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Review

Prospects for the Development of Hydrogen Energy: Overview of Global Trends and the Russian Market State

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Abstract: This review is devoted to an overview of the prospects for the development of the global hydrogen market and the strategies of individual countries aimed at transforming energy systems in favor of decarbonization and greening through the use of hydrogen. Special attention is paid to the prospects for the development of the Russian hydrogen market. The authors of the review used the method of comparative analysis and analytical generalization of publications, programs and regulatory documents from different countries. The results of the comparative analysis led to the conclusion that most of the publications currently focus on the technical and technological aspects of hydrogen energy, solving the problem of increasing the efficiency of methods for the production, transportation, distribution and storage of hydrogen fuel. The results of the analytical generalization led to the conclusion that in all countries of the world, the technology for the production of highly environmentally friendly "green" hydrogen is at an early stage, which makes it highly dependent on government initiatives to develop hydrogen projects and government funding of both scientific research in this area and realizable projects. In addition, the peaks of interest in the field of hydrogen energy are associated with market changes in the fossil energy markets, which makes the development of this technology unstable and dependent on market conditions. Moreover, the focus of attention of a number of authors is the prospects for the development of the hydrogen market. It is concluded that many countries are ready to invest in the development of hydrogen energy and, given the growth in demand for hydrogen, are ready to export it at an affordable price. That is, in the future, the international hydrogen market, as technical, technological, and economic problems are solved, will grow. The results of the study also indicate the fundamental co-direction of the trends in the development of hydrogen energy in Russia with global trends. At the same time, it should be emphasized that the high resource and scientific and technological potential allows Russia to fully focus its strategy on its implementation, not only developing the domestic market but also acting as an exporter of hydrogen and expanding international cooperation in this area.

Keywords: keyword hydrogen energy; hydrogen strategies; energy decarbonization; hydrogen projects; Russia

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1. Introduction

The current stage of the development of hydrogen energy, both on a global scale and at the level of individual countries, can still be considered only the beginning of the era of hydrogen. Many innovations have appeared in this area so far, unfortunately, mainly at the level of ideas that do not always successfully pass the experiment stage in companies and research centers using various sources of funding.

On the one hand, a powerful impetus to the development of hydrogen energy around the world is given by the "green agenda" being pursued not only at the economic but also at the political level, related to ensuring the energy transition to renewable energy sources. This agenda has become especially relevant as a result of the current energy problems and the unprecedented rise in prices for hydrocarbon resources. As a result, state and international organizations have stepped up the process of adopting and implementing incentive measures, including financial, tax and other measures aimed at ensuring not only the decarbonization of the energy sector but also the uninterrupted supply of national energy systems with reliable energy sources. The search for solutions to the problems of innovative development of the oil and gas industry, as well as the identification of opportunities for the development of "green energy" in order to ensure the energy security of the countries of the Eurasian Economic Union, including the Russian Federation, was reflected in previous studies by the authors of the review [1,2].

On the other hand, the technical possibilities for the development of hydrogen energy are still associated with high production costs, problems of storage and delivery of hydrogen to consumers. That is why the emphasis of the developers of hydrogen energy technologies is not only on projects that are cheaper in terms of current and investment costs but also on those that will best solve consumer problems, including in terms of introducing into production and using the capabilities of the existing infrastructure.

Solving production problems in the field of hydrogen energy, as well as ensuring the transportation of hydrogen raw materials with minimal losses, will allow in the foreseeable future to overcome the local scale of its capabilities and bring hydrogen energy to the international level, including replacing traditional gas or using it as a resource.

In line with global trends, the development of hydrogen energy in the Russian Federation is taking place. It is necessary to note the existing scientific groundwork and significant competitive advantages in this area. Prospects for the development of the Russian hydrogen industry are set out in the adopted strategic documents, which define the export-oriented orientation of the industry as a further trend and the development of hydrogen infrastructure as a necessary condition for its implementation.

In the context of a difficult geopolitical situation, the prospects for international cooperation in the framework of hydrogen projects and, as a result, the shift of the center of gravity from the European market to the market of the Asia-Pacific region remain unclear. Moreover, a big problem is the uncertainty of the model of the emerging hydrogen market and the difficulty of predicting the structure of hydrogen energy. It is these issues that were the focus of this review.

The methodological basis of the review was a comparative analysis and analytical generalization of publications in the field of hydrogen energy development. Leaving technological and technical issues of production, transportation and use of hydrogen outside the scope of the study, the authors focused on a review of publications covering global trends, country strategies and projects aimed at the development of hydrogen energy.

The main purpose of the review was to assess the prospects for the development of the Russian hydrogen energy market within the framework of global trends.

In the logic of dialectics of development, the authors explored the objective dialectical relationships of properties and phenomena that take place in the development of hydrogen energy in various countries of the world. Further, on the basis of identifying common features, the authors form the transition from specific projects and initiatives to the general, revealing the content of emerging development trends in this area. The next stage of building a review occurs in the logic of ascent from the abstract to the concrete. The authors moved from studies of global trends to the problems and prospects for the development of hydrogen energy and the hydrogen market in Russia, which cannot develop outside of global trends. The authors identified general trends while, at the same time, focusing on special features and their manifestation, which are unique to Russia.

A distinctive feature of this review is a comparative analysis of global and Russian trends in the development of hydrogen energy, both within the framework of declared hydrogen strategies and in the practice of implementing specific projects. At the same time, the authors relied on the experience of countries that are currently demonstrating positive results in the implementation of hydrogen projects, as well as those that have adopted strategic documents that form the main trends in the development of the hydrogen economy. Not all countries and projects were in the field of view of the authors, which can serve as the basis for further research related to determining the outlines of future models of regional hydrogen markets, which have their own characteristics.

2. Overview of Key Trends in the Development of Hydrogen Energy

To date, in many countries of the world, there is already serious groundwork in the form of implemented hydrogen projects. This prompted the governments of these countries to draw up framework documents regulating the development of this area—hydrogen strategies. The main focus of the adopted strategies is aimed at ensuring the economic feasibility of introducing promising technologies developed in the field of hydrogen energy. The fact is that traditional methods of producing hydrogen are, firstly, energy-consuming, and secondly, they are associated with carbon dioxide emissions. Therefore, it is necessary to ensure the production of hydrogen with a low carbon footprint and at an acceptable cost, as well as to solve the technical and technological problems of its storage and transportation.

Among the examples of successful implementation of projects in the field of hydrogen energy, we can highlight the commissioning in 2021 of the world's largest power plant on hydrogen fuel cells (Icheon, Korea). The Shinincheon Bitdream power plant generates about 80 MW of electricity, providing electricity to 250,000 households and heat to 44,000 households. The construction of the power plant was carried out for 5 years, and since 2017, the costs have amounted to USD 292 million. In order to provide the power plant with raw hydrogen materials, it is planned to launch a plant for the production of liquefied hydrogen with a capacity of 30 thousand tons per year in 2023. Another project has been launched in Hwaseong. In 2024, it is also planned to launch an 80 MW hydrogen fuel cell power plant.

The implementation of such projects in South Korea is based on the idea of not so much reducing the cost of electricity (currently, this is not possible) but increasing its environmental friendliness [3].

Another trend in the development of hydrogen energy is associated with the use of two types of fuel in the operation of power plants—natural gas and hydrogen. Therefore, in 2023–2024, the Tallawara B power plant is planned to be commissioned in Australia. It is assumed that the power plant will run on natural gas for the first 10 years, and then, gradually being modernized, it will be configured to burn environmentally friendly hydrogen. The power plant capacity is 300 MW, providing electricity to 150 thousand households; the project cost is USD 64 million. Despite the debatability of this project (due to the fact that the transition to hydrogen raw materials will occur only after 10 years), it can be considered as a variant of moving along the path of developing hydrogen energy and implementing energy decarbonization [4].

The next trend is hydrogen transport. Hydrogen engines have been known to exist since the 19th century. However, hydrogen cars exist mainly as a concept, and only a few models have been able to reach party production. This is due to the fact that despite significant advantages in terms of quality, hydrogen fuel remains expensive. In addition, the problems related to the storage of hydrogen and the harmful effects on the metal parts of the cylinder–piston group of the machine have not been fully resolved, and the gas station infrastructure has not been developed. Nevertheless, well-known automobile concerns, including VW, GM, Daimler AG and BMW, are showing interest in the development of this direction in the automotive industry. The governments of a number of countries are solving infrastructural problems. Thus, by 2030 China plans to install at least 1000 hydrogen filling stations, Japan already has more than 100, and Germany has more than 50.

Currently, there is practically no serial production of cars with hydrogen engines. However, there are several models that have already gained recognition: Toyota Mirai, Honda Clarity, Ford Airstream, BMW Hydrogen 7, Hyundai Nexo and some others [5].

Hydrogen buses are on the market. For example, Geely Automobile Holdings Limited, one of China's largest automotive companies, has unveiled the F12 hydrogen-powered bus designed to travel long distances without additional refueling [6]. The Korean company Hyundai began supplying Xcient Fuel Cell hydrogen tractors to the markets of the USA and Europe [7]. It is known that a number of automotive companies such as Kenworth, Toyota, Nikola and Mercedes-Benz are implementing projects for the production of hydrogen trucks, although their projects are still at the level of concepts.

Significant results in this direction were achieved by the Chinese company Higer Bus Company Limited, which has come out on top in the world in the production of heavy trucks powered by hydrogen fuel. At the same time, Baowu Clean Energy has played a key role in the research and development of commercialization technology for hydrogen fuel cells in relation to the needs of heavy trucks. Issues of production and storage of hydrogen, provision of refueling and operation of vehicles were worked out [8].

In Germany, they began to serve passengers of the Coradia iLint train on hydrogen fuel cells. It is too early to talk about the mass use of such trains; however, the start has already been given [9].

The use of hydrogen fuel in aviation, although it has a number of examples, has not yet reached the level of successful mass use. However, research in this direction continues. Thus, specific intentions can be noted in research aimed at developing a cryogenic hydrogen system to power electric aircraft. It is known about the concept of a USD 6 million NASA-supported project, which will be carried out by the Center for Cryogenic High-Efficiency Electrical Technologies for Aircraft (CHEETA, Urbana, IL, USA). The CHEETA project is a consortium of eight members, including the Air Force Research Laboratory, Boeing Research and Technology, General Electric Global Research and a number of universities and research institutes. Despite the fact that the project is still at the conceptual stage, there is a fairly clear idea of the technology and its potential [10].

A large number of works related to the development of hydrogen energy in certain regions are devoted to the study of key limitations of the large-scale use of hydrogen energy, including existing technical and technological problems, the use of new materials, storage and transportation of hydrogen, as well as promising areas for the development of hydrogen energy based on the use of hybrid systems. Various examples of the use of solar and wind energy resources for hydrogen production are given. For example, Ayodele et al. (2021) evaluated the prospects for using solar energy to produce hydrogen to power hydrogen vehicles at a gas station in South Africa [11]. Sarma et al. (2022) presented a case study to assess the wind power potential for seven locations in India. At the same time, the authors focused on small wind turbines operating in an additional hybrid mode with a hydrogen generation system. Small wind turbines can generate power at lower turn-on rates to maximize the potential of wind power, and electrolyzed hydrogen from wind power can be stored and used to meet peak power demand [12].

Ye R. et al. (2022) investigated fuel cells and copper-based catalysts used in methanol reforming and analyzed the main factors affecting the stability of catalysts [13].

A fairly large number of studies are devoted to improving the technology of hydrogen extraction, among which the works of Chen et al. (2020), Sun (2019) and a number of others can be noted [14,15].

Li, Z. et al. (2020) study technologies for multi-energy supplementation of a hydrogen energy system, as well as strategies for coordinated control, energy storage and power distribution, energy management and hydrogen production technologies using water electrolysis. The authors consider the problems of creating a multi-energy complementary system and the issues of building a production chain in the field of hydrogen energy, which can serve as a guideline for improving the technology of hydrogen production and the use of hydrogen energy in a system of complementary renewable energy [16]. Li, J. et al. (2022), studying the prospects for the development and improvement of the efficiency of currently used projects related to the production of hydrogen fuel, also focused on the use of hybrid systems as more productive and economically feasible. Hybrid systems are configured in such a way that they can produce hydrogen fuel, as well as thermal and electrical energy [17].

Interest in the use of hybrid energy systems is observed by many researchers. This is due to the need to level the stochastic nature of renewable energy sources. By using mathematical modeling methods, analysts proved that the hybridization of energy systems could increase their productivity and efficiency, ensure uninterrupted operation and reduce specific emissions [18]. Belsky, A.A. et al. (2020) [19] studied the use of hybrid energy storage to balance the electrical load profile of enterprises.

A number of researchers have focused on solutions for the siting, distribution and security of hydrogen energy networks. Derse et al. (2022) devoted their study to the problem of optimizing the location of a plant for the production of hydrogen from renewable energy sources based on the development of a mathematical software model that integrates solutions related to production, storage, transportation, security, optimal location and distribution of personnel, taking into account minimization of costs [20].

Schrotenboer et al. (2022), in their work, focused on the study of strategies for the operation of integrated energy systems, proposing to use the theory of the Markov decision process for this. By developing an optimal decision-making policy regarding the volumes of production, use, storage, purchase and sale of hydrogen, the authors paid attention to the key conditions for concluding deals on hydrogen, pricing and using various distribution channels [21].

Finally, a number of scientists focused on the decisive role of government in ensuring the transition to clean energy. Thus, Thurbon et al. (2021) proposed a new approach to the analysis of the strategic role of the state based on the synthesis of the Schumpeterian understanding of "creative destruction" and technical and economic changes with the advanced theory of the state of development, focused on the "ecologicalism" of this development. This approach allows us to explain the mixed results of the transition to clean energy that has taken place in the last 10–12 years, as well as the manifestation of more consistent steps towards the greening of national economies [22].

Yue et al. (2021) focused on the development of hydrogen technologies related not only to production but also re-electrification, as well as hydrogen storage. Based on the analysis of projects implemented in various countries of the world, the authors identified the main criteria for the technical and economic status of hydrogen technologies, such as cost, efficiency and durability. At the same time, they associated the competitiveness of the hydrogen economy not only with technical parameters but also with the level of productivity, the manifestation of economies of scale and government support [23].

3. Prospects for the Development of Hydrogen Energy on a Global Scale

3.1. Global Strategies and Global Market Prospects

According to the Bloomberg New Energy Finance (BNEF) Research Center, there are more than USD 90 billion in projects currently underway related to hydrogen energy. In 2021, BNEF made an energy forecast, which is a long-term analysis of scenarios for the future of the energy economy. Three climate scenarios were presented, consistent with the Paris Agreement (2015) and achieving zero emissions by 2050 [24].

According to the "green scenario", the demand for hydrogen on a global scale in 2050 may reach 1310 million tons, i.e., 22% of total final energy consumption (currently 0.002%). At the same time, the focus is on "green hydrogen" as the most environmentally friendly. The Gray Scenario assumes demand for hydrogen at the level of 190 million tons. The "Red Scenario" does not provide for the widespread use of hydrogen energy. In addition, in this direction, it is planned to operate special nuclear power plants that produce the so-called "red (orange) hydrogen" [25].

"Red (orange) hydrogen", similar to "green", is produced by electrolysis. At the same time, nuclear power plants are the source of energy. Despite the fact that there are no hydrocarbon emissions, this method cannot be classified as absolutely environmentally friendly [26].

There is a conditional classification within which several types of hydrogen are distinguished according to the method of production and the degree of carbon intensity, which differ in color. The high carbon footprint of hydrogen production leaves "grey" and "brown" hydrogen; a low carbon footprint is from the "red (orange)" and "blue" methods of hydrogen production; and there are close to zero traces of "green" hydrogen [27].

In Figure 1, the authors indicated which technology is mainly used for the production of various types of hydrogen energy and what its average cost of production is according to sources [28–30].

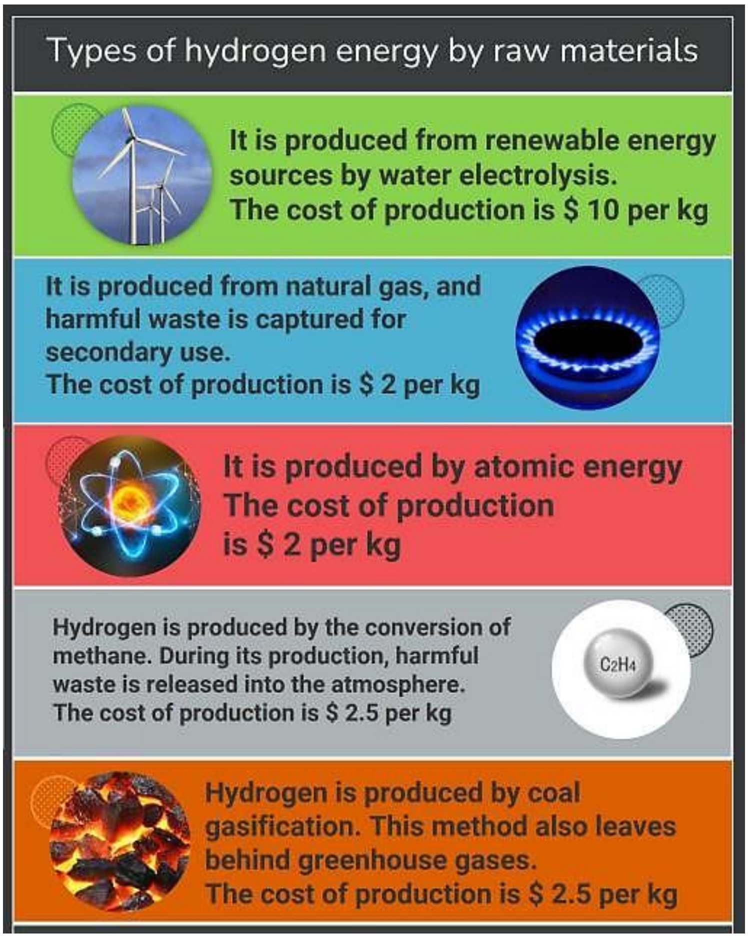

Figure 1. Main types of hydrogen, compiled by sources [28–30].

In addition to the technologies listed in Figure 1, there are a number of hydrogen production methods that are still being used only in pilot mode, including:

- Thermochemical and biochemical processing of biomass;
- Pyrolysis and anaerobic digestion of household waste;
- Synthesis by algae from sea water or sewage;
- Photoelectrocatalysis (hydrogen production from sunlight without electrolysis);
- Direct thermolysis (including using heat from high-temperature nuclear reactors) and others.

At present, hydrogen is almost completely used directly at the points of consumption (in the oil refining industry, the production of ammonia, methanol, etc.), so the world trade of H_2 is carried out on a very limited scale—according to Trade Map data, in 2020 the world hydrogen market was estimated at only USD 134 million. In the future, both an increase in the volume of trade in hydrogen and an expansion of the directions for its use are expected. Figure 2 shows data on hydrogen projects declared in the world.

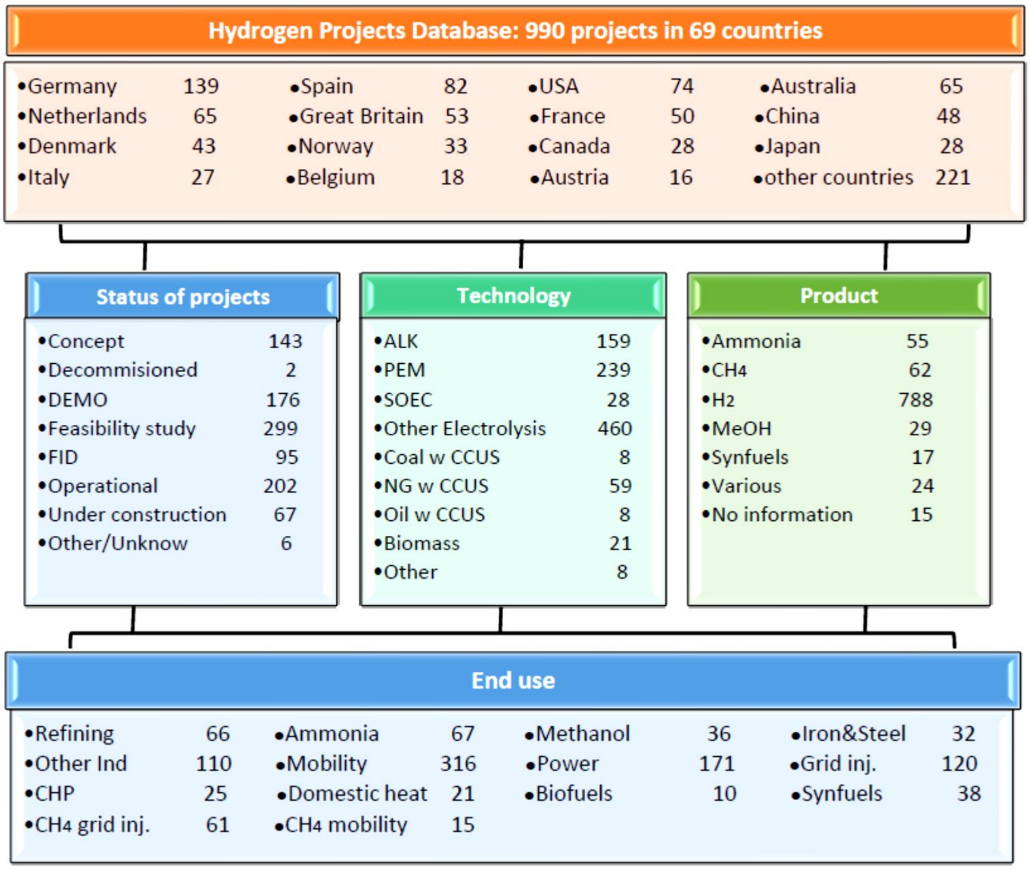

Figure 2. Characteristics of hydrogen projects declared and implemented in the world, compiled by source [31].

Designations and abbreviations. *Hydrogen supply technologies:* ALK—alkaline electrolysis; PEM—proton exchange membrane electrolysis; SOEC—solid oxide electrolysis cells; coal w CCUS—hydrogen production from coal gasification coupled with CO_2 capture, utilisation and storage; NG w CCUS—hydrogen production from natural gas reforming coupled with CO_2 capture, utilisation and storage; oil w CCUS—hydrogen production from oil-based processes coupled with CO_2 capture, utilisation and storage. *End-use product:* CH_4—synthetic methane; H_2—hydrogen in molecular form; methanol; synfuels—synthetic liquid fuels (e.g., gasoline, diesel, jetfuel equivalent). *End-use sector:* refining—use of hydrogen in the refining of oil products; ammonia—use of hydrogen in ammonia production; methanol—use of hydrogen in methanol production; iron and steel—use of hydrogen in steelmaking; other ind.—use of hydrogen in high-temperature heat; mobility—use of hydrogen in vehicles; power—use of hydrogen in the supply of electricity to the electricity grid with gas turbines, reciprocating engines or fuel cells; grid inj.—injection of hydrogen in the natural gas grid; CHP—use of hydrogen in heat and power via CHPs, for example in fuel cells or turbines; domestic heat—direct use of hydrogen in building for water and space heating; biofuels—use of hydrogen in biofuels production; synfuels—production of synthetic liquid fuels; CH_4 grid inj.—injection of synthetic methane in the natural gas grid; CH_4 mobility—use of synthetic methane in vehicles.

Figure 2 shows that the number of announced projects is approaching 1000. However, if we talk about real ongoing projects, their number barely reaches 200. According to IEEFA.org (2020), in 2020, only about 50 viable projects for the production of "green hydrogen", the implementation of which produces up to 4 million tons of hydrogen per year. At the same time, the capacity of renewable hydrogen energy will be 50 GW. The required volume of capital investments is USD 75 billion [32].

Of course, most of the announced projects are still at the stage of concluding memorandums, so their implementation will begin, at best, in the next 5 years. Some projects may not be implemented at all due to unfavorable global economic situations or due to funding problems. For the successful implementation of projects, it is necessary to expand the production of electrolyzers and other special equipment, to significantly reduce the cost of transporting hydrogen, including by sea.

The key issue is funding. We would like to note that most of the research is funded by the state. Figure 3 shows data reflecting spending on government research and development in the field of hydrogen and fuel cells. Investments of private investors are minimal. This is due to the riskiness of projects and their strategic focus and the inability to obtain a quick return.

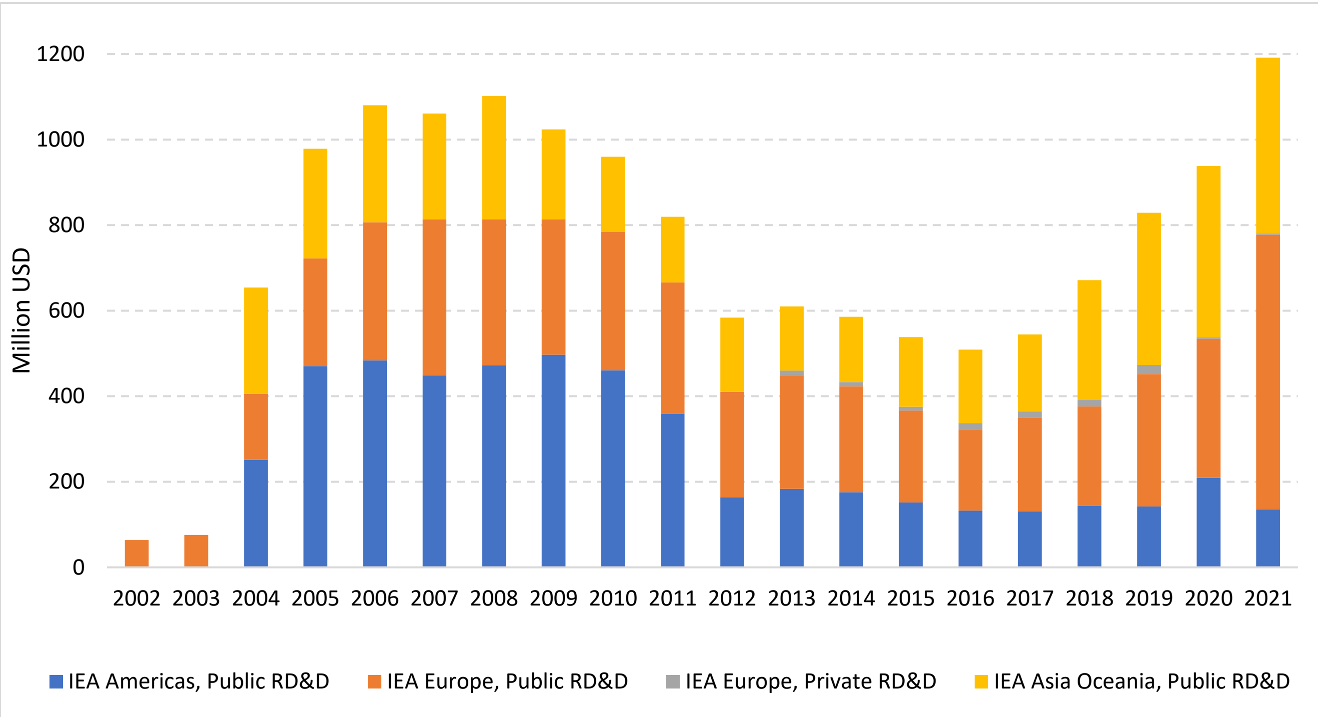

Figure 3. Public RD&D for hydrogen and fuel cells, spending in million USD (2021 prices and exchange rates), compiled by source [33].

As can be seen from the figure, investments are undulating in nature, increasing during periods of exacerbation of energy problems and decreasing during periods of relative prosperity in the energy markets. From this, we can assume that the upward phase of the wave will continue after 2021 as a response to the energy crisis that the world is currently experiencing.

As noted above, the technical possibilities for the development of hydrogen energy are still associated with high production costs, problems of storage and delivery of hydrogen to consumers. Of course, theoretically, any country can produce hydrogen. The problem lies in the cost of its production and provision of storage. Therefore, for some countries, it is more economically feasible to purchase hydrogen than to produce it on their own. Here, the problem will already be the cost of transporting hydrogen over long distances. By 2050, globally, hydrogen is expected to account for at least 12% of final energy demand (and if we take into account the so-called "green scenario", then twice as much). At the same time, 25% of world demand will be met through trade [34]. In this regard, the problems associated with reducing the cost of transporting hydrogen, developing the appropriate infrastructure and resolving issues of legal regulation and certification in the field of hydrogen energy are becoming relevant.

Hydrogen imports can be attractive if the purchase price and the cost of transportation are lower than the cost of domestic production. Therefore, as transport technologies improve (transportation of liquefied hydrogen, ammonia, the distillation of hydrogen in the gaseous state through pipelines) and the development of global supply chains, as well as due to lower production costs, the hydrogen market will expand. According to the calculated data of the Institute for Energy Research of the Russian Academy of Sciences in 2019, one can judge the costs of hydrogen production using various technologies in the countries of the world [35] (Table 1).

Table 1. Costs of hydrogen production by different technologies by country, 2019.

Country	Hydrogen Production Costs by Types, $/kg	
	"Green Hydrogen"	"Blue Hydrogen"
Russia	6.7	0.4
Great Britain	5.0	1.5
South Korea	5.0	2.3
Germany	4.3	1.6
France	4.0	2.2
Italy	3.6	2.0
USA	3.3	0.7

Compiled from source [35].

Therefore, despite the fact that the market for hydrogen as an energy carrier has not yet formed, it can be argued that this is a matter for the foreseeable future. At the same time, it is still difficult to assume the prospective scale of the market. Will it be a large international market, similar to the oil and gas markets, or will it be more local and limited to some countries and certain regions? Many researchers, for example, Litvinenko, V.S. et al. [36], drew attention to obstacles to the introduction of hydrogen initiatives in the context of sustainable development of global energy. Nevertheless, according to experts, there are many indications that the hydrogen market, sooner or later, will turn into a global market since not all countries interested in hydrogen have sufficient potential for its production, including using renewable energy sources, as well for meet the ever-increasing demand for this type of fuel.

3.2. Key Vectors of Hydrogen Strategies of Individual Countries

According to the IEA, in 2021, nine countries formulated their hydrogen strategy. Additionally, in 2022, 26 countries already intended to use hydrogen as a source of clean energy in their energy system. National targets for electrolysis capacity deployment are 145–190 GW, doubling the 2021 target of 74 GW [37].

Ambitious plans for the development of hydrogen energy are, first of all, the countries of the European Union. Moreover, on 8 July 2020, the European Commission presented a new strategy providing for the expansion of projects for the production of "green hydrogen", which will be implemented in three stages [38]:

Stage 1—2020–2024: installation in the EU of hydrogen electrolysis plants with a capacity of at least 6 GW with the production of up to 1 million tons of environmentally friendly hydrogen;

Stage 2—2025–2030: installation of hydrogen electrolysis plants with a capacity of at least 40 GW with the production of up to 10 million tons of "green hydrogen";

Stage 3—2030–2050: large-scale implementation of renewable hydrogen technologies in all sectors that are difficult to decarbonize.

According to forecast estimates, the implementation of the strategy will require the EU to invest in clean hydrogen at the level of EUR 430 billion by 2030 [32]. This will require support in the form of grants and subsidies at the level of EUR 145 billion [39].

The EU plan for the development of hydrogen energy is focused on environmentally friendly hydrogen, which cannot be said about other countries. Thus, China aims to increase the share of hydrogen energy to 10% of the country's total energy by 2050 (about 60 million tons of hydrogen per year), as well as to ensure the construction of 10,000 hydrogen filling stations [32]. However, this plan is based mainly on "grey hydrogen" produced from natural gas. As is known, in the production of "grey hydrogen", carbon dioxide is released in the course of a chemical reaction in almost the same volumes as in the combustion of natural gas, and energy is also spent on conversion [26].

According to Korea's Hydrogen Economy Roadmap to 2040, the bulk of the hydrogen supply will be "blue hydrogen" produced by the steam reforming of methane. At the same time, however, carbon capture and storage take place, which provides a two-fold reduction in its emissions [26]. The use of "blue hydrogen" is still considered more economically feasible than the use of liquefied "green hydrogen". "Green hydrogen" produced by electrolysis is the most environmentally friendly. Additionally, if, at the same time, electricity is generated by renewable energy sources, then CO_2 emissions are completely absent. However, according to experts, the cost of "green hydrogen" will not be competitive until 2050.

The Korean government's goal is to increase the number of hydrogen vehicles to 6.2 million by 2040; install 1200 hydrogen charging stations; commission 40,000 hydrogen-powered buses, 80,000 taxis and 30,000 trucks; and develop local production of relevant auto parts. The development of hydrogen ships, trains and other mechanisms will be supported. Fuel cell production or power generation will be encouraged to achieve a combined capacity of 15 GW by 2040. Due to this, 940,000 households will be provided with electricity [40].

Japan was one of the first countries in the world to adopt a national hydrogen strategy back in 2017. In 2020, Japan adopted an environmental innovation strategy to achieve carbon neutrality by 2050. In order for hydrogen to become a full-fledged source of energy, it is planned to create a ubiquitous hydrogen ecosystem here. Additionally, to make hydrogen affordable, an intention has been formed to create a global supply chain and build global hydrogen storage facilities. By 2030, it is planned to reduce the cost of hydrogen to USD 3/kg due to the continuous improvement of technologies for the production, transportation and storage of hydrogen. We refer to highly efficient water electrolysis, artificial photosynthesis, highly efficient hydrogen liquefiers, energy carriers and proton-conducting solid oxygen fuel cells. However, in the short term, the focus will again be on "blue hydrogen" [41].

In 2021, the United States approved a national strategy and roadmap for the development of hydrogen energy. It is planned to allocate USD 550 billion for the implementation of the national strategy. Of these, USD 9.5 billion will be spent on the development of "green hydrogen", including a number of measures to reduce its cost to USD 2/kg by 2026. It is planned to create four regional centers related to the production and use of "green", "blue" and "red (orange)" hydrogen [42]. McKinsey estimates that by 2050, the share of hydrogen in the US energy mix should reach 14% [43].

Based on the strategies considered, the authors compiled a comparative description of the hydrogen strategies of some countries, which reflects the main targets of the current strategies, the amount of funding and the governing body (Figure 4).

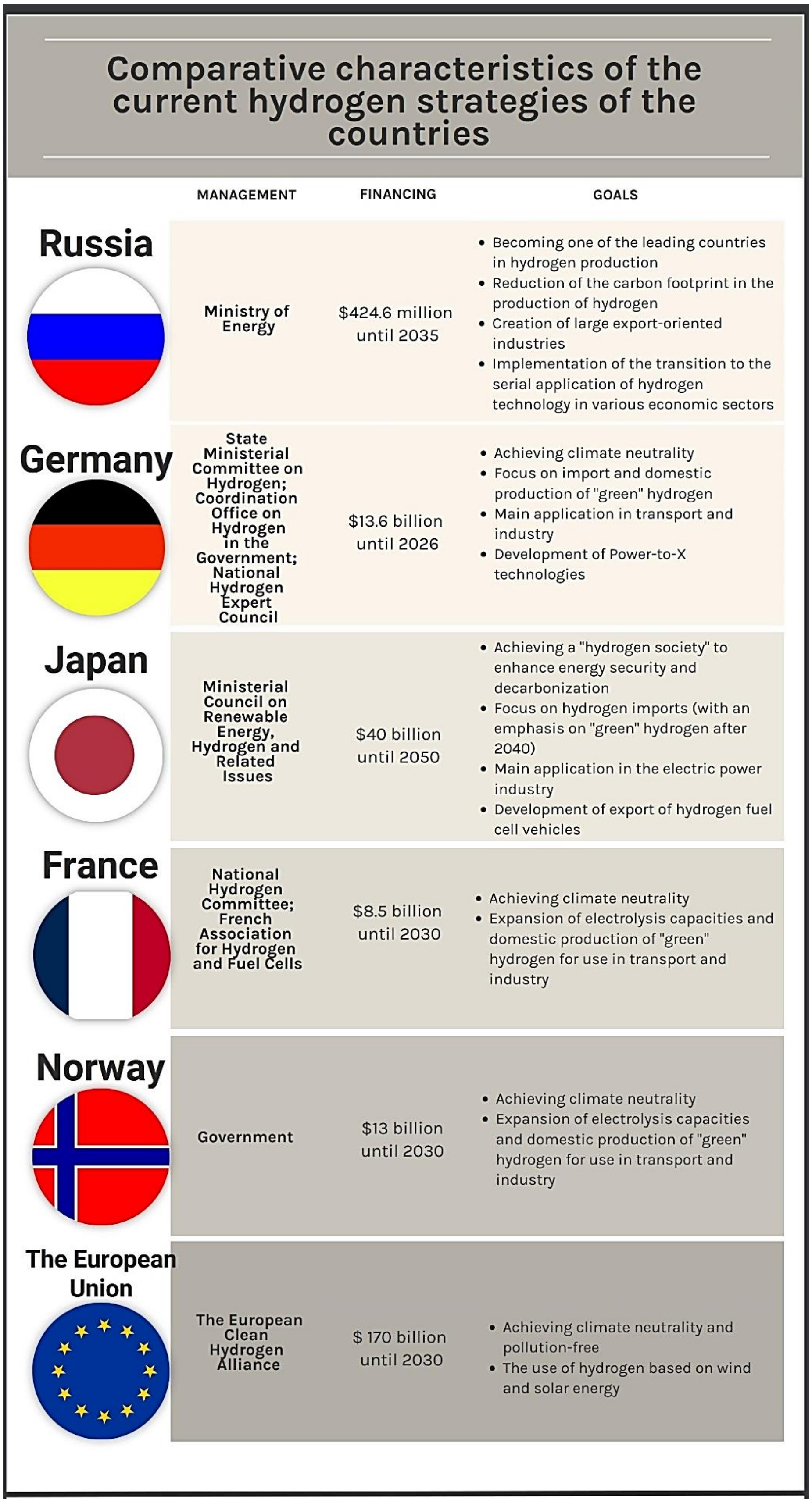

Figure 4. Comparative characteristics of the current hydrogen strategies of some countries, compiled by sources [35,44].

4. Development Strategy for the Russian Hydrogen Market

Focusing on global decarbonization trends, the Russian Federation is also quite active in research and development in the field of hydrogen energy, given that it has significant experience in the field of hydrogen energy technologies. Head of the Analytical Center for Energy Policy and Security of the Institute of Oil and Gas Problems of the Russian Academy of Sciences A. Mastepanov (2020) [45], citing sources [46,47], while reviewing the development of hydrogen energy in Russia, notes that, in fact, hydrogen research in Russia began back in the 1930s (the effect of hydrogen additives to gasoline on automobile engines was studied). Examples of the use of hydrogen as a motor fuel during the Second World War are noted. More extensive research in the field of development and application of hydrogen technologies was carried out in the 1970s as part of the implementation of the state program “Hydrogen Energy”. At the same time, the emphasis was on the use of atomic energy for the production of hydrogen. Significant state investments in hydrogen energy in the Soviet period made it possible to create a significant scientific and technical reserve in this area, which, however, was largely lost after the collapse of the Soviet Union.

A new stage of energy development began in the early 2000s. Thus, in 2003, the non-profit National Hydrogen Energy Association was established, whose tasks included research in the development of the fuel cell industry. As in in foreign countries, there are certain results in the Russian Federation: hydrogen cars, trams and the first hydrogen filling stations began to appear. Developments are being made on the use of hydrogen at nuclear power plants as energy storage devices. Hydrogen is used in the production of ammonia, methane, oil refining, etc. Currently, the production of hydrogen in the Russian Federation is about 5 million tons per year.

In June 2020, Russia adopted the Energy Strategy for the period up to 2035 [48], the purpose of which is to develop the production and consumption of hydrogen in the Russian Federation and ensure Russia’s entry into the ranks of the world leaders in its production and export. The main objectives of the strategy include the following:

- Creation of infrastructure to provide the transportation and use of pure hydrogen and as part of various mixtures;
- Expansion of hydrogen production from natural gas, using renewable energy sources and nuclear power plants;
- Further development of low-carbon hydrogen production technologies;
- Expansion of the domestic market;
- Improvement of the regulatory and legal framework in the field of hydrogen energy;
- Development of international cooperation and access to foreign markets.

At the same time, it is planned to expand hydrogen exports from 0.2 million tons in 2024 to 2 million tons in 2035 [48]. The global target is to ensure that by 2030, the cost of producing “green hydrogen” does not exceed USD 2/kg.

It is assumed that potentially by 2030, Russia will be able to meet the internal and external demand of consumers in hydrogen in the amount of 10.5 million tons. At the same time, it is noted that it is necessary to develop renewable energy sources specifically to increase the production of “green hydrogen”, which will be exported since the share of environmentally friendly hydrogen remains very small due to the high costs of its production.

In October 2020, the Government of Russia approved the Action Plan “Development of Hydrogen Energy in Russia until 2024”, the purpose of which is to organize work on the formation in the Russian Federation of a highly productive export-oriented field of hydrogen energy based on the use of modern technologies and involving highly qualified specialists [49].

In order to achieve this goal, it is necessary, according to the Action Plan, to improve the regulatory framework, to ensure state support for the most effective projects in the field of hydrogen energy, as well as to intensify research and development work, thereby strengthening the positions of Russian companies in the hydrogen markets.

In August 2021, another fundamental document in the field of hydrogen energy development in Russia was approved—the "Concept for the Development of Hydrogen Energy in the Russian Federation", which was developed in accordance with the Action Plan. The concept defines the goals and objectives in the field of hydrogen energy development in Russia, key measures for the medium-term (until 2024) and long-term (until 2035) periods, as well as some basic guidelines for the longer term (until 2050) [44,50].

As part of the first (mid-term) stage of the concept, specialized hydrogen clusters will be created in Russia, pilot projects for the production and export of hydrogen will be implemented, and the use of hydrogen energy carriers in the Russian market is also envisaged. At the moment, three territorial production clusters have been identified:

- The North-West Cluster (St. Petersburg and the Leningrad region, located on the Baltic coast of Russia) will export hydrogen to European countries, and it will also specialize in the implementation of measures to reduce the carbon footprint of export-oriented enterprises;
- The Eastern Cluster (Sakhalin Region, an island in the Russian Far East) will export hydrogen to the countries of the Asia-Pacific region, and it will also specialize in the development of hydrogen infrastructure in the field of transport and energy;
- The Arctic Cluster (Yamal-Nenets Autonomous Okrug, in the North-West of Siberia) will provide a low-carbon electricity supply to the Russian Arctic.

In the future, the creation of the Southern Cluster, located near large export ports, is being considered. The Southern Cluster will focus on hydrogen production using renewable energy sources [51].

Within the framework of the approved three specialized clusters, 41 projects are planned for implementation. It is noteworthy that Russia has only one project listed in the Hydrogen Projects Database—Kola Nuclear Power Plant, with an announced size of 40 m^3 of hydrogen in an hour.

The geographical location of hydrogen projects in Russia is shown in Figure 5.

Figure 6 shows a general description of hydrogen projects in Russia.

Gazprom and Rosatom will become the first producers of hydrogen In 2024, the companies will launch pilot plants for the production of hydrogen—at nuclear power plants, gas production enterprises and raw material processing plants. Until 2024, Gazprom will study the use of hydrogen and methane–hydrogen fuel in gas installations (GTE, gas boilers, etc.) and as a motor fuel in various types of transport. In 2024, Rosatom will build a test site for hydrogen-powered rail transport for the subsequent transfer of trains to hydrogen fuel cells.

The costs associated with the production of hydrogen directly depend on the efficiency of the applied technologies. Table 2 shows data reflecting the present value of hydrogen production in Russia (calculated data from the Energy Research Institute of the Russian Academy of Sciences 2020). Calculations of the present value of hydrogen production are based on a formula of three components, discounted over the entire life horizon of the technology: capital costs, costs for the incoming energy carrier and semi-fixed operating costs. The economic meaning of the reduced cost indicator is that it reflects the minimum level of the price of hydrogen, which guarantees the break-even investment in the "hydrogen factory" [52]. The present value indicators are higher than the simple costs of hydrogen production reflected in Table 1.

Figure 5. Hydrogen projects in Russia [51]. Note: the map of Russia shows the location and numbers of projects. The project profile is presented in Appendix A.

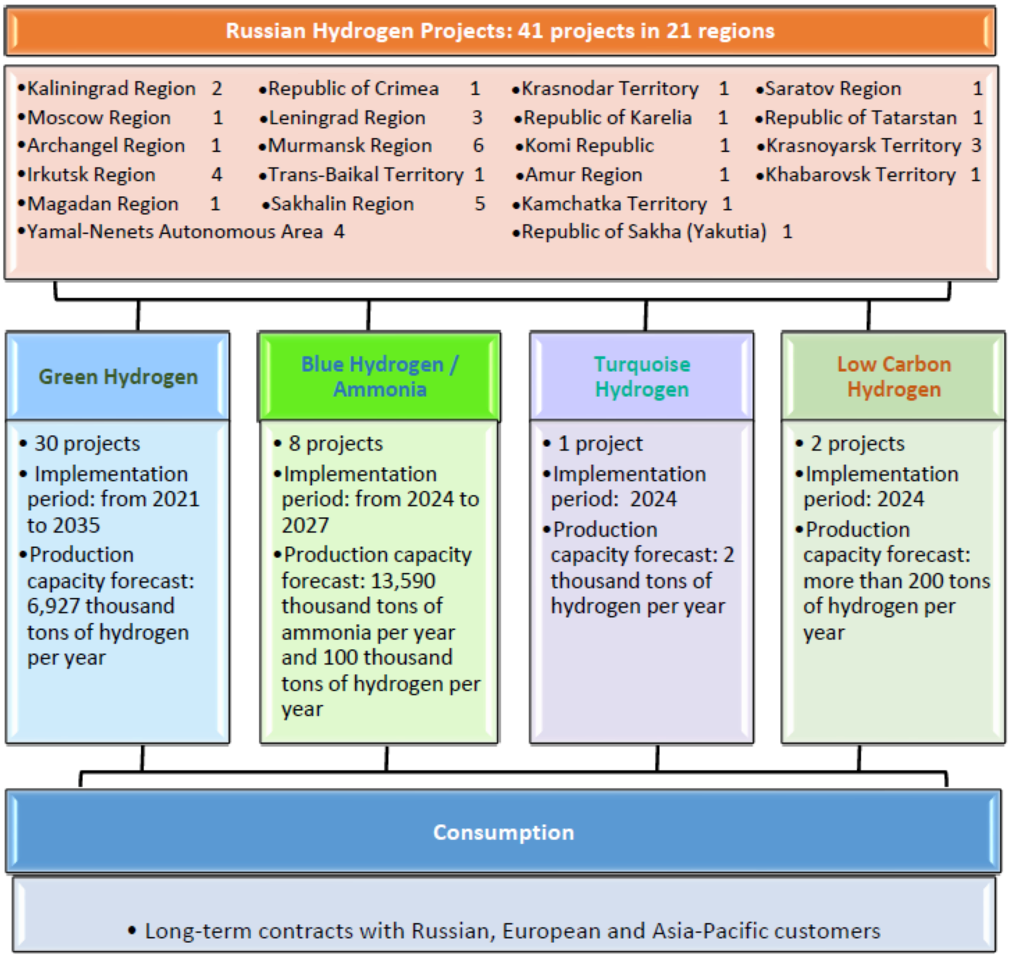

Figure 6. Characteristics of hydrogen projects in Russia, based on Appendix A.

Table 2. Present value of hydrogen production in Russia based on electricity from various sources and methane.

Applied Technology	Present Value of Hydrogen Production by Years, $/kg	
	2020–2025	2030–2035
Based on electricity from: solar power plant	12.2	5.6
wind power station	6.7	4.0
hydroelectric power station	3.5	3.0
nuclear power station	3.2	2.3
Steam reforming of methane plus CO_2 capture and storage	1.7	1.6

Compiled from source [52].

Great economic prospects for the symbiosis of nuclear and hydrogen energy in combination with renewable energy for Russia were considered in the study by Zhiznin S.Z. et al. [53]. The authors believed that the implementation of these technological areas in Russia will allow the formation of a new sustainable global energy system—alternative energy.

Activity in the development of the Russian Arctic zone has increased the demand for autonomous hydrogen energy supply projects. Prospects and features are discussed in detail in the study by Kolomeytseva, A.A. et al. [54]. Solving the problems of energy supply to isolated regions of the Far North and the Far East, including on the basis of hydrogen energy, is considered in the studies of the following authors: Kopteva, A. et al. [55], Kirsanova, N.Y. et al. [56], Berezikov, S.A. et al. [57].

European countries, primarily Germany, as well as countries in the Asia-Pacific region, such as South Korea, China and Japan, can act as potential foreign partners.

Prospects for international cooperation in the framework of hydrogen projects in Russia: German authors in their study write that "Even though Russia remains somewhat skeptical about hydrogen's much-vaunted transformative potential, it is interested in using its natural gas wealth to become a leading exporter of this new energy carrier and views Germany as a key partner in this effort" [58]. In December 2020, Russian Deputy Prime Minister for Energy Alexander Novak announced the development of a Russian-German roadmap for hydrogen and the possible implementation of pilot deliveries of hydrogen to Germany [59]. In April 2021, the Russian Federation and Germany signed a Declaration on cooperation in the field of sustainable energy, one of the areas of which is hydrogen energy [60]. It was assumed that the Declaration would become the basis for cooperation in the field of hydrogen energy, the development of innovative technologies and research in this area, the promotion of technical and economic cooperation of interested organizations and assistance in attracting investors; however, the difficult geopolitical situation and the imposition of multiple sanctions against Russia violate outlined plans.

The possibilities of a pilot project for the supply of Russian hydrogen to Japan are also being studied in detail: the Japanese Development Institute NEDO is focused on the test implementation of hydrogen import supply chains as part of the roadmap of the program for building a hydrogen society [61].

Research and Markets consider in detail the market and the main actors of hydrogen projects in Russia [62]. The list of specific projects, their participants and prospective production volumes and the technologies used are given in Appendix A.

Experts note [63] that when entering the global hydrogen market, Russia can take advantage of its competitive advantages, such as a significant energy base (large reserves of gas, coal, the potential of nuclear power plants and renewable energy sources), a developed oil refining and chemical industry that uses steam reforming of methane and electrolysis, geographic proximity to potential consumers of hydrogen (Europe and the countries of the Asia-Pacific region), the existing scientific background, and the existing transport infrastructure. Russia has real opportunities to create export-oriented production of low-carbon ("blue") hydrogen from natural gas, as well as environmentally friendly ("red (orange)" and "green") hydrogen based on water electrolysis using nuclear power plants and renewable energy sources.

The Institute for Natural Monopolies Problems, in the analytical report "Hydrogen: Market Formation and Prospects for Russia", compared potential hydrogen exporters in terms of some indicators that characterize their strengths and weaknesses in this area (Table 3). It can be noted that in each of the considered exporting countries, there are both strengths and weaknesses.

The prospects for hydrogen exports from Russia to world markets look moderate. Russia's main advantages are its proximity to potential sales markets and the availability of significant fresh water resources. The weaknesses of Russia are the low level of international activity in this area and the lack of technologies tested in Russia for the production of "low-carbon" and "renewable" hydrogen and for its transportation. All countries engaged in the production of "low-carbon" hydrogen, unlike Russia, have experience in implementing technologies for capturing and storing carbon dioxide.

Table 3. Comparison of Russia and its potential competitors in the export of hydrogen.

Indicator	Russia	Australia	Chile	Norway	Saudi Arabia	Oman	UAE	Morocco	Tunisia	Namibia	Mauritania
Priority type of hydrogen that the country plans to produce	low carbon	low carbon	renewable	low carbon	low carbon	renewable	low carbon	renewable	renewable	renewable	renewable
Degree of geographical proximity, including to markets:											
EU countries	high	low	low	high	average	average	average	high	high	low	average
Japan and South Korea	high	average	low	low	average	average	average	low	low	low	low
Agreements at the national level in the field of hydrogen, including:											
with Germany	−	+	+	−	+	+	−	− *	+	+	−
with Japan/South Korea	+/−	+/+	−/−	−/−	+/−	−/−	+/+	−/−	−/−	−/−	−/−
Current projects for the production of "renewable" hydrogen	−	+	+	+	−	−	−	−	−	−	−
Current CCS projects	−	+	−	+	+	−	+	−	−	−	−
Installed RES capacities (SPP and WPP), GW	3.5	27.1	5.4	4.1	0.4	0.2	2.5	2.1	0.3	0.2	0.1
Level of fresh water scarcity	low-medium	high	high	low	very high	very high	very high	high	high	high	medium-high

Note: * The agreement on cooperation in the field of hydrogen between Morocco and Germany was concluded in June 2020. In May 2021, its validity was terminated by Morocco, Source [64].

Let us compare the prospects of Russia with some countries in terms of the planned volumes of import and export of hydrogen, taken from the strategic documents of the countries (Table 4). Japan's hydrogen needs outlined in the country's hydrogen roadmap can theoretically be met by Australia and Chile both by 2030 and 2050. At the same time, the hydrogen strategies of these countries involve diversifying hydrogen supplies and reaching other markets. Germany's needs by 2030 may be substantial enough that Russia could take advantage of it under favorable circumstances. At the same time, Russia's optimistic plans to export 30 million tons of hydrogen by 2050 do not seem entirely justified, given that Japan plans to consume only 5–10 million tons by this period. In this regard, the indicator of 11 million tons looks optimal, provided that cooperation with Japan and South Korea is boosted.

Table 4. Planned volumes of imports and exports of hydrogen according to the hydrogen strategies and road maps of countries, million tons [64].

Country	2030	2035	2050
	Planned import volume		
Germany	2.3–2.9	1.9–2.5	no data
Japan	0.3	no data	5–10
	Planned export volume		
Australia	0.5	no data	6.75
Chile	0.6	no data	18
Russia	2.75–2.9 (6.4)	no data	11.3–11.9 (30)

Notes: for Russia, in parentheses are optimistic export plans.

The degree of conditionality of such estimates is extremely high; since the data are not available for all countries, they are incomplete but allowed us to draw some conclusions:

- The speed with which decisions should be made, including international cooperation in the field of hydrogen, is important;
- It is important to develop technologies to occupy their niche in the emerging global hydrogen market.

In addition to the advantages (proximity to potential markets and availability of significant fresh water resources), there are also serious limitations, among which are the high cost of environmentally friendly hydrogen, the lack of technologies for capturing, storing and transporting carbon, problems with the legal regulation of hydrogen energy, the inadequacy of the standardization and certification system, the low level of investment activity in this area, as well as the lack of state support and, of course, the difficult geopolitical situation and powerful sanctions pressure.

Another "trap" that may await Russia as a hydrogen exporter is that the hydrogen market model differs from the model, for example, of the oil and gas market, which is often suggested to be taken as a model. This is especially true for "green hydrogen". The main difference is that thanks to renewable energy sources, the production of "green hydrogen" is not tied to sources of raw materials. Centralized hydrogen production, although it can provide a cost reduction, however, this reduction can be offset by the cost of transporting hydrogen, especially over long distances. Therefore, it is difficult to say which structure of hydrogen energy—centralized or decentralized—will prevail. This determines whether Russia will be able to realize its advantages or other factors will be decisive.

5. Conclusions

A number of conclusions can be drawn from this review.

First of all, it should be noted that the development of hydrogen energy is one of the promising areas of carbon-neutral economic development, which is reflected in strategic documents, road maps and many adopted and implemented programs and projects of the most developed countries of the world. Serious research work is being carried out in this direction. Significant amounts of budgetary funds are allocated to support the development of the industry. At the same time, the prospects for the global hydrogen market remain rather vague. There is no unequivocal answer to the question of whether potential importing countries of hydrogen will buy it abroad or, perhaps, will produce and consume it domestically. The question of the environmental friendliness of the consumed hydrogen remains open. Whether only "green hydrogen" will be in demand or "blue" and "red (orange)" will also have a strong position in the market. What will be the structure of the hydrogen market and at what level will the equilibrium price be established in 10, 15 or more years? The predictive estimates of the market capacity also vary greatly depending on the scenario.

In conditions of high uncertainty, waiting for a clarification of the situation is not a way out because, often, it is the one who actively acts, developing projects, concluding international agreements and participating in international cooperation, integrating into existing and creating new "production-consumption" chains, which form the future market defining its construction.

An analysis of the development prospects and the existing potential of Russia in the field of hydrogen energy allows us to conclude that it is predominantly export-oriented. However, the economic feasibility of exporting hydrogen to the Russian Federation depends on the difference between the cost of hydrogen production within the country and in potential importing countries, as well as on the cost of transporting hydrogen from producer to consumer. Based on the calculated data of the Energy Research Institute of the Russian Academy of Sciences [52], it can be concluded that in the short term until 2035, the most attractive for Russia will be the export of "blue hydrogen", obtained on the basis of steam conversion of methane with the capture and disposal of CO2, as well as "red (orange) hydrogen, produced using nuclear power. However, the question of considering nuclear generation as acceptable in terms of decarbonization policy remains open. It is also necessary to pay attention to the estimate of transport costs for hydrogen export, which currently remains uncertain due to the presence of unresolved technological problems in this area. However, to ensure the sustainable competitiveness of Russian hydrogen, the export margin must exceed the value of transportation costs. Otherwise, the economic feasibility of exporting hydrogen is lost.

In general, it can be noted that the margin of hydrogen export in the eastern direction is noticeably higher than in the western direction, regardless of the choice of hydrogen production technology. Moreover, much larger prospective consumption volumes are also a factor stimulating the orientation of the Russian export potential in the Asia-Pacific region.

Therefore, the development of hydrogen energy and the hydrogen market is a promising trend for the foreseeable future, which Russia should by no means ignore. On the contrary, it is necessary to actively integrate into the emerging international structures, influencing the emerging architecture of the new industry in terms of its production and technological structure, territorial distribution of capacities and designing a model of an emerging market.

Further development of the authors' research will be based on the formation and interpretation of models of the emerging hydrogen market, as well as the search for approaches to forecasting the structure, identifying and assessing the influence of various factors on the configuration of future markets, since this can become decisive knowledge in the implementation and possible adjustment of strategic and tactical documents for the development of hydrogen energy not only in Russia but also in other countries of the world.

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Appendix A

Table A1. Hydrogen projects in Russia.

	Project Description	Implementation Period	Location	Target Markets	Production Capacity Forecast	Participants	Project Scheme
1	Green hydrogen production via hydro power plant electrolysis	2023	Kaliningrad Region, the city of Svetly	domestic market of Russia, European countries	2700 tons of hydrogen per year	The Kronshtadt Group, Sodrugestvo, Atomenergomash, Others	Hydro power plant: Electricity generation, Electrolysis: Green hydrogen production, Logistics: Hydrogen transportation to customers within Russia and European countries, Consumption: Long-term contracts with Russian and European customers
2	Green hydrogen production via wind power plant electrolysis	2024	Kaliningrad Region	domestic market of Russia, European countries	No information	Rosatom, Others	Wind power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and European countries Consumption: Long-term contracts with Russian and European customers
3	Green hydrogen production via wind power plant electrolysis	2023	Republic of Crimea	domestic market of Russia	10,000 tons of hydrogen per year	H2, Others	Wind power plant: Electricity Generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia Consumption: Long-term contracts with Russian customers
4	Green hydrogen production via solar power plant electrolysis	2023	Krasnodar Territory, the city of Krasnodar	domestic market of Russia, European countries	13 tons of hydrogen per year	Lukoil, Others	Solar power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and European countries Consumption: Long-term contracts with Russian and European customers
5	Blue ammonia production by steam conversion of methane with CO2 capture	2026	Saratov Region, Mikhailovsky village	domestic market of Russia, European countries and the Asia-Pacific region	2026: 20,000 tons of ammonia per year, 2030: 170,000 tons of ammonia per year	Special Project Company Gornyj, Others	Steam methane conversion: Blue ammonia production CO2 capture and utilization with microalgae Logistics: Hydrogen transportation to customers within Russia, European countries and the Asia-Pacific region Consumption: Long-term contracts with Russian, European and Asia-Pacific customers
6	Green hydrogen production via the Uglichsk HPP and the Zagorsk HPP electrolysis	2021	Moscow Region, the city of Peresvet	domestic market of Russia	400 tons of hydrogen per year, Production capacity forecast by 2024: 800 tons of hydrogen per year	Research and Test Center of Rocket and Space Industry, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia Consumption: Long-term contracts with Russian customers

Table A1. *Cont.*

	Project Description	Implementation Period	Location	Target Markets	Production Capacity Forecast	Participants	Project Scheme
7	Green hydrogen production via wind power plant electrolysis	2023	Leningrad Region	domestic market of Russia, European countries	3500 tons of hydrogen per year	Agency for Economic Development of the Leningrad Region, Others	Wind power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and European countries Consumption: Long-term contracts with Russian and European customers
8	Green hydrogen production via small hydro power plant electrolysis	2023	Leningrad Region	domestic market of Russia, European countries	1000 tons of hydrogen per year	Agency for Economic Development of the Leningrad Region, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and European countries Consumption: Long-term contracts with Russian and European customers
9	Blue hydrogen/ammonia production by steam conversion of methane with CO2 capture at Gas Chemical Enterprises in Leningrad Region	2023	Leningrad Region	domestic market of Russia, European countries	1000 tons of hydrogen per year	Agency for Economic Development of the Leningrad Region, Other	Steam methane conversion: Blue hydrogen/ammonia production Carbon capture Logistics: Hydrogen transportation to customers within Russia and European countries Consumption: Long-term contracts with Russian and European customers
10	Green hydrogen/ammonia production via the Ondsk hydro power plant electrolysis	2024	Republic of Karelia, the village of KamennyBor	domestic market of Russia, European countries	5200 tons of hydrogen per year	En+ Group, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Selection of storage and transportation technology Consumption: Long-term contracts with Russian and European customers
11	Green hydrogen production via the Nizhnekamsk hydro power plant electrolysis	2024	Republic of Tatarstan	domestic market of Russia, European countries and the Asia-Pacific region	2500 tons of hydrogen per year	Tatenergo, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia, European countries and the Asia-Pacific region Consumption: Long-term contracts with Russian, European and Asia-Pacific customers
12	Green hydrogen production via the Mezensk tidal power plant electrolysis	2030	Archangel Region, Mezensky Area, Mezensky Bay	domestic market of Russia, European countries and the Asia-Pacific region	2030: 500,000 tons of hydrogen per year; 2033: 1 million tons of hydrogen per year	Regional Development Agency of the Arkhangelsk Region, NordEnergoGroup, Others	Tidal power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia, European countries and the Asia-Pacific region Consumption: Long-term contracts with Russian, European and Asia-Pacific customers

Table A1. *Cont.*

	Project Description	Implementation Period	Location	Target Markets	Production Capacity Forecast	Participants	Project Scheme
13	Green hydrogen production via the Kolsk wind power plant electrolysis	2024	Murmansk Region	domestic market of Russia, European countries	12,000 tons of hydrogen per year	Rusnano, Enel, Others	Wind power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Selection of storage and transportation technology Consumption: Long-term contracts with Russian and European customers
14	Low carbon hydrogen production via the Kolsk nuclear power plant electrolysis	Pilot production launch: 2024 Achieving industrial production capacity: 2030	Murmansk Region	domestic market of Russia, European countries	2024: 150 tons of hydrogen per year	Rosatom, Others	Nuclear power plant: Electricity generation Electrolysis: Hydrogen production Liquefaction and storage Logistics: Hydrogen transportation to customers within Russia and European countries Consumption: Long-term contracts with Russian and European customers
15	Green hydrogen/ammonia production via hydro power plant electrolysis	2024	Murmansk Region	domestic market of Russia, European countries and the Asia-Pacific region	2024: 17,000 tons of hydrogen per year, 2030: 170,000 tons of hydrogen per year	H4Energy, H2Trasition Capital, Eurasia Mining, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia, European countries and the Asia-Pacific region Consumption: Long-term contracts with Russian, European and Asia-Pacific customers
16	Green hydrogen production via hydro power plant electrolysis	2025	Murmansk Region	domestic market of Russia, European countries	16,000 tons of hydrogen per year	H2 Clean Energy, TGC-1, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and European countries Consumption: Long-term contracts with Russian and European customers
17	Green hydrogen production via wind power plant electrolysis	2024	Murmansk Region	domestic market of Russia, European countries	10000,tons of hydrogen per year	H2, Others	Wind power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and European countries Consumption: Long-term contracts with Russian and European customers
18	Green hydrogen/ammonia production via hydro power plant electrolysis	2024	Murmansk Region	domestic market of Russia, European countries	2024: 2000 tons of hydrogen per year 2030: 20000 tons of hydrogen per year	Gazprom Energoholding Group, TGC-1, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and European countries Consumption: Long-term contracts with Russian and European customers

Table A1. *Cont.*

	Project Description	Implementation Period	Location	Target Markets	Production Capacity Forecast	Participants	Project Scheme
19	Turquoise hydrogen production by methane pyrolysis at the Sosnogorsk GPP	2024	Komi Republic, the city of Sosnogorsk	domestic market of Russia, European countries and the Asia-Pacific region	2000 tons of hydrogen per year	Komi Center for Entrepreneurship Development, Others	Methane pyrolysis: Turquoise hydrogen production Logistics: Hydrogen transportation to customers within Russia, European countries and the Asia-Pacific region Consumption: Long-term contracts with Russian, European and Asia-Pacific customers
20	Natural gas processing complex with production of hydrogen, ammonia and other low-carbon products using CO2 capture and long-term underground storage technologies	2027	Yamalo-Nenets Autonomous Area, Yamal Peninsula (Sabetta)	domestic market of Russia, European countries and the Asia-Pacific region	2.2 million tons of ammonia per year	NOVATEK, Others	Refining and gas chemistry Carbon capture and injection into geological formations Logistics: Hydrogen transportation to customers within Russia, European countries and the Asia-Pacific region Consumption: Long-term contracts with Russian, European and Asia-Pacific customers
21	Blue ammonia production by steam conversion of methane with CO2 capture technologies and long-term underground storage	2025	Yamalo-Nenets Autonomous Area, Baidaratskay Bay	domestic market of Russia, European countries and the Asia-Pacific region	2.2 million tonnes of ammonia per year	Corporation Energy, TOYO Engineering Corporation, ITOCHU PlantechInc, Others	Steam methane conversion: Blue ammonia production CO2 capture and long-term underground storage Logistics: Hydrogen transportation to customers within Russia, European countries and the Asia-Pacific region Consumption: Long-term contracts with Russian, European and Asia-Pacific customers
22	Green hydrogen production via wind power plant electrolysis	2025	Yamalo-Nenets Autonomous Area, Baidaratskay Bay	domestic market of Russia, European countries and the Asia-Pacific region	No information	Corporation Energy, Others	Wind power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia, European countries and the Asia-Pacific region Consumption: Long-term contracts with Russian, European and Asia-Pacific customers
23	Blue ammonia production by steam conversion of methane with CO2 capture technologies and long-term underground storage	2026	Yamalo-Nenets Autonomous Area, Seyakha (settlement)	domestic market of Russia, European countries and the Asia-Pacific region	2.2 million tonnes of ammonia per year	Corporation Energy, TOYO Engineering Corporation, ITOCHU PlantechInc, Others	Steam methane conversion: Blue ammonia production CO2 capture and long-term underground storage Logistics: Hydrogen transportation to customers within Russia, European countries and the Asia-Pacific region Consumption: Long-term contracts with Russian, European and Asia-Pacific customers

Table A1. *Cont.*

	Project Description	Implementation Period	Location	Target Markets	Production Capacity Forecast	Participants	Project Scheme
24	Low carbon hydrogen production via pulverized coal power plant electrolysis	2024	Krasnoyarsk Territory, Taimyr Peninsula, Syradasaysk Reservoir	domestic market of Russia, European countries and the Asia-Pacific region	No information	North Star, Others	Conversion of an industrial product obtained as a result of coal enrichment Pulverized CPP: Electricity generation Electrolysis: Hydrogen production Logistics: Selection of storage and transportation technology Consumption: Long-term contracts with Russian, European and Asia-Pacific customers
25	Blue ammonia production by lignite gasification using CO2 capture and injection into oil reservoirs	2027	Krasnoyarsk Territory	domestic market of Russia, the Asia-Pacific region	800,000 tons of ammonia per year	SUEK, Others	Coal gasification: Blue ammonia production Carbon capture: CO2 injection into oil reservoirs Logistics: Transportation to customers within Russia and the Asia-Pacific region Consumption: Long-term contracts with Russian and Asia-Pacific customers
26	Green hydrogen/ammonia production via the Motyginsk hydro power plant electrolysis	2030	Krasnoyarsk Territory, Motygino Settlement	domestic market of Russia, the Asia-Pacific region	115,600 tons of hydrogen per year	En+ Group, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Selection of storage and transportation technology Consumption: Long-term contracts with Russian and Asia-Pacific customers
27	Green hydrogen/ammonia production via the Bratsk hydro power plant electrolysis	2024	Irkutsk region, the city of Bratsk	domestic market of Russia, the Asia-Pacific region	3000 tons of hydrogen per year	En+ Group, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Selection of storage and transportation technology Consumption: Long-term contracts with Russian and Asia-Pacific customers
28	Green hydrogen/ammonia production via the Ust-Ilimsk hydro power plant electrolysis	2024	Irkutsk region, the city of Ust-Ilimsk	domestic market of Russia, the Asia-Pacific region	5400 tons of hydrogen per year	En+ Group, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Selection of storage and transportation technology Consumption: Long-term contracts with Russian and Asia-Pacific customers
29	Green hydrogen/ammonia production via the Irkutsk hydro power plant electrolysis	2024	Irkutsk region, the city of Irkutsk	domestic market of Russia, the Asia-Pacific region	4200 tons of hydrogen per year	En+ Group, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Selection of storage and transportation technology Consumption: Long-term contracts with Russian and Asia-Pacific customers

Table A1. *Cont.*

	Project Description	Implementation Period	Location	Target Markets	Production Capacity Forecast	Participants	Project Scheme
30	Green hydrogen production via the Mamakansk hydro power plant electrolysis	2025	Irkutsk Region, BodayboArea	domestic market of Russia	6000 tons of hydrogen per year	H2 Clean Energy, Polyus, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia Consumption: Long-term contracts with Russian customers
31	Green hydrogen production via solar power plant electrolysis	2023	Trans-Baikal Territory	domestic market of Russia, the Asia-Pacific region	3200 tons of hydrogen per year	Unigreen Energy, Special Design Engineering Bureau in Electrochemistry with Experimental Factory, Others	Solar power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and the Asia-Pacific region Consumption: Long-term contracts with Russian and Asia-Pacific customers
32	Green hydrogen production via hydro power plant electrolysis	2027	Amur Region	domestic market of Russia, the Asia-Pacific region	110,000 tons of hydrogen per year	Agency of the Amur Region for Attracting Investment, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and the Asia-Pacific region Consumption: Long-term contracts with Russian and Asia-Pacific customers
33	Blue ammonia production based on gas fields with CO2 capture technologies	1st stage implementation: 2026, 2nd stage implementation: 2030	Republic of Sakha (Yakutia)	domestic market of Russia, the Asia-Pacific region	2026: 3 million tons of ammonia per year, 2030: 6 million tons of ammonia per year	NORTH-EAST ALLIANCE, Gas production companies in Western Yakutia, Others	Steam methane conversion: Blue ammonia production Carbon capture: CO2 injection into oil reservoirs Logistics: Delivery to the terminal in tanks. Transportation to customers within Russia and the Asia-Pacific region Consumption: Long-term contracts with Russian and Asia-Pacific customers
34	Green hydrogen production via the Tugurtidal power plant electrolysis	2035	Khabarovsk Territory, TugurBay	domestic market of Russia and the Asia-Pacific region	350,000 tons of hydrogen per year	Joint Stock Financial Corporation «Sistema», Tyazhmash, Khabarovsk Krai Investment and Innovation Promotion Agency, Others	Tidal power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and the Asia-Pacific region Consumption: Long-term contracts with Russian and Asia-Pacific customers
35	Green hydrogen production via the Ust-Srednekansk hydro power plant electrolysis	2025	Magadan Region	domestic market of Russia, the Asia-Pacific region	16,000 tons of hydrogen per year	H2 Clean Energy, RusHydro, Others	Hydro power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and the Asia-Pacific region Consumption: Long-term contracts with Russian and Asia-Pacific customers

Table A1. *Cont.*

	Project Description	Implementation Period	Location	Target Markets	Production Capacity Forecast	Participants	Project Scheme
36	Blue hydrogen/ammonia production by methane steam conversion with CO2 capture	2024	Sakhalin Region, Sakhalin Island	domestic market of Russia, the Asia-Pacific region	2024: 30,000 tons of hydrogen per year 2030: 100,000 tons of hydrogen per year	Rosatom, AirLiquide, Others	Steam methane conversion: Blue hydrogen production CO2 capture and injection into geological formations Liquefaction and storage Logistics: Hydrogen transportation to customers within Russia and the Asia-Pacific region Consumption: Long-term contracts with Russian and Asia-Pacific customers
37	Green hydrogen production via wind power plant electrolysis	2025	Sakhalin Region, Sakhalin Island	domestic market of Russia, the Asia-Pacific region	No information	Rosatom, Others	Wind power plant: Electricity generation Electrolysis: Green hydrogen production Liquefaction and storage Logistics: Hydrogen transportation to customers within Russia and the Asia-Pacific region Consumption: Long-term contracts with Russian and Asia-Pacific customers
38	Green hydrogen production via wind power plant electrolysis	2025	Sakhalin Region, Sakhalin Island	domestic market of Russia, the Asia-Pacific region	50,000 tons of hydrogen per year	H2 Clean Energy, Others	Wind power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and the Asia-Pacific region Consumption: Long-term contracts with Russian and Asia-Pacific customers
39	Green hydrogen production via wind power plant electrolysis	2024	Sakhalin Region, Sakhalin Island	domestic market of Russia and the Asia-Pacific region	2024: 16,000 tons of hydrogen per year, 2030: 150,000 tons of hydrogen per year	H4Energy, H2Trasition Capital, Eurasia Mining, Sakhalin Oil Company, Others	Wind power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and the Asia-Pacific region Consumption: Long-term contracts with Russian and Asia-Pacific customers
40	Green hydrogen production via wind power plant electrolysis	2023	Sakhalin Region, Kunashir Island	domestic market of Russia, the Asia-Pacific region	10,000 tons of hydrogen per year	H2, Others	Wind power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and the Asia-Pacific region Consumption: Long-term contracts with Russian and Asia-Pacific customers
41	Green hydrogen production via the Penzhinskaya tidal power plant electrolysis	2031	Kamchatka Territory, Penzhinskaya Bay	domestic market of Russia, the Asia-Pacific region	5 million tons of hydrogen per year	H2 Clean Energy, Development Corporation of Kamchatka, Others	Tidal power plant: Electricity generation Electrolysis: Green hydrogen production Logistics: Hydrogen transportation to customers within Russia and the Asia-Pacific region Consumption: Long-term contracts with Russian and Asia-Pacific customers

Compiled from source [51].

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