Hydrogen Energy and Decarbonisation: Evidence from Regions of the World

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Abstract Hydrogen, as a potential energy carrier, has certain physical and environmental advantages, and the promotion of ideas and plans for the development of the "hydrogen economy" is most often explained by environmental considerations—the need to decarbonize the economy. Currently, a number of regions, primarily in the Western Europe and Japan, have announced large-scale plans to increase the production of hydrogen, with the implementation of ambitious scenarios—by an order of magnitude, and the share of hydrogen in the energy balance should grow to 20% or more by the middle of this century. The chapter discusses plans for the development of the hydrogen economy in the world and in a number of regions. Technological, environmental, and economic barriers to implement ambitious growth scenarios for hydrogen production and consumption are identified, and the feasibility of these scenarios is assessed. The widespread claim about hydrogen as a decarbonizing agent and the validity of the ecological argument of the hydrogen economy are disputed. A number of possible real reasons for promoting the ideas and plans of the hydrogen economy are considered. Hydrogen has been produced and used for a long time, but in recent years there has been a strong increase in interest in it as a potential energy resource, and the term "hydrogen economy" has become widespread, and a number of countries have announced plans to multiply the production of hydrogen. In recent years, many publications have appeared on hydrogen topics in various formats, including books, articles, and materials from numerous forums and conferences. We can say that the interest in hydrogen as a potential energy source has become explosive. First of all, hydrogen is positioned as an environmental-friendly fuel that does not leave a "carbon footprint when burned", and the growth of its production and use is considered in the context of "decarbonization" (decarbonization) and reduces resource consumption.

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1 Introduction

Finally, hydrogen can be used in various ways—both for generating thermal and electrical energy—including as a battery of energy and as a transport fuel.

In this regard, a number of countries are now adopting or developing programs for the development of the hydrogen economy.

In addition, the prospects of creating a global hydrogen market with the conversion of hydrogen into an exchange commodity [2] with large trading volumes are considered.

Currently, the total volume of hydrogen production in the world is 55–65 million tons, with an average annual growth rate over the first two decades, i.e. XXI centuries did not exceed 2%.

Its main consumers are the chemical and oil refining industries, and the main method of producing almost 70% of all hydrogen is methane conversion, while electrolysis accounts for only 5%.

Until recently, the energy use of hydrogen, in particular as a transport fuel, was rather experimental in nature, represented by separate projects—in particular, the hydrogen highway project HyNor in Norway and similar projects in other European countries, the USA, and Japan.

Currently, a number of countries have adopted large-scale hydrogen programs that involve a multiple increase in the production of hydrogen with the prospects of using it already for energy purposes—for generating heat and electricity, as well as a transport fuel (Bhuiyan et al., 2022b; Conteh et al., 2021; Daniali et al., 2021; Denisova et al., 2019; Huang et al., 2021a; Huang et al., 2021b; Khan et al., 2021; Liu et al., 2021a; Liu et al., 2021b; Mikhaylov, 2018a; Mikhaylov, 2018b; Mikhaylov, 2022a; Mikhaylov, 2022b; Mikhaylov et al., 2019; Nyangarika et al., 2019a; Nyangarika et al., 2019b; Sediqi et al., 2022).

In particular, the EU adopted a Roadmap for the development of the hydrogen economy. According to the European roadmap, as of 2015, the total final energy demand in the EU was about 14,000 TWh, of which hydrogen accounts for 2%, or 325 TWh (equivalent to about 8 million tons of hydrogen). Next, we consider two scenarios: inertial—business as usual and ambitious—ambitious (Table 1). In all cases, the use of hydrogen is expected to increase in all sectors of the economy. At the same time, an overall reduction in energy demand is expected-by 35% by 2050. Under the inertial scenario, the annual volume of hydrogen supplies to the EU market should reach 12 million tons by 2030, more than 18 million tons by 2050; under the ambitious scenario, more than 16 million and about 55 million tons, respectively (Adalı et al., 2022; Yüksel et al., 2022a; Yüksel et al., 2022b).

Japan has a similar Roadmap—Strategic Roadmap for Hydrogen and Fuel Cells assumes an increase in the use of hydrogen to 10 million tons per year by 2050.

A total of 228 hydrogen projects have been announced worldwide on all continents, with most of them in the Western Europe and the East Asia.

Table 1 Growth plans for the use of hydrogen according to the EU Hydrogen Roadmap

Indicator	2015	2030		2050	
Total energy demand, TWh	14,100	11,500		9300	
The script	–	Business as usual	Ambitious	Business as usual	Ambitious
Hydrogen content, %	2	4	6	8	24
Amount of hydrogen, TWh	325	481	665	780	2251
Equivalent in tons	8 million rubles	12 million rubles	16 million rubles	19 million rubles	55 million rubles
Including by sector:					
Existing industrial plants	325	427	427	391	391
New industrial production facilities	–	11	62	1	257
Industrial power engineering	–	11	8	53	237
Heat and electricity for buildings	–	11	33	207	579
Transport	–	11	70	85	675
Power generation, storage (buffering)	–	11	65	43	112

2 Literature Review

In Russia, in turn, a program for the development of hydrogen energy is under development. The Energy Strategy of the Russian Federation until 2035 also provides for the promotion of hydrogen production in Russia, the development of low-carbon technologies for its production, and the tasks of increasing exports (up to 0.2 million tons by 2024 and up to 2 million tons by 2035). So far, only the Sakhalin hydrogen cluster project can be named among specific large-scale hydrogen projects in Russia.

As a result, the market for hydrogen is expected to grow by tens of millions of tons annually in the next decades. At the same time, market forecasts vary dramatically.

According to the relatively conservative estimates IRENA, Shell, ARENA the annual volume of the global hydrogen market will be 500–2000 TWh by 2050.

Note that this means an increase in the share of hydrogen in the global energy balance to only 0.251.0%. This also means an increase in global hydrogen production of 12–50 million tons per year, or 20–80% relative to the current level, which is lower even than the single ambitious European scenario. At the same time, more ambitious forecasts for the global market are 5–10 times higher, up to 15,000 TWh (400 million tons), or 7–8% in the global energy balance, and higher (Dayong et al., 2020; Mikhaylov et al., 2018; Nyangarika et al., 2018; Danish et al., 2020; Danish et al., 2021; An et al., 2021; Uyeh et al., 2021; Tamashiro et al., 2021; Shaikh et al., 2021).

Furthermore, by some estimates, up to 24% of global energy consumption by 2050 will be covered by hydrogen (which is equivalent to the production of about 40,000 TWh or 1 billion tons of hydrogen). However, there is currently no answer to the question of the availability of resources for such a powerful increase, especially if we are talking about the production of exclusively "green" hydrogen at the expense of renewable energy sources. We will come back to that later (An et al., 2019b; An et al., 2019a; Mikhaylov, 2020a, Mikhaylov, 2020b, Mikhaylov, 2020c; Mikhaylov & Tarakanov, 2020; An et al., 2020c; An et al., 2020a; An et al., 2020b; Moiseev et al., 2020; Moiseev et al., 2021; Grilli et al., 2021; Gura et al., 2020; Dooyum et al., 2020; Mikhaylov et al., 2022; Mikhaylov, 2021a; Varyash et al., 2020; Zhao et al., 2021a; Zhao et al., 2021b; An & Mikhaylov, 2020; Alwaelya et al., 2021; Yumashev & Mikhaylov, 2020; Yumashev et al., 2020; Mutalimov et al., 2021; Morkovkin et al., 2020a; Morkovkin et al., 2020b; An & Mikhaylov, 2021).

A wide range in estimates is inevitable, based on the fact that the plans for the development of the hydrogen economy do not yet have enough specifics, and the figures presented are mostly declarative in nature.

3 Problems of Using and Increasing Hydrogen Production

Plans for a strong increase in hydrogen production, primarily in the Western Europe and Japan, and their motivation (decarbonization of the economy) raise questions (Fang et al., 2021; Kostis et al., 2022; Serezli et al., 2021; Zhao et al., 2021a; Zhao et al., 2021b).

The main problem is that hydrogen is not a primary energy carrier, and its production itself is energy intensive and requires a developed energy infrastructure and the involvement of large energy resources.

A method of producing hydrogen that is considered environmental friendly—water electrolysis—requires about 40–50 MWh of electricity per 1 ton of hydrogen, while the calorific value of 1 ton of hydrogen is lower than 40 MWh (about 36 MW) even at 100% efficiency. Thus, the energy cost of producing hydrogen during electrolysis is higher than the energy value of the resulting hydrogen (Bhuiyan et al., 2021; Dong et al., 2021, Mikhaylov, 2021b; Baboshkin et al., 2022; Barykin et al., 2022; Baig et al., 2022a; Liu et al., 2022a, Liu et al., 2022b; Bhuiyan et al., 2022a; Danish et al., 2022; Baig et al., 2022b; Saqib et al., 2021; Yüksel et al., 2021b; Yüksel et al., 2021a; Yuksel et al., 2021; Mukhametov et al., 2021, Candila et al., 2021; Mikhaylov & Grilli, 2022).

At the same time, it is unlikely that hydrogen, even obtained by electrolysis, can be considered "green" if the electricity for its production is generated on fossil fuels. Its production makes ecological sense only on the basis of renewable energy sources.

The EU's ambitious plans call for an increase in annual hydrogen consumption to 50 million tons by 2050. To produce such an amount of hydrogen by electrolysis of water, at least 2000 TWh of electricity will be required. In 2019, electricity production in the EU countries amounted to less than 4000 TWh, of which RES, including hydropower, accounted for about 1500 TWh, or 38%. Thus, to produce the claimed amount of hydrogen, it would be necessary to use more than 50% of all electricity currently produced, and all electricity generation from renewable energy sources would not be enough.

The same is true for Japan. The production of 10 million tons of hydrogen by electrolysis requires more than 400 TWh of electricity. In 2019, a total of 1040 TWh was produced in Japan, including about 200 TWh from renewable energy sources (including hydroelectric power plants), or about 20%. The declared production of hydrogen, in this case, requires 40% of all electricity produced in the country and is two times higher than all the electricity production due to renewable energy sources.

Thus, the stated ambitious plans, first of all, do not have a resource base; second, they would not mean decarbonization, but the reverse process—an increase in carbon emissions due to an increase in the production of electricity—needed to produce hydrogen from non-renewable sources (Kou et al., 2022; Liu et al., 2021a; Liu et al., 2021b; Liu et al., 2021c; Meng et al., 2021; Mukhtarov et al., 2022; Xie et al., 2021; Zhe et al., 2021; Zhou et al., 2021).

If we consider the import of hydrogen by these countries as an option, then carbonation is simply "dumped" into exporting countries, and the EU and Japan maintain or even increase their dependence on energy imports.

Technological problems are largely related to the physical properties of hydrogen with a high-heat transfer per mass as it has a low density: 0.09 kg/m^3, which is 8 times lower than that of the natural gas (0.75 kg/m^3 Thus, the heat transfer per volume of hydrogen is 2.5–3 times lower than that of the natural gas. However, hydrogen is also a highly explosive gas. All this creates great difficulties with the storage and transportation of hydrogen.

The existing gas infrastructure is not suitable for transporting and storing hydrogen. The creation of the actual hydrogen infrastructure is associated with high costs. In particular, only the construction of a hydrogen gas transmission network in Europe (with a length of more than 20,000 km) is estimated at $27–64 billion. A 3–4-fold increase in the world's hydrogen storage infrastructure will require more than $600 billion in investment by 2050.

The total cost of producing hydrogen by electrolysis is 2–6 €/kg or 5–15 euro cents/kWh in terms of energy equivalent with an efficiency of 100%. By data IEA, the cost of producing "green" hydrogen from renewable energy sources in 2018 was $3.0–7.5/kg. Thus, the cost of producing 1 million tons of hydrogen at current prices will amount to more than €2 billion, and for 50 million tons more than €200 billion per year. This does not take into account the cost of storing and transporting hydrogen.

In addition, in the future, hydrogen transport is considered as a competitor to electric transport. However, as recent research conducted by Scania, hydrogen engines are losing to electric ones both in terms of cost and other indicators.

Finally, the question of the environmental consequences of large-scale use of hydrogen, including the inevitable leakage of a certain amount, remains unresolved.

In particular, concerns are expressed, which are not excluded at the moment, about the possible negative impact of hydrogen on the stratosphere.

Based on this, the idea of a large-scale increase in hydrogen production for the purpose of decarbonizing the economy seems unfounded.

4 Possible Real Reasons for the Growing Interest in Hydrogen

It is possible that the growing interest in hydrogen is not due to environmental reasons, but due to some other, though less frequently named, reasons.

First of all, hydrogen can be considered as an energy accumulator. The growing share of renewable energy sources in energy consumption increases the instability of the energy system and the increased need for storage (Dinçer et al., 2022; Ding et al., 2021; Dong et al., 2022; Haiyun et al., 2021; Li et al., 2022). Hydrogen can be considered as a way to solve this problem. In other words, the development of the hydrogen economy should go hand in hand with renewable and, possibly, nuclear energy.

Renewable energy is the basis for a new technological breakthrough.

In 2014, it was impossible to abandon Russian oil.

In 2021, the excess supply of oil is 8%. The share of Russian oil is 11% of the demand.

In the United States, Japan, and Western Europe, energy consumption is declining. In the EU countries (including the UK), the peak of energy consumption occurred in 2006—21.9 thousand tons TWh, after which it gradually decreases up to 20.5 thousand rubles TWh in 2019; electricity consumption—respectively, from 3.7 thousand TWh in 2008, up to 3.5 thousand TWh in 2019. In Japan, total energy consumption decreased from 6.2 thousand tons TWh in 2005 to 5.2 thousand TWh in 2019; electricity—from 1.2 thousand TWh in 2008 to 1.04 thousand TWh in 2019. In the US, annual energy consumption since 2000 varies in the range of 25–27 thousand rubles TWh with a peak in 2007 of 26.9 thousand TWh; electricity—since 2007 fluctuates around the level of about 4.4 thousand tons TWh-h. A further decline in energy production and consumption in the western countries is likely.

This can be attributed both to success in energy conservation and to changes in the economic structure—the shift of energy-intensive industries to other regions and general economic problems. This may result in the formation of an excess of generating capacity that requires loading. In addition, the creation of a new growth zone—hydrogen production—can be considered as an incentive for economic development and a means of overcoming economic stagnation, possibly in conjunction with any other areas of technological development.

Finally, in the long run, hydrogen is seen as an exchange-traded commodity, which means that it can be used as a new global financial instrument.

At the same time, this set of reasons can hardly fully explain the ambitious plans and maximum forecasts for increasing hydrogen production. Also, the transition to a "hydrogen economy" does not have a clear positive economic and environmental impact on society as a whole, which raises additional questions.

Based on this, the most realistic are the moderate, conservative forecasts of global hydrogen production growth presented above.

5 Conclusions

At the same time, hydrogen is not a primary energy carrier, but, on the contrary, requires high-energy costs during production, exceeding the energy value of the resulting hydrogen, which in itself means not decarbonization, but the opposite process—an increase in emissions to the environment. Moreover, there is insufficient energy capacity in the Western Europe and Japan to produce the declared amounts of hydrogen.

In addition, the creation of an infrastructure for storing, transporting, and using hydrogen will require high costs, and the operation of this system may be associated with unrecognized negative environmental effects.

Based on this, it can be assumed that the real reasons for the promotion of hydrogen differ from those most often declared and are primarily related to the need to accumulate energy, in a broader sense—to revive the economy of western countries, and possibly other motives that are not yet fully understood and require further research. At the moment, conservative forecasts of an increase in global hydrogen production by the middle of the year seem to be the most adequate. Within 20–80% of where we are now in the twenty-first century.

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