ВОЗОБНОВЛЯЕМАЯ ЭНЕРГЕТИКА
RENEWABLE ENERGY

СОЛНЕЧНАЯ ЭНЕРГЕТИКА
SOLAR ENERGY

СОЛНЕЧНО-ВОДОРОДНАЯ ЭНЕРГЕТИКА
SOLAR-HYDROGEN ENERGY

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IMPACT OF HYDROGEN ON THE ENVIRONMENT*

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The present work considers the impact of hydrogen fuel on the environment within the cycles of its generation and combustion. Hydrogen has been portrayed by the media as a fuel that is environmentally clean because its combustion results in the formation of harmless water. However, hydrogen first must be generated. The effect of hydrogen generation on the environment depends on the production process and the related byproducts. Hydrogen available on the market at present is mainly generated by using steam reforming of natural gas, which is a fossil fuel. Its by-product is CO_2, which is a greenhouse gas and its emission results in global warming and climate change. Therefore, hydrogen generated from fossil fuels is contributing to global warming to the similar extent as direct combustion of the fossil fuels. On the other hand hydrogen obtained from renewable energy, such solar energy, is environmentally clean during the cycles of its generation and combustion. Consequently, the introduction of hydrogen economy must be accompanied by the development of hydrogen that is environmentally friendly. The present work considers several aspects related to the generation and utilisation of hydrogen obtained by steam reforming and solar energy conversion (solar-hydrogen).

Keywords: hydrogen energy; climate change; solar-hydrogen; hydrogen generation; air pollution.

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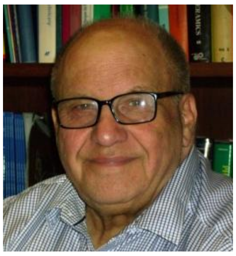
В настоящей работе рассматривается влияние водородного топлива на окружающую среду в циклах его образования и сгорания. Средства массовой информации изображают водород как экологически чистое топливо, потому что его сгорание приводит к образованию безвредной воды. Однако сначала должен быть получен водород. Влияние генерации водорода на окружающую среду зависит от производственного процесса и связанных с ним побочных продуктов. Водород, доступный на рынке в настоящее время, в основном генерируется с помощью паровой конверсии природного газа, который является ископаемым топливом. Побочным продуктом природного газа является CO_2 (парниковый газ), выбросы которого приводят к глобальному потеплению и изменению климата. Следовательно, водород, образующийся из ископаемого топлива, способствует глобальному потеплению в той же степени, что и прямое сжигание ископаемого топлива. С другой стороны, водород, полученный из возобновляемой энергии, такой как солнечная энергия, является экологически чистым во время циклов производства и сжигания. Следовательно, внедрение водородной экономики должно сопровождаться разработкой водорода, который является экологически чистым. В данной работе рассматриваются несколько аспектов, связанных с выработкой и использованием водорода, полученного паровым риформингом и путём преобразования солнечной энергии (солнечный водород).

Ключевые слова: водородная энергия; изменение климата; солнечный водород; производство водорода; загрязнение воздуха.



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1. Introduction

The world is heading towards hydrogen economy with the general perception that hydrogen as a fuel is environmentally clean because its combustion results in the generation of harmless water. Consequently, the enthusiasts of hydrogen economy picture the environment that is free of air pollution, which can be achieved as early as gasoline as fuel is replaced by hydrogen. This picture seems to be correct for urban areas where air pollution is generated mainly by toxic exhaust gases of cars. It is essential to note, however, that hydrogen generation from fossil fuels, such as natural gas and coal, leads to the emission of greenhouse gases and, therefore, is not environmentally friendly. Consequently, in the development of hydrogen technologies we must realise that hydrogen generation is environmentally friendly only when obtained by using renewable energy.

The present work does not pretend to be an overview on hydrogen generation or its utilization. The aim is to consider the effect of hydrogen on the environment in the cycles of its generation and combustion. It is shown that not any hydrogen generation technology is environmentally friendly. The specific aim of the present work is to convey the following key messages:

• Hydrogen generated from fossil fuels, such as steam reforming of natural gas, is not environmentally clean. While the costs of hydrogen production by steam reforming are relatively low, the costs related to its impact on the community are very high.

• Hydrogen is environmentally friendly only when is generated by using renewable energy. Despite that production costs of such hydrogen, at least in the initial stage, are high, only this type of hydrogen is environmentally friendly.

• Hydrogen generated from water by using solar energy (solar-hydrogen) is environmentally friendly and, therefore, is expected to be the fuel of the future.

2. Hydrogen economy

What is so special about hydrogen that media are pinning their hopes on it to solve many of the world's fuel and environmental problems?

First, there is a general expectation that hydrogen can reduce our increasing dependence on oil and natural gas, which so far have been imported from politically uncertain areas. However, entering into the hydrogen economy we must realise of all the positive and negative aspects related to the global replacement of fossil fuels by hydrogen [1, 2].

Another reason for the great hopes related to hydrogen economy is the relatively low cost of hydrogen available on the market at present, which is already lower than the price of oil.

Finally, there is a common perception that hydrogen as a fuel is environmentally friendly because its combustion results in the formation of harmless water. This perception is correct only to a certain extent. On one hand the use of hydrogen powered cars will certainly reduce the emission of greenhouse gases in urban areas. On the other hand, however, the process of hydrogen generation from fossil fuels also results in emission of greenhouse gases.

One may estimate that the potential market for hydrogen as a fuel will be comparable to the present markets for natural gas, coal and gasoline combined. Therefore, the availability of hydrogen will have a major impact on the global energy scenario and the environment.

The development of hydrogen-related technologies and implementation of hydrogen economy is coordinated internationally by the International Partnership for Hydrogen Economy (IAHE) (see http://www.iphe.net). Its aim includes:

• Intensification of bilateral and multilateral collaboration on hydrogen technologies

• Recommendation of research priorities

• Development of standards and regulations

• Address emerging technical, financial, legal, socioeconomic and policy issues

If hydrogen is a remedy for the global energy security, why has its potential not been exploited before?

The main reason for the lack of interest in the development of hydrogen so far was the fact that gasoline has been relatively cheap and widely available. In some countries petrol was cheaper than water. Therefore, for a long time the increasing consumption of gasoline resulted in an increase of its production without, as it seemed, any limitations. The recent sharp increase of the price of oil sends a strong signal that the resources of fossil fuels (oil, gas and coal) are limited. Another increasingly apparent impediment for using fossil fuels is their effect on climate change, which is already apparent. Awareness is growing that we must stop pumping CO_2 and other greenhouse gases into the atmosphere in order to protect future generations from an environmental disaster.

3. Education

Hydrogen has already been used by NASA as a fuel for spacecraft but soon it will be the fuel for aircraft, buses, trains and, most visibly, cars (2). Already, there are prototype hydrogen powered cars and buses on the road. The major car manufacturers, including BMW, Honda, Toyota and Daimler Benz, have undertaken efforts to produce experimental models that are powered by hydrogen, using either combustion engines or fuel cells. It is only a matter of time before gasoline stations begin to adapt their infrastructure to hydrogen distribution. Therefore, it is realistic to expect that in the near future the network of gasoline stations will be replaced by a hydrogen distribution system [1e3]. This will require to develop all hydrogen-related technologies. The universities offering career opportunities in these hydrogen technologies may expect a booming interest in analogy to the presently growing world-wide interest in the information technology.

What will be the impact of hydrogen on our everyday life and how can we prepare for the hydrogen age?

These questions need to be addressed in newly established programs of educational institutions that are expected to have a leading role in facing the challenges of the hydrogen economy. Therefore, there is an urgent need to establish teaching programs in several hydrogen-related areas, including:

• Hydrogen generation. Almost the total hydrogen production at present is based on the steam reforming technology [1], with noticeable exception of selected countries, such as Iceland [3]. It is essential, however, that the teaching programs include the use of renewable energy for hydrogen generation.

• Hydrogen as the storage medium of photovoltaic electricity. Awareness is growing that conversion of photovoltaic electricity into hydrogen is the promising option of energy storage.

• Hydrogen storage. This technology aims at the development of materials and devices for the most effective and safe storage of hydrogen fuel.

• Hydrogen transportation and distribution. This aims at the development of efficient means for hydrogen transportation from the production to distribution sites, such as the stations distributing hydrogen to vehicles.

• Hydrogen utilisation. The major type of hydrogen utilisation will be in transportation. There have been efforts to develop cars based on both combustion engines and fuel cells. The latter are more energy efficient.

• Hydrogen safety. The safety requirements will leads to the development of hydrogen sensing devices able to detect hydrogen on the workplace and triggering alarming systems, when its concentration is above the safe level.

• Impact of hydrogen in the environment. It is essential that implementation of hydrogen economy is consistent with global efforts to reduce global warming.

The universities introducing the teaching programs on the wide range of hydrogen technologies are expected to prepare the cohort of experts able to face the challenge in the implementation of hydrogen economy. There is an increasingly urgent need to implement such programs before it is too late. Government assistance is expected to help universities in overcoming the hurdles in the implementation of these educational program.

The first and the most far-reaching effect of hydrogen technologies on civilization will be in transportation [1]. This will be accompanied by the emergence of new ancillary industries that involve hydrogen production, storage and utilization. While all these hydrogen technologies are important, the effect of hydrogen on the environment must first be considered in terms of its generation.

The steam reforming technology can be viewed as already entrenched. Therefore, there is an urgent need to increase the proportion of hydrogen produced from renewable sources. One should expect that this level of demand will fuel the research and development into alternative methods of hydrogen production. Likewise, increasing recognition of the environmental consequences of greenhouse gas emissions can be expected to drive the development of the production of hydrogen by using renewable energy sources.

4. Hydrogen generation versus utilisation

On Earth, hydrogen hardly exists as naturally-occurring source. However, hydrogen is abundant in many compounds. The most abundant raw material containing hydrogen is water. Hydrogen is also present in natural gas, petroleum, and biomass. Therefore, hydrogen must first be generated from these compounds.

There are several methods of hydrogen generation. The most commonly applied method is based on steam reforming of natural gas [4]. However, a by-product of this method is carbon dioxide, CO_2. Its emission increases in an alarming pace [5–7].

Climate change resulting from global warming is forcing us to search for new sources of energy that must be based on renewable energy and must not produce greenhouse or pollutant gases. Therefore, an important qualifier is the fact that hydrogen generated using renewable energy is environmentally friendly [8]. Accordingly, hydrogen generated using renewable energy is expected to join solar electricity to form the foundation of a sustainable modern energy system. If this is not done, then the introduction of the hydrogen economy will not lead to the protection of the environment.

Hydrogen utilisation is entirely environmentally clean, because its combustion results in the formation of harmless water, however, its generation from fossil fuels, such as steam reforming of natural gas, is not.

4.1. Reforming of natural gas

If hydrogen is generated from natural gas, coal, petroleum, or biomass, it will produce CO_2 as by-product (Table 1). When the CO_2 escapes into the atmosphere it leads to global warming and climate change [7].

At present the atmosphere has been a dump for greenhouse gases. The CO_2 emissions over the period 1700–2000, which is shown in Fig. 1 [5–7], is increasing in an alarming pace.

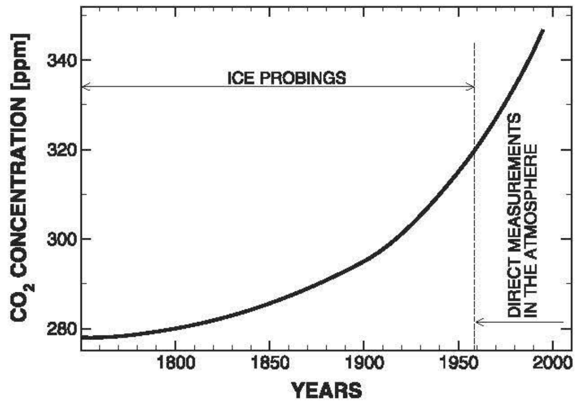

Fig. 1 – The increase of carbon dioxide concentration in the atmosphere
Рис. 1 – Увеличение концентрации углекислого газа в атмосфере

It is important to realise that hydrogen generation from fossil fuels results in the emission of CO_2 to the same extent as direct combustion of these fuels. In this case the place of emission of greenhouse gases is moved out from urban areas to industrial areas where hydrogen generation plants are located. Consequently, while the urban areas will be less polluted when gasoline cars are replaced by hydrogen cars, the generated greenhouse gases will be pumped to the same atmosphere surrounding the planet Earth. Therefore, the vision of urban areas to be free of air pollution when hydrogen powered cars are introduced is correct only to a certain extent.

Hydrogen may also be produced from water by the conventional electrolysis using the coal-generated electricity grid. This process, however, also contributes to the emission of greenhouse gases during the stage of the production of electricity.

In order to reduce pollution by cars, there have been efforts to replace the gasoline combustion engine by fuel cells and by using alternative fuels, such as methanol and ethanol [1]. The reduction of carbon emissions may also be achieved through the development of hybrid cars, combining electrical and combustion engines, and fuel cell powered cars. While in the latter case the carbon emission is reduced substantially, the total elimination of carbon emission may be achieved only by using renewable energy, such as solar energy. Therefore, there is an increasing international pressure to invest in the development of technologies that allow the production of environmentally clean energy, such as solar-hydrogen and solar electricity [8]. This technology is especially promising for countries where the insolation is high, such as Australia, Africa, Asia and both South and North America. There is a widespread perception that carbon emission may be reduced by its sequestration underground or at the ocean floor [7]. While the concept of sequestration is considered by some high polluting industries as a solution, this technology requires energy, which contributes to carbon emission as well [9].

4.2. Solar-hydrogen

Awareness is growing that hydrogen generated by water splitting using solar energy (solar-hydrogen) or other renewable energy is expected to be the fuel of the future because it is obtained from a renewable material (water) using renewable energy (solar energy). The solar-hydrogen may be generated mainly in the following two ways:

• Photo-electrochemical decomposition of water in solar-hydrogen cell. Fujishima and Honda first reported successful photo-electrochemical water splitting. However, this technology is still not commercialized.

• Electrolysis of water using photovoltaic electricity [4]. This process has been already applied in the generation of hydrogen in environmentally friendly fashion.

Solar-hydrogen produced by photo-electrochemical cells may be formed within a single step. Its concept is shown in Fig. 2.

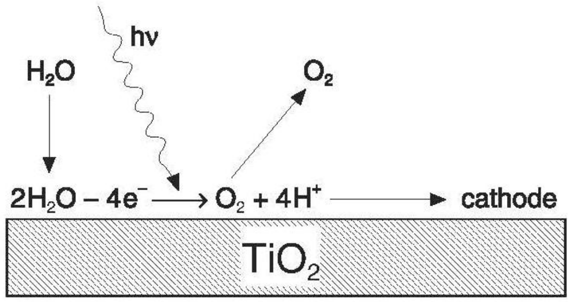

Fig. 2 – The concept of photo-catalytic water splitting
Рис. 2 – Концепция фотокаталитического разложения воды

On the other hand water electrolysis involves two steps and, therefore, it requires two devices, including a photovoltaic solar panel and an electrolyser as it is schematically represented in Fig. 3 [10]. The application of other methods, such as thermal decomposition of water, is limited.

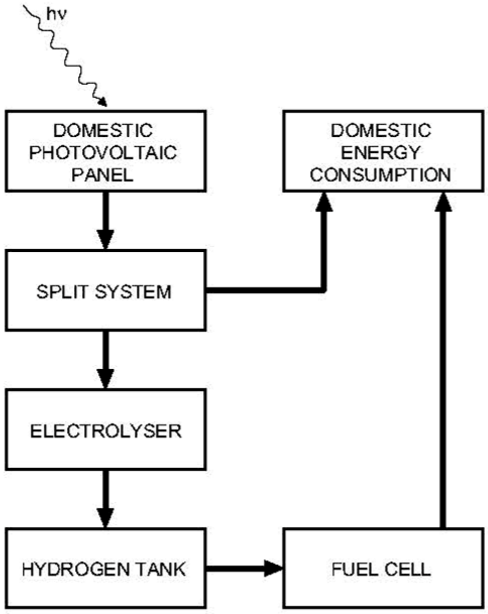

Fig. 3 – Schematic representation of the domestic solar energy system including the generation of photoelectricity and hydrogen. (Reproduced from T. Bak, Oxide Semiconductors. Copyright 2010 T. Bak)
Рис. 3 – Схема отечественной солнечной энергетической системы, включая генерацию фотоэлектричества и водорода (Т. Баком «Оксидные полупроводники». Copyright 2010)

Table 1

By-products of hydrogen generation by steam reforming of natural gas and water splitting

Таблица 1

Побочные продукты образования водорода путем парового риформинга природного газа и разложения воды

Reforming of natural gas		**Solar-hydrogen**	
Process	By-product	Process	By-product
Generation:		Generation:	
$CH_4 + 2H_2O \rightleftarrows 4H_2 + CO_2$	CO_2	$H_2O \rightleftarrows H_2 + 1/2\ O_2$	O_2
Combustion:		Combustion:	
$H_2O + 1/2\ O_2 \rightleftarrows H_2O$	H_2O	$H_2O + 1/2\ O_2 \rightleftarrows H_2O$	H_2O

It seems that the most promising means of producing hydrogen using a renewable energy source and precluding the generation of greenhouse gases production is through water photolysis [11]. This involves water splitting into its component gases (oxygen and hydrogen) using photo-electrochemical cells. As seen in Table 1, the by-products of solar hydrogen generation and combustion is oxygen and water, respectively.

Fujishima and Honda [12] first reported the experiment of water electrolysis using solar energy as the sole driving force for water decomposition. Their concept is based on the ability of photo-sensitive materials, such as titanium dioxide (TiO_2), to split water under light (Fig. 2). The availability of new materials allow to develop solar-hydrogen photo-electrochemical cells with the increasing efficiency of the conversion of solar energy into the chemical energy required to generate hydrogen. The concept of photo-electrochemical generation of solar hydrogen has been outlined extensively elsewhere [11].

Solar-hydrogen resolves the issue of the availability of a fuel that is 100% environmentally clean. Countries that will have access to such hydrogen generation technologies will be able to export solar energy in the form of hydrogen. Consequently, the development of hydrogen technologies will reduce the dominance of resource rich nations in international energy markets.

The race to harvest the energy of the Sun, and to use it for hydrogen production, is escalating and it even has expanded beyond the global realm. A substantial research project has been initiated by the National Space Development Agency (NASDA) of Japan and the Institute for Laser Technology (ILT) [13]. Its aim is the development of a hydrogen generation system using a space-based solar unit, which will harvest exterrestrial solar energy, and the transfer this energy to a titania-based electrochemical device located on Earth. This technology involves (i) the space-based solar collector of solar energy orbiting in space, (ii) laser generator transforming the solar energy into a laser beam and sending it to a groundbased photo-catalytic device, and (iii) the photo-catalytic device consisting of a TiO_2 powder suspended in water to produce oxygen and hydrogen.

The progress in research on photo-electrochemical hydrogen generation using solar energy will be determined by the development of novel photo-sensitive materials that are required for high-performance photo-electrochemical cells [11]. The research aims to develop a new generation of solar materials that are able to harvest solar energy within a wide spectrum, including the UV range and the visible light range.

The future production scale of hydrogen using different technologies will be determined by their costs. Solar hydrogen can be expected to be the winner owing to the following reasons:

• Large parts of continents have an abundance of solar energy.

• The novel materials used to capture solar energy, such as photo-sensitive oxide semiconductors [11], are relatively inexpensive.

• Solar-hydrogen generating units could be adapted easily to the needs of individual households, which provides a driving force for mass production.

5. Cost-related aspects

The production costs of fuels have been mainly considered in terms the direct production costs. It appears, however, the use of fossil fuels includes also indirect costs related to the consequences of air pollution, global warming and climate changes. These costs, which are substantial, so far have been bared by the community. Therefore, the global warming may be effectively addressed when the costs related to carbon emission are included in the costs of fossil fuels. This issue may be addressed through a tax policy, which must be revised so that the costs related to the emissions of greenhouse gases are borne by the industries emitting these gases rather than by the community. Imposition of such tax is urgently needed in order to make renewable energy cost competitive.

The negative aspect of such tax is that the cost of energy generated from fossil fuels will increase and that cost will be passed on to the community. The clear advantage of the carbon tax is that this will subsidize the development of the technologies based on renewable energy.

Fig. 4 shows the production costs of fuel, including gasoline and hydrogen, and its prediction for the next 20 years. As seen, presumably driven by the relative costs of hydrogen and gasoline one should anticipate that hydrogen production will increase substantially by the next 10–20 years.

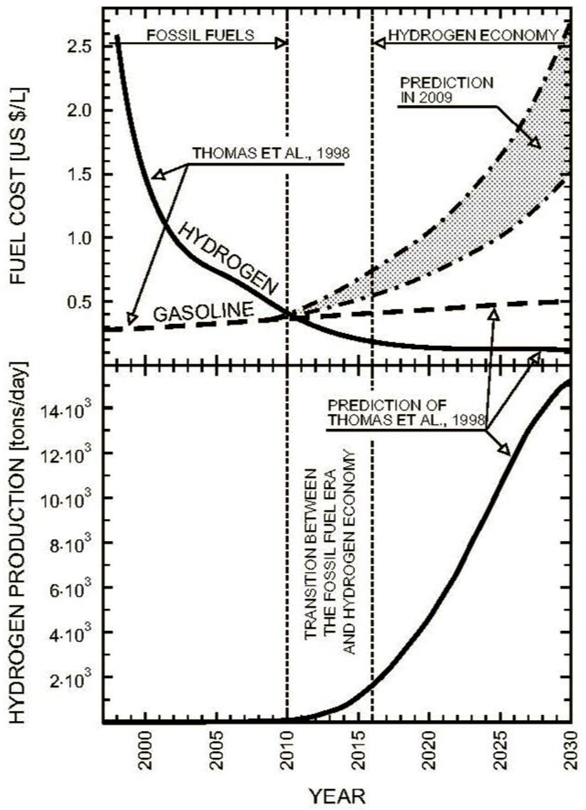

Fig. 4 – The costs of gasoline and hydrogen (upper part) and the hydrogen production (lower part) predicted for the period until 2030 according to Thomas et al. [1] (the amount of hydrogen is in units equivalent to the same amount of oil)
Рис. 4 – Стоимость бензина и водорода (верхняя часть) и производство водорода (нижняя часть) прогнозируются на период до 2030 г. согласно Thomas et al. [1] (сумма водорода в единицах, эквивалентных тому же количеству нефти)

The widely reported costs of hydrogen generation from natural gas are questioned by Bockris [14], who is one of the pioneers of solar-hydrogen. He claims that these costs, which are purely limited to the production, ignore the hidden costs related with its utilisation. Specifically, Bockris claims that these costs do not take into account the enormous costs related to consequences of air pollution and global warming, including:

• Melting ice (Antarctic and Greenland), leading to rising sea level. In consequence, we must be to prepared to absorb 150–300 M refuges from the Pacific rim countries as soon as their countries are flooded due to increased sea level. The related costs are real and must be addressed within the next 20–50 years.

• More intense storms and floods result in damages of the infrastructure and the losses in the production of food. Also more intense droughts results in the losses in the production of food. The related costs are substantial.

• The costs of the destruction of biodiversity are difficult to estimate.

• The costs related to the effect of air, water and soil pollution on human health are enormous.

The awareness of the impact of the use of carbon-emitting fuel on the community has been made by the unprecedented move of the government of California considering a legal action against the main manufacturers of gasoline-powered cars, which are responsible for air pollution. While this action is unprecedented, there is a need to rectify the picture through a legislative approach by imposing a carbon-related tax on industries emitting greenhouse gases or those delivering goods that lead to air pollution. This tax will encourage the carbon-emitting industries to have a carbon credit through the investment in the development of renewable energy. This, in consequence, will lead to enhanced development of environmentally friendly fuels.

The increasing amount of research reports on the development of solar-hydrogen indicates intensification of the race in its development. The efficiency of the solar-to-chemical conversion for the most recently reported solutions reached the impressive level of 18% [15]. So far, however, these solutions do not meet the commercial maintenance requirements as the materials used for the construction of solar cells exhibit high corrosion in water.

The pace of the commercialization of solar-hydrogen will be determined by the costs of its production. The latter is determined by the efficiency of the conversion of solar energy into chemical energy, which is the key parameter in assessing the progress in the solar-hydrogen technology. In other words, the production costs may be reduced when the conversion efficiency is increased.

At present it is very difficult, if possible at all, to predict the price of hydrogen produced from water using solar energy. The report of Morgan and Sissine [4] indicates that the solar energy conversion efficiency around 10% may be economical. According to the US Department of Energy, the energy conversion efficiency, ECE = 12% for solar-hydrogen may be achieved by 2015 [4]. The critical issue in the development of hydrogen solar cell of high efficiencies is the processing of the photo-electrode. Consequently, there is a race in the development of the electrode materials, which are resistant to corrosion and photocorrosion and at the same time exhibit a high conversion efficiency.

It has been claimed, based on preliminary estimates, that the cost of hydrogen manufactured using the Japanese technology [13] will be a modest 20 Japanese yen for an amount of hydrogen equivalent to 1 L of gasoline. This value, corresponding to US$5.8 per GJ, is close to the present market price of hydrogen obtained from methane [16].

Bockris has estimated the costs of solar-hydrogen based on the present costs of photovoltaic electricity used for the generation of solar-hydrogen. These costs, including the production of the equipment and its maintenance, is US$28 per GJ. This figure, compared to the cost of hydrogen from natural gas (US$6) appears to be discouraging. According to Bockris, however, the cost associated with the combustion of fossil fuels and resulting in air pollution is equivalent to US$33/GJ. Therefore, the actual cost of the combustion of these fossil fuels is US$39/GJ. Consequently, taking into account that costs of pollution are very high, solar-hydrogen is an ultimate winner. Further, when the high cost of the siliconsolar cell is replaced by the low cost photo-electrodes made of oxide semiconductors, the cost estimate of US$28/GJ will fall substantially (the costs of the solar-hydrogen production by the photovoltaic route is $44.5/GJ [10].

The most promising candidate for photo-electrode for the production of solar-hydrogen is titanium dioxide, TiO_2, due to the following reasons [11]:

• TiO_2 exhibits an outstanding resistance to corrosion and photocorrosion in aqueous environments.

• While photosensitivity of a standard (commercial) TiO_2 is limited to ECE = w1%, its photosensitivity may be easily enhanced through appropriate engineering of its semiconducting properties [17].

Realistic price figures may become available when solar-hydrogen technologies reach the stage of commercial maturity. However, it is inevitable that some estimates of such costs must be made at this very pre-commercial stage of the development of these technologies. While some estimates of these costs are available, these figures must be considered to be premature.

6. Summary

Introduction of hydrogen economy will have many positive aspects on the global energy scenario and the environment. The immediate results of the replacement of gasoline by hydrogen will be stabilisation of the market for the fuel that can be produced everywhere taking into account that hydrogen may also be generated by electrolysis of water.

One may expect that introduction of hydrogen economy will have an impact on heavy industries, which at present are based on coal and that at present lead to a substantial air pollution, such as metallurgical industry. Specifically, the use of hydrogen may lead to substantial changes in the processing of the reduction of ores.

However, the introduction of hydrogen as fuel will have a beneficial effect on the environment only, if hydrogen is generated using renewable energy. The hydrogen fuel available on the market at present is mainly generated using steam reforming of natural gas. Its generation leads to the emission of greenhouse gases at the same level as in the combustion of fossil fuels. On the other hand, hydrogen obtained from renewable energy, such as solar-hydrogen, is environmentally friendly, because its generation and combustion do not lead to carbon emission. The effect of hydrogen generation and utilization on carbon emission, compared with the emission level by using fossil fuels, is shown schematically in Fig. 5.

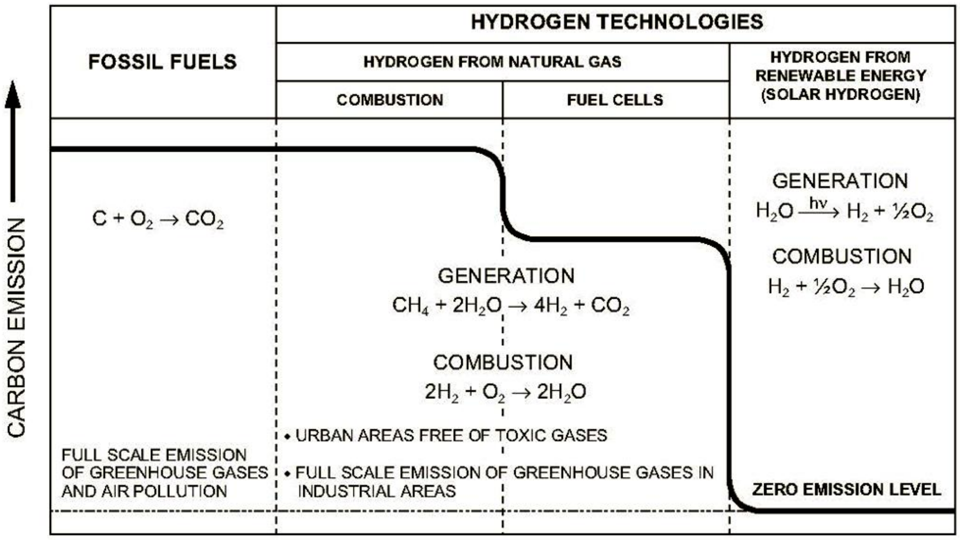

Fig. 5 – The effect of hydrogen generation and combustion on carbon emission
Рис. 5 – Влияние генерации и сжигания водорода на выброс углерода

As seen, the implementation of hydrogen economy involves several stages. Consequently, the introduction of hydrogen economy must be accompanied by the development of hydrogen generation technologies, which are environmentally friendly.

Momirlan and Veziroglu [18] have reported an extensive overview of the current status of hydrogen economy including the hydrogen production.

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