second problem concerns the security of the thermal process of energy production by exploitation of the fuels.

Regarding environmental damage, today the growth of energy requirement is the main reason concerning the emission of large amounts of pollutants, such as $SO_x$, $N_xO_y$, particulate, carbon monoxide, carbon dioxide and water, which cause serious environmental and living condition problems [17–19].

To provide an idea of the effects on air pollution associated with the continuous augment of the use of fossil fuel, the production of $CO_2$ and other mentioned chemical pollutants in more industrialized countries is reported in Table 1 [20].

In this context, it is important to focus on the problem of the increase in $CO_2$, which has grown since 1890–2009 from about zero to $22 \times 10^{12}$ kg/year. In other terms, $CO_2$ has grown from zero to about 360 ppm, corresponding to a level of 800 mg/Nm$^3$ [21].

**Table 1**
Comparison between the main pollution emissions in the more industrialized countries.

| State | Pollutants products from combustion (in $10^3$ ton) | | | | |
|---|---|---|---|---|---|
| | Sulphur dioxide $SO_2$ | Nitrogen oxides $N_xO_y$ | Suspended particles | Carbon oxide CO | Carbon dioxide $CO_2$ |
| USA | 23,200 | 20,300 | 8300 | 77,400 | 4,166,000 |
| Japan | 1314 | 1435 | – | – | 831,000 |
| German | 3200 | 3100 | 725 | 8650 | 666,000 |
| UK | 4670 | 1812 | 442 | 8891 | 517,000 |
| France | 3460 | 1847 | 278 | 5200 | 404,000 |
| Italy | 3205 | 1506 | 433 | 5487 | 322,000 |
| Spain | 3756 | 792 | 1521 | 3780 | 198,000 |
| Holland | 450 | 525 | 150 | 1450 | 130,000 |
| Belgium | 856 | 317 | 267 | 839 | 107,000 |

Nowadays, this concentration can appear to be not very high considering a limit of 9000 mg/m$^3$ in closed environments imposed by actual standards; generally this limit is never reachable hypothesizing the possibility of providing the indoor environment with ventilation systems for renewal needs.

Contrarily, the concentration of $CO_2$ and other gases contributes for 55% of the so-called greenhouse effect (see Fig. 2), the main reason for the earth's average temperature increment, with consequent melting of the great glaciers which could be responsible for serious problems in coastal areas around the world.

The trend in global temperature due to the increase of $CO_2$ in the atmosphere, adjusted considering the rate absorbed by the oceans and the mainland, is shown in Fig. 3.

Recent studies have made it possible to hypothesize how in the next 200–500 years, an augment of the sea level up to 3–4 m may be possible, while there will be an increment of 0.2–1.5 ml only in the next century [24].

Fig. 4 shows that the majority of $CO_2$ originates from the combustion of coal, oil and methane and, to a lesser extent, from deforestation; other productive activities, such as cement factories, are responsible for another small part of $CO_2$.

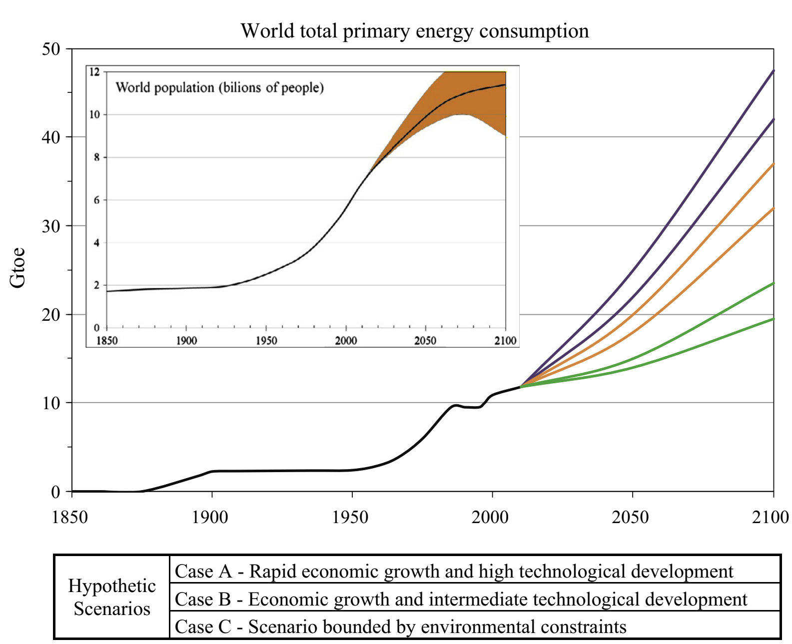


**Fig. 1.** Trend of primary energy requirements and world population growth until 2100 according to three different scenarios [8–10].

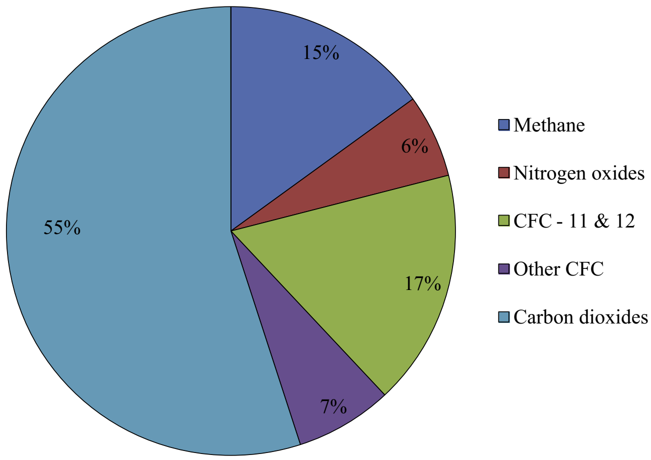


**Fig. 2.** Percentage contribution provided by different greenhouse gases to the earth's average temperature increment [21–23].

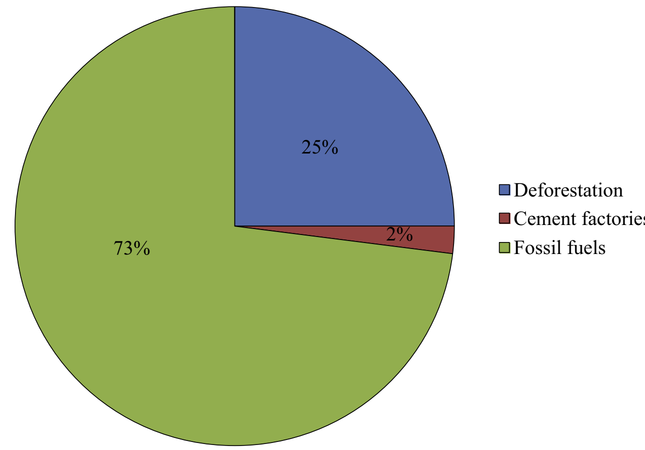


**Fig. 4.** Main $CO_2$ sources [25,26].

Similarly, a significant increase in all other air pollutants produced by fossil fuels employed in different energy systems has been observed, leading to serious problems for human health and for the living conditions of people, especially, in large cities [27].

The scenario that has just been shown, demonstrates how it makes sense to employ energy systems supplied by low impact fuels, such as hydrogen [28].

From the point of view of the fuel combustion safety, the aspects involved are the toxicity and the properties of blaze and explosion which can occur when they are burned [29–32].

The parameters that contribute to the maximization of safety of a fuel use are shown in Fig. 5. Beyond the combustion production, the fuels themselves can be toxic, in direct relation with the increase of the carbon/hydrogen ratio. Molecular hydrogen and its main combustion products (water or water vapour) are not toxic. However, the $NO_x$ that can be produced by the combustion of hydrogen in the presence of air (as well as fossil fuels) has toxic effects.

In Table 2, the main physicochemical properties of interest in order to assess the relative properties of blaze and explosions, have been listed for three investigated fuels.

In the latter table, the properties concerning coal are missing, because it is a solid fuel and in combustion processes it does not create significant problems of expansiveness and flammability.

A careful analysis carried out on the listed data allows for the formulation of some conclusions concerning the exploitation of hydrogen as a fuel:

- It disperses in the atmosphere more quickly than any other fuel, representing an evident advantage in the case of accidental discharge in open places but an evident disadvantage in confined spaces or in poorly ventilated indoor environments.
- It has the widest flammability range without causing safety problems (its lower limit of flammability in air is rather limited). Thus, in case of gas loss, hydrogen behaves much better than gasoline but not as well as methane.
- It has a flame speed 7 times greater than that of natural gas or gasoline. Compared to other fuels, this aspect increases the probability of a hydrogen flame that evolves in deflagration or detonation.
- It has a greater range of explosion than methane and gasoline, but, in contrast, it becomes deflagrating with greater volumetric concentrations.
- It burns with low submissiveness, so it is consumed quickly with limited damage to persons and objects in hypothetical cases of surrounding fire.

Table 3 summarizes and compares the safety aspects of gasoline, methane, and hydrogen. The analysis shows that for eight of

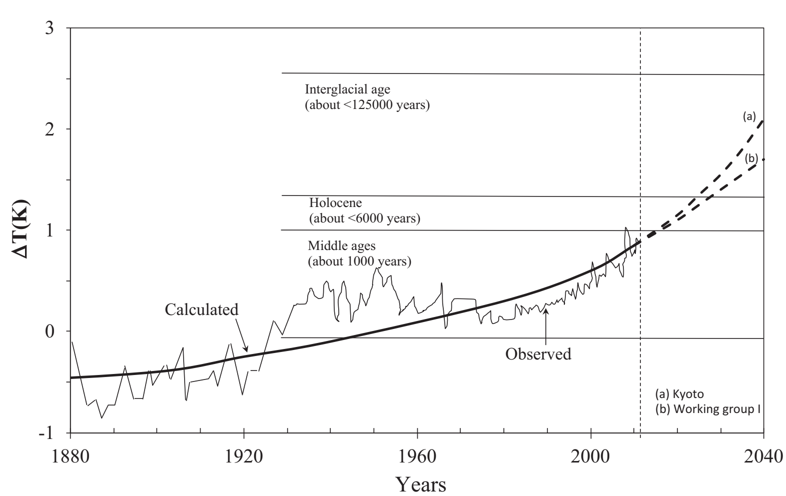


**Fig. 3.** Average yearly temperature trend of the earth's surface [21–23].

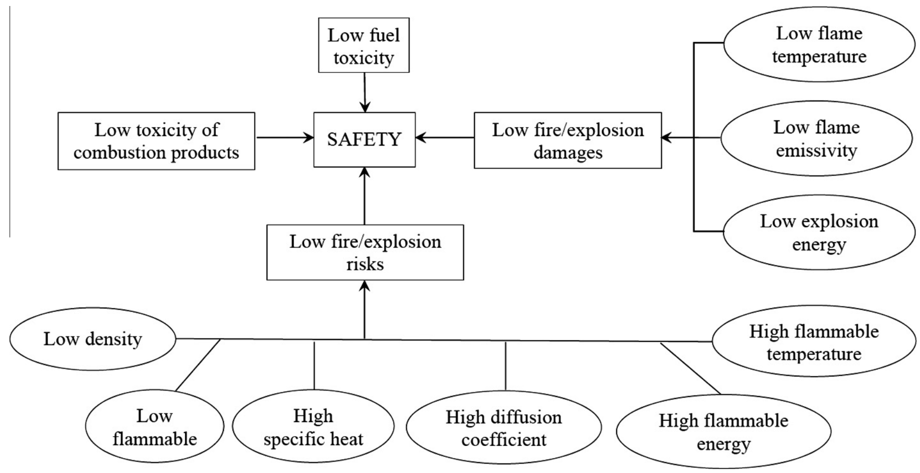


**Fig. 5.** Parameters for safety maximization in fuel exploitation [33].

**Table 2**
Physics and chemical properties for safety consideration of three investigated fuels [33].

| Property | Gasoline | Methane | Hydrogen |
|---|---|---|---|
| Density (kg/m$^3$) | 4.40 | 0.65 | 0.84 |
| Diffusion coefficient in air (cm$^2$/s) | 0.05 | 0.16 | 0.610 |
| Specific heat at constant pressure (J/kg K) | 1.20 | 2.22 | 14.89 |
| Flammable limit in air (vol%) | 1.0–7.6 | 5.3–15.0 | 4.0–75.0 |
| Flammable energy in air (MJ) | 0.24 | 0.29 | 0.02 |
| Flammable temperature (K) | 501–744 | 813 | 858 |
| Flame temperature in air (K) | 2470 | 2148 | 2318 |
| Explosion limit in air (vol%) | 1.1–3.3 | 6.3–14.0 | 13.0–59.0 |

**Table 3**
Safety level reached in the combustion processes of gasoline, methane and hydrogen [33].

| Characteristic | Safety level[a] | | |
|---|---|---|---|
| | Gasoline | Methane | Hydrogen |
| Fuel toxicity | * | ** | *** |
| Combustion products toxicity | * | ** | *** |
| Density | * | ** | *** |
| Diffusion coefficient | * | ** | *** |
| Specific heat | * | ** | *** |
| Flammable | *** | ** | * |
| Flammable energy | ** | *** | * |
| Flammable temperature | * | ** | *** |
| Flame temperature | * | *** | ** |
| Explosion energy | * | ** | *** |
| Flame emissivity | * | ** | *** |

[a] *** More safety; ** intermediate safety; * less safety.

the eleven examined parameters, hydrogen is the safest among the investigated fuels. However, these properties do not make hydrogen the safest fuel during the combustion process, as the security parameters do not have all the same weight (and it is very difficult to assign an objective weight to each).

The wide range and low flammable energy are the main negative aspects that affect hydrogen and, probably, they are more influential than other parameters on the overall safety of the fuel (and on people perception of safety).

In conclusion, hydrogen in the production of thermal energy presents comparable risks to those provided by combustion of natural gas and gasoline.

## 2. Technical and environmental comparison indexes

For the comparison of different types of investigated fuels, a methodology that requires the preparation of appropriate quality indices has been proposed. These quality indexes can be linked to several aspects:

(a) Pollution produced by the combustion reaction of coal, methane, gasoline and hydrogen.
(b) Flammability and combustion temperature of investigated fuels.
(c) Expansiveness in relation to the explosive potential of the different considered fuels.

These indices depend on the thermo-physical fuel properties [34–36] (see Table 4) the pollutant content that is produced by their standard combustion from the content of pollutants produced by their standard combustion (see Table 5) [37–39].

In Table 4 $v''$ has been used to indicate the specific volume of the different fuels in the liquid state, calculated conventionally in critical or quasi-critical conditions (for coal the value corresponding to its oxide has been considered), while with $v'''$ the specific volume of each fuel in a gaseous state or vapour has been indicated. The thermo physical properties of the carbon reported in Table 4 concern the values of its oxide.

Thus, the following quality indexes are introduced:

– Pollution index:

$$i_{jk} = \left(1 - \frac{\dfrac{x_{jk}}{\mathrm{LHV}}}{c_p \cdot T_0}\right)_{\substack{j=a\to d\\ k=1\to 6}} \tag{1}$$

where $x_{jk}$ is the mass concentration of the pollutant substances ($kg_{pollutants}/kg_{fuel}$); LPC is the lower calorific power (J/kg); $c_p$ is the specific heat at constant pressure (J/kg K); $T_0$ is the flammable temperature (K); $j$ is the reference of the considered fuel; $k$ is the type of pollutant substance.

– Expansiveness index:

$$i_{jv} = \left(1 - \frac{\dfrac{v'''}{v''}\Big/ LHV}{c_p \cdot T_0}\right)_{j=a\to d} \tag{2}$$

where $v''$ and $v'''$ (m$^3$/kg) are respectively the fuel specific volumes in liquid and gashouses phases.

**Table 4**
Some thermo-physic properties of investigated fuels.

| Fuel | Specific heat $c_p$ (kcal/kg °C) | Specific volume $v$ (m$^3$/kg) | Lower heating value LHV (kcal/kg) | Combustion temperature $T_c$ (°C) | Flammable temperature $T_c$ (°C) |
|---|---|---|---|---|---|
| $H_2$ | 3.40 | $v'''$ = 11.20<br>$v''$ = 0.033 | 25,000 | 2322 | 571 |
| C | 3.40 | $v'''$ = 0.80<br>$v''$ = 0.033 | 7620 | 2000 | 609 |
| $CH_4$ | 3.40 | $v'''$ = 1.40<br>$v''$ = 0.006 | 11,900 | 1745 | 632 |
| $C_8H_{18}$ | 3.40 | $v'''$ = 0.236<br>$v''$ = 0.001 | 9000 | 3500 | 550 |

**Table 5**
Weighted percentage of pollutant in combustion flue.

| Fuel | | Combustion products in the flues (kg/kg of fuel) | | | | | |
|---|---|---|---|---|---|---|---|
| No. | | $CO_2$ | $SO_2$ | $N_xO_x$ | Particulate and unburnt | $H_2O$ | From Anti-knock agents |
| *a* | $H_2$ | 0 | 0 | 0.016 | 0 | 7 | 0 |
| *b* | C | 1.893 | 0.012 | 0.008 | 0.1 | 0.633 | 0 |
| *c* | $CH_4$ | 2.75 | 0.03 | 0.0075 | 0 | 2.154 | 0 |
| *d* | $C_8H_{18}$ | 3.09 | 0.010 | 0.0115 | 0.85 | 1.254 | 0.001 |
| | | 1 | 2 | 3 | 4 | 5 | 6 |

– Flammability index:

$$i_{jT} = \left(\frac{T_C - T_0}{T_C}\right)_{j=a\to d} \tag{3}$$

where $T_C$ is the combustion temperature (K).

By Eq. (1), 24 indexes $i_{jk}$ have been evaluated, where the weight concentrations of the six pollutants have been correlated to their dimensionless energy content ($LHV/c_p \cdot T_0$) for each of the four investigated fuels. The use of Eq. (2) and of Eq. (3) allows to evaluate four expansiveness indexes and four flammability indexes. All the indexes were made dimensionless by using some physical parameters which characterize the thermodynamic efficiency of every fuel, such as the lower heating value, the specific heat and the combustion temperature. The obtained indexes assume values lower or equal than 1, therefore a normalized value evaluated with reference to its maximum has been calculated:

$$i^* = \frac{i}{i_{MAX}} \tag{4}$$

In this way, in relation to the different properties of pollution, expansiveness and flammability, Eq. (4) allows to highlight better the positioning of the investigated fuel in the ranking: the lower the index, the worse is the fuel. A first and significant technical-environmental comparison between the investigated fossil fuels and the hydrogen can be carried out by using the following composed indexes:

$$i_{G1} = \prod i^*_{jk} \qquad \text{where :} \quad i^*_{jk} = \frac{i_{jk}}{(i_{jk})_{MAX}} \tag{5}$$

$$i^*_{jv} = \frac{i_{jv}}{(i_{jv})_{MAX}} \tag{6}$$

$$i^*_{jT} = \frac{i_{jT}}{(i_{jT})_{MAX}} \tag{7}$$

The obtained values have been shown in form of histograms in Figs. 6–8.

A further elaboration of the indexes to highlight other aspects in the comparison between methane, hydrogen, gasoline and coal has been carried out by the following equations:

$$i_{G2} = \prod \left(i^*_{jv} \cdot i^*_{jT} \cdot i^*_{d6}\right) \tag{8}$$

$$i_{G3} = \prod \left(i^*_{jv} \cdot i^*_{jT} \cdot i^*_{d6}\right) \cdot \prod i^*_{jk} \tag{9}$$

$$i_{G4} = \prod i^*_{jT} \cdot \prod i^*_{jk} \quad \text{(without water)} \tag{10}$$

Eq. (8) represents, in terms of comparison between the investigated fuels, the global aspects of the safety including, in the gasoline combustion, the contribution of the anti-knock agents; in fact $i^*_{d6}$ is the normalized index related to the latter

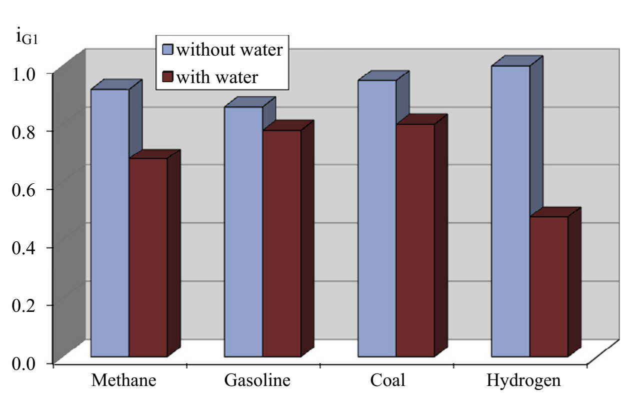


**Fig. 6.** Normalized pollution index for the investigated fuels.

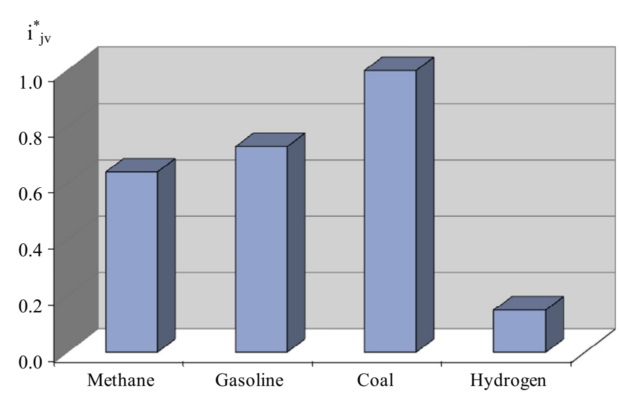


**Fig. 7.** Normalized expansiveness index for the investigated fuels.

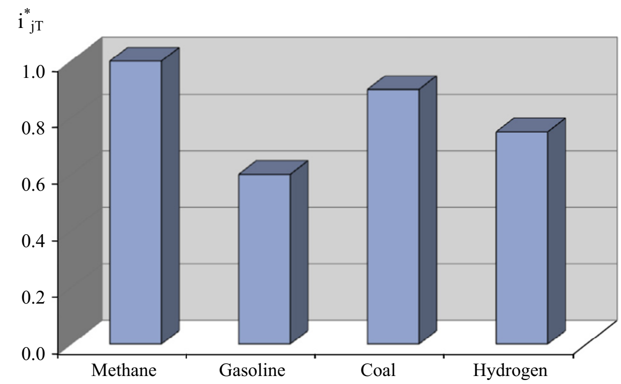


**Fig. 8.** Normalized flammable index for the investigated fuels.

substances. By Eq. (9) the global safety indexes are correlated also with the chemical pollution due to the several combustion products. Finally, $i_{G4}$ is the index used to compare, under the aspects of flammability and chemical pollution, the traditional fossil fuels and hydrogen. Only in this case, the water vapour has not been considered as pollutant in the combustion products; instead in the other evaluations for all the fuels the index referred to the water vapour ($i_{a5}$) has been considered as a pollutant. The results obtained from the prior equations and the values of $i_{G1}$ obtained by Eq. (5) are listed in Table 6.

The hypothesis to consider the water vapour as pollutant penalizes the $H_2$ indexes and it should be excluded in the calculation of $i_{G1}$. Assuming $H_2$ stored in liquid phase at a temperature $T_{cr}$ = 20 K, also the expansiveness index of hydrogen is penalized, but this condition should not be considered if a correct use of the hydrogen accumulators is guaranteed. The high expansiveness of the liquid–vapour phase is dangerous in presence of heat sources, for example the solar radiation incident on the storage systems. Moreover the low temperature inside the accumulators allows to freeze possible infiltrated humidity traces, to form ice thermal bridges which transfer the heat with low thermal resistance. In this context is indubitable that a correct thermal insulation, associated to a rigorous waterproofing and an apposite air exsiccation inside the storage systems air gap, represent suitable techniques to minimize the risk of explosion. Alternatively the storage of $H_2$ in its gaseous form by using accumulators at high pressure ($P$ = 80–100 bar) appears to be more suitable.

Finally, an apposite combination of the prior indexes allows to define a new index which quantifies the whole environmental impact correlated to the use of a specific fuel, in function of a definite sector of employment. For heating application in residential sector, for example, the following relationship can be used:

**Table 6**
Some indexes for the four investigated fuels.

| Fuel | $i^*_{d6}$ | $i_{G1}$ | $i_{G2}$ | $i_{G3}$ | $i_{G4}$ |
|---|---|---|---|---|---|
| C | 1 | 0.9374<br>0.9518<br>(no $H_2O$) | 0.1236 | 0.1159<br>0.1176<br>(no $H_2O$) | 0.8004 |
| $CH_4$ | 1 | 0.8655<br>0.9215<br>(no $H_2O$) | 0.0880 | 0.0762<br>0.0811<br>(no $H_2O$) | 0.9215 |
| $C_8H_{17}$ | 0.9999 | 0.8395<br>0.8749<br>(no $H_2O$) | 0.4339 | 0.3664<br>0.3796<br>(no $H_2O$) | 0.3797 |
| $H_2$ | 1 | 0.4545<br>0.9987<br>(no $H_2O$) | 0.0385 | 0.0175<br>0.0384<br>(no $H_2O$) | 0.6751 |

**Table 7**
Global environmental index for the investigated fuels.

| Fuel | Environmental impact ($i_{env}$). |
|---|---|
| Methane | 0.90 (no $H_2O$)<br>0.80 |
| Gasoline | 0.76 (no $H_2O$)<br>0.72 |
| Coal | 0.82 (no $H_2O$)<br>0.78 |
| Hydrogen | 0.95 (no $H_2O$)<br>0.45 |

$$i_{env} = \left(\prod i_{G1} \cdot i^*_{jv} \cdot i^*_{jT}\right)^{\frac{p}{p!}} \tag{11}$$

where $p$ is the number of factors related to safety aspects and to chemical pollution; for the examined case, $p$ = 3. With reference to the investigated fuels, the values obtained from Eq. (11) are listed in Table 7 and hydrogen achieves the highest score if the water vapour is not considered as pollutant combustion product.

## 3. Hydrogen as a non conventional energy system

Fossil fuels such as oil, methane and coal currently satisfy the majority of the world's energy demand (see Fig. 6) but they are destined to run out in a few years [10,40,41]. Moreover, their combustion is the main reason for global problems such as the greenhouse effect, the reduction of the thickness of the ozone layer, acid rain and widespread general pollution, so their impact on the environment is extremely dangerous.

The data reported in Fig. 9 are important and significant because highlight that today about the 80% of the global energy requirement is covered by fossil fuels, and the remaining 20% by other energetic sources such as nuclear and renewable energy.

A possible solution to solve the global energy problem is the replacement of the actual energy system supplied by fossil fuels with another energy system, based, this time, on the exploitation of renewable sources and on low-pollution fuels such as molecular hydrogen ($H_2$) [42–44].

Hydrogen is the most widespread element in the universe but it does not exist in nature in a molecular form, therefore hydrogen has to be produced starting from water requiring a certain rate

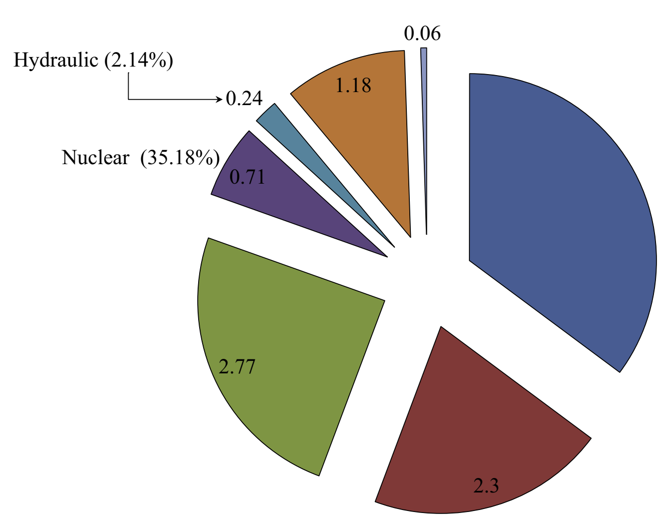


**Fig. 9.** Global distribution of energy consumption in function of the primary sources [10,40,41].

of energy to separate it from oxygen. Another way is the production by hydrocarbons but it also requires substantial energy to separate hydrogen from carbon atoms. When produced, hydrogen can be stored and carried by an appropriate network (hydrogen pipeline) [45] or it can be liquefied and stored in low temperature accumulators to be used as fuel in different applications such as power generation and transport. Hydrogen exploitation does not imply an environmental impact or reduce it to minimal values: in fact, with reference to combustion products, if hydrogen is burned by pure oxygen it provides only water, while if it is burned by air also nitrogen oxides can be produced. These oxides together with other pollutants contribute to the formation of acid rain. Hydrogen can be seen as a fuel and energy carrier and it offers undoubted advantages if compared with fossil fuels [46]; its attributes include: a high ecological quality, the wide versatility during its employment and the possibility to obtain a specific energy for unity of mass three times greater than gasoline combustion. However, the low density values at liquid and gaseous forms render its comparison with gasoline negative if the specific energy is referred to the unity of volume.

In function of the energetic and environmental hydrogen qualities, the exploitation of hydrogen as a primary source and energy carrier requires the complete solution of many problems concerning the technologies employed for its production, transport, accumulation and use.

Currently, hydrogen can be produced in several ways:

– Starting from fossil sources by reforming and gasification processes.
– Starting from renewable sources by electrolysis, gasification or pyrolysis.
– Exploiting nuclear energy by appropriate thermo-chemical processes.

The main problem to produce molecular hydrogen starting from fossil fuels and biomass, is represented by $CO_2$ separation and its confinement, because this greenhouse gas is obtained in all the mentioned methods [47,48]. The electrolysis process allows the production of pure molecular hydrogen, but at very high costs [49,50]. Concerning the problems of hydrogen transportation and accumulation it is important to remember that:

– Hydrogen distribution requires the construction of appropriate pipelines characterized by high investment costs.

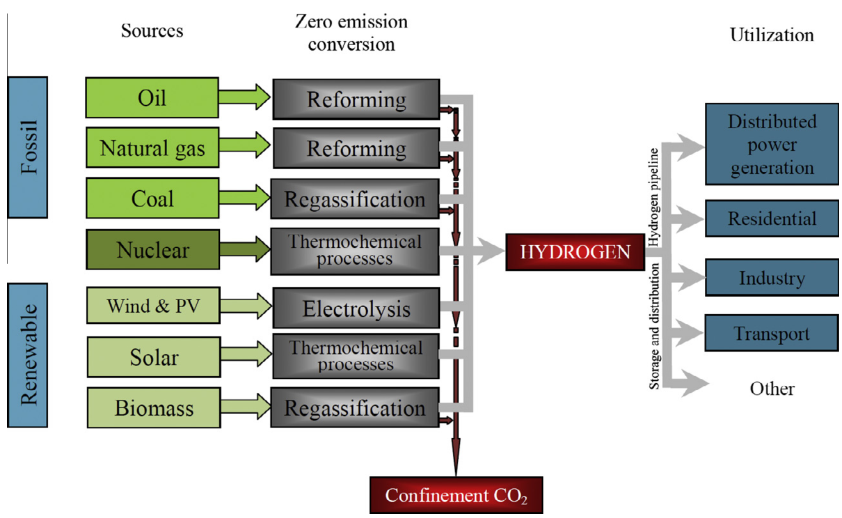


**Fig. 10.** Possible energetic scheme concerning production, transport, accumulation and use of hydrogen [51,52].

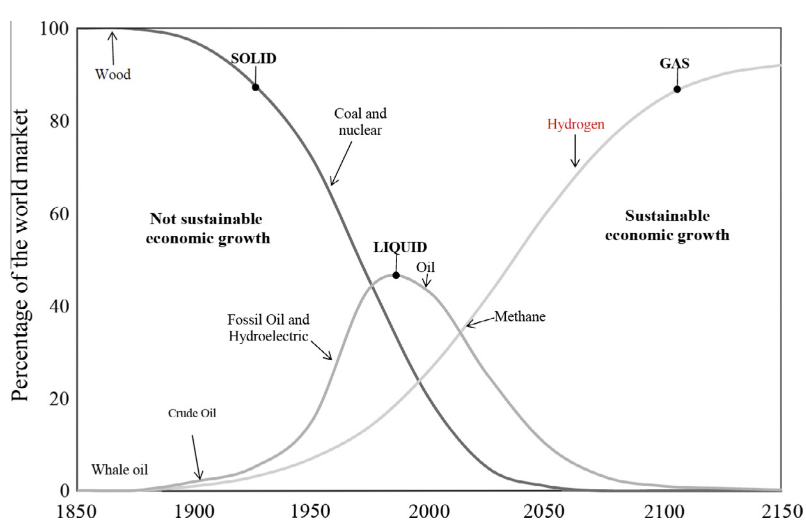


**Fig. 11.** Possible scenario regarding energy sources consumption for sustainable economic growth [51,54].

– Its low density recommends a liquefaction process at a low temperature (about 20 K) or a compression process at high pressure to limit storage volumes, but the two processes require very high energy consumption.

The most efficient way to exploit hydrogen energy is its recombination with oxygen carried out by fuel cells, to produce directly electric energy with a conversion efficiency that is higher than those obtainable starting from the combustion of gasoline, methane and coal.

Hydrogen can be used with evident advantages also as a fuel in internal combustion engines, gas turbines or generic burners [51,52]. In Fig. 10, if the prior mentioned technical problems are solved and if costs are competitive, a possible scheme of a desirable energetic economy supplied by hydrogen as energy carrier and primary source is reported.

A possible percentage frame concerning fuel exploitation from 1850 to the current day and a projection of their exploitation in the future is reported in Fig. 11. It is evident how a sustainable economic growth is achievable if the diffusion of a clean fuel, such as hydrogen, is obtainable in the near future [53,54].

## 4. Conclusion

In this paper, a comparison between traditional fossil fuels and hydrogen by using appropriate dimensionless indexes, which appear very expressive and significant to highlight the quality of their combustion on a technical-environmental point of view, has been carried out.

In particular, related to the general chemical pollution, the hydrogen is preferable among the investigated fuels if the water vapour is excluded from the combustion products. In fact hydrogen is placed at the top of the ranking, followed from coal (0.95), methane (0.92) and gasoline (0.86). Moreover considering the water vapour as pollution product, the possibility to recover it by a simple condensation process could be evaluated. A different consideration has to be done for the expansiveness index: the values of 0.15, 0.64, 0.73 and 1.00 have been obtained respectively for hydrogen, methane, gasoline and coal. In this ranking, hydrogen is strongly penalized due to its high expansiveness when it is stored in liquid form at low temperature, but the position can be considerably improved if the calculation of the correspondent index is conducted considering directly the storage volume in the gaseous phase at high pressure.

Concerning the flammability characteristics, the hydrogen position is better than the gasoline one (0.75 versus 0.60), but it is worse than methane and coal owing to their high combustion temperature. Further advantage in comparison to gasoline, is the $H_2$ low flame velocity (2.65 versus 25); however the hydrogen flame velocity remains higher than the methane flame velocity (0.35).

Another consideration on hydrogen properties concerns the risks of fire. Hydrogen is less dangerous because the radiance of hydrogen flames is very low, as well as the thermal emissivity. Instead the flames fed by fossil fuels have an high temperature and they irradiate more thermal energy. Consequently objects located close to a mass of burning hydrogen could be not damaged, while objects located near the flame of fossil fuels could be strongly damaged or destroyed.

A combination of the investigated indexes, in the specific field of utilization, allows to evaluate for each fuel a global environmental index; for the residential sector, in heating application, hydrogen has reached the highest score of 0.95, supposing the water vapour as a no pollutant substance in the combustion products. Otherwise hydrogen presents the worse score with a value of 0.45.

According to the obtained values for the global environmental indexes and for the other indexes, in a long period scenario the replacement of traditional fossil fuels with other fuel with low environmental impact appears an obligated solution to reduce the problems concerning the depletion of the fossil sources, the environmental degradation and the growth of pollutant emission.

In this sense the employment of a new energetic economy supplied by hydrogen is desirable; the introduction of this energy system allows to have more flexibility because hydrogen could be used in different sectors, such as the electric generation, the residential heating application, industrial and transport. The large exploitation of hydrogen could lead at a considerable reduction of dangerous environmental problems, such as the greenhouse effect and the diffuse chemical pollution.

The hypothesis of hydrogen as a new energy fuel and energy carrier offers evident advantages over traditional energy systems, with particular attention to environmental quality resulting from the processes which derive from its use. The renewability of hydrogen depends on the possibility to produce it from renewable source, for example hydrolysis processes supplied by photovoltaic fields, and moreover it can be used as an energy carrier and a clean energy accumulator. Alternatively hydrogen can be produced also from fossil fuels, biomass and nuclear energy. Furthermore the advantage to use hydrogen is correlated not only on its derivability from other energy sources and on its storage properties, but on its employment by fuel cells and internal combustion engines, which provide lower environmental emissions. Together with these aspects, it is necessary to conduct other evaluations concerning the technical problems related to its utilization. First, it is necessary to develop devices supplied by hydrogen that are capable of reaching high performance values. Successively, it will be necessary to address the aspects concerning its distribution by appropriate infrastructures, the safety aspects linked to its storage needs and, finally, the costs relating to its production.

## References

[1] Nicoletti Gi. L'impatto ambientale dei combustibili generalmente impiegati per il riscaldamento urbano degli edifici. In: Proceeding of Italian conference 56 Congresso Nazionale ATI, Naples; 2001.
[2] Churchill SW. The reduction of air pollution by improved combustion. Fuel Energy 1997;September:338.
[3] ENEA Journal, Italian society for alternative energies, N. 23, Sustainable Development: Hydrogen: Energy for the future; 2004.
[4] Sheer H. Die Gespeicherte Sonne – Wassersfall Als Losung des Energie und Uniwelt Problems. Munchen: R. Piper GmbH&C. KG; 1987.
[5] Nejat Veziroglu T, Sahın S. 21st Century's energy: Hydrogen energy system. Energy Convers Manage 2008;49:1820–31.
[6] Midilli A, Dincer I. Hydrogen as a renewable and sustainable solution in reducing global fossil fuel consumption. Int J Hydrogen Energy 2008;33:4209–22.
[7] Jain IP. Hydrogen the fuel for 21st century. Int J Hydrogen Energy 2009;34:7368–78.
[8] Chamie J. Scenarios for the development of the world population. GENUS 2005;61(3/4):69–89.
[9] IEA – International Energy Agency, Energy technology perspectives 2010. Scenarios and strategies to 2050, Paris; 2010.
[10] IEA – International Energy Agency – World Energy Outlook 2010, Paris; 2010.
[11] Shinnar R. The hydrogen economy, fuel cells, and electric cars. Techno Soc 2003;25:455–76.
[12] Fry MR. Twenty-first century power generation – fuel cells, a review. Fuel Energy 1995;6:434.
[13] Niknam T, Bornapour M, Gheisari A, heat Combined. power and hydrogen production optimal planning of fuel cell. Energy Convers Manage 2013;66:11–25 (power plants in distribution networks).
[14] Nicoletti Gi. Hydrogen as solar energy storage – technical and economical aspects. In: Proceedings of international congress hypothesis, Cassino (Rome); June 1995.
[15] Okken PA. Cost effective integration of hydrogen in energy systems with $CO_2$ constraints. Fuel Energy 1996;3:181.
[16] Gutierrez F, Mendez F. Entropy generation minimization for the thermal decomposition of methane gas in hydrogen using genetic algorithms. Energy Convers Manage 2012;55:1–13.
[17] Quadrelli R, Peterson S. The energy-climate challenge: recent trends in $CO_2$ emissions from fuel combustion. Energy Policy 2007;35:5938–52.

[18] Barreto L, Makihira A, Riahi K. The hydrogen economy in the 21st century?: a sustainable development scenario. Int J Hydrogen Energy 2003;28:267–84.
[19] Haasler JB. Natural gas as a fuel. Environmental damage or advantage. Fuel Energy 1995;36:464.
[20] Boling B, Kheshgi H. On strategies for reducing greenhouse gas emissions. Proc Natl Acad Sci USA 2001;98:4850–4.
[21] Nicoletti Gi, Alitto G, Anile F. Il Controllo della $CO_2$: Misure e Strategie. In: Proceedings of Italian conference ATI, L'Aquila (ITALY); 2009.
[22] Report Kyoto Protocol: Status of Ratification, United Nations Framework Convention on Climate Change; January 2009.
[23] Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Working Group I: The Physical Basis for Climate Change, edited by Susan Solomon IPCC; 2007.
[24] IPCC. Climate Change. Synthesis Report. New York: Cambridge University Press; 2001.
[25] Bruzzi L, Boragno V, Verità S. Sostenibilità ambientale dei sistemi energetici. ENEA report: Tecnologie e Normative; 2007.
[26] Weimer T. Comparison of $CO_2$ sources for fuel synthesis. Fuel Energy 1997;38:118.
[27] Sovacool BK, Brossmann B. Symbolic convergence and the hydrogen economy. Energy Policy 2012;38:1999–2012.
[28] Veziroglu TN. Quarter century of hydrogen movement 1974–2000. Int J Hydrogen Energy 2000;25:1143–50.
[29] Carcassi MN, Fineschi F. Deflagrations of $H_2$-air and $CH_4$-air lean mixtures in a vented multi-compartment environment. Energy 2005;30:1439–51.
[30] Carcassi MN, Marangon A. Proceedings of the international conference on hydrogen safety, Pisa, Italy; 2005.
[31] Matthijsen AJCM, Kooi ES. Safety distances for hydrogen filling stations. Fuel Cells Bull 2006;11:12–6.
[32] Ghenai C, Zbeeb K, Janajreh I. Combustion of alternative fuels in vortex trapped combustor. Energy Convers Manage 2013;65:819–28.
[33] Marini A. Idrogeno: perché? I problemi che devono essere risolti e quelli che il suo uso può risolvere, Internal report Chemical – Physics Department ''M. Rolla'' – Pavia University, Italy; 2005.
[34] Nicoletti Gi. The Hydrogen option for energy: a review of technical, environmental and economic aspects. Int J Hydrogen Energy 1995;20:759–65.
[35] Handbook of Chemistry and Physics. 94th ed., New York: CRC Taylor and Francis Press; 2013.
[36] Handbook of Chemistry. 8th ed., New York: Perry McGraw-Hill; 2007.
[37] Arienti R, Nicoletti Gi, Buttiglieri M. Quality indices of hydrogen and other fuels. In: Proceeding of ninth international heat transfer conference, Jerusalem, Israel; 1990.
[38] Smith KR. Fuel combustion, air pollution exposure, and health: the situation in developing countries. Annu Rev Energy Environ 1993.
[39] Choy YS, Zhen HS, Leung CW, Li HB. Pollutant emission and noise radiation from open and impinging inverse diffusion flames. Appl Energy 2012;91:82–9.
[40] Clo A. Il rebus energetico. Tra politica, economia e ambiente, Il Mulino edition; 2008.
[41] Hoel M, Kverndokk S. Depletion of fossil fuels and the impacts of global warming. Fuel Energy 1996;37:460.
[42] Dunn S. Hydrogen futures: toward a sustainable energy system. Int J Hydrogen Energy 2002;27:235–64.
[43] Solomon BD, Banerjeeb A. A global survey of hydrogen energy research, development and policy. Energy Policy 2006;34:781–92.
[44] Dincer I, Rosen MA. Sustainability aspects of hydrogen and fuel cell systems. Energy Sustain Dev 2011;15:137–46.
[45] Leighty WC, Holbrook JH. Alternatives to electricity for transmission, firming storage, and supply integration for diverse, stranded, renewable energy resources: gaseous hydrogen and anhydrous ammonia fuels via underground pipelines. Energy Proc 2012;29:332–46.
[46] Marini A. Idrogeno Come Vettore Energetico. In: Proceedings of workshop on energy and renewable sources, Chemical Department, University of Pavia, Italy; 2011.
[47] Ewan BCR, Allen RWK. A figure of merit assessment of the routes to hydrogen. Int J Hydrogen Energy 2005;30:809–19.
[48] Ni M, Leung DYC, Leung MKH, Sumathy K. An overview of hydrogen production from biomass. Fuel Proc Technol 2006;87:461–72.
[49] Adamson KA. Hydrogen from renewable resources: the hundred year commitment. Energy Policy 2004;32:1231–42.
[50] Peng X, He C, Fan X, Liu Q, Zhang J, Wang H. Photovoltaic devices in hydrogen production. Int J Hydrogen Energy 2014;39:14166–71.
[51] Verhelst S. Recent progress in the use of hydrogen as a fuel for internal combustion engines. Int J Hydrogen Energy 2014;39:1071–85.
[52] Momirlan M, Veziroglu TN. Current status of hydrogen energy. Renew Sustain Energy Rev 2002;6:141–79.
[53] Cherry RS. A hydrogen utopia? Int J Hydrogen Energy 2004;29:125–9.
[54] Padró CEG, Putsche V. Survey of the economics of hydrogen technologies. National Renewable Energy Laboratory. NREL/TP-570-27079; 1999.