ORIGINAL ARTICLE

DOI: https://doi.org/10.18599/grs.2023.3.25 Russian Original 2023. Vol. 25. Is. 3. Pp. 216–226

Prospects for the development of hydrogen energy in the Russian Federation

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Abstract. Currently, in the energy strategies presented by Japan, the Republic of South Korea, the Russian Federation and the countries of the European Union, hydrogen is considered as a promising energy carrier that should replace fossil fuels (oil, gas, coal) and be used for accumulation, storage and delivery of energy to different regions of the world. The improvement of hydrogen energy technologies plays a special role in the low-carbon development of the world economy. The main advantages of hydrogen are the possibility of obtaining it from various sources and the absence of carbon dioxide emissions when it is used as an energy carrier, which is especially important against the backdrop of the current climate agenda. In the meantime, this energy carrier is artificially created, since there are no deposits of free hydrogen in nature. Therefore, hydrogen should be perceived precisely as a "carrier" of energy, and not as a fuel. The purpose of this study is to substantiate the feasibility of building tidal power plants, the development of hydrogen technologies and industrial complexes in the Russian Federation.

Keywords: hydrogen, renewable energy sources, hydrogen energy, water electrolysis method, tidal power plants

Recommended citation: Razmanova S.V. (2023). Prospects for the development of hydrogen energy in the Russian Federation. *Georesursy = Georesources*, 25(3), pp. 216–226. https://doi.org/10.18599/grs.2023.3.25

Introduction

In the last decade, the climate agenda has become a significant factor in changes in the global economy and energy. One of the benchmarks for the development of sectors of the world economy is the low level of greenhouse gas emissions. To achieve the goals of the Paris Agreement, the Russian Federation (RF) is implementing "a state climate policy aimed at reducing and preventing anthropogenic emissions of greenhouse gases, including by expanding the scope of low-carbon energy carriers and introducing the best available technologies" (Concept, 2021). The task of forming a new climate policy in the Russian Federation is one of the priorities of the current stage of the country's socio-economic development (Zhigalov et al., 2018). Given the increased risk of global climate change, as well as new legislative initiatives on decarbonization policies adopted at the national and international levels, the state needs to implement a proactive policy to achieve sustainable long-term competitiveness and successful integration of domestic business into global economy (Pakhomova et al., 2022).

Current technologies promoted in the international agenda for low-carbon economic development include hydrogen energy technologies. At the same time, the emphasis is placed on the fact that hydrogen, currently used in the chemical and petrochemical industries, in the future is capable of playing the role of an energy resource, replacing hydrocarbon energy resources. Many countries around the world have chosen the transition to hydrogen energy as the most effective means of achieving climate neutrality by 2050. The Energy Union[1], created in 2015, contributes to the promotion of European strategies in the field of climate and energy security. Subsequently, in 2019, the "Green Deal for Europe"[2] was adopted, which covered a set of strategies, goals and initiatives in the field of combating climate change and announced the transition of European countries to a zero-carbon balance as a benchmark for 2050.

[1] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank. A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0080

[2] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. EUR-Lex. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=C0M%3A2019%3A640%3AFIN

Since July 2021, the EU Green Deal[3] has had a significant impact on the energy policy of the European Union, according to which EU carbon neutrality by 2050, as well as reduction to 55% in greenhouse gas emissions by 2030 compared to the level of 1990, are settled as mandatory goals of the Climate Law. The course towards hydrogen energy is fixed in the National Strategy for the Development of Hydrogen Energy of the Federal Republic of Germany (FRG) (June 2020). The long-term goal is to create a climate-neutral economy with a reduction in CO_2 emissions by 95% of the 1990 level.

Basic Hydrogen Strategy of Japan (2017) notes that hydrogen can become a key energy resource in ensuring energy security and preventing further climate change. Strategic Energy Plan for Japan's for 2030 (4th Strategic Energy Plan for 2030), approved in 2020, in addition to the transition to renewable energy sources, provides for the creation of a so-called "hydrogen society" (Kornev, 2021; Mastepanov, Hirofumi, 2020a; Mastepanov, Hirofumi, 2020b).

The researchers note that the role of renewable energy sources such as solar, wind, wave and tidal power will increase over the next few decades. It is quite natural that the demand for hydrogen fuel produced from renewable energy sources will also increase (Chun et al., 2014; Chung et al., 2014; El-Shafie et al., 2019; Fazelpour et al., 2016 ; Iordache et al., 2013; Stygar, Brylewski, 2013).

The researchers emphasize that the concept of a "hydrogen economy" arose in the early 1970s in response to the first oil crisis (Mastepanov, 2020; Moliner et al., 2016). There is no doubt that hydrogen will play an important role in the future energy scenario, but this energy resource should not be viewed in terms of dominance, but rather in competition and complementarity with other types of energy resources (Mastepanov, 2020; Moliner et al., 2016; Grib, 2019; Litvinenko et al., 2020; Mastepanov, 2022). The Energy Strategy of the Russian Federation states that "the objective of hydrogen energy is the development of the production and consumption of hydrogen, as well as the inclusion of the Russian Federation among the world leaders in its production and export"[4]. Adapted to the conditions of domestic business, the Millennium Development Goals within the framework of the strategy for sustainable development of humanity of the United Nations (UN) suggest that such principles of sustainable development as circular economy and efficient use of resources should prevail in all aspects of the Russian economy. The Russian Federation has also been developing hydrogen technologies over the past 80 years, has extensive experience in many years of research and serious potential in this area (Mastepanov, 2022; Timofeev, 2019; Filippov et al., 2020; Kantyukov et al., 2021). Back in the 1970s, within the framework of the USSR state program "Hydrogen Energy", the concept of hydrogen energy was developed, based on gas production using energy generated at nuclear power plants (NPPs) (Kolbantsev et al., 2021; Mastepanov, 2020). A number of researchers review and analyze various hydrogen production technologies, comparing the cost and efficiency of various methods for its production (Veselov, Solyanik, 2022; Kholkin, Chausov, 2021; Acar, Dincer, 2018; Badgett et al., 2022; Ball, Weeda, 2016; Kayfeci et al., 2019; Sojoudi et al., 2021).

Meanwhile, it should be noted that in the modern world the geopolitical situation has an extremely strong influence on the global economy. The development of global energy is based on a whole complex of changing factors, most of which are outside the energy industry and relate to the spheres of politics, economics and social dynamics. Ensuring access to hydrocarbons has been the cornerstone of world politics for more than a hundred years. According to the American political scientist D. Ergin, the oil business includes "...90 percent politics and 10 percent oil" (Ergin, 2022). The desire to bring the energy resources of other states under its control is accompanied by a wide range of methods used to acquire this control. Moreover, if one of the reasonable methods is peaceful negotiations, then the extreme expression of the methods used is a military invasion. The climate agenda, the course of which was recently outlined by Western countries, should also be considered from the perspective of political influence.

At the beginning of the 20th century, the development of technologies in terms of the use of fossil natural resources with direct lobbying of companies, which today belong to the so-called supermajors (Shell, BP, Chevron, ExxonMobile and Royal Dutch Shell), relied on the use of hydrocarbons. Sources of wind and solar energy were considered as alternative ideas. However, they did not receive any promotion at that time. For example, solar cells first found their use within the space programs of the United States and the Soviet Union in the late 1950s. Only when costs were reduced did the technology begin to be used on Earth, but its use has certain limitations. The most obvious disadvantage of solar and wind energy is the intermittent nature of energy generation, which puts power grids at increased risk of frequency variations. "Green energy" in the form in which it is presented now is a dead-end direction in energy supply. Unfortunately, European countries are actively trying to join the existing list of

[3] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'). EUR-Lex. https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A32021R1119

[4] Order of the Government of the Russian Federation dated 06/09/2020 N 1523-r "On approval of the Energy Strategy of the Russian Federation for the period until 2035" (in Russian)

countries that have relied on "green energy" and received negative experience (Ghana and Sri Lanka) (Chernova, Razmanova, 2022a; Chernova, Razmanova, 2022b).

The purpose of this work is to substantiate the feasibility of developing centers for the production of "green" hydrogen in the Russian Federation based on the construction of tidal power plants (TPPs). The following basic questions are cross-cutting for the ongoing research: first, to determine the main driver for the development of hydrogen energy in the Russian Federation. Secondly: should hydrogen production from renewable sources be located in close proximity to sales markets?

Methods

The work used statistical reporting data for the European Union, statistical books of the People's Republic of China (1991–2020), reports of energy corporations, international consulting companies. A significant number of scientific works and Internet sources were subject to analysis. The information base for the research was the scientific works of both domestic and foreign scientists on the identified issues. During the research process, general scientific research methods (comparison, generalization), techniques of logical-theoretical analysis, and methods of technical and economic analysis were used.

The research methodology covers the following stages:

- Stage 1. Consider the existing terminology in the field of hydrogen production technologies;
- Stage 2. Assess the current and future costs of various methods of hydrogen production;
- Stage 3. Outline the prospects for the global hydrogen market and identify problematic aspects;
- Stage 4. Analyze the advantages of creating centers for the production of "green" hydrogen in the Russian Federation.

Hydrogen economy: terminology, comparative assessment

The term "hydrogen economy" refers to an economy based on the use of "clean" hydrogen as the main source of energy, the production of which is not accompanied by carbon dioxide emissions (Center for Economic Forecasting, 2019). Despite the fact that the term "hydrogen economy" is presented today as "a vision of the future for the global economy, in which hydrogen becomes the new global energy resource" (Mitrova et al., 2019), as it begins to play a role comparable to the importance of fossil oil, gas, coal, as well as energy generated by hydroelectric power plants (HPPs), nuclear power plants, renewable energy sources and bioenergy, the authors are not inclined to believe that such a role of hydrogen will ever be fully realized. Rather, we should talk about "hydrogen energy", which involves the development of the production and consumption of hydrogen. Hydrogen energy is today seen as a key solution to combat global climate change.

Experts in the field of hydrogen energy (one gets the impression that a decade earlier they were experts in shale and liquefied natural gas (LNG)) are already in full use of the concepts of "green", "turquoise" hydrogen and other, no less colorful terms in relation to a potential energy resource, which in reality is colorless and has nothing in common with the proposed palette.

Table 1 shows the most common "color" terminology used today by experts in the field of hydrogen energy to indicate the appropriate gradation of hydrogen, depending on the type of production. Note that the officially published energy strategies of the EU and Germany do not contain a "color" classification, but are divided into types according to the degree of impact of the production process on the environment.

Of course, such a classification will be adjusted over time. However, its vector will remain the same – focus on the production of "green", clean and renewable hydrogen. In Russia, according to the Concept for the Development of Hydrogen Energy (The concept for the development of hydrogen energy in the Russian Federation, 2021), by 2024 it is planned to create hydrogen clusters and implement pilot projects to achieve hydrogen exports in the amount of 0.2 million tons by 2024, as well as the production of methane-hydrogen mixtures; production of turbo units capable of operating on hydrogen; and production of hydrogen transport. Gazprom PJSC is developing technology for the production of "blue" and "turquoise" hydrogen, while Rosatom JSC is improving the technology for producing "orange/yellow" hydrogen. At the VI Eastern Economic Forum, Gazprom PJSC, Rosatom JSC and the authorities of Sakhalin (after a successful feasibility study of the project) entered into an agreement on cooperation in the construction of a plant for the production of hydrogen from natural gas. Corporations like NOVATEK, Rosneft, Rostec, and institutes of the Russian Academy of Sciences have also intensified development and marketing research in the field of hydrogen production and export (Mastepanov, 2020; Mastepanov, 2022).

Domestic and foreign scientists note that electrolysis as a means of converting excess electricity from renewable sources into hydrogen (with or without underground storage) is an extremely expensive method in modern conditions. This is due to the fact that "green" hydrogen produced by electrolysis cannot compete in cost with other methods of hydrogen production (Badgett et al., 2022; Ball, Weeda, 2016). To more accurately characterize the differences in the cost of hydrogen production depending on the type of its production, it is necessary to evaluate the differences

Classification	Type of production	Characteristics	Terminology used in the European classification of hydrogen by production method
Green	Utilizes the electrolysis method of water, using electricity from any renewable energy sources.	There is no carbon footprint when producing green hydrogen, and other environmental costs are kept to a minimum.	Renewable hydrogen. The term is equivalent to the term “green hydrogen” Clean hydrogen. The term is equivalent to the term "Renewable Hydrogen". Electrolysis hydrogen obtained by electrolysis without reference to a source of electricity Low-carbon hydrogen
Pink/red/orange/yellow	The method of electrolysis of water is used, however, a nuclear power plant acts as a source of electricity to ensure the process.	The production of “orange/yellow” hydrogen has no carbon footprint but creates thermal pollution of the environment and requires disposal of radioactive waste.	*Low-carbon hydrogen* is hydrogen produced with significantly reduced life-cycle greenhouse gas emissions compared to existing fossil hydrogen production. This category includes both fossil hydrogen with carbon capture and electrolysis hydrogen.
Turquoise	The method of pyrolysis is used by decomposing methane into hydrogen and solid carbon.	In the production of “turquoise” hydrogen, there are no emissions into the atmosphere, since carbon is obtained not in the form of carbon dioxide, but in almost pure solid form (soot), and therefore can be either recycled or used as a raw material for industry.	*Low-carbon hydrogen*
Gray	The method of steam reforming of methane is used, where the feedstock is natural gas.	When producing “gray” hydrogen, a chemical reaction produces carbon dioxide in the same volumes as during the combustion of natural gas, plus energy costs for conversion.	*Fossil-based hydrogen* is hydrogen produced from fossil fuels using classical technology. *Low-carbon hydrogen*
Blue	The method of steam reforming of methane is used, however, on the condition that carbon is captured.	When producing “blue” hydrogen, there is a twofold reduction in carbon emissions compared to traditional methods (“gray” and “brown” hydrogen).	*Fossil-based hydrogen with carbon capture* is hydrogen produced from fossil fuels using classical technology, subject to the implementation of measures to capture carbon and its compounds. *Low-carbon hydrogen*
Brown	Brown coal is used as a raw material in production.	During the production of “brown” hydrogen, synthesis gas is formed - a mixture of carbon dioxide, carbon monoxide, hydrogen, methane and ethylene, as well as a small amount of other associated gases. Classified as the most non-ecological.	*Fossil-based hydrogen*

Table 1. Classification of hydrogen by type of production

in the cost of capital and operating costs. General financial assumptions, such as internal rates of return, tax rates and depreciation rates, remain the same for all technologies considered. The results obtained in this way provide an objective assessment of the cost differences between technologies.

An analysis of the costs of hydrogen production in the United States shows that the cost of electrolytically generated hydrogen is significantly higher due to the high proportion of third-party electricity consumed in its production (Sojoudi et al., 2021). In particular, when producing hydrogen by electrolysis using RES, the highest production costs per kilogram of hydrogen are formed: for wind RES – from 5.89 to 6.03 USD/kg), for solar RES – from 5.78 to 23.27 USD/kg (Kayfeci et al., 2019). A comparison of the normalized ranking of the selected hydrogen production options led to the conclusion that, in terms of energy efficiency, options running on fossil fuels and biomass are closest to ideal characteristics. At the same time, the average normalized ratings of hydrogen production methods based on photonic technologies are due to low system efficiency and production costs, despite significantly low CO_2 emissions (Acar, Dincer, 2018).

The results of calculating the cost of hydrogen production in Russia, carried out by scientists from the Energy Research Institute of the Russian Academy of Sciences (Veselov, Solyanik, 2022), reflect the comparative effectiveness of various production technologies in the conditions of our country (Table 2).

According to the estimates of experts from the Energy Research Institute of the Russian Academy of Sciences, it follows that at the moment the least expensive method of producing hydrogen is steam conversion of methane – 1.7 USD/kg. Electrolysis from wind and solar generation is significantly inferior to other production methods in terms of economic efficiency. In the future, a twofold reduction in cost is expected for this category (due to cheaper electrolyzers and renewable energy installations). However, the specific discounted cost of 1 kg of "green" hydrogen will remain 2.5–3.5 times higher than for "blue" hydrogen (Veselov, Solyanik, 2022).

In general, the expected value of the unit cost of "green" hydrogen by 2050, according to Statista (https://www.statista.com/statistics/1086695/green-hydrogen-cost-development-by-country), will be in the range of 1.25–2.75 USD/kg (Fig. 1).

According to a report by the International Energy Agency (IEA), by 2050, global demand for hydrogen should reach 528 million tons (in 2020, the volume was 87 million tons). The share of hydrogen consumption in the global market structure is expected to be 18%, including the consumption of "green" hydrogen, which is projected to account for 10% of the global market.

Today, the main raw materials for hydrogen are predominantly hydrocarbons. More than 68% of hydrogen is produced from natural gas, 16% from oil, 11% from coal, and 5% from water by electrolysis (Rozentsvet, 2022).

Currently, the scope of hydrogen use covers the chemical industry (63%), oil refining (31%), and manufacturing industry (5%). And only less than 1% of hydrogen is used as fuel and in the semiconductor industry (Rozentsvet, 2022). The National Strategy for the Development of Hydrogen Energy in Germany assumes that hydrogen, to which the transport, metallurgical and petrochemical industries will be transferred, will play a leading role in the future of these industries. They are actively trying to use hydrogen in the transport industry: Japan, the Republic of South Korea, Germany (light vehicles), the French Republic (railway transport). However, hydrogen remains an extremely inconvenient gas for use in transport, primarily due to the fact that it cannot be stored for a long time, it leaks into the atmosphere and, accordingly, brings losses to owners using such transport.

At the same time, experts note that the prospects for the global hydrogen market are not clearly visible and it is quite problematic to estimate future volumes

Classification characteristic/method of production	Value of specific discounted costs for hydrogen production, USD/kg	
	2020–2025	2030–2035
green/ solar RES	>12.0	>6.0
green/ wind RES	7.8	9.5
red / nuclear power plant	3.2	2.3
orange/ hydro-electric power stations	3.5	3.0
blue / steam methane reforming	1.7	1.6

Table 2. Comparison of the cost of domestic hydrogen production technologies

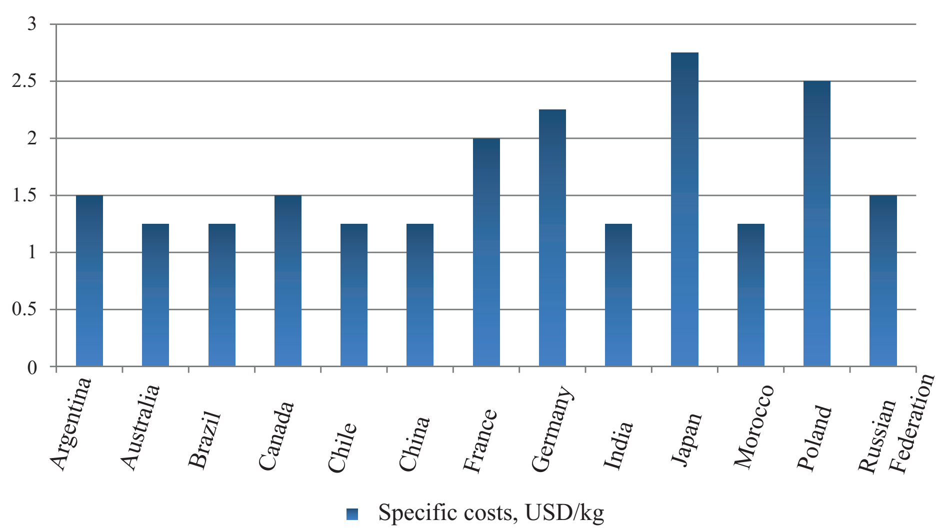

Fig. 1. Forecast of the cost of green hydrogen by 2050. Source: https://www.statista.com/statistics/1086695/green-hydrogen-cost-development-by-country/

of hydrogen production and consumption in the global economy today (Grib, 2019; Litvinenko et al., 2020).

A preliminary analysis of the volumes of the global hydrogen market and the expected increase in hydrogen imports was made by experts from ACIL ALLEN Consulting and the EnergyNet Infrastructure Center (Kholkin, Chausov, 2021) (Fig. 2, 3).

A number of questions still remain unanswered. Let us outline the key problematic aspects of the development of the global hydrogen market:

- Dynamics of the volume of global import supplies of hydrogen for the future 10 or 15 years;
- At what level of hydrogen prices will equilibrium be established in the market, and what will be the design of the hydrogen market in the future;
- Will there be a tendency for countries to produce hydrogen exclusively for domestic consumption;
- The dominant production method for hydrogen production;
- Will "yellow" and "blue" hydrogen retain strong positions in the market, or will the market give preference only to "green" hydrogen?

The future architecture of global hydrogen energy depends on the solution of these aspects.

The Russian hydrogen strategy, first of all, should prioritize national energy security, focusing on the domestic market and friendly foreign markets. The outlines of the promising industrial hydrogen structure are still unclear; there is a high probability of copying the gas industry model. A significant danger when implementing a hydrogen strategy is the long-term planning of strategic action, assessment of investment opportunities, and their subsequent implementation (by analogy with the LNG market, which the Russian Federation entered with a significant delay), since in this case there will be a delayed effect from the use of hydrogen technologies.

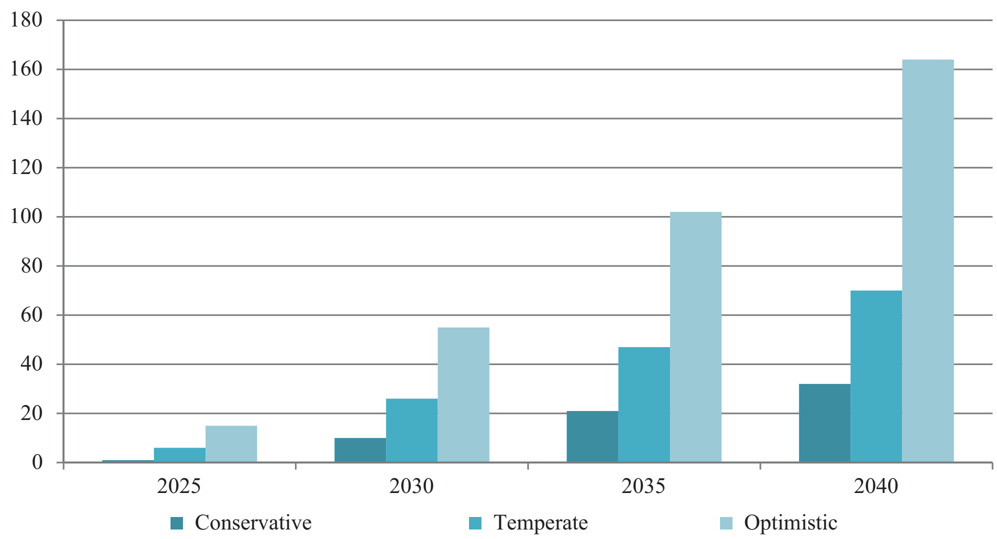

Fig. 2. Forecast of the global hydrogen fuel market, billion dollars per year. Sources: ACIL ALLEN Consulting, analysis by EnergyNet IC (Kholkin, Chausov, 2021)

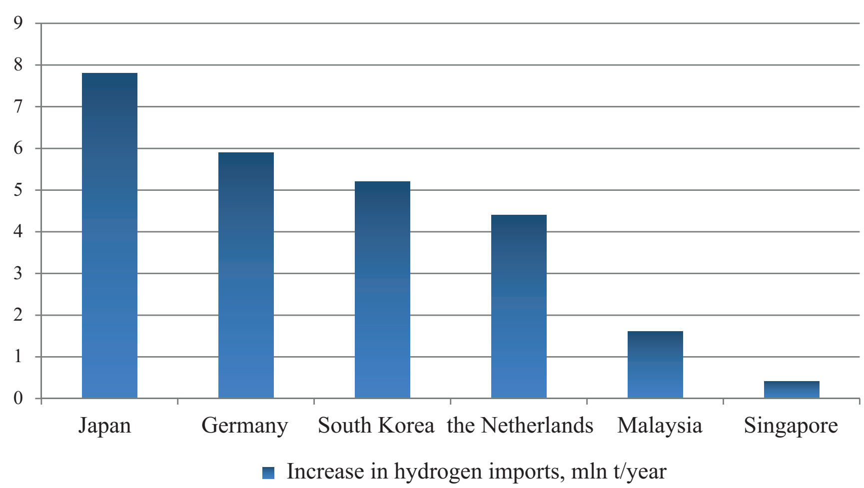

Fig. 3. Expected annual increase in hydrogen imports by 2040 (compared to 2020 figures), million tons. Source: analysis by the EnergyNet Information Center (Kholkin, Chausov, 2021)

From "gray" to "blue" and "green" hydrogen: Russian prospects

In the previous section, we mentioned methods for generating hydrogen, ranging from coal gasification, steam reforming and methane pyrolysis to water electrolysis. In principle, it can be obtained from algae or municipal solid waste. However, coal gasification technology is associated with a large amount of harmful emissions into the atmosphere. At the moment, this is one of the most proven methods by which about 25% of hydrogen is produced in the world. Municipal solid waste and algae as raw materials are not entirely suitable as a starting point for the development of hydrogen production. Therefore, methane and water remain as sources of raw materials for hydrogen production.

Methane, a commercial product of hydrocarbon processing, accounts for 75% of ammonia production. Refineries use methane as a fuel and source of hydrogen for the catalytic cracking and hydrotreating of gasoline and diesel; at gas processing plants – for the synthesis of methanol, used as a hydrate formation reagent and in the chemical industry; in gas chemistry – in the synthesis of ammonia necessary for the production of nitrogen fertilizers and carbamide.

The main advantage of hydrogen produced from methane is its cost – 1.7 USD/kg. (Table 2), while hydrogen obtained from the electrolysis of water is among the most expensive and its specific cost is in the range of 3.5–12 USD /kg. True, as recent events in the world show, much depends on what source of electricity will be used (traditional or renewable energy sources) and how much natural gas will cost in regional markets.

Today, the Russian Federation is more focused on the production of hydrogen from natural gas or on the basis of nuclear power plants, so the talk about the production of "green", "turquoise" or "blue" hydrogen on the part of domestic corporations is not so obvious. However, the state strategy for the development of hydrogen energy has already outlined the creation of centers for the production of "green" hydrogen and ammonia using energy generated by solar power plants in the Arctic region and the Far East.

In the meantime, it should be noted that the Russian Federation focuses specifically on expanding potential sources of energy resources. In the new reality, there is a place for both renewable and fossil energy sources, since this helps maintain energy security and sustainability of the economy of Russia and the countries to which it supplies energy resources. Thus, Russia, which has huge hydrocarbon reserves, retains the attractiveness of these resources, but at the same time plans to declare its desire to take part in the production of hydrogen on a global scale.

The key condition for the economic feasibility of constructing tidal power plants is that the difference in water levels must be at least four meters. Therefore, TPPs are built in areas of the highest sea level rise. The world's largest thermal power plant, commissioned in 2011, is located in the Republic of South Korea and has an installed capacity of 254 MW. The People's Republic of China (PRC), France and Canada also have tidal power plants (TPP).

In Russia, the highest tides are observed in the Penzhinskaya Bay area (Sea of Okhotsk), the coast of the Mezen Bay (White and Barents Seas) and reach levels of up to 13 and 10 meters, respectively.

Today in the Russian Federation there are several tidal power plants that are at the operating or design stage: Kislogubskaya TPP, Malaya Mezenskaya TPP, Severnaya TPP, Penzhinskaya TPP, Tugurskaya TPP (Table 3). It should be noted that all of the listed stations are located in northern latitudes: in the Arctic zone of the Russian Federation (White and Barents Seas), as well as on the Kamchatka Peninsula and Khabarovsk Territory (Sea of Okhotsk).

Generating electricity using tidal energy has not become widespread in the Russian Federation, for reasons of economic feasibility. For example, the Kislogubskaya TPP, operating in the Russian Federation since 1968, does not provide energy even for the process of its own operation and is registered with the state only as a monument of science and technology. However, the

Project name	Main characteristics of the project
1. Active	
1.1 Kislogubskaya TPP	
Electric power	1.7 MW
Turbine type	orthogonal
Number of turbines	2 sets
Number of generators	2 units
Switchyard	35 kW
1.2 Malaya Mezenskaya TPP	
Electric power	1.5 MW
Turbine type	orthogonal
Number of turbines	1 set
Number of generators	1 unit
2. Promising	
2.1 Severnaya TPP	
Design capacity	12.0 MW
Annual electricity output	23.8 million kW·hour
2.2 Penzhinskaya TPP	
Design capacity	21.4 GW
Annual electricity output	50.0–240 billion kW·hour
2.3 Tugurskaya TPP	
Design capacity	8.0 GW
Annual electricity output	20.0 billion kW·hour

Table 3. Main technical characteristics of existing and promising domestic projects for the construction of tidal power plants

experimental installation "Malaya Mezenskaya TPP" (2007) during testing confirmed the efficiency of the power unit at 70%.

Experts from the EnergyNet Infrastructure Center note that "the accumulation of renewable energy in the form of hydrogen will significantly (by 15–20%) reduce energy supply costs in many isolated areas of the country, especially in the Arctic, Kamchatka, Kuriles, Irkutsk and Tomsk regions, in Yakutia" (Kholkin, Chausov, 2021).

Electricity from tidal power plants can be used to convert coal into flammable hydrocarbons (synthetic oil, methanol); construction of power lines in the Khabarovsky and Primorsky regions; transmission of electricity to China, USA, Japan and other countries; hydrogen production on the Kamchatka Peninsula. Hydrogen production seems to be most promising in the Kamchatka Territory. The construction of tidal power plants will allow for the cost-effective production of hydrogen, which will then be combined with carbon-containing substances to produce liquid fuel (Shamin, Sheveleva, 2021). In the future, with the development and improvement of hydrogen energy technologies, hydrogen can be used in its pure form.

Thus, the Penzhinskaya and Tugurskaya tidal power plants should act as independent energy systems focused on electricity production:

- to ensure energy security (including due to the growth of domestic consumption) of the Far Eastern region;
- for the export of electricity to energy-deficient countries bordering the Russian Federation (primarily China);
- for the production of hydrogen through the electrolysis of water and its sale on the domestic and foreign markets.

The socio-economic significance of future tidal power plants is as follows:

- creation of new jobs in the Khabarovsk region and the Kamchatka Peninsula through the construction and commissioning of industrial complexes of power plants, hydrogen and ammonia production, as well as the development of the housing market, relevant social and transport infrastructure;
- increasing the investment attractiveness of the region;
- prospects for expanding domestic and external tourism in the Far Eastern region (FER).

In 2021, China, the largest source of climate-warming greenhouse gases, committed to carbon neutrality, setting dual CO_2 emissions targets of peaking by 2030 and neutrality by 2060 (Steblyanskaya et al., 2022). Published data from the National Bureau of Statistics (NBS) shows the country's progress in the transition to low-carbon technologies. The PRC aims to ensure that by 2025 the total consumption of renewable energy in the country reaches 1 billion tons of coal equivalent. By 2030, China expects to increase its total wind and solar power plant capacity to 1200 GW, which is almost twice the current values, through the construction of large renewable energy bases in the northwestern desert regions (Qin et al., 2021) . The National Development and Reform Commission (NDRC) said renewable energy will account for more than half of new energy consumption growth between 2021 and 2025, but China has the opportunity to build fossil fuel power plants during this period as it focused on enhancing its own energy security (Niu et al., 2021).

The PRC is potentially interested in purchasing electricity and hydrogen in the Far East (Erokhin, Tianming, 2022). At the same time, the PRC is considering the purchase of hydrogen in the Far East on competitive terms, on par with options for its purchase in other countries. By expanding promising cooperation in hydrogen energy, the PRC will solve a set of problems in terms of vigorous development of environmentally friendly industries and environmental protection, expanding the scale of environmentally friendly industries, developing energy saving industries, environmentally friendly production and environmentally friendly energy. For example, Heilongjiang Province, located in the northeast of the People's Republic of China, is today its old industrial region, however, the province generates carbon dioxide emissions, the reduction of which will have a positive impact on achieving China's climate change goals. The natural advantages of the province's economy include direct rail and road connections with the Russian border regions of the Far East and Transbaikalia, as well as natural resource potential that is significant in scale and structure. The benefits of cooperation between the PRC and the Russian Federation in the field of hydrogen energy are explained not only by the strengthening of the environmental component in the PRC energy system, but also by fairly successful logistics in terms of future export supplies of hydrogen with a relatively small transport "leverage". Experts from the Energy Research Institute of the Russian Academy of Sciences predict that the marginality of hydrogen exports in the eastern direction turns out to be noticeably higher than in the western direction, regardless of the choice of hydrogen production technology (Kholkin, Chausov, 2021). For hydrogen produced from electrolysis using RES, the profit range is –0.5...0.2 USD/kg when exported to Europe and about 0.8–2.1 USD/kg when exported to Japan (range limits determined by the cost of hydrogen production from different renewable energy technologies). However, the assessment of transport costs for hydrogen export currently remains uncertain due to the presence of technological barriers in this area.

Discussion of the results

The analysis showed that at the moment the main factors in the growth of global demand for hydrogen are the development of the chemical, oil and gas refining, manufacturing and transport industries. It still seems impossible to achieve a significant reduction in CO_2 emissions within the framework of existing technologies, therefore, at the moment, promising projects are being implemented in two directions: replacing hydrocarbon feedstock with hydrogen and using CO_2 capture technologies ("turquoise" and "blue" hydrogen). Most methods for producing hydrogen have not yet reached technological maturity, but when humanity realizes how energy should actually be used wisely, appropriate technical and technological solutions will be found.

The future architecture of global hydrogen energy does not yet have clear outlines, which, of course, carries with it high risks for investors. It is difficult to fully determine the global volume of hydrogen consumption in the future and the level of cost of commercial products. If the pricing mechanism is determined by analogy with prices for hydrocarbons and other energy resources, then for the end consumer of hydrogen the price may turn out to be extremely high. And this is despite the improvement and reduction in cost of technologies for the production, storage and transport of hydrogen, which, according to experts, will definitely happen in the future.

The key catalyst for the development of hydrogen energy in the Russian Federation should be the domestic market. Initially, it is necessary to determine the vector of development of hydrogen energy in the Russian regions and the country's needs for hydrogen, taking into account the interests of state energy security, in order to subsequently be able to ensure reliable supplies to external markets.

The construction of hydrogen production plants in the Russian Federation must be carried out in potentially large centers of its consumption, starting from steam conversion and pyrolysis plants at existing oil refineries, water electrolysis complexes at nuclear and hydroelectric power plants, which are initially located near large cities. For example, Rosatom JSC plans to create and launch a water electrolysis test complex at the Kola Nuclear Power Plant by 2025. As part of the project, the company is designing a nuclear reactor for hydrogen synthesis without emitting CO_2 into the atmosphere.

Russian oil and gas companies need to prepare for the production of hydrogen from renewable sources in close proximity to sales markets – primarily for countries that share a common border with the Russian Federation. China's growing demand for electricity can be met not only through the export of electricity, but also through the supply of hydrogen as an environmentally friendly energy source. In the medium term, the main limitation to expanding gas supplies to China is the lack of technologies for storing and transporting hydrogen.

As the domestic market develops, Russian business must implement international projects related to the creation of hydrogen infrastructure (for example, pyrolysis plants, networks of hydrogen filling stations), develop industry standards, principles of competitive pricing, and propose concepts for the sale of hydrogen and its products (carbon, ammonia).

Thus, the Russian Federation has significant potential for the production of "green" hydrogen using renewable energy sources. Scientists believe that the presence of a long coastline and offshore potential make it possible to count on the production of "green" hydrogen not only for the domestic but also for the external market (Pakhomova et al., 2022). Meanwhile, the volume of "green" hydrogen for export by 2035 could range from 2 to 12 million tons.

Conclusion

Climate policy and reduction of carbon emissions into the atmosphere, promoted by developed countries, presents hydrogen as an energy resource capable of occupying its own niche in the global energy resource structure in the future. Today, hydrogen is the optimal decarbonization lever for many industries, given the fact that sooner or later all industrial companies will be subject to a carbon tax. To develop and implement domestic hydrogen energy technologies, it is still necessary to create a scientific and technological infrastructure that unites carriers of competence in the field of hydrogen energy, and to create on their basis the best technologies for the production, storage and transportation of hydrogen. The creation of a tidal power station in Kamchatka and the development of a hydrogen cluster on Sakhalin, as expected, by 2050 can ensure annual exports from Russia of environmentally friendly types of hydrogen worth 100 billion dollars. Experts note that by building the Penzhinskaya TPP alone, "the Russian authorities will receive so many carbon credits that all fossil fuel supplies from Russia will immediately become carbon neutral..." (Bakhtina, 2022). The prerequisites for the transition to hydrogen energy in the Russian Federation are quite obvious. This is a huge mineral resource base of hydrocarbons, the presence of nuclear and hydro, and in the future, tidal power plants, qualified scientific and engineering personnel, as well as serious institutional support.

Further directions for the development of the presented research is a comparative analysis of the effectiveness of technologies for the production of "blue" and "turquoise" hydrogen, which are the most promising strategies for hydrogen production in the domestic gas industry.

Ackmowledgements

This work was supported by the Ministry of Science and Technology of the People's Republic of China with the title "Potential cooperation between China and Russia in the field of energy within the framework of the "Carbon neutrality" goal: new methods, new horizons and new strategies" (The Project Number: DL2021180001L).

The author would like to thank the reviewers for their valuable comments that improved the article.

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Manuscript received 7 March 2023;
Accepted 14 July 2023;
Published 30 September 2023