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## ENERGY SAVING, NEW AND RENEWABLE ENERGY SOURCES

# Will Hydrogen Be Able to Become the Fuel of the Future?

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**Abstract**—The results of exploring the prospects of hydrogen economy are presented. The complete production chains are investigated considering various technologies of production, storage, and subsequent utilization of hydrogen in transportation and electric power generation. Comparative analysis of the economic competitiveness of these chains with each other and with solutions based on the use of alternative fuels has been performed. Potential segments for the commercial application of the technologies and the conditions required have been evaluated. The analysis has established the most promising directions in the development of hydrogen economy. They primarily include the use of hydrogen in the defense industry and power supply of critical facilities, where the energy generation costs are not a determining factor. To be competitive in the civil consumption sectors, such as transportation and the power industry, hydrogen technologies have to become significantly less expensive or to receive the corresponding regulatory support. In many countries, the environmental sustainability of hydrogen production will have great significance. The authors conclude that hydrogen can become one of the fuels of the future; to effect this, however, we will have to tread a difficult path of technological progress under stiff competition with continuously developing alternative power-generation methods.

*Keywords:* hydrogen, hydrogen fuel economy, electrolytic cell, consumption, technologies, economy, competitiveness

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It has been known for a long time that hydrogen can be used as an energy source. The first practical experiments were conducted in this sphere as early as in the 18th century. In the early 19th century, works were conducted in several countries on the use of hydrogen as a fuel for internal combustion engines. Hydrogen began to be widely used as a fuel for airships, including those designed for trans-Atlantic flights. The most intense works in hydrogen fuel economy were conducted in Germany, Great Britain, the Soviet Union, and the United States. In the 1940s, hydrogen was used in airships in Leningrad under siege; under a severe shortage of fuels and lubricants, approximately 500 vehicles were switched to hydrogen fuels [1]. However, the decline of the era of airships against the background of severe crashes and the development of aircraft manufacture resulted in a decline in the interest in using hydrogen.

Serious attention was given to the concept of hydrogen fuel economy during the 1970s oil crisis. Hydrogen, being the commonest element of Mendeleev's periodic system, then began to be considered as the key energy carrier of the future [2]. The impending depletion of conventional fossil power sources and the aggravated problems of atmospheric air pollution in large cities became the main incentives to conduct research in this field [3]. Liquid hydrogen was proposed as an alternative to oil fuels for transportation. Its advantages seemed to be obvious since the reserves of this element were practically inexhaustible and, being fired, it released harmless water vapors.

In later studies, the prospects of storing electric power in fuel cells was discussed [4]. This technology cluster was considered one of the key methods for utilization of electric power produced by NPPs during off-peak hours [5, 6]. By the early 1990s, the world had focused its attention on the combination of renewable energy sources (RESs) and electrolytic cells as the key hydrogen production technology; moreover, the development of such technologies, in which over 160 million dollars were invested during 1996–2001 in the form of public grants, underlay the United States' energy policy [7].

Starting from the second half of the 2010s, against the background of the strengthening global environmental strategy, the prospects of hydrogen fuel economy were again considered to be one of the potential key lines of transforming the global energy system. More than 20 countries adopted strategic programs on the development of hydrogen fuels and fuel cells [8]. Some participants of the energy market consider hydrogen to be a promising business asset [9–13]. Some expert organizations promise a multiple increase in the consumption of hydrogen as early as in the nearest 20–30 years outside the petrol-and-gas processing and chemical industries, which are presently the key consumers of hydrogen [14–17].

The aims of this work are to consider the technical and economic parameters of the existing technologies of production, storage, and transportation of hydrogen; to identify the potentially appealing market niches and sectors of its application; to form and evaluate complex hydrogen supply chains from the production to the end user; and to establish those of them in which hydrogen fuel economy may prove to be more competitive than alternative solutions.

## HYDROGEN PRODUCTION TECHNOLOGIES

Hydrogen is produced by several technologies; three of them, viz., catalytic gas reforming, solid fuel pyrolysis, and water electrolysis, are considered to be the most promising and widely used.

### *Catalytic Reforming (Conversion) of Methane, Propane, Ethane, and Butane*

This method is the most widespread worldwide. Its wide application is determined by the availability of natural gas reforming plants installed directly at oil and gas refineries from which the produced hydrogen is immediately supplied as the technological hydroprocess feedstock. The cost of hydrogen production by this method is the lowest among all alternatives, 1.0–4.5 \$/kg depending on the price of the raw feedstock [18–20]. Hydrogen produced by this process, however, cannot be classified as an environmentally friendly and carbon-free product. In the course of converting methane, in addition to carbon dioxide $CO_2$, extremely toxic carbon monoxide is released. Recent studies on the production of hydrogen are aimed at reducing the carbon dioxide emissions by disposing of carbon oxides released, which, according to the International Energy Agency, increases the production costs by 1.5 times at least [21]. Another variant is the adiabatic methane conversion, which ensures reduced $CO_2$ emissions and enables the process to be performed at lower temperatures and, consequently, with lower power and money input [22]. This technology, however, involves the reduction in the yield of the target product, pure hydrogen, since part of it combines with carbon forming a valuable energy material, a high-calorific methane–hydrogen mixture (MHM), which results in a reduction in carbon dioxide emissions.

### *High-Temperature Pyrolysis of Heavy Raw Materials (Coal or Solid Biomass)*

This hydrogen production technology is even less environmentally friendly than methane conversion due to the formation of a large amount of carbon dioxide. The costs of producing hydrogen by gasification of solid fuels are 1.3–4.5 \$/kg [23].

### *Water Electrolysis*

Water electrolysis yields oxygen and hydrogen. The economic characteristics of the production process depend on the costs of the electric energy consumed and the utilization level of the facilities. So-called "green hydrogen" is produced solely at power stations run on RESs or in nuclear reactors. Nevertheless, it is not zero-emission hydrogen since the carbon footprint, i.e., emissions along the entire power-generation chain, is frequently not mentioned in research studies. The production costs of such hydrogen are 3.5–10.0 \$/kg [24]. This engineering solution involves a considerable increase in the hydrogen production costs owing to low and nonuniform utilization of electrolytic cell capacities. Thus, with a reduction in the electrolytic cell loading from 100 to 10%, the costs of producing every kilogram of hydrogen increase from two- to fourfold depending on particular equipment and the starting price of electric power. The costs of producing hydrogen by electrolysis using RESs depend on natural conditions, such as solar radiation intensity, wind strength, and seasonal changes. The cost forecast considering potential reductions in prices is shown in Fig. 1.

In general, the hydrogen production costs are affected by the prices of the feedstock (such as hydrocarbon gases, solid fuels, and water, which may reach 30–65% in the final costs), the scale of production (with the savings reaching approximately 30% depending on the production scale [25]), and the utilization of the capacities. At the same price of the feedstock, the production costs increase by approximately three times when the utilization level changes from 100 to 10% [26].

It is important to note that the generation of hydrogen solely by electrolytic methods ensures emission-free production at the electric-power–hydrogen stage. When using alternative methods, greenhouse gases are emitted in highly significant amounts, the capture and disposal costs of which gases considerably increase the hydrogen production costs.

In the future, hydrogen production processes considered by the research community as potentially efficient technologies, viz.:

(1) partial oxidation of methane into synthesis gas on palladium, nickel, cobalt, and copper catalysts [27, 28],

(2) production of hydrogen from cerium sulfates in photocatalytic reactors [29], and

(3) electrochemical processes for production of hydrogen on a catalytic iridium, ruthenium, nickel dioxide, and vanadium monolayers [30], may be added to water electrolysis, solid fuel pyrolysis, and methane conversion.

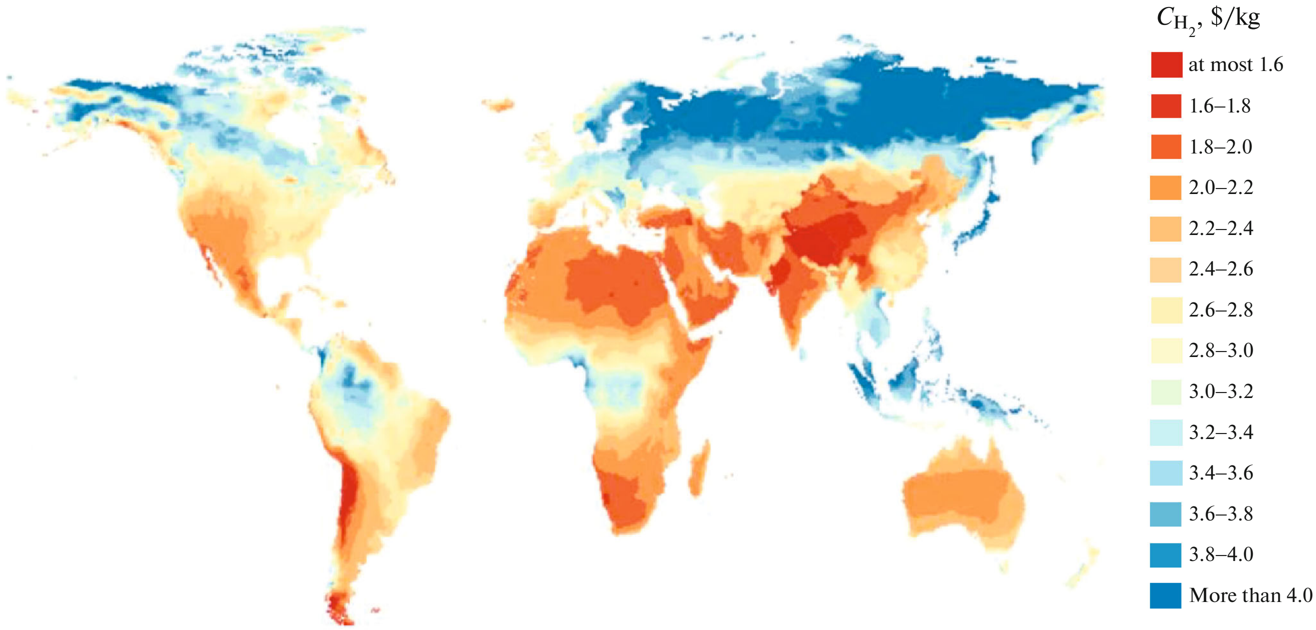


**Fig. 1.** Predicted long-term hydrogen production costs $C_{H_2}$, $/kg, using electric power generated by solar panels and onshore wind power plants [13].

Currently, the above technologies are under research and development and have not been trialed on a commercial scale.

## HYDROGEN TRANSPORTATION AND STORAGE

It is reasonable to classify the hydrogen storage and transportation methods as physical and chemical ones.

Hydrogen gas is stored and transported in vessels (the physical method) in which hydrogen molecules do not interact with the ambient medium. Pipelines, salt caverns, water-bearing rocks, gas holders, and multiwall cylinders in which hydrogen is stored in the compressed state (hydrogen gas in cylinders) are best suited for this purpose. Theoretically, conventional gas pipelines are suitable for transportation of hydrogen. However, one should bear in mind that, despite a high energy content of hydrogen per unit mass—it is 2.4 times higher than that of methane and 2.8 times higher than that of gasoline [31]—its energy content per unit volume is 3.7 times lower than the energy content of petroleum products and 3.0 times lower than the energy content of natural gas. Consequently, if hydrogen is transported through a gas pipeline, the volume of the transmitted energy equivalent will be reduced compared with the volume of the natural gas, which results in a commensurate increase in the transportation costs by approximately 1.5–2.0 times [32].

There is also the problem of the adverse impact of hydrogen on the metal of the pipelines of most transportation systems in operation. Therefore, it is reasonable to think of the transportation of hydrogen through conventional gas pipelines mixed with natural gas with up to 30% of hydrogen. In this case, the hydrogen transportation costs through existing 100-km long gas pipelines that have already recouped their costs will be approximately 0.3 $/kg at a gas transportation tariff of $ 2.5 per thousand cubic meters for the same distance. This will require extra expenses on separation of hydrogen from the methane–hydrogen mixture at the consumption site if hydrogen is further used in its pure form.

The storage and transportation of hydrogen in cylinders involve a serious danger due to its high volatility and explosive hazard when in contact with air. This explains the extremely high material intensity of such a transportation method—a container with a weight of approximately 20 kg per 1 kg of hydrogen transported—which, accordingly, has a negative effect on the transportation prices. According to the US Department of Energy, the transportation costs—corrected for the current prices of fuel for truck loading—of 1 kg of hydrogen in the gaseous state for a distance of 100 km are 3–5 $/kg by road and 2.1–2.4 $/kg by rail. The depressurization of hydrogen additionally increases the delivery costs by 0.4–0.8 $/kg. In consideration of the handling charges and the train making-up time, transportation by rail proves to be more appealing than transportation by road only for long distances.

The physical methods also include the transportation of hydrogen in liquid state, which reduces the weight of the container material by 4–5 times compared with gas cylinders [33]. This method however, involves considerable technological difficulties related to the liquefaction of hydrogen that remains in a liquid state within a very narrow temperature range from its boiling point of 20 K (−253.15°C) to its freezing point of 17 K (−256.15°C). The hydrogen liquefaction costs are 0.5–2.4 $/kg depending on the weight of the liquefaction plant. A rather expensive cryotank increases the delivery costs by another 1.1 $/kg on average, and the need for liquid hydrogen terminals increases the aggregate liquid hydrogen delivery costs up to 5–10 $/kg [25, 33].

The most thoroughly studied method for storing chemically bound hydrogen storage in the form of metal hydrides when the hydrogen atoms are incorporated into the crystal lattice of metals, such as magnesium, sodium, lithium, lanthanum, and titanium. The transportation and storage of hydrogen in the hydride form are comparatively safe since hydrogen is not separated from metal compounds under normal conditions. Moreover, the direct costs of production of hydride compounds are lower than hydrogen liquefaction costs. This transportation and storage method allows for partially solving the problem of the material intensity by reducing the capacity of the transported container by 30–300% [34] compared with the container with liquid hydrogen. The weight of hydrogen is only 5–10% of the hydride plant weight. To separate pure hydrogen from hydrides, the latter has to be heated.

The costs of incorporating hydrogen into a hydride depends to a considerable degree on the price of the metal and the dissociation temperature. For example, magnesium hydride is relatively inexpensive; its dissociation temperature, however, is 560–570 K (286.85–296.85°C), while hydrogen is separated from considerably more expensive vanadium at a temperature of 270 K (−3.15°C). The transportation of hydrogen in granulated hydride compounds (nanostructured hydrides) somewhat reduces the material intensity of the process but makes it more expensive [35]. The main advantages of storing hydrogen in metal hydrides compared with the physical methods are the small space occupied by the plant and the separation of hydrogen from some hydrides at a temperature of 100°C. This allows the hydride plants to be used as fuel tanks and hydrogen to be fed directly into a power-generating unit, e.g., a vehicle engine. Such experiments on substituting hydride plants for hydrogen tanks were conducted by Toyota and GM at the turn of the 21st century [36]. However, due to the great weight of metal plants, the carmakers returned again to cylinders with compressed hydrogen in their more recent models. The costs of incorporating hydrogen into a hydride is approximately 1 $/kg, while the delivery of metal hydrides by rail or road is 10–30% (1.5–2.0 $/kg) cheaper than the transportation of hydrogen in cylinders [37].

The chemical methods include the storage of hydrogen in the form of nonmetal hydrides, e.g., hydrazine, a nitrogen compound. Hydrazine is used as a propellant; it is an extremely explosive and highly toxic substance. However, under certain conditions, it can be safely stored releasing hydrogen when in contact with warm water. The production of hydrazine is an expensive process; the price of this substance is approximately 9 $/kg with the content of pure hydrogen equaling approximately 120 g/kg, i.e., the price of hydrogen separated from hydrazine is approximately 100 $/kg.

Hydrogen can be transported in high-molecular hydrocarbons like polysaccharides and organic acids at a comparatively low material intensity; but one has to realize the possibility of releasing carbonic acid or carbon monoxide when producing hydrogen at its consumption sites.

Further, a method for storing hydrogen in clathrate hydrates, compounds, the crystal lattice of which is represented by water molecules and the hydrogen atoms are located in polyhedral lattice vacancies, is known [38]. Such storage of purely hydrogen hydrates requires abnormally high pressures above 100 MPa; with decreasing pressure, the compounds drastically lose stability. Research in this area is aimed at exploring the potentialities of transportation of hydrogen in binary clathrate hydrates, which, in addition to hydrogen, contain other molecules, e.g., molecules of methane. Such compounds are far more stable; however, when being decomposed, they form carbon oxides.

The hydrogen transportation and storage technologies are perhaps the key obstacle to the development of hydrogen fuel economy. Conventional physical methods involve great danger and great losses in the target product as well as an extremely high material intensity determined by high volatility of hydrogen and its ability to “embrittle” the metal. Today’s chemical methods allow for almost completely solving the problem of hydrogen losses during transportation and storage; however, they do not frequently allow solving the problem of the material intensity. Moreover, many of them can be implemented if the “semifinished product” is transported, and the separation of hydrogen from which entails generation of hazardous substances (see Table 1). Furthermore, nearly all transportation methods double the price of hydrogen.

## SEGMENTS OF CONSUMPTION AND COMPETITION

Due to high prices of hydrogen produced by recent technologies, the worldwide consumption of the pure product had been only 55–65 million t by 2017 according to different estimates. Hydrogen is most widely used as a raw material required for various technological processes rather than a source of energy. The development of the oil-and-gas industry, in particular,

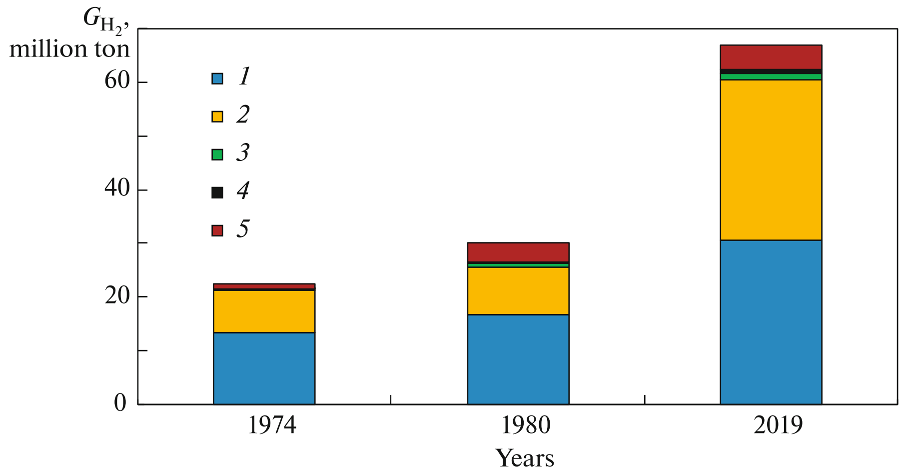


**Fig. 2.** Demand for hydrogen $G_{H_2}$ by the consumption sectors [5]: (*1*) production of ammonia and methanol, (*2*) petroleum refining, (*3*) metallurgy, (*4*) electronics, and (*5*) other industries.

the increase in the scale of hydrogenation and hydrocracking of petroleum fractions, has become the main driver of the global demand for hydrogen, while petrochemistry, especially, the production of ammonia and methanol, has ranked second in the demand for hydrogen $G_{H_2}$ and its share in the aggregate consumption [39] (Fig. 2).

The use of hydrogen in the power industry is still restricted by a set of natural causes, predominantly high costs of its production. It is important to realize that there is highly intense competition with the available and potential alternative fuels in all consumption sectors in which hydrogen can be used as a source of energy. To explore the potentialities of hydrogen competing in several consumption niches, the complete economic supply chains have been considered (Fig. 3).

## USE OF HYDROGEN IN ELECTRIC POWER GENERATION

In electric power generation, hydrogen has prospects in two main areas. The first area is the balancing of the load when the excess electricity is converted into hydrogen by electrolysis and, at the power deficit periods, hydrogen will serve as a fuel for power stations.

**Table 1.** Characteristics of the basic hydrogen storage and transportation methods

| Form of storage | Hydrogen content*, wt % | Danger level | Storage loss | Emissions | Transportation costs |
|---|---|---|---|---|---|
| Gaseous (in cylinders) | 5 | Moderate | 1–3%/day | None | 2.5–6.0 \$/kg per 100 km if transported in cylinders |
| Liquid | Approximately 20 | ″ | 0.06–3.0%/day | ″ | 5–10 \$/kg |
| Metal hydrides | 5–10 | None | 0 | ″ | 2.0–2.5 \$/kg; there is a possibility of using the fuel cell directly as part of the power-generation system |
| Hydrazine | Approximately 12 | High | 0 | NO | Over 60 \$/kg |
| High-molecular hydrocarbons | 4–6 | Low | 0 | CO | 1.0–1.5 \$/kg and approximately 1.0–1.5 \$/kg for aftertreatment |
| Methane–hydrogen mixture | Approximately 23 | Moderate | Insignificant | CO, $CH_4$ | 0.3 \$/kg through pipelines for a 100-km distance + approximately 1.0 \$/kg for separation of pure hydrogen at the consumption site |
| Clathrate hydrates | Approximately 5 | Low | Insignificant | None | Under study |
| Molecular sieves | Approximately 5 | ″ | 0 | ″ | Idem |

* Weight percentage of hydrogen in the total weight of the substance to be transported/container.

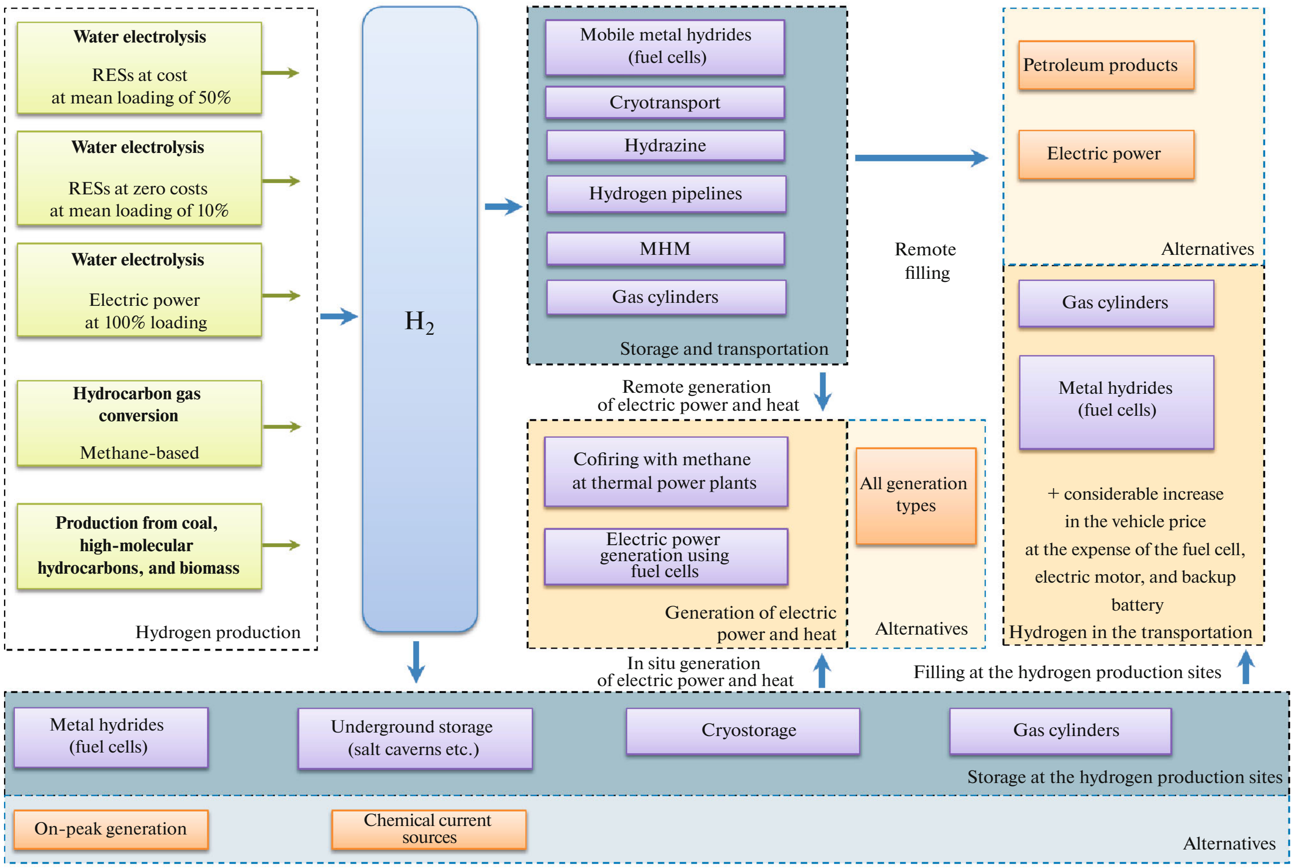


**Fig. 3.** Hydrogen production, transportation, storage, and consumption chains.

The second area is the use of hydrogen in electric power generation as a heat carrier in a hydrogen–methane mixture fed into the gas turbine.

In the first case, hydrogen competes with various types of electric power storage devices and backup capacities based on fossil fuels. With respect to average electric power storage costs at the present stage of the technological development, hydrogen is inferior to pumped storage hydropower plants, underground compressed-air energy storage systems, supercapacitor energy storage systems, and flywheel energy storage systems so far and is in the same competition zone as intensely developing lithium-ion, sodium–sulfur, lead, and redox flow batteries (Fig. 4).

Energy storage systems are frequently compared based on the energy content per unit, i.e., the electric energy contained in a battery with a mass of 1 kg. This parameter may be a significant but not the determining characteristic of a mobile storage system and an insignificant characteristic for stationary energy storage systems. The storage costs play an important role; moreover, hydrogen, having a comparatively high energy content in terms of mass, has an extremely low energy content in terms of volume, which determines the large dimensions of the storage systems. Nevertheless, in terms of the energy content per unit, at present, the hydrogen storage systems considerably surpass the chemical power sources; for example, the energy content of hydrogen stored in containers at a pressure of 35 MPa is 524 W h/kg. Among the available technologies, the lithium-ion batteries, which are five times less capacious than the hydrogen storage systems, are the closest with respect to this characteristic. In the future, however, this gap may narrow. For example, the theoretical energy content potential of the hydrogen storage systems is 700–1300 W h/kg and that of promising sodium–sulfur batteries is 925 W h/kg (see Table 2) [40–42].

One of the drawbacks of using hydrogen as an energy storage means—even provided that it is delivered along a short supply chain without being transported—is a considerably long idle time of the expensive plant, the electrolysis cell, which results in a considerable increase in the hydrogen production costs at constant prices of the incoming electric power (Fig. 5). However, with the electrolysis cell being loaded to capacity, the electric power storage costs prove to be higher than the generation costs using fossil fuels.

As mentioned above, in the second area, hydrogen is used as a heat carrier in the methane-hydrogen mix-

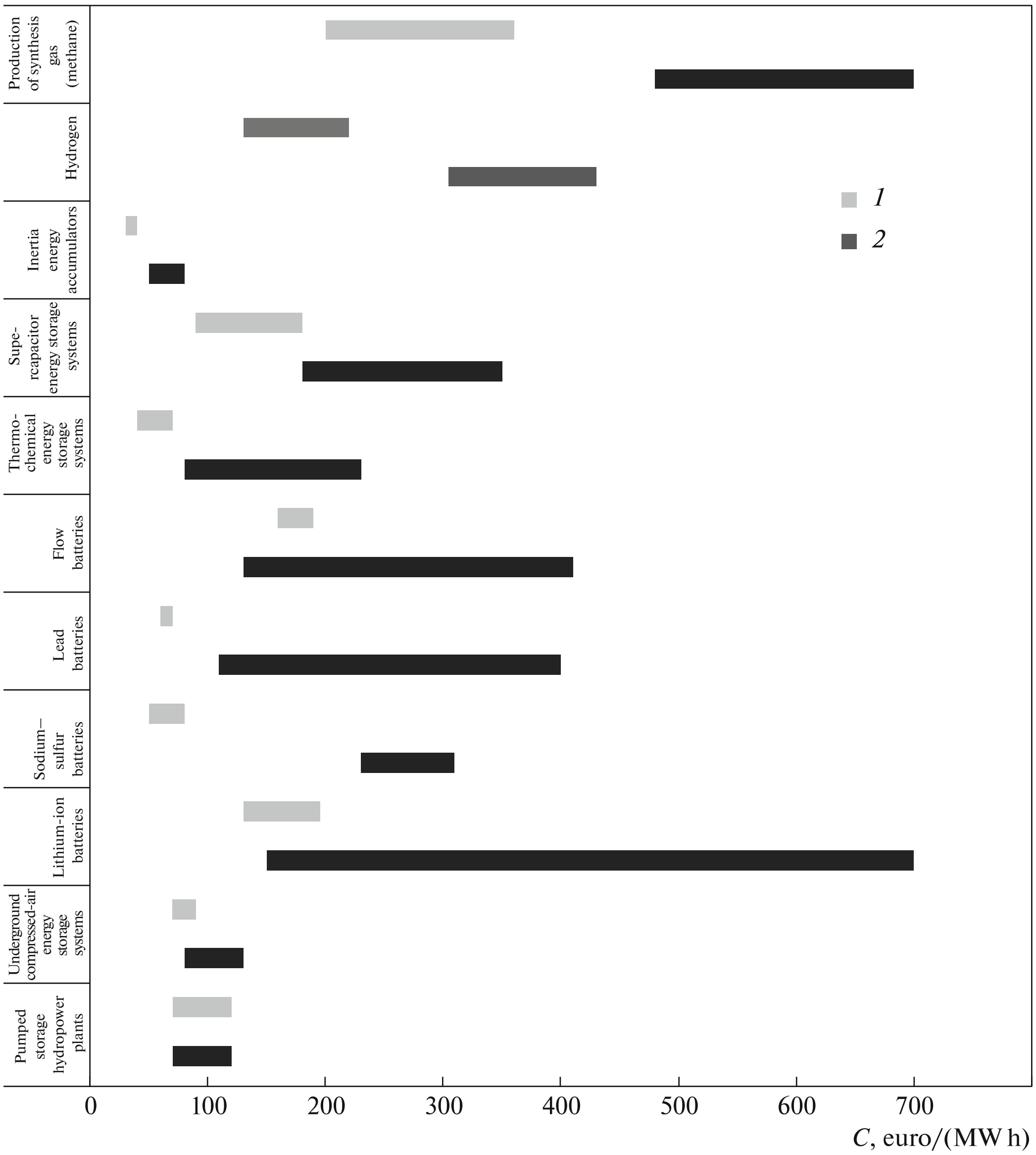


**Fig. 4.** Mean energy storage costs $C$ in (*1*) 2030 and (*2*) 2015 [39].

ture (MHM) fed into a gas turbine. Since hydrogen, when interacting with air, forms inflammable mixtures, the use of the MHM allows a reduction in the consumption rate of the air required to burn methane [43]. In this case, more complete combustion of natural gas and accompanying gases occurs, which reduces nitrogen oxide, carbon dioxide, and carbon monoxide emissions by approximately 30%. The efficiency of the power plants increases by approximately 10%; however, the price of the fuel produced increases by 40–140 $ per thousand cubic meter of the fired gas depending on the hydrogen source (Fig. 6).

Another advantage of the above technology is the possibility of using the existing gas-transportation infrastructure. In this case, natural gas can also be used as one of the hydrogen sources. The adverse

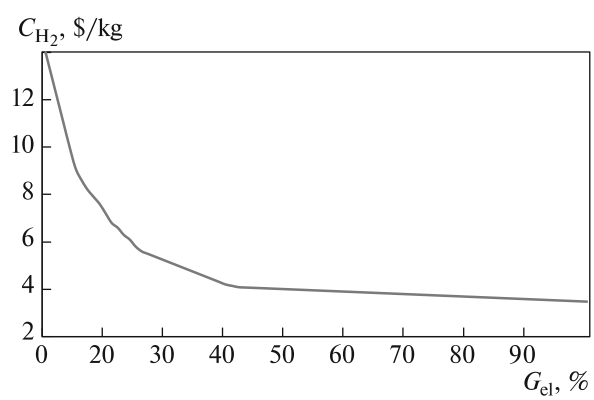


**Fig. 5.** Dependence of the hydrogen production costs $C_{H_2}$ on the loading level of the electrolytic cell $G_{el}$ [24].

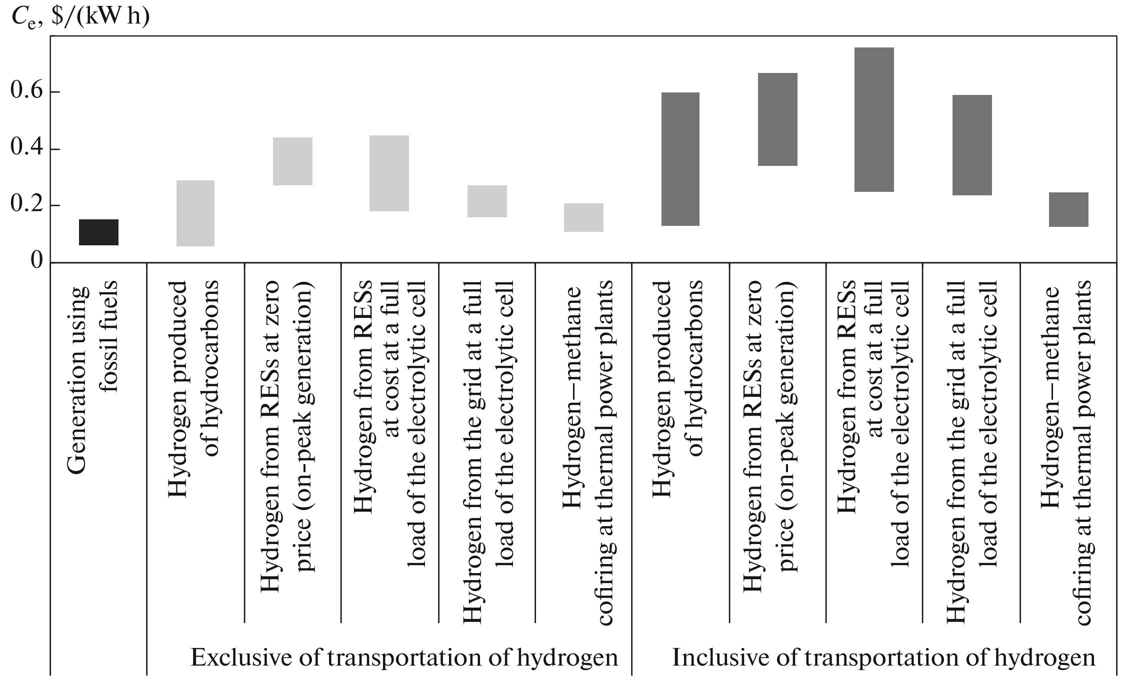


**Fig. 6.** Cost of electric power $C_e$ generated by different processes.

impact of hydrogen on the gas pipelines [44] and the necessity of separating hydrogen for the users that need only methane can be technological restrictions. It should be noted that, according to some research studies, the gas pipelines are able to preserve their technical parameters at a low content of hydrogen [45, 46]. The problem of embrittlement of the pipeline metal at the increased hydrogen content can be solved by manufacturing pipes of novel technological materials; this will need, however, cost-intensive modernization of gas supply networks.

Despite the fact that the electric power generated using hydrogen is more expensive than the electric power generated of fossil fuels, hydrogen has certain prospects of being integrated into the energy balance structure under the current state of the technologies. The increased emission charges may considerably reduce the economic indicators of the electric power generated from fossil fuels and, consequently, enhance the competitiveness of the systems for generation of electric power using hydrogen.

The situation when hydrogen needs to be transported for considerable distances looks worse. All existing methods for transportation of pure hydrogen increase its price for the end user by 1–10 $/kg; when it is transported, for instance, in the MHM, it has to be additionally purified at the consumption sites. Consequently, the electric power generation costs increase, especially in the transportation segment.

**Table 2.** Specific energy content of electric energy storage systems

| Energy storage system | Energy content per unit, W h/kg | |
|---|---|---|
| | average according to the 2018 data | predicted |
| Battery: | | |
| nickel–cadmium | 50 | – |
| nickel–metal-hydride | 60–70 | 300 |
| sodium–sulfur | 100–125 | 925 |
| lithium-ion | 110–190 | 250 |
| Redox flow battery | 32 | 32 |
| Supercapacitor energy storage systems | 6–10 | 83 |
| Hydrogen systems | 524 | 700–1300 |

**Table 3.** Characteristics of vehicles that use different energy sources

| Parameter | Hydrogen-driven vehicle | Petrol-/diesel-powered vehicle | Electric vehicle |
|---|---|---|---|
| Price, $ | 50000 | 5000 at least | 100000 at least |
| Volume of the space intended for storing the energy source and equipment that propels the vehicle | Large | Moderate | Small |
| Cruising range, km | Below 400 | The greatest among analogue vehicles with commensurate power and weight | 100–600 |
| Dependence on low temperatures | Low | Low | High |
| Filling/charging time, min | 10 | 10 | From 40 min to 8 h |
| Condition of the infrastructure | Undeveloped | Developed | Local |

## USE OF HYDROGEN IN THE TRANSPORTATION SECTOR

In the transportation sector, there are two fundamental areas of using hydrogen, namely, as an additive to conventional fuels that enhances the engine power due to increased completeness of hydrocarbon combustion and as a fuel for a fuel element. Hydrogen can be fed into the engine in the gaseous state—this requires systems for storage and transportation of compressed hydrogen—or supplied to the system under heating of the metal-hydride fuel cell. In terms of most key parameters, the hydrogen-driven vehicles are considerably inferior to the available alternatives so far. Hydrogen gas requires storage containers of increased capacity compared with those intended for petroleum products, which involves alterations in structural parameters of the means of transport and has an adverse effect on the consumer-oriented characteristics. The storage of hydrogen in metal-hydride compounds results in a considerable increase in the weight of the means of transport and, as a consequence, in impairment of their dynamic characteristics. Furthermore, gaseous hydrogen is explosive; therefore, special requirements are imposed on the air-tightness of the storage tanks to prevent the leakage of hydrogen when used. The fuel cells used in the power plants of the vehicles frequently prove to be far more expensive than the conventional internal combustion engines or electric motors with commensurate power, which makes the hydrogen-driven vehicles significantly more expensive than their analogues (see Table 3).

Fuel price estimation per 100 km travelled by a mean typical vehicle at an equal amount of the energy consumed shows that, when used in the transportation sector, hydrogen proves to be comparable with petroleum products and natural gas in terms of the costs but more expensive than electric power that propels electric cars (Fig. 7). One should take into account that the data on the prices of petroleum products and electric energy are provided in the figure inclusive of taxes, which may constitute approximately 70% of the end price of the energy for the users.

When buying a car, the user considers not only the price of the fuel but also the equivalent annual costs of the car, i.e., the aggregate expenses on the purchase and use of the car over its lifetime, in terms of which hydrogen is significantly inferior to alternative energy carriers [47] (see Fig. 8). In the rail transportation sector, the key drawback of hydrogen is its price. It can be used only in the nonelectrified network sections under very strict requirements imposed on emissions. The use of hydrogen in aviation is restricted by the need for large-sized fuel tanks, which affects the airplane and helicopter designs and reduces the payload area compared to analogous aircraft propelled by kerosene. Only strict environmental restrictions may lead to commercial developments in this sphere. In the waterborne transportation sector, the use of hydrogen is restricted by its high price, increased vessel manufacture costs, and a nearly complete absence of a fueling infrastructure.

Presently, there are pilot prototypes of hydrogen-driven means of transport, such as vehicles, airplanes,

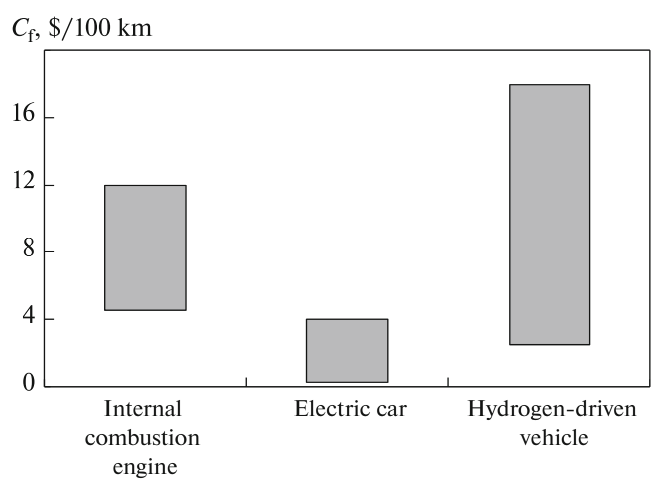


**Fig. 7.** Cost of fuel $C_f$ per 100 km for different means of transportation.

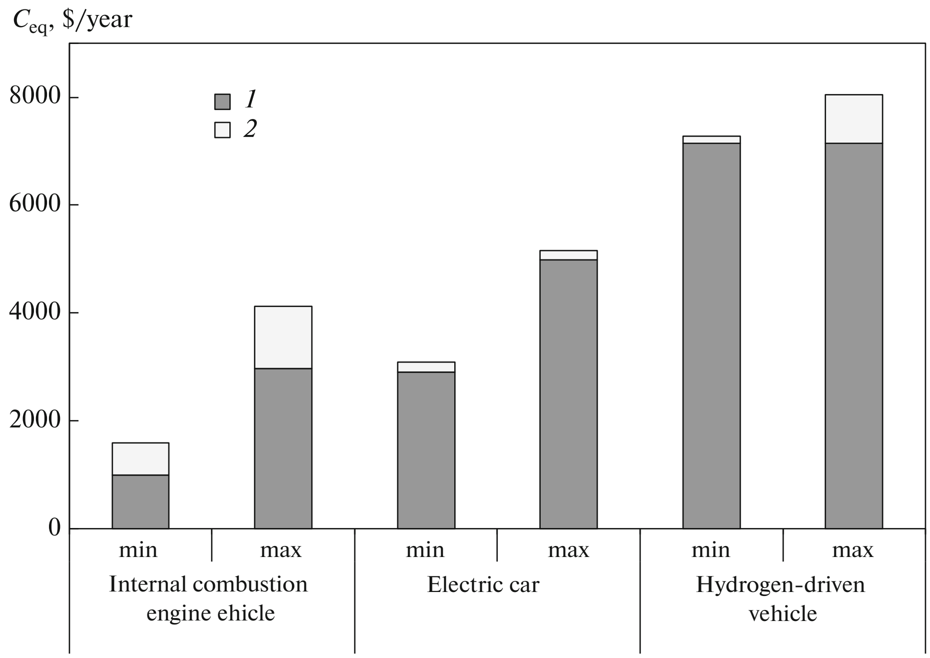


**Fig. 8.** Mean annual equivalent costs $C_{eq}$ of a car at (*1*) the purchase price and (*2*) the fuel cost.

trains, and ships [48]. In each of the above sectors, the use of hydrogen offers both certain advantages and involves disadvantages (see Table 4). Nevertheless, all cases are examples of exploring the feasibility of technologies still very far from being commercially competitive.

In addition to the price, sizes of the equipment, and the absence of the required infrastructure, the use of hydrogen as a fuel for transportation has another major drawback. The potential energy of hydrogen is converted into kinetic energy when the facility is in motion; the fuel cell that effects such conversion has a very limited lifetime. For instance, in electrochemical plants with an alkaline electrolyte installed on German submarines before the 1990s, the life of fuel cells was only 10000 h (slightly longer than 1 year). Later, the plants were replaced by more efficient ones with a solid polymeric electrolyte, whose cells' lifetime was 20000 h (slightly longer than 2 years). However, this lifetime is also comparatively short. For example, the overhaul life of a commensurate nuclear-powered submarine is 10 years.

The technology that uses fuel cells with solid polymeric electrolyte found later application in the automobile industry. This is the technology that Toyota applies and Honda and BMW are planning to introduce. The service life of the Toyota Mirai fuel cell is 100 000 miles or approximately 160000 km, while the mean lifetime of a conventional internal combustion engine is 300000–350000 km and the lifetime of a Tesla electric battery is 482000 km with the capacity failure starting from 250000 km. Consequently, the fuel cells for the transportation sector prove to be not only an expensive but also a worse solution in terms of their lifetime parameters.

The positions of the fuel cells in terms of their reliability in the power supply sector look somewhat better. The service life of modern power-generating units with liquid phosphoric-acid-based electrolyte by European and Japanese manufacturers is 40000–60000 h or 5.0–7.5 years, while that of power units with polymeric membranes is approximately 20 000 h or 2.5 years at electric power outputs of 200–400 kW [49]. The overhaul life of diesel-generating sets of a commensurate power output starts from 25000 h [50].

One of the promising application areas in which hydrogen is really in great demand is the defense industry, in which higher expenses are frequently acceptable to improve the technical parameters. In particular, this refers to unmanned aircraft, which, when driven by hydrogen, can stay in air rather long and relatively noiselessly and without releasing much heat and travel for long distances. The noiselessness and self-sustainability may be required in small submarines, in which the use of nuclear reactors is impracticable and diesel-generating sets do not ensure the required secrecy of traveling.

## CONCLUSIONS

(1) Presently, it is difficult for hydrogen to compete with alternative fuels used in electric power generation and the transportation sector. The main factor that restricts its use in transportation is the high prices of vehicles despite relatively acceptable fuel-consumption rates. In the fight for environmental sustainability,

**Table 4.** Application areas of hydrogen in power industry

| Application area | Competing key energy carriers | Advantages of hydrogen | Drawbacks of hydrogen |
|---|---|---|---|
| Cofiring with natural gas to generate electric power | Natural gas, coal, fuel oil, and RESs | More complete combustion of hydrocarbon fuels and reduction in emissions | Increased prices of raw materials for power stations within the range 40–140 \$/thous. $m^3$ |
| Self-contained power supply | Liquefied hydrocarbon gases, liquefied natural gas, and RESs | High environmental characteristics | More expensive than alternative energy carriers and need for infrastructure |
| Rocket propellants (liquid-hydrogen–liquid-oxygen mixture) | Kerosene, dymethylhydrazine, dinitrogen tetroxide, and ammonium perchlorates | Best environmental characteristics among all analogues and comparatively high efficiency | High production and storage costs (approximately 80 \$ per 1 kg of hydrazine against 20–30 \$/kg for alternative energy carriers) |
| Aviation fuel (airplanes and helicopters) | Kerosene, aviation gasoline, and solar panels in the near future | High environmental characteristics, high heat capacity of the fired fuel compared with kerosene | The necessity of increasing the tank capacity of the aircraft currently in operation or increasing the weight of the aircraft preserving the capacity when using metal-hydride fuel cells. Potential increase in the prices and structural sophistication of the means of transport |
| Aviation and marine fuels (unmanned aircraft and small submarines) | Diesel fuel, liquefied hydrocarbon gases, liquefied natural gas | Noiselessness, relatively long self-sustainability | High costs |
| Use of chemical hydrogen fuel sources (nickel–hydrogen batteries) | Other current sources (energy storage devices) | High specific characteristics of the battery | Comparatively high prices: 300–400 \$/(MW h), approximately 100 \$/(MW h) for pumped storage hydropower plants and underground storage systems and 120–400 \$/(MW h) for alternative chemical current sources |
| Road transport | Gasoline, diesel fuel, natural gas motor fuel, biofuel, and electric power | Higher combustion rate and, as a consequence, higher efficiency of the engine | At least five-times higher price of the vehicle |
| Railroad transport (fuel cells) | Diesel fuel and electric power | Higher environmental characteristics and no need for track electrification | Three to five times higher costs compared with diesel engines or electric power and higher infrastructure costs |

hydrogen-driven vehicles enter difficult competition with the intensively developing electric transportation and lag far behind the latter in terms of the key cost parameters so far.

(2) Under today's market conditions, the most economically acceptable solution in electric power generation is the production of hydrogen of hydrocarbons followed by its independent combustion or cofiring in a methane–hydrogen mixture. The impracticability of storing energy using hydrogen is determined by the current mechanisms of supporting the renewable energy sources and the failure to take into consideration system effects for electric power generation, which do not provide sufficient incentives to search for energy accumulation solutions. The prospects of using hydrogen as an energy storage means will depend to a considerable extent on the advances in the alternative storage technologies that have been intensively developing recently, especially in the area of chemical current sources.

(3) Analysis of a wide spectrum of possibilities of producing and using hydrogen allowed for establishing the most promising spheres for the development of hydrogen fuel economy. However, in each of these

spheres, a considerable cut in costs is required for hydrogen to compete successfully with alternative energy carriers. An obviously great advantage of hydrogen fuel economy compared with numerous alternative fuels is a reduction in hazardous emissions; however, this factor can become an incentive provided that the emission charges are increased.

(4) Hydrogen can become one of the fuels of the future; to effect this, however, we will have to tread a difficult path of technological progress.

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