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Barriers to implementation of hydrogen initiatives in the context of global energy sustainable development

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Abstract. Modern trends in the global energy market linked to the Sustainable Development Goals often lead to the adoption of political decisions with little basis in fact. Stepping up the development of renewable energy sources is an economically questionable but necessary step in terms of its social and ecological effects. However, subsequent development of hydrogen infrastructure is, at the very least, a dangerous initiative. In connection with mentioned above, an attempt to examine hydrogen by conducting an integral assessment of its characteristics has been made in this article. As a result of the research conducted, the following conclusions concerning the potential of the widespread implementation of hydrogen in the power generation sector have been made: as a chemical element, it harms steel structures, which significantly impedes the selection of suitable materials; its physical and volume characteristics decrease the general efficiency of the energy system compared to similar hydrocarbon solutions; the hydrogen economy does not have the necessary foundation in terms of both physical infrastructure and market regulation mechanisms; the emergence of widely available hydrogen poses a danger for society due to its high combustibility. Following the results of the study, it was concluded that the existing pilot hydrogen projects are positive yet not scalable solutions for the power generation sector due to the lack of available technologies to construct large-scale and geographically distributed infrastructure and adequate international system of industry regulation. Thus, under current conditions, the risks of implementing such projects considerably exceed their potential ecological benefits.

***Key words*:** Hydrogen; sustainability; hydrocarbons; fuel and energy sector; global power generation sector; renewable energy sources

Introduction. The power generation sector forms the backbone of the economy and is a fundamental driver of its development. In connection with mentioned above, issues of facilitating universal access to inexpensive, reliable, safe and green energy sources are one of the priorities in the context of global sustainability development. This is directly shown within the framework of Goal 7 and indirectly traced in the other Sustainable Development Goals, the achievement of which depends on the efficient use (rational production and consumption) of natural resources, including raw material resources.

The basic development trajectory of the green power generation sector is the widespread use of renewable energy sources (RES). To name a just a few, governments of European Union countries are attempting to decarbonize their economies by directing all resources toward the use of energy carriers with low carbon footprints both by introducing strict tax regulation measures (Fig.1) and by implementing programs to co-finance society's transition to alternative power generation, which amounts to billions of Euros. This policy is sufficiently debatable [21], although it is positioned by many scientists as well as political figures as the only correct one.

At the same time, the insufficient economic effectiveness of RES in view of the low efficiency of the energy transformation process has been under discussion for the past few decades. Even today, the price of electric power from some RES may be compared with that of hydrocarbons, but only with substantial state support. Nevertheless, the possibility of receiving comparatively inexpensive and decentralized energy from RES is fraught with the instability of the energy generation process and the lack of methods by which excessive energy can be retained for subsequent use.

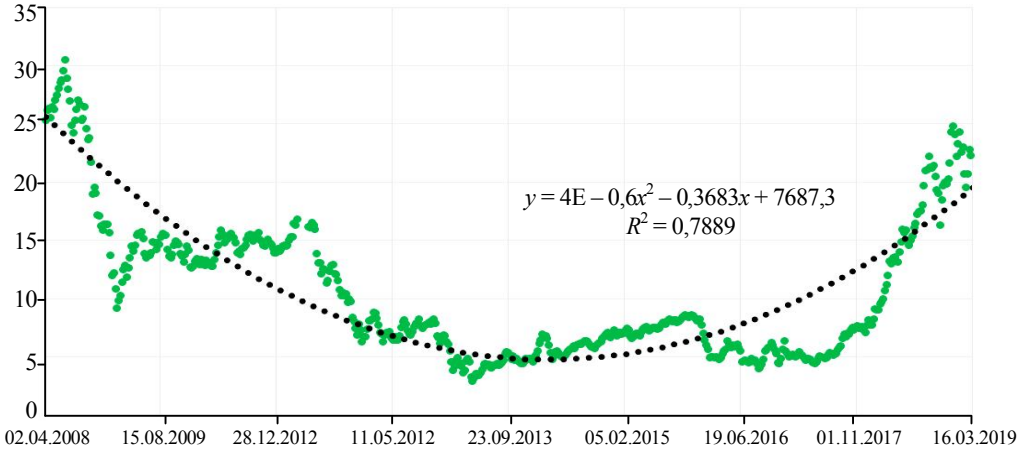


Fig.1. Average rate of carbon tax in Europe, euro/ton of CO_2 [31]

Hydrogen has been proposed as one of the promising energy carriers capable of solving this problem. Hydrogen is a potential solution for several energy generation issues, typical both for RES and hydrocarbon resources. On the one hand, its production, in theory, will enable the conversion, accumulation and storage of energy generated from any primary source in the long run [15]. On the other hand, hydrogen is recognized as a green secondary energy source as it does not produce pollutant emissions during combustion [16]. Despite this, the hydrogen power generation sector is at its primary stage of development and is not ready to be implemented extensively into the world energy system on a large scale. It should be clearly recognized that, while RES are a discussed, widely used group of technologies, the cluster of technical solutions for the hydrogen power generation sector is at the very initial stage of its development, although the first studies in the area of hydrogen use to facilitate sustainability processes began as far back as in the middle of the previous century [10], and the element itself has been studied for more than one century. Debates about the fate of hydrogen as an energy carrier in modern scientific works have been generally conducted in one of the following areas:

• At present, there are no economically effective means of producing hydrogen on an industrial scale, despite the fact that there are over 100 different methods of producing it (combinations of raw materials and technical methods) [11].

• There is no necessary infrastructure for the widespread development of both mobile and stationary hydrogen power generation [25]. At the same time, the issues of infrastructural development in many contemporary studies [22] are limited to the separate stages of production and logistic chain (production, transportation, storage or consumption) or combinations thereof. This is linked to the fact that while there are about 3,000 km of hydrogen gas pipelines worldwide [34], the assessments of the resources required to modernize existing energy distribution systems are still hampered.

• Research into the effect of hydrogen on metals has been carried out for decades. Thus, for example, back in 1967 in the USSR the scientific discovery “Depreciative effect of hydrogen on metals” was made (N 378), however, the reactivity of hydrogen is still not sufficiently studied, whereas its negative effects have already become a substantial technical issue (stress corrosion). So, for example, the negative impact of hydrogen on metal influenced the prospects of its use as a fuel for modern spacecrafts. Similar negative consequences are observed in existing pipeline systems, especially for the junctions of the structural parts. Due to stress corrosion Gazprom replaced over 5,000 km of large-diameter pipelines. A comprehensive study of the spatial and energy distribution of hydrogen in metal emerging in the course of operating technical systems must be made in each specific case for the purpose of assessing the service life of elements while taking into account fatigue failure [23].

In view of mentioned above, hydrogen should be considered comprehensively, that is: as a chemical element, as an energy carrier, as a raw material, and, more generally, as a source of possibilities and risks. The consideration of hydrogen in the context of one scientific discipline, in any case, leads to the loss of substantial pieces of information and, consequently, unfounded conclusions about its potential and barriers to its implementation.

Thus, the purpose of this article is to provide an integral analysis of the viability of ideas on the widespread development of the hydrogen power generation sector in the short term, which have been developing within the framework of strategic programs implemented by a number of leading world economies aimed at reducing carbon intensity.

Technical aspects of hydrogen production, transportation and storage. Unlike hydrocarbon sources, hydrogen is typically a secondary energy source since it is difficult to extract from the natural environment, although there are examples of such projects in international practice [38].

Many concepts and technologies have been developed to generate hydrogen [8], which can be provisionally divided into two key groups: RES ("green" hydrogen) and hydrocarbons ("blue" and "gray" hydrogen). The first group uses thermochemical or biological processes, the second – the processes of reforming and pyrolysis of hydrocarbons. The main problem is that most accessible technologies have not been sufficiently tested for their industrial implementation.

Hydrogen production. Currently, global production of hydrogen amounts to over 85 million tons. The main consumers are the chemical industry (up to 70 %), oil refineries (more than 20 %) and metallurgy (about 7 %), whereas the portion used in the transport power generation sector does not exceed 1 % within the overall consumption structure [11].

There are more than 100 promising hydrogen production technologies, of which the most widespread are chemical technologies for the conversion of hydrocarbon derivatives (natural gas and coal) [28]. The main industrial technology is the steam conversion of natural gas, or SMR (steam methane reforming), but carbon-dioxide conversion, or DRM (dry reforming of methane) is also applied, along with non-catalytic partial oxidation (POX) and combinations of the above-mentioned methods, among which autothermal reforming (ATR) is extremely widespread [17, 32].

Depending on the source, hydrogen is provisionally divided into "green", "gray", "blue" and "yellow". These categories do not correspond to the color of the gas but rather simplify public perception of these differences. "Green" hydrogen is formed along with oxygen during the electrolysis of common water. This process is simple from a technical point of view but extremely energy intensive. "Gray" hydrogen is produced when hydrocarbons reform, which also generates greenhouse gases. If CO_2 capture chains are realized simultaneously with this process [35], the obtained hydrogen is referred to as "blue". It can also be obtained by via hydrocarbon pyrolysis technologies. "Yellow" hydrogen is associated with the nuclear power generation sector. However, taking into account objective issues with the social perception of these atomic power plants as well as their limited role in the global energy balance, this hydrogen resource is insignificant [36].

It is worth mentioning the extremely promising technologies of hydrogen production from methane without access to oxygen (direct pyrolysis, low-temperature plasma, etc.) and consequently without CO_2 emissions [2]. Similar studies on the establishment of reactors are being conducted by European companies through public and private financing at BASF New Business GmbH, BASF SE, VdEh Betriebs Forschungs Institut, HTE GmbH, Linde AG, Thyssenkrupp Industrial Solutions AG, TU Dortmund, Verbundnetz Gas and other companies ranked among world leaders in the sphere of greenhouse gas emission reduction. In theory, pyrolysis technologies are capable of providing not only zero carbon emissions but a negative carbon footprint through the use of agricultural waste and products [18]. Without delving into the details of the technological processes, we will cite only general information related to them (Fig.2).

Hydrogen storage and transportation. Transportation and storage are also weak links in hydrogen energy systems [9]. Increasing the effectiveness of these processes is related to the resolution of two key issues: the transformation of hydrogen into a form with higher density (for example,

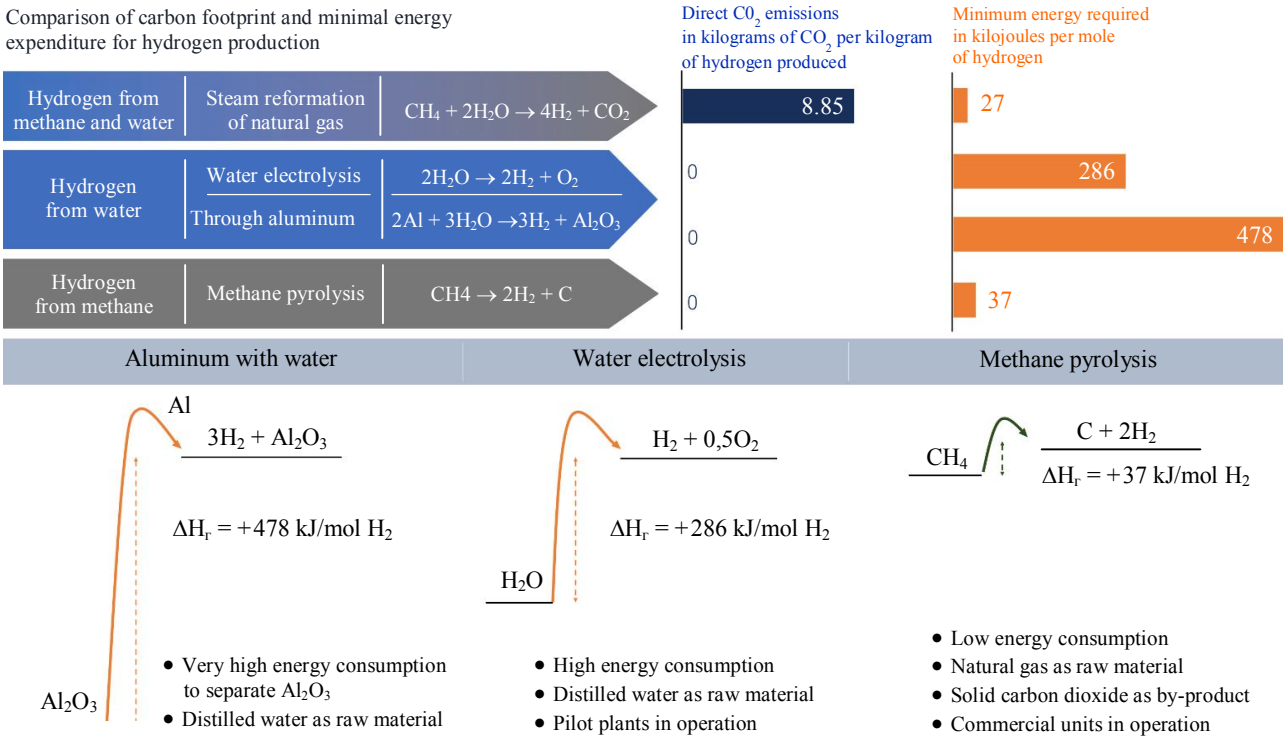


Fig.2. Comparative analysis of hydrogen production methods

liquefaction), and improving the safety of tanks and conveyor systems. Moreover, whereas the first problem already has some practical solutions, issues linked to the safe handling of hydrogen have not yet been studied [21].

Volume and physical characteristics. An example of potential hydrogen transportation project is Nord Stream 2, which is currently the most debated gas transportation project.

For the purpose of retaining its position on the European market, Gazprom PJSC needs to reduce the carbon intensity of supplied energy resources to comply with the established environmental standards, which implies that existing and planned processes will have to be modernized. Under the pressure of the European Union (EU), as a response measure, specialists at Gazprom PJSC are considering the possibility of transitioning mainline compressor turbines to a methane-hydrogen mixture (20 %), thereby reducing carbon dioxide emissions by approximately 30 %. For this purpose, it will be necessary to install equipment for hydrogen production at each compressor station (of which there are more than 250 in Russia). Otherwise, it will be necessary to transport natural gas mixed with hydrogen to the EU initially, gradually increasing the proportion of hydrogen as the EU transitions to "carbon-neutral" economics.

In this context, there are a number of difficulties in transitioning pipelines to this kind of mixture, which are linked to the physical and chemical properties of hydrogen. Upon detailed examination of those difficulties, sophisticated issues for gas transmission systems emerge. In particular, the effectiveness of gas pipeline transportation is directly contingent upon the quantities of the product, and thus on the density of the gas. Fig.3, *a* presents the dependence of the density of the methane-hydrogen mix, from which it may be observed that as the concentration of hydrogen increases from 10 to 90 %, the density of the mixture decreases more than four times.

Furthermore, the high energy capacity of this gas is noted, thus justifying the benefits of hydrogen. At the same time, the heat of combustion is considered for mass unit, which does not allow assessing the true picture. Fig.3, *b* shows the dependence for heat of combustion of heating mixtures with various concentrations. From this, it can be observed that the energy obtained from one volume of hydrogen is 3.5 times lower than the energy obtained from methane.

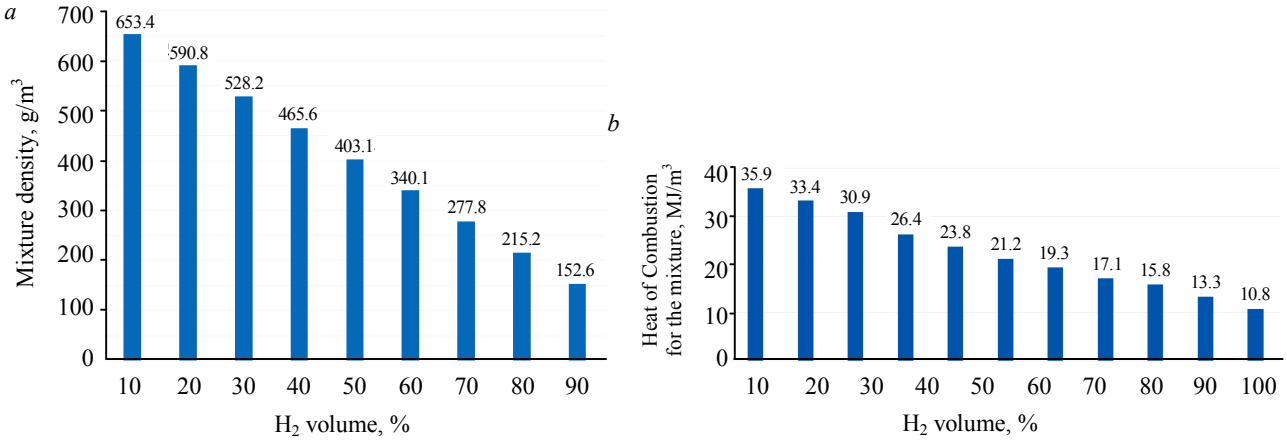


Fig.3. Density of the methane-hydrogen mix (*a*) and heat of combustion (*b*) in relation to the volume of hydrogen

Figure 4, *a* represents increase in energy required to compress 1 kg of the mixture to raise the pressure by 1 MPa with increasing proportion of hydrogen. From this, it is possible to conclude that energy costs are raised by around a factor of 8.5, which makes the pipeline delivery process of hydrogen-containing mixtures less energy efficient. This is linked the fact that the kinematic viscosity of hydrogen under reference conditions is 91.05 cSt versus 14.7 cSt for methane, which is the basis of natural gas. Due to the large kinematic viscosity of the methane-hydrogen mixture, pressure losses in a pipeline increase, which means that either large excess pressure must be generated at compressor stations for existing pipelines or the distance between compressors for designed pipeline systems must be reduced.

In terms of the explosion risks of the methane-hydrogen mixture, it is necessary to understand how the inflammation area of such gas will change in line with an increased volume proportion of H_2. As may be observed from Fig.4, *b*, which shows relationships of lower (LFL) and higher (HFL) flammability levels, an increasing proportion of hydrogen in the mixture increases the inflammation area. In this instance, LFL has barely changed, while HFL has increased from 15 up to 74 volume percents when mixed with air, which acts as an oxidizer. A mixture with a concentration of combustible gas, which has fallen within the flammability range, poses an explosion hazard. The wider the flammability range and lower the LFL, the greater is the risk of explosion for the combustible gas.

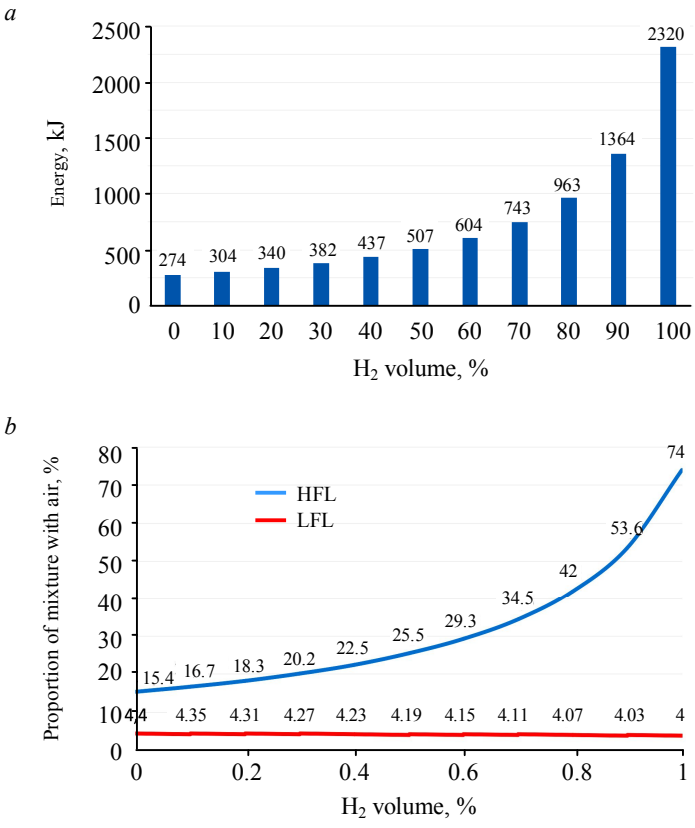


Fig.4. Energy required to compress 1 kg of the methane-hydrogen mixture with pressure of 1 MPa (*a*) and change in the flammability area of the methane-hydrogen mixture (*b*) in relation to the volume of hydrogen

As an alternative to pipeline transport, hydrogen liquefaction, by analogy with liquefied natural gas, could be considered, which makes it possible to diversify markets and simplify the storage process. Methane is liquefied at atmospheric pressure and temperature below –161.5 °C, it liquidizes with the density of 415 kg/m^3, with the volume 600 times less than its gaseous form. Hydrogen liquefies at atmospheric pressure

and temperature below –252.87 °C, it reduces in volume to 848 times. It should be taken into account that the closer the temperature of a substance to absolute zero, the more quantum properties such as superfluidity, superconductivity, etc. begin to appear in it, which require additional study for each material in contact with liquid hydrogen. The density of liquid hydrogen is about 70 kg/m^3, which is 5.9 times less than the density of liquefied natural gas, which means that under the same conditions and the same tank capacity it is possible to store or transport almost 5.9 times more liquefied natural gas than liquid hydrogen.

The complexity of transportation and storage is also complicated by the fact that when liquid hydrogen is stored in special thermally insulated containers, it is extremely difficult to maintain its stability at a low temperature required for its storage in liquid state. At the same time, due to evaporation, the pressure in the tank rises till the moment when a pressure relief valve actuates. Although this procedure has no negative environmental impact, it does lead to significant losses of hydrogen in case of long-term storage.

One cannot ignore the fact that hydrogen has extremely high penetrating ability (molecule diameter $2.47 \cdot 10^{-8}$ cm) – its molecules spread faster than molecules of all the other gases in the media of another substance and penetrate through almost any metal. Due to high permeability of hydrogen, there are strict requirements to welds and tightness of joints. The ability of hydrogen to penetrate through heated metal creates difficulties and hazards in handling it at high temperatures and pressures. Since the permeability of hydrogen is directly proportional to the pressure differentials, temperature and time, pressurized hydrogen is capable of escaping even from airtight tanks during long-term storage.

Thus, key physical and volume characteristics indicate that transporting hydrogen via pipeline systems, as well as the specific conditions for storing it, results not only in substantially decreasing its overall efficiency but in increasing the explosion hazards of such infrastructure.

Chemical processes of the effects of hydrogen on metals. There are other problems, among which the most critical is the interaction of hydrogen with pipeline metal [19].

Accumulation of even insignificant volumes of hydrogen in crystal lattice traps as well as on borders of non-metallic inclusions triggers a rise in internal tensions in steel and, as a result, causes formation of fractures and its subsequent destruction. In this connection, there are quite a number of conditions under which free hydrogen can form in gas-filled pipes, including due to the impact of special thermodynamic factors.

From an electrochemical point of view, the sulfide corrosion cracking process is triggered by the products of hydrogen ions cathode reduction (Fig.5, *a*). The conventional mechanism of carbon-dioxide corrosion is linked to a series of electrochemical reactions (Fig.5, *b*) which are produced on surface of the steel.

The relationship of partial hydrogen pressure in a transported mixture with respect to the hydrogen embrittlement process has been examined in other works [13, 27]. As can be seen in Table, increasing the pressure and volume proportion of hydrogen in the mixture increases the partial pressure of H_2, which leads to accelerated velocity of hydrogen diffusion into steel.

Role of Hydrogen in the Global Energy Agenda. The role of raw material resources and innovative technologies, which explore, process and consume them, in the context of sustainable economic development on a global scale, is underestimated. Thus, through the conception of cumulative value designated under the industrial matrix of the SDGs, the raw material sectors of the economy are placed on an equal footing with other sectors without taking into account specific inter-industrial relationships [10].

Partial pressure of hydrogen in a mixture in relation to its volume

Mixture pressure, MPa	Hydrogen volume in mixture, %				
	20	40	60	80	100
70.0	14	28	42	56	70
6.0	1.2	2.4	3.6	4.8	6
1.1	0.22	0.44	0.66	0.88	1.1
0.1	0.02	0.04	0.06	0.08	0.1

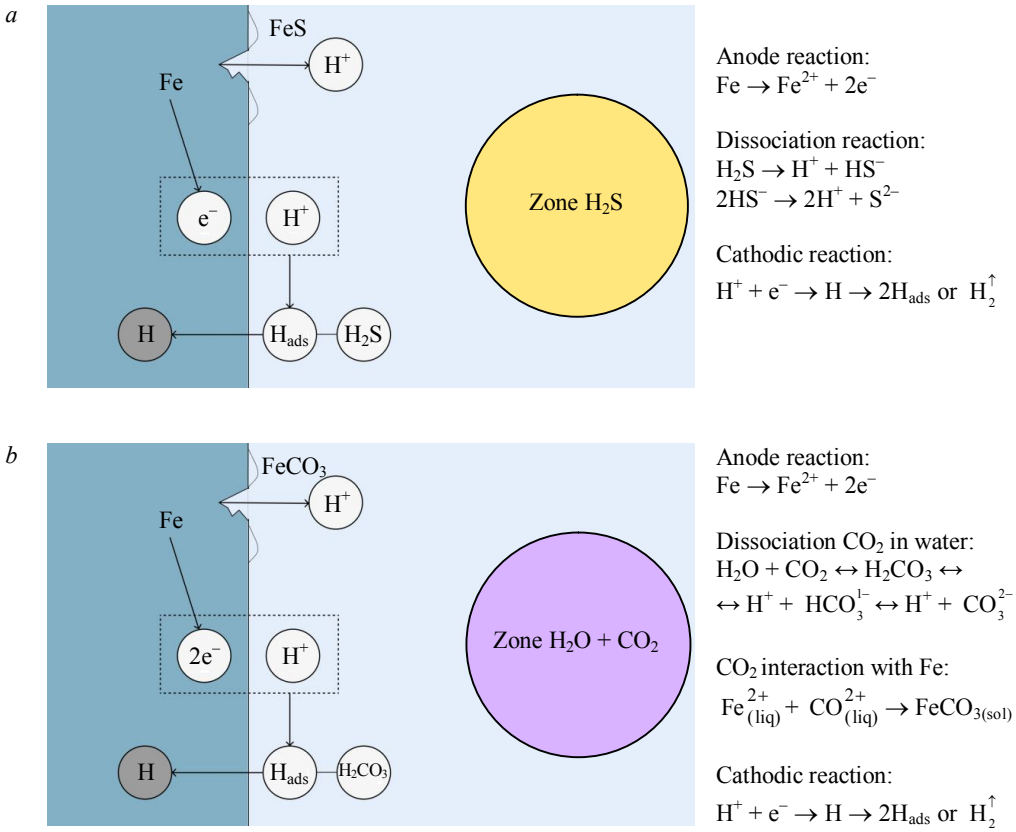


Fig.5. Electrode process of interaction for a hydrogen sulfide-containing medium (*a*) and a carbonic acid medium (*b*) with a metallic surface [1]

Against this backdrop, the raw materials sector of the global economy experiences problems with access to investment resources as well as the influence of the discriminative policy which hampers the fully-fledged realization of strategic initiatives geared towards exploring the transition to sustainable energy [3, 4].

At the same time, many countries set the task of achieving carbon neutrality, which requires the complete phase-out of hydrocarbon resources and their derivatives. Colossal financial resources are directed towards protecting existing non-competitive industries of renewable power generation and the ambitious strategies which accompany them, particularly those aimed at developing the hydrogen economy. This policy delivers a serious blow to the existing power system structure, primarily to conventional markets of oil, gas and coal in particular.

From an environmental standpoint, hydrogen looks more attractive than hydrocarbons, albeit only because it forms water as it burns, without releasing greenhouse gases. However, even this fact cannot be considered as an absolute truth. For example, the experience of the company Enel in the construction of a hydrogen power station near Vienna has shown that costs of power generation at such facilities are 5 times higher than for conventional gas heat power stations, and nitrogen emissions counterweigh the reduction in CO_2 emissions [14].

It should be acknowledged that numerous theoretical and practical laboratory investigations of hydrogen technologies [5] confirm that the task of producing and using hydrogen in power generation units has already been solved. Nevertheless, the efficiency of the transformation processes is far from optimal [29], thereby the potential to use these technologies on a large scale and their competitiveness on a free market with conventional hydrocarbon resources cause justified distrust and scepticism.

One can say that the cost of hydrogen production is quite high due to the initial stage of technology development, and this does not allow it to compete with conventional hydrocarbons. One study [12] includes a comparative analysis of 19 technologies for the production of hydrogen fuel.

Based on the analysis, the authors made several important conclusions in terms of the potential to develop hydrocarbon resources. First, reforming hydrocarbon raw materials has the highest energy efficiency among all the options considered. Second, the energy efficiency of reforming hydrocarbons is one of the highest (45-50 %), beaten only by biomass gasification (60 %). Third, it is shown that the cheapest hydrogen can also be obtained from the raw hydrocarbon with a cost of nearly 0.75 $/kg H_2. The use of technologies such as water electrolysis will enable generation of hydrogen at a cost 1.5 times higher.

Cost-specific advantages of hydrogen generation based on hydrocarbons are seen in [28] as well, according to which generation based on natural gas varies from 1.34 $/kg (without CO_2 sequestration) to 2.27 $/kg (with sequestration), compared with 1.34 $/kg to 1.64 $/kg for coal, while the majority of other generation methods are 1.5-6 times more expensive. The generation of hydrogen based on methane pyrolysis is the most cost effective option at a cost of 1.22 $/kg. The authors do not point out a single potentially leading production technology, but state that a preference shall be given to hybrid methods.

Equivalent results are also obtained in study [6], proving that the highest technical and cost effectiveness as well as the level of both readiness and reliability is typical for technical chains based on hydrocarbon resources.

As for the creation of motor transport infrastructure, the numerous positive results regarding the creation of hydrogen motor car prototypes are not an indicator of the readiness of the industry, and much less of the public [26]. For objective reasons it is doubtful that such production can be massive. First of all, it is necessary to provide hydrogen transport filling stations, construction of which is problematic due to the properties of the gas (i.e. reactivity and high combustibility) [7]. Second, the volume characteristics of hydrogen make it less attractive, even when compared with gasoline [21].

It is necessary to understand that widespread use of hydrogen technologies bears colossal risks for the public. This applies to both various projects of motor transport infrastructure [24] and gas pipeline delivery [20, 30].

In this connection, the processes of manufacturing, transporting and using hydrogen primarily require highly skilled and trained personnel who can ensure the safe performance of such systems. Moreover, it is necessary to have a number of strict requirements, standards and codes to ensure safety. At present, there are no such mechanisms of industrial regulation in world practice.

Thus, under the conditions of geopolitical confrontation, active promotion of hydrogen technologies within the global energy system, involving the substitution of coal, oil and gas as well as the provision of colossal resources by the EU for such programs – seems to be a largely political rather than economic or environmental initiative.

Conclusion. To understand the processes of ensuring universal access to inexpensive, reliable, sustainable and modern sources of global energy, it is necessary to have an in-depth knowledge of the search for and implementation of the advanced technologies, which are accelerating the energy transition.

The consideration of hydrogen under the EU-led policy to reduce the intensity of carbon as an energy carrier and means for storing superfluous energy requires an inter-disciplinary approach and "big-picture" thinking not constrained by a set of analytical tools to assess its environmental characteristic. Fragmental analysis of the situation without regard for the properties of hydrogen as a chemical element distorts a true picture and, when it comes to forecasting hydrogen infrastructure, may result in unrealistic expectations of the technological and technical possibilities. An integral approach to this issue allows to organize and harmonize the separate pieces of scientific knowledge about hydrogen as a global power generation resource, the potential of which could be realized in the long term.

The unilateral and comparatively simple policy of supporting one group of hydrogen based technologies has a substantial negative effect on the formation and implementation of a scientifically substantiated portfolio of energy strategies [33], which would take into account not only ecological needs but the possibilities of scientific and technical progress as well.

This article contains the inter-disciplinary analysis of the consistency of the belief that, despite its chemical and physical characteristics, hydrogen may be considered as a global power generation resource. The following conclusions have been made on the basis of this analysis:

1. The raw materials sector plays one of the leading roles in achieving the goals of sustainable economic development on a global scale. The current trends of increasing power generation based on RES and involving hydrogen in power system processes may turn out to be impracticable due to the objective disadvantages of existing technologies.

2. In the majority of modern studies, the cost of hydrogen is defined on the basis of separate stages in the production and logistic chain or combinations thereof (production, transportation, storage, and consumption). However, issues related to the need to modernize the entire energy infrastructure of a project implementation region are practically not considered. In light of such modernization, both the resource intensity of replacing separate units within the power distribution system and the hydrogen negative influence on metallic structures should be considered, along with the resulting reduction in their operational lifetime, which has a direct effect on the financial results of such projects.

3. The effect of hydrogen on various metals have not yet been studied completely. In this connection, issues surrounding the lack of international safety standards and rules for hydrogen infrastructure usage have arisen. Such rules are necessary to construct a fully-fledged power system, particularly if we speak about international deliveries since the greater the concentration of hydrogen in a transported gas mixture, the greater its explosion risks are.

4. Discussions about the competitiveness of separate stages of hydrogen process chains have been ongoing for decades. What's more, the aggregation of technologies with comparatively low levels of efficiency (for example, RES – electricity – hydrogen – transportation – electricity) will result in the synergetic collapse of the efficiency of the whole system, which makes its competitiveness in comparison with traditional hydrocarbon resources at least controversial.

5. In the past, the most ambitious of implemented development strategies in the green power generation sector were based on a combination of RES and hydrocarbon resources (preferably natural gas), which made it possible to achieve an environmental and economic balance of power generation system. Implementing a hydrogen strategy in practice will destroy this ecological and economical balance as the "hydrogen element" either catastrophically reduces the economical effectiveness of the process chain, including the need to provide the whole range of safety measures, or leads to additional environmental consequences, as experienced by the company Enel.

6. Despite the potential for hydrogen in the long run, the current level of global economic readiness for the development of hydrogen infrastructure is even lower than that of the renewable energy sector. There are neither mechanisms for functioning of the markets, nor technologies and infrastructure enabling the efficient generation, distribution and storage of hydrogen, and there are huge problems surrounding safety characteristic of the technologies at the initial stages of development.

Thus this article makes an attempt to involve scientists and field specialists in the debate to ensure a wide-ranging discussion and conduct mutual inter-disciplinary research aimed at creating a comprehensive approach to understanding the role of hydrogen in future global energy system. The highlighted theoretical and practical aspects do not allow to speak about the real possibility of introducing a widely accessible hydrogen power system in the near future.

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