

Hydrogen and Metal Hydride Energy Technologies: Current State and Problems of Commercialization

B. P. Tarasov^a, * and M. V. Lototsky^a

^a Federal Research Center for Problems of Chemical Physics and Medicinal Chemistry, Russian Academy of Sciences, Chernogolovka, Moscow oblast, 142432 Russia

*e-mail: tarasov@icp.ac.ru

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Abstract—The need for the transition to carbon-free energy and the introduction of hydrogen energy technologies as its key element is substantiated. The main issues related to hydrogen energy materials and systems, including technologies for the production, storage, transportation, and use of hydrogen are considered. The application areas of metal hydrides as promising materials for hydrogen energy technologies are presented. Prospects for the commercialization of hydrogen and metal hydride technologies are discussed, including those using cheap hydride-forming materials based on titanium–iron alloys.

Keywords: hydrogen energy, current state, development problems, hydrogen storage and transportation, metal hydride technologies, titanium alloys with iron

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INTRODUCTION

The challenges of climate change, environmental pollution, and limited reserves of natural organic energy sources have necessitated structural changes in power generation and related sectors, including industry and transport. These changes should be aimed at decreasing the consumption of fossil fuels and reducing harmful emissions, including greenhouse gases [1, 2]. According to forecasts of the International Energy Agency [3], the share of hydrocarbon fuels in the world energy structure should decrease from 67% in 2019 to 24% in 2040. More than half of primary energy will be generated from renewable energy sources (RES), including solar and wind energy (Fig. 1).

Energy production using renewable energy sources is characterized by significant seasonal and daily imbalances between production and consumption. Hydrogen energy technologies make it possible to produce hydrogen by water electrolysis using excess electricity and generate electricity during periods of its shortage by oxidizing hydrogen in fuel cells. Considering the fact that the energy storage density using hydrogen and fuel cell technologies is 0.33–0.51 MW h/m³, which significantly exceeds the parameters of alternative technologies (0.27 kW h/m³ for pumped storage hydropower units and up to 0.14 MW h/m³ for electric storage batteries) [4], the interest in hydrogen energy technologies is growing sharply.

Currently, in Russia and almost all developed and developing countries of the world, there is a rapid increase in the intensity of work in this area, primarily devoted to the commercialization and large-scale implementation of hydrogen energy technology systems [5–7].

The concept of hydrogen energy was proposed in the mid-1970s as a response to global challenges associated with the depletion of natural organic fuels and environmental pollution due to their use [8]. The subsequent intensive research and development in the field of hydrogen energy technologies laid the foundation for the implementation of this concept in the 21st century [5, 6].

This article provides a brief overview of the current state of the art in the field of hydrogen energy technologies with an emphasis on the challenges hindering their commercialization. Particular attention is paid to metal hydride technologies for compact, safe, and technologically flexible storage of hydrogen in a bound state, as well as to prospects for reducing the cost of these technologies through the use of hydride-forming materials based on titanium–iron alloys.

HYDROGEN ENERGY TECHNOLOGIES

Hydrogen energy technologies are based on the use of hydrogen as a universal, efficient, and environmentally friendly energy carrier. Hydrogen has the highest energy intensity per unit mass, significantly surpassing conventional fossil and synthetic hydrocarbon fuels in

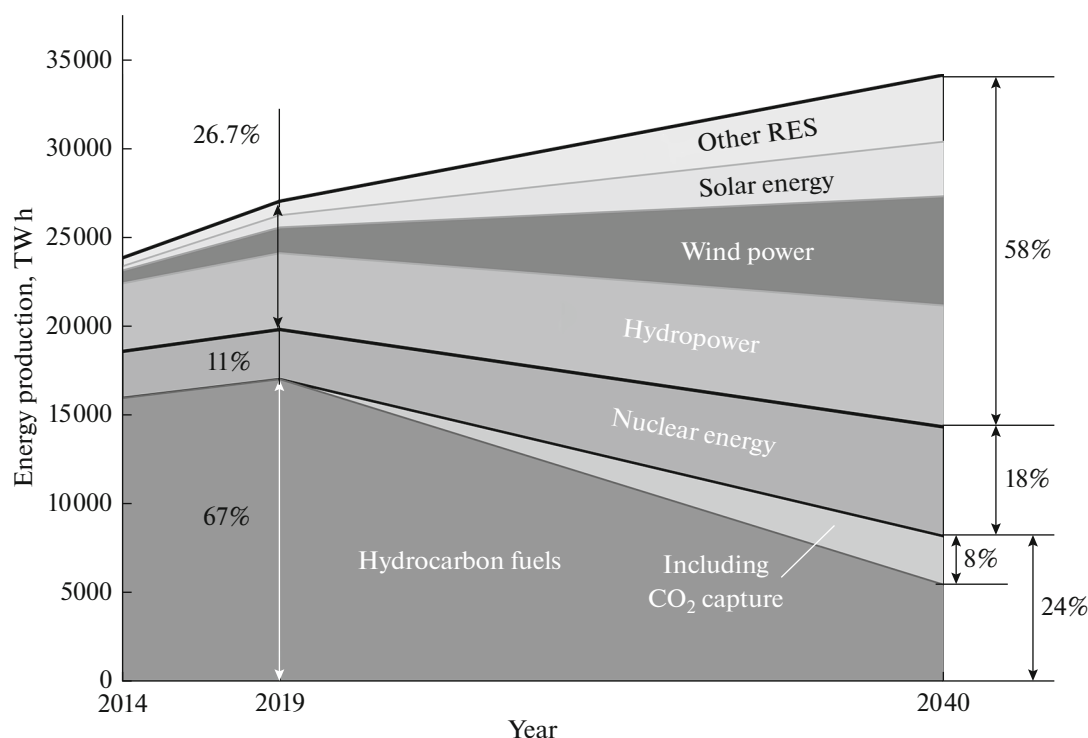


Fig. 1. Changes in the structure of world energy according to International Energy Agency 2014–2019 data and forecast for 2020–2040.

this parameter (Fig. 2a) [9]. Unlike hydrocarbon fuels, the combustion of which is accompanied by significant emissions of greenhouse (carbon dioxide) and toxic (sulfur and nitrogen oxides) gases into the atmosphere, the hydrogen combustion product is water vapor alone with minor admixtures of nitrogen oxides formed by the interaction of nitrogen and oxygen in the air at high temperatures (Fig. 2b) [10]. In the case of generating electricity by low-temperature oxidation of hydrogen in fuel cells, no nitrogen oxides are produced and the only emission is water vapor.

Other advantages of hydrogen as an energy carrier are the possibility of carrying out various energy conversion processes involving hydrogen (in heat engines or electrochemical generators) [5, 6] and unlimited resources of feedstock for its production (water, natural hydrocarbons, biomass) [11].

Existing hydrogen production methods and their features are listed in Table 1 [11, 12]. Depending on the environmental impact of hydrogen production processes (associated CO₂ emissions or carbon footprint), the following “color” classification is adopted:

- “Green” hydrogen: carbon-free—electrolysis of water powered by renewable energy sources.
- “Yellow” hydrogen: carbon-free—electrolysis of water powered by nuclear energy.
- “Turquoise” hydrogen: low carbon—pyrolysis of methane (natural gas).

- “Blue” hydrogen: medium carbon—steam reforming of methane or coal with CO₂ capture and storage.

- “Grey” hydrogen: high carbon—steam reforming of methane.

- “Brown” hydrogen: high carbon—gasification or steam reforming of coal.

In hydrogen production, the main emphasis is on electrolytic water splitting using renewable (“green” hydrogen) and nuclear energy (“yellow” hydrogen), as well as on the thermal or plasma-assisted decomposition of methane and other hydrocarbons (“turquoise” hydrogen). As an intermediate option, the production of hydrogen by steam reforming of natural gas (“grey” hydrogen) with the capture and storage of the resulting carbon dioxide (“blue” hydrogen) is considered [11–13].

There are several types of electrolysis hydrogen generators differing in the type of electrolyte used (Table 2). For large-scale hydrogen production, it is necessary to reduce their cost and increase efficiency and service life [6, 14–16].

Energy is produced by the oxidation of hydrogen in gas turbines; internal combustion engines; or fuel cells (see Table 3) including alkaline (AFC), solid polymer electrolyte (PEMFC), solid oxide (SOFC), and phosphoric acid (PAFC) fuel cells. In terms of efficiency and environmental friendliness, fuel cells have a clear

advantage and will be used in the future to generate electricity [17, 18].

The main obstacles to the commercialization of hydrogen energy technologies currently are

- high cost of “green” hydrogen, high safety requirements, lack of infrastructure;
- high cost of equipment for the production, transportation, and use of hydrogen;
- high costs of ensuring the safety of hydrogen infrastructure;
- limited legal framework for the use of hydrogen fuel;
- existing problems in the field of environmental protection, health care, and industrial safety; and
- insufficient number of specialists in the field of hydrogen energy.

The main problem of hydrogen energy is the development of effective and safe methods for compact storage and transportation of hydrogen [5, 13, 19–22]. The main cause of this problem is that hydrogen gas under normal conditions (1 atm, 0°C) has an extremely low density (0.09 kg/m³), the increase of which requires the use of physical methods (compression or liquefaction) or chemical bonding. Accordingly, while outperforming conventional fuels in terms of energy intensity per unit mass, hydrogen is significantly inferior to them in specific energy intensity per unit volume (Fig. 2a). Even at high pressures, the density of H₂ gas remains too low, amounting to only 20 kg/m³ at $P = 350$ atm and $T = 25^\circ\text{C}$. Storing hydrogen in a liquid state (density 70 kg/m³; $T = -253^\circ\text{C}$) requires significant energy consumption up to 30% of the higher heating value (HHV) of hydrogen fuel. Similar energy consumption (up to 25% of HHV) is also typical for the chemical binding of hydrogen in organic compounds. Due to the high permeability, reactivity, and explosiveness of hydrogen, the safety problems of its storage and transportation (Table 4) have also not been completely resolved.

Thus, along with the need to increase efficiency and service life and reduce the cost of the main components of hydrogen energy systems (electrolyzers and fuel cells), solving problems associated with hydrogen storage and transportation is a determining factor in their competitiveness during commercial implementation. One possible solution to this problem is discussed in the following sections.

METAL HYDRIDE MATERIALS AND TECHNOLOGIES

Metal hydrides (MHs) are characterized by a volumetric density of bound hydrogen up to 150 kg/m³ and present a promising alternative to traditional methods of hydrogen storage (Table 4). The advantages of MHs as materials for hydrogen storage include compactness, safety, simplicity of design and operation, and

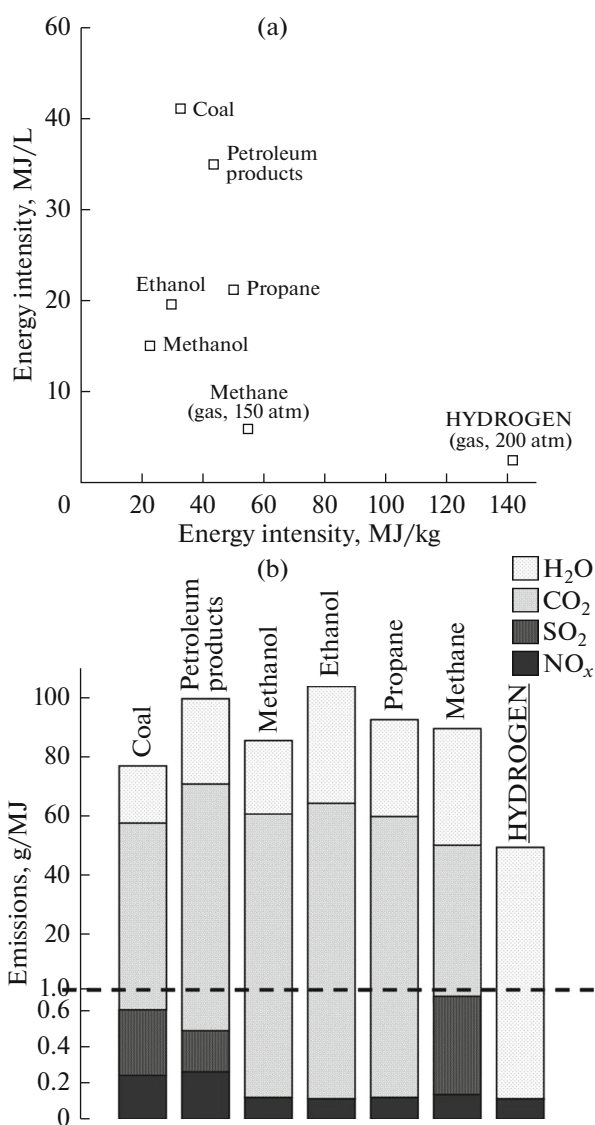


Fig. 2. (a) Energy intensity and (b) atmospheric emissions by burning conventional fuels and hydrogen.

technological flexibility of systems based on them. The energy consumption for the decomposition of “low-temperature” MHs with the release of hydrogen gas is 20–30 kJ/mol H₂ [23], which corresponds to approximately half of the energy consumption required for the release of hydrogen bound in organic compounds (55–70 kJ/mol H₂ [20]).

Metal hydride technologies are important for creating components of integrated hydrogen energy systems that ensure the intake of hydrogen from an electrolyzer, its compact storage, and controlled supply to consumers including fuel cell power plants. At the same time, metal hydride components of an integrated energy system make it possible to utilize waste heat generated during its operation, thereby significantly increasing the round-trip system efficiency [18, 24].

Table 1. Hydrogen production processes

Process	Feedstock	Type/source of primary energy	Development
Steam (steam–oxygen) reforming	Fossil (gas, oil, coal) or synthetic (methanol) fuel, biomass Water	Chemical, heat/hydrocarbon raw materials	Industrial, large-capacity
Electrolysis	Water	Electricity/RES, nuclear fuel (NPP), fossil hydrocarbons (CHP)	Industrial
Pyrolysis	Natural gas	Chemical/hydrocarbon feedstock, electricity/renewable energy sources, nuclear fuel (NPP), fossil hydrocarbons (CHP)	Industrial, pilot
Thermolysis	Water	Heat/nuclear fuel (NPP), RES (solar concentrators)	Industrial, pilot
Hydrolysis (iron–steam method)	Water Iron	Chemical, heat/ hydrocarbon or nuclear (NPP) fuel, renewable energy sources (solar concentrators)	Industrial, pilot
Hydrolysis	Water Metals or hydrides	Chemical/energy costs for production of parent metals or hydrides	Industrial, small scale Laboratory
Photolysis	Water	Light radiation / sun	Laboratory
Biochemical	Water	Photosynthesis/sun	Laboratory

Metal hydride hydrogen storage and processing systems fit well into a number of niche applications and allow the combination of several functions (for example, hydrogen storage, purification, and compression) in a single multifunctional metal hydride device [24–27].

Metal hydride technologies use the reaction of a hydride-forming metal, alloy, or intermetallic compound with hydrogen to form a hydride, the reversible process of formation/decomposition of which can follow two mechanisms [24]. One is the interaction of a hydride-forming metal (intermetallic compound) with gaseous hydrogen, and the other is electrochemical hydrogenation of the metal (or decomposition of the hydride) in an electrolyte solution. Accordingly, hydride applications can be divided into two groups, gas phase and electrochemical (Fig. 3). Gas-phase applications include (a) compact and safe hydrogen batteries with capacities ranging from a few liters to several hundred cubic meters (STP) of hydrogen, (b) thermosorption hydrogen compressors (TSC), (c) heat storage and conversion systems, (d) systems for extraction of hydrogen from gas streams and its purification, and (e) low-pressure systems for evacuation out and supplying hydrogen isotopes to vacuum plasma devices, as well as some other materials and processes used in catalysis and powder metallurgy [24, 28]. Electrochemical applications of MHs primarily include nickel–metal hydride power sources,

which currently stand out as the most commercially developed [29]. Some research and development works are devoted to the creation of fuel cells with MH electrodes [30] and MH electrodes for lithium-ion batteries [31].

The combination of several unique properties of hydrogenation/dehydrogenation processes (Fig. 4) results in highly efficient metal hydride applications, especially those that allow multiple operating functions (such as hydrogen storage, purification, and thermal compression) to be combined in a single multifunctional device.

The main problem in creating high-performance metal hydride systems is to select or targetedly develop metal hydride materials whose properties best meet the technical requirements of the end user, primarily in terms of operating temperatures and hydrogen pressures. An important role here is played by modeling the relationships between the composition of a hydride-forming alloy and its hydrogen sorption properties on one hand [32] and between the thermodynamic properties of a hydrogen–intermetallic system and the operating characteristics of a hydride system on the other hand [33]. In addition, it is necessary to ensure the stability of hydrogen sorption properties during cycling, rapid hydrogenation–dehydrogenation kinetics, and high effective thermal conductivity of the material in a metal hydride reactor. One of the effective methods for solving these problems is the cre-

Table 2. Types of electrolysis hydrogen generators and their characteristics

Type Electrode reactions	Parameter	Value		
		Current state	By 2030	Beyond 2030
Alkaline electrolyzers <u>Cathode:</u> $2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2(\text{OH})^-$ <u>Anode:</u> $2(\text{OH})^- \rightarrow 1/2\text{O}_2 + \text{H}_2\text{O} + 2\text{e}^-$	Operating temperature, °C	60–80	60–80	60–80
	Operating pressure, bar	1–30	1–30	1–30
	Load range, %	10–110	10–110	10–110
	Efficiency, %	63–70	65–71	70–80
	Specific capital investments, US dollars per 1 kW	500–1400	400–800	200–700
Electrolyzers with proton-conducting ion-exchange membrane <u>Cathode:</u> $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$ <u>Anode:</u> $\text{H}_2\text{O} \rightarrow 1/2\text{O}_2 + 2\text{H}^+ + 2\text{e}^-$	Operating temperature, °C	50–80	50–80	50–80
	Operating pressure, bar	30–80	30–80	30–80
	Load range, %	0–160	0–160	0–160
	Efficiency, %	56–60	63–68	67–74
	Specific capital investments, US dollars per 1 kW	1100–1800	650–1500	200–900
Solid oxide electrolyzers <u>Cathode:</u> $\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + \text{O}^{2-}$ <u>Anode:</u> $\text{O}^{2-} \rightarrow 1/2\text{O}_2 + 2\text{e}^-$	Operating temperature, °C	650–1000	650–1000	650–1000
	Operating pressure, bar	1	1	1
	Load range, %	20–100	20–100	20–100
	Efficiency, %	74–81	77–84	77–90
	Specific capital investments, US dollars per 1 kW	2800–5600	800–2800	500–1000

Table 3. Types and characteristics of fuel cells

Characteristic	Type				
	Solid polymer (PEMFC)	Alkaline (AFC)	Phosphoric-acid (PAFC)	Molten carbonate (MCFC)	Solid oxide (SOFC)
Electrolyte	Proton exchange membrane	30–50% aqueous KOH solution	Concentrated phosphoric acid	Molten carbonate (Li_2CO_3 , Na_2CO_3 , K_2CO_3)	Ion-conducting ceramic (ZrO_2 modified by $\text{Y}_2\text{O}_3/\text{YSZO}$)
Temperature, °C	70–80	70–90	150–200	600–700	800–1000
Fuel	Pure H_2	Pure H_2	Pure H_2	H_2 , CO, CH_4	H_2 , CO, CH_4
Oxidant	Air	Pure O_2	Air	Air	Air
Electrical efficiency, %	38	50	42	47	50

ation of hydride composites containing additives of graphene-like materials modified with nickel nanoparticles [34].

Along with the development of high-performance metal hydride materials, an important factor contributing to the improvement of the dynamic characteristics of metal hydride systems is enhancement of heat and mass transfer in metal hydride reactors. This engi-

neering problem is solved by optimizing the geometry, layout, and characteristic dimensions of reactors and reactor systems using computer simulation methods [35]. Examples of power systems developed at the Federal Research Center for Problems of Chemical Physics and Medicinal Chemistry and the HySA Systems Competence Center (South Africa) are presented in [36].

Table 4. Safety issues during hydrogen storage and transportation

Storage/transport method	Operating principle	Safety concerns
Compressed hydrogen	Compression up to 80–100 (gas pipelines), 150–200 (steel cylinders), or 350–700 (composite cylinders) atm	High pressures (problems related to the safety and reliability of hydrogen compressors). Possibility of explosion in the case of damage of cylinder or gas pipeline. Hydrogen embrittlement of structural materials.
Liquid hydrogen	Liquefaction of hydrogen by cooling to $T = 20\text{ K}$ (-253°C)	Possibility of uncontrolled release of hydrogen gas upon damage of thermal insulation. Possibility of oxygen solidification in liquid H_2 . Constant evaporation of hydrogen from the storage system. Embrittlement of materials at low temperatures.
Chemically bonded hydrogen in organic compounds	Reversible catalytic hydrogenation of double bonds in unsaturated and aromatic compounds	Possible spill of organic compounds (fire hazard, toxicity). High temperatures during hydrogenation and dehydrogenation.
Hydrogen in metal hydrides	Reversible interaction of hydrogen with hydride-forming metals and alloys	Possible carryover of finely divided metal powder (hydride). Possibility of self-ignition of finely divided metal powder (hydride) upon contact with air.

PROBLEMS OF COMMERCIALIZATION OF METAL HYDRIDE ENERGY TECHNOLOGIES AND WAYS TO SOLVE THEM

In addition to the aforementioned materials science and engineering challenges, the main factor limiting the commercialization of metal hydride energy technologies is a high cost of MH-based hydrogen storage systems.

Figure 5 shows a cost breakdown for manufacturing a stationary MH hydrogen storage tank developed at the HySA Systems Competence Center for an integrated power system including an electrolyzer and a fuel cell. The tank provides storage of up to 4 kg H_2 and

is a cylindrical stainless steel container ($\varnothing 219 \times 2500\text{ mm}$) equipped with an internal finned copper tube heat exchanger and filled with 260 kg of AB_5 type intermetallic hydride powder [24].

From the data in Fig. 5 it can be seen that the main cost items for the manufacture of an MH hydrogen storage in the form of an individual container with an internal heat exchanger are the costs of manufacturing the MH container and the purchase of MH material. Taking into account that the high cost of containers is mainly associated with the individual production of these rather sophisticated devices on custom order, we can expect its reduction (according to the authors' estimates, approximately by half) if mass production is

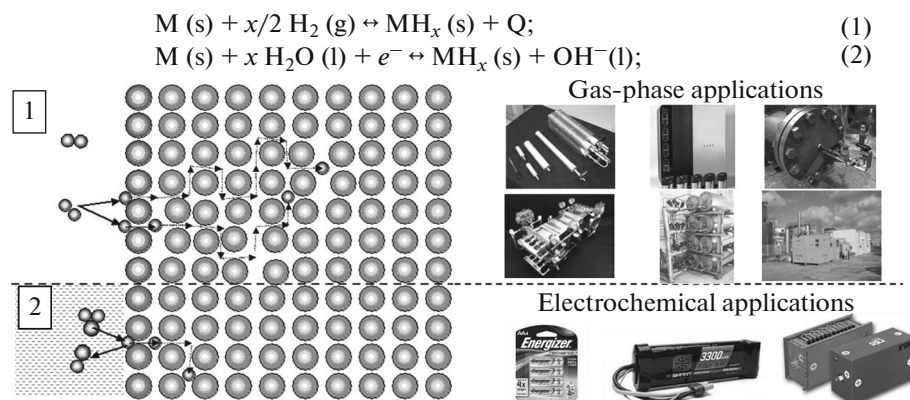


Fig. 3. (1) Gas-phase and (2) electrochemical mechanisms of formation/decomposition of metal hydrides and corresponding applications.

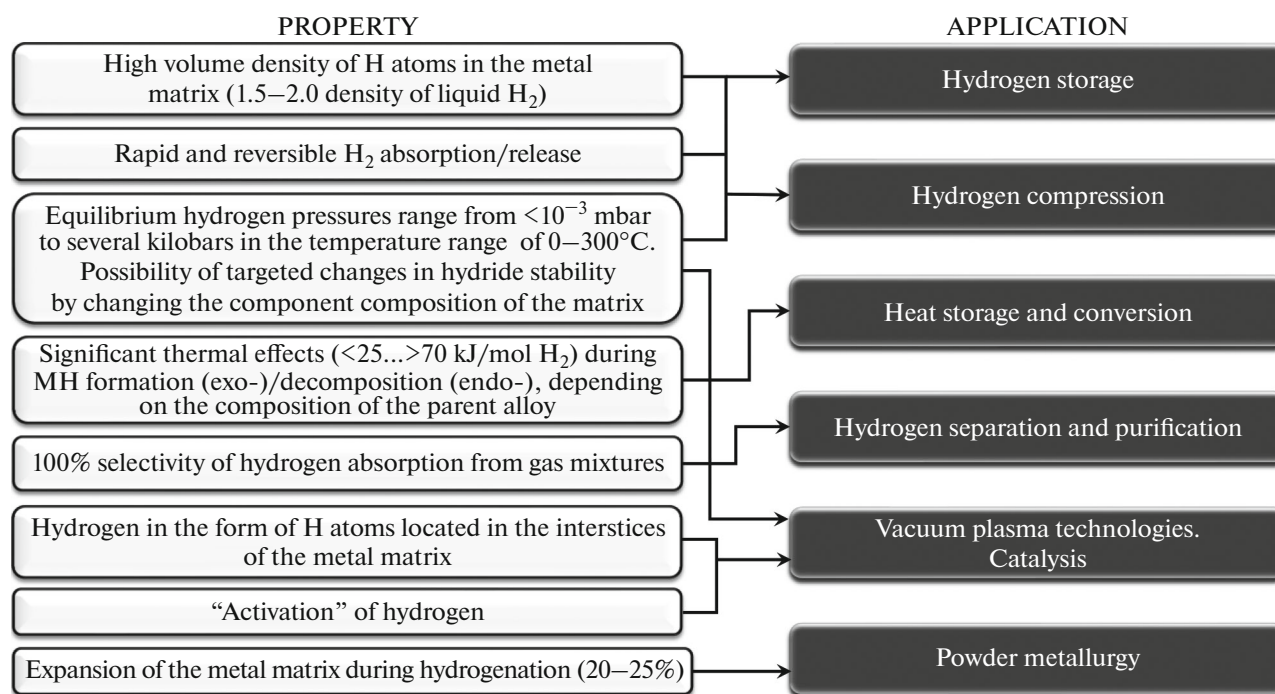


Fig. 4. Special properties and applications of metal hydrides.

launched. The cost of MH material can be reduced by switching to less expensive alloys based on titanium and iron.

The hydrogen-storing properties of the TiFe intermetallic compound were discovered back in 1974 by Reilly and Wiswall [37]. It was shown that this intermetallic reversibly absorbs up to 1.86 wt % hydrogen, forming two hydrides TiFeH and TiFeH₂. Accordingly, there are two pressure plateaus in the ranges of 1–2 atm at 0°C and 10–30 atm at 50°C on the pressure–composition isotherms in the H–TiFe system.

The relatively high reversible hydrogen capacity of TiFe, achieved at temperatures close to room temperature and moderate hydrogen pressures, immediately attracted the attention of researchers to its use as a hydrogen storage material. This was primarily due to economic considerations, since the cost of the starting metals, titanium and iron, in terms of 1 g of stored hydrogen (\$0.3 in 1999) is significantly lower than the cost of the starting metals for producing hydride-forming intermetallic compounds of types AB₅ and AB₂ (up to 1.2 USD/g H₂ in 1999) [38]. Later, the possibility of further reducing the cost of TiFe was shown by obtaining it via direct reduction of iron titanate (FeTiO₃), a cheap and widely available raw material (ilmenite mineral) [39–41].

In addition to smelting the starting metals [37, 38] and direct reduction of FeTiO₃ or a mixture of titanium and iron oxides by metallothermy [39, 40, 42] or high-temperature molten salt electrolysis [41, 43], TiFe and its derivatives can be obtained by sintering

powders of the starting metals in an inert gas or hydrogen atmosphere, by mechanochemical treatment of a mixture of titanium or its hydride powders with iron in a ball mill, or by a combination of these methods [44–50]. An analysis of factors affecting the quality of titanium alloys (including Ti–Fe hydrogen absorbers) prepared by induction melting was carried out in 2020 by an international group (South Africa, Russia, China), including the co-authors of this paper [51].

Despite the fact that research into the TiFe intermetallic compound and its derivatives as hydrogen storage materials has been ongoing for more than 50

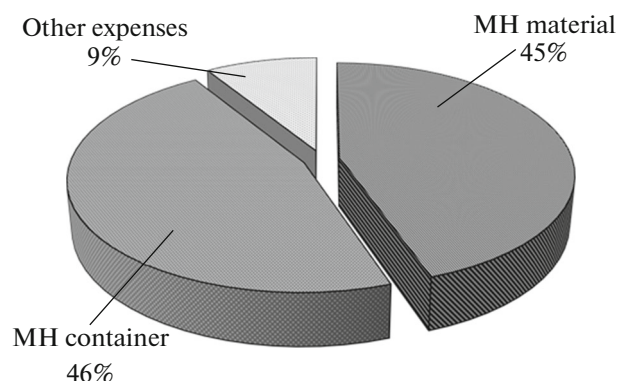


Fig. 5. Cost breakdown for the production of a stationary hydrogen battery at the HySA Systems Competence Center (South Africa).

years, the intensity of work in this area has increased sharply in recent years. For 2020–2022 only, 4 reviews [52–55] and more than 60 experimental and theoretical works have been published on this topic. This is primarily due to the need to identify the causes of significant differences in the hydrogen capacity values of these materials (from 0.67 to 1.86 wt % H), obtained by similar methods with similar compositions [56]. Particular attention was paid to the analysis of factors responsible for the disadvantages of the TiFe intermetallic compound as a hydrogen-storing material, some of them were identified in the early stages of its study, including the high sensitivity of the hydrogen sorption properties of the intermetallic compound to the Ti/Fe stoichiometry, the presence of two plateau segments, high hydrogen absorption/desorption hysteresis [37], as well as the difficulty of activation and a sharp deterioration in absorption kinetics, accompanied by a drop in reversible hydrogen capacity in less than ten hydrogenation/dehydrogenation cycles in hydrogen containing only 1000 ppm (0.1%) gas impurities including oxygen and water vapor, the presence of which is typical for electrolytic hydrogen [38, 57]. It was found that the reason for the difficulty of activation and deterioration of the hydrogen sorption properties of the alloy in operations with contaminated hydrogen is the difficulty of forming iron clusters at room temperature, which are active centers of dissociative chemisorption of hydrogen, and their passivation by impurities in hydrogen. Studies into this effect began in the late 1970s [58]; however, they have been resumed in recent years using modern computational, theoretical, and experimental techniques [59–61].

Numerous experimental and theoretical studies carried out in the last decade have shown the possibility of significantly improving the hydrogen sorption properties of TiFe-based alloys by

- Alloying with metal additives, primarily manganese, vanadium, and chromium [62]. The greatest positive effect including maintaining a high hydrogen sorption capacity; merging two segments of the pressure plateau; and improving the hydride formation/decomposition kinetics, activation, and resistance to “poisoning” by gaseous impurities is achieved by introducing several transition metals that replace both titanium (Zr, Hf) and iron (Mn, Ni, Cr, Co, V) at a stoichiometric ratio A/B ($A = \text{Ti} + \text{Zr} + \dots$; $B = \text{Fe} + \text{Mn} + \dots$) between 1.05 and 1.1, as well as small (up to 3 at %) rare earth metal additives that act as a deoxidizer during the preparation of the alloy [63–95].

- Controlled introduction of oxygen additives, leading to milder activation conditions of an initial alloy and improving the kinetics of hydrogen absorption by the alloy [56, 62, 96]. At the same time, an excess of oxygen in the TiFe-based alloy leads to a significant decrease in its reversible hydrogen capacity due to the disproportionation of the TiFe intermetallic compound into the α -phase $\text{Ti}_4\text{Fe}_2\text{O}_{(1-x)}$ and the

Laves phase of TiFe_2 . The former compound is easily hydrogenated and catalyzes the saturation of the main phase of TiFe with hydrogen; however, it forms too stable a hydride that does not decompose under operating conditions of a hydrogen storage ($P > 1$ atm, $T < 100^\circ\text{C}$); and the TiFe_2 Laves phase does not form hydrides at moderate hydrogen pressures. As a result, when the oxygen concentration in the alloy reaches about 2.5 wt %, all TiFe is disproportioned into $\text{Ti}_4\text{Fe}_2\text{O}_{(1-x)}$ and TiFe_2 , leading to a drop in the hydrogen capacity of the alloy to zero. It was shown that the introduction of oxygen into the TiFe alloy (quite likely during induction melting of the alloy in oxide crucibles) should be below 0.2 wt % [96]. It has also been shown that annealing of oxygen-containing titanium alloys with iron leads to a decrease in the amount of the $\text{Ti}_4\text{Fe}_2\text{O}_{(1-x)}$ phase with the dissolution of oxygen in the TiFe matrix, resulting in an increase in hydrogen capacity and a slight decrease in the stability of the intermetallic hydride. The aforementioned discrepancies in the hydrogen capacity of TiFe alloys are most likely due to different (uncontrolled) oxygen contents in the alloys [56]. Another way to increase the reversible hydrogen capacity of titanium and iron alloys with excess oxygen (in particular, those formed during the metallothermic reduction of FeTiO_3) can be the additional alloying with Zr, Cr, Mn, Ni, and Cu; in this case, the phase composition of the alloy changes with the formation of Laves phases having acceptable hydrogen sorption characteristics [40, 97].

- Modification of the surface of TiFe-based alloys with nanoparticles of metals, including palladium, nickel, or a mixture of them, that are active catalysts for dissociative chemisorption of hydrogen [98–101]. Although this approach may require the use of noble metals, for example Pd, its implementation in the case of using unique deposition technologies that allow the use of solutions of noble metal salts in low concentrations (including wastewater from relevant industries) [102] will not lead to a significant increase in the cost of the final product with a significant improvement of activation characteristics and hydrogen absorption/desorption kinetics and with exceptional durability of hydrogen sorption characteristics when operating on impure hydrogen.

- Creation of composites with carbon nanomaterials that protect the surface of the base hydride-forming alloy from interaction with impurities in hydrogen and make it possible not only to enhance the hydrogenation kinetics, but also improve heat transfer in hydride reactors and suppress the undesirable effect of sintering of material particles at high temperatures. Most of the studies in this direction, described in the review [103], as well as numerous works carried out at the Federal Research Center for Chemical Physics and Medicinal Chemistry on nickel–graphene carbon nanostructures as additives [104–107], were devoted

to the study of “high-temperature” hydride composites based on magnesium hydride. However, encouraging results for “low-temperature” intermetallic hydrides have also been obtained in some studies [108]. Expansion of this approach to Ti–Fe alloys (composites containing additives of graphene-like materials with deposited nickel nanoparticles, especially in combination with the above-described methods for the surface modification of base Ti–Fe alloys) will deepen the existing understanding of the effect of surface modification of hydride-forming materials on their hydrogen sorption properties and thereby propose new approaches to creating inexpensive but highly efficient hydride materials for hydrogen storage.

CONCLUSIONS

This brief review substantiates the relevance of research in the field of hydrogen and metal hydride energy technologies. The main methods of hydrogen production, storage, and use are considered. It has been found that due to high permeability, reactivity, and explosiveness of hydrogen, the challenges of its safe storage and transportation present a limiting factor in its use for energy applications. The need for research and development works to improve the main elements of integrated energy systems based on renewable energy sources, including electrolyzers, fuel cell batteries, materials, and hydrogen storage and supply systems, is substantiated. A promising direction in the creation of elements of the latter group is the development of compact and safe hydrogen storage systems and related auxiliary technologies based on the use of metal hydrides. The main problem with the commercialization of such systems is the high cost of the hydride-forming alloys used. This problem can be solved by using titanium–iron alloys, which combine high reversible hydrogen capacity, the ability to operate efficiently at moderate temperatures and hydrogen pressures, and a moderate cost. However, despite the large amount of work being done around the world on the use of Ti–Fe alloys in hydrogen and metal hydride technologies, the problems of scientific support for the mass production of such alloys with stable and reproducible hydrogen sorption characteristics have not yet been completely resolved.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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