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Prospects for Energy Transition to Hydrogen Fuel: Analysis of World Experience and Russian Practice

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ABSTRACT

A significant depletion of natural energy reserves and a sharp rise in its cost of production amidst a civilizational energy crisis, greenhouse gas issue, and increasing energy consumption have called for an urgent and radical change in the global energy agenda. An idea to promote hydrogen as an alternative energy emerges from the global energy transition agenda. In this article, our aim is to assess the prospect of hydrogen, as a potential, environmentally friendly, yet expensive and technological-demanding resource, to be developed globally. The scientific novelty of the research consists in systematizing the world experience and Russian practice of implementing energy efficiency projects within the framework of public-private partnership (PPP), substantiating, and forecasting the prospects for the use of this resource in order to decarbonize the economy and solve environmental problems, as well as determining the main directions of the national energy strategy in Russia. We have developed recommendations to eliminate the identified problems that impede the increase in the energy efficiency of industrial production and operation of facilities. It is concluded that the use of "green" hydrogen obtained with the help of renewable energy sources is promising in solving environmental problems and building a climate-neutral economy characterized by zero greenhouse gas emissions. The results of the work can be useful in well-supporting hydrogen ecosystem.

Keywords: Energy Crisis, Energy Efficiency, Public-private Partnership, Green Economy, Hydrogen Fuel, Carbon Footprint
JEL Classifications: O13, P28, Q43, Q47

1. INTRODUCTION

The development of new technologies is inseparable from the emergence of environmental risks that can cause serious harm to the environment and all of humanity. This implies the need to predict the potential threats of the technologies used for the environment and future generations, as well as an objective assessment of the degree of impact of industrial activity on the quality of life of the population. Today, mankind is faced with a severe energy crisis, primarily due to technogenesis and anthropological activities, which can lead to new environmental risks and a climate catastrophe.

The principles of sustainable economic development are associated with the processes of incorporating innovative achievements into such basic areas of human life as economic, environmental and social. In addition, the main direction of effective economic development is the process of forming a "green" economy, which is aimed at reducing the sharply negative impact of human activities on the natural environment and is designed to maintain a balance between the growth of energy consumption and the satisfaction of the growing needs of society, technological development, the introduction of innovative technologies and the growth of production capacities without harming the environmental situation. The concept of a "green" economy includes three main elements: an efficient economy based on "green" energy, efficient human capital and environmental well-being. According to the International Energy Agency (IEA), the energy efficiency potential currently lies in the range of 38-42% of total energy consumption (Energosovet, 2015). The closest in meaning to the concept of a "green" economy is the concept of "green" growth, which implies economic development that is efficient in terms of the use of natural resources, clean in terms of minimizing the negative impact on the environment, and sustainable in the context of taking into account possible natural events, force majeure circumstances, uncertainty and risks.

Environmental risks, greenhouse gas emissions and serious pollution from the operation of internal combustion engines globally become one of the biggest problems due to the negative impact on the environment and human health. These negative factors can lead to the death of living organisms, deterioration in the quality of life of the population and significant economic losses, depletion of natural resources, air, water and soil pollution, and significant climate change. Therefore, the topic of the study, devoted to assessing the prospects for the transition of energy to hydrogen fuel in Russia and abroad, is recognized as relevant and topical.

In world energy practice, a large-scale hydrogen modernization of transport is already being carried out today. In the USA, China, Japan and the countries of the European Union, programs are being implemented for the production and operation of hydrogen cars, buses, eco-trams (PRC), eco-ships, for example, catamaran Energy Observer (France) and eco-trains (France,). According to experts, until 2050 the transport energy sector will remain combined, involving a combination of hydrogen fuel engines, traditional internal combustion engines and electric engines. The geopolitical situation in the world, as well as economic expediency and efficiency, will remain the determining factor influencing the situation. In the period 2022-2025, the process of energy transition to new types of fuel is declared, for example, on August 24, 2022, a declaration of intent was signed between the governments of Canada and Germany to create a special alliance to export clean energy to Germany in 2025 based on hydrogen technologies (TASS, 2022). Government-funded venture projects in hydrogen shipbuilding are being implemented in Finland, Norway and Russia (Portal Russian-Shipping, 2016).

The text of the Energy Strategy of the Russian Federation until 2035 notes that the energy intensity of production of key industrial goods is on average 1.2-2.0 times higher than the world average, the best world samples are 1.5-4.0 times higher, and, as a result, the economy is characterized by a large carbon footprint and a low level of competitiveness of a number of Russian industrial sectors in the European market.

The pandemic of a new corona virus infection and the introduction of restrictive measures in 2019-2020 led to the emergence of a non-systemic crisis in the economies of the world, accompanied by a decrease in economic activity compared to 2018, a reduction in demand for energy resources by 16% against the backdrop of falling prices for them (ICIS, 2022). The aggravation of environmental problems and the introduction of a “green” energy agenda at the end of 2021, indicated, in particular, in the text of the Paris Agreement on preventing the negative impact of global warming (United Nations, 2015), require national economies to increase the competitiveness of industry, reduce the energy intensity of GDP and sharply reduce the carbon footprint.

The purpose of the study is to formulate base principles of the development of the "green" hydrogen economy, to develop recommendations for the implementation of hydrogen projects in the conditions of the public-private partnership (PPP) model.

The object of research is industrial and anthropogenic activity.

The achievement of this goal was carried out by solving the following tasks:

1. Studying the principles of building a "green" economy
2. Systematization of the theory and practice of the occurrence of environmental problems in the process of using traditional energy sources
3. Development of recommendations to eliminate the identified problems and the application of new models of hydrogen energy PPP projects.

2. THE WORLD HYDROGEN-LED ENERGY TRANSITION: THE EMERGENCE OF PUBLIC PRIVATE PARTNERSHIP STRATEGY (PPP)

The accumulated world experience in the implementation of investment energy-efficient projects indicates that the most effective form of implementation of energy-efficient industrial, infrastructure and socially significant projects and programs is the institution of public-private partnership (PPP). Based on the identified problems and consequences of an inefficient state energy policy, the authors developed practical recommendations for eliminating the identified problems that impede the improvement of the energy efficiency of industrial production and operation of facilities, identified promising areas for solving problems in creating a specialized public-private partnership (PPP) on energy efficiency (Energy agent), the main functions of his activity are formulated.

Theoretical and practical significance due to a fact that certain conclusions and generalizations can be applied in the process of forming and adjusting the state program “Energy Efficiency and Energy Development,” in particular, when developing measures to improve the energy efficiency of projects and industries, in particular public transport, in tax incentives for energy efficiency, providing state guarantees and benefits, etc. Three considerations of the importance of hydrogen for energy transition from the perspective of Russian energy transition are as follows:

1. The change of carbon energy to hydrogen, and in connection with this, the transition of traditional transport energy to the energy of direct conversion technologies (electronic energy carrier technologies) is an objective necessity and the most probable reality of the 21st century

2. The use of hydrogen fuel in a green economy is the main direction of solving energy problems, overcoming the energy crisis, increasing the energy efficiency of the economy
3. Russia needs to make maximum use of the existing achievements and opportunities for the development of technologies for direct transformation and modernization on this basis of energy and transport-natural national priorities at the state level within the framework of national projects and programs.

The authors of the study formulated the main scientific hypotheses for the long-term development of global energy and advanced technologies, in particular an inevitable change in the technological structure and the replacement of carbon energy with hydrogen, in this regard, the most likely transition from traditional transport technologies to the energy of direct conversion technologies; in the Russian Federation, it is necessary to modernize the energy industry as part of the energy transition with the adoption of an appropriate national program that provides for the development and adoption of new technical regulations, the creation of a new technological infrastructure, and also to provide for a national system for the training and retraining of engineering and managerial personnel and engineers-specialists in the development and operation of said energy technologies (Ferraris et al., 2019). It should be noted that for the current period of time in Russia, the Concept for the Development of Hydrogen Energy has already been adopted[1], which provides for Russia to become one of the world leaders in the production, export and use of hydrogen fuel, as well as in the development of industrial hydrogen products and equipment.

"Green" hydrogen, produced using renewable energy sources, is assigned a key role in building a climate-neutral, green economy, characterized by zero emissions of greenhouse gases and harmful substances in the production process, heating facilities, transport operation, as well as the possibility of off-season energy storage for a long period of time and use over large areas (Shayakhmetov, 2017). As part of the decarbonization of various sectors of the economy in the United States, EU countries, China, South Korea, Japan and the Russian Federation, special roadmaps for the development of hydrogen energy have been developed and are being implemented in order to reduce the cost of producing "green" hydrogen compared to hydrogen obtained from natural gas (Salnikova, 2022).

It should be emphasized that solving the problem of increasing the energy efficiency of the Russian economy is one of the state priorities that affect the country's competitiveness in the world market. In the context of the energy transition of developed countries to a green economy and restrictions, the Government of the Russian Federation adopted a number of legislative initiatives in this area. In particular, Decree of the President of the Russian Federation No. 889[2], which sets the target for reducing the energy intensity of GDP by 2020 by at least 40% of the 2007 level; Federal Law of November 23, 2009 No. 261-FZ "On Energy Saving"[3], the main task of which is to form the legal, economic and organizational foundations for stimulating energy saving and increasing the energy efficiency of the Russian economy; the Energy Strategy of Russia for the period up to 2035[4], aimed primarily at a significant increase in energy efficiency; the state program "Energy Development"[5], the basic goals of which are the reliable supply of the country with fuel and energy resources, increasing the efficiency of their use, as well as reducing the anthropogenic impact of energy and production on the environment (Goremyko and Sokolov, 2018).

Research and development of industrial innovations in the field of hydrogen application are a priority in the EU countries. The hydrogen strategy of the EU member states was adopted in July 2020 and aims to accelerate the development of clean hydrogen technologies. The European Clean Hydrogen Alliance, which is a forum that brings together public authorities, private industry, transport and civil society in order to effectively coordinate financing and investment, is an impetus and an opportunity to apply public-private partnership (PPP) mechanisms.

In the process of implementing the Framework Programs for Research on Hydrogen Projects in the EU, PPP Fuel was formed Cells and Hydrogen joint Undertaking (FCH JU) that received financial support from the European Commission for the period 2021-2030. It should be noted that the world's largest green hydrogen demonstration projects implemented under PPPs in Belgium and Germany have a negative net present value, but a high synergistic social effect.

An analysis of the experience of implementing energy projects in the EU countries and energy initiatives makes it possible to draw the following conclusions:

- Stimulation of the implementation of innovative energy projects is carried out within the framework of contractual and institutional forms of PPP, aimed primarily at improving the

1. Decree of the Government of the Russian Federation No. 2162-r dated August 5, 2021 "Concept for the development of hydrogen energy in the Russian Federation". - [Electronic resource]. – Access mode: https://demo.garant.ru/#/document/401596102/paragraph/1/doclist/688/showentries/0/highlight/Decree%20of the Government%20of the Russian%20 Federation%20No.%202162-p%20of %205%August 20%202021%20:2 (Accessed 22.08.2022).
2. Decree of the President of the Russian Federation of 04.06.2008 No. 889 "On Certain Measures to Improve the Energy and Environmental Efficiency of the Russian Economy". - [Electronic resource]. – Access mode : https://demo.garant.ru/#/document/193388/paragraph/1/doclist/28/showentries/0/highlight/ Decree% 20 of the President% 20889% 20 of% 204% June 20% 202008: 2 (accessed 15.05. 2022).
3. Federal Law No. 261-FZ dated November 23, 2009 "On Energy Saving and Improving Energy Efficiency and on Amendments to Certain Legislative Acts of the Russian Federation". - [Electronic resource]. – Access mode : https://demo.garant.ru/#/document/12171109/paragraph/33264/doclist/30/showentries/0/highlight/Federal%20law%20 dated%2023.11.2009%20 No.%20261-FZ:4 (date appeals on May 15, 2022).
4. Energy strategy of the Russian Federation for the period up to 2035. - [Electronic resource]. – Access mode: https://minenergo.gov.ru/node/1026 (accessed 05/14/2022).
5. Decree of the Government of the Russian Federation of April 15, 2014 No. 321 "On approval of the state programs of the Russian Federation *« Development energetics »*. - [Electronic resource]. – Access mode: https://demo.garant.ru/#/document/70644238/paragraph/1081176/doclist/33/showentries/0/highlight/state%20program%20Development%20energy:6 (accessed 14.05.2022 .).

energy efficiency of industry, capital facilities and transport (Lesyukova and Lapchenko, 2020) (Bogoslavsky, 2019).

- The energy transition to a carbon neutral economy is carried out by attracting large private businesses through PPP, despite the negative cost (NPV) of green hydrogen pilot projects (Lashina, 2021; Matute et al., 2023).
- The Common Energy Policy of the European Union includes the possibility of implementing pure hydrogen import operations outside the EU territory in order to ensure the decarbonization of economic activity (Levinonva, 2022).

Funding for the development of hydrogen technologies and fuel cells in the United States is provided by the US Department of Energy and amounts to more than $150 million per year (U.S. Department of Energy, 2002).

According to experts, the development of the hydrogen industry will support US energy leadership and security, create new highly innovative jobs, significantly reduce carbon emissions and support the economic growth of the US economy (Stolyarevsky, 2015; Fuel Cell and Hydrogen Energy Association). The practice of transferring the US energy system to the principles of green energy and abandoning fossil resources shows that the state has taken the main course to modernize obsolete infrastructure from energy generation to the transport sector (Smirnov, 2018). Special lending and support grant programs are currently being implemented by individual state governments for the purpose of energy efficient economic transformation and the development of hydrogen energy (US Department of Energy, 2002). It should be noted that in the medium term, a significant proportion of the energy consumed in the United States will be stored in fossil fuels.

The People's Republic of China is a leader in the use of natural gas as a motor fuel and considers its use as an essential element of the state policy to reduce greenhouse gas emissions. The experience of China's energy crises in 2017-2018. and 2021, caused by an acute shortage of gas in the domestic market, led to the adoption in March 2021 of a 5-year economic development plan, in which the priority is the gradual elimination of dependence on foreign energy resources and ensuring the country's energy security at the expense of its own energy potential (Gromov, 2022). In addition, national and regional programs set targets for expanding the construction of hydrogen filling stations and developing basic hydrogen technologies through the activities of the China Hydrogen Alliance, established by major state-owned equipment manufacturers, as well as participants in the automotive and energy sectors.

The main factors hindering the development of hydrogen energy in China include the underdevelopment of part of the hydrogen fuel value chain, the lack of pipeline infrastructure, legal restrictions on the purposes of hydrogen use, the possibility of producing hydrogen fuel exclusively within chemical companies, the absence of special rules and production standards, and inefficiency of the storage and delivery system. In addition, there are restrictions in China on the application of green energy from renewable energy sources for hydrogen production due to the geographic disparity between power generation areas in northwest China and consumption areas in coastal areas. Examples include Re-Fire, which manufactures high-quality fuel cell power systems, and SinoHytec, which produces fuel cell stacks with a reduced platinum dosage, which has significantly reduced this cost item. The 2022 Winter Olympics, held in Beijing and Zhangjiakou, demonstrated the feasibility and safety of using hydrogen using fuel cell electric vehicles as an example (Qian et al., 2019).

The PPP model is considered by the Chinese government as an effective, but rather complex tool for extracting economic effects from innovations to achieve government goals in the context of sustainable development and decarbonization of the economy (Nowotny et al., 2014). An important factor in realizing the potential of PPP in the implementation of energy projects is the provision of state guarantees and economic support at all stages of their life cycle.

Due to the tightening of carbon footprint requirements in the chain of production of industrial goods, in order to maintain the competitiveness of goods and services produced in China, it is necessary to introduce advanced technologies across sectors of the economy and switch to alternative fuels with a lower carbon footprint (Piskunov et al., 2021).

3. METHODOLOGY

The scientific basis of the study is the analysis of publications of scientists devoted to the problems of improving the energy efficiency of the economy in the context of the global energy crisis, the energy transition to new energy sources, the adoption of a "road map" for the development of hydrogen energy and the realization of national potential in the production, export, and use of hydrogen and industrial products for hydrogen energy.

The information base of the study is the legislative and regulatory legal acts of the Russian Federation, the data of the Federal and Territorial Services of State Statistics of the Russian Federation, the results of previous scientific research by the authors, publications in special editions and the Internet. The methodological basis of scientific research was formed by general scientific methods of cognition methods of economic and logical analysis, system method, synthesis, formulation of the approximation problem, economic and mathematical modelling.

The text of the above Concept for the Development of Hydrogen Energy provides that by 2050 the Russian Federation will be able to export from 7.9 to 33.4 million tons of hydrogen per year, receiving an annual income of 100 billion US dollars (RBC, 2021), provided that a balance is established between the size of exports, satisfaction of domestic demand in the country for hydrogen, the development of hydrogen technologies and the reduction of the carbon footprint (Dontsova et al., 2020). It should be noted that the modern Russian economy is inferior to almost all large countries in terms of energy efficiency: The energy intensity of the Russian economy exceeds that of the EU by 2 times, the USA - by 1.5 times, China - by 1.1 times (Gorodnova and Berezin, 2022).

3.1. Discussion: The Technical and Economic Aspects of Hydrogen for Energy Transition

3.1.1. Technical aspect

The development of the field of hydrogen energy implies the development, implementation and modernization of technologies for the production, storage and transportation of hydrogen fuel, the generation of electrical and thermal energy using low -temperature solid polymer and high-temperature solid oxide fuel cells.

Fundamentally, a fuel cell is a galvanic cell in which the process of converting the chemical energy of fuel into electrical energy is carried out by electrochemical means. A fuel cell is an intermediate market product with a sufficiently low power of a single cell, which requires a serial connection of single cells into a battery to set voltage and power, equipping with special devices for supplying hydrogen fuel and an oxidizer, as well as systems for removing reaction products (water) and thermal energy, which requires the creation of an appropriate infrastructure.

A fuel cell power plant is a special unit for generating electricity and heat, consisting of fuel cell stacks, storage and supply systems for hydrogen fuel and an oxidizer, a system for removing chemical reaction products, a system for converting voltage and electric current into a system for utilizing heat generated in a fuel cell element or generating electricity in a steam or gas turbine.

Examples are a fuel cell electric vehicle based on a fuel cell stack, marine hybrid power plants with a diesel fuel converter and exhaust gas heat recovery in a turbine generator, as well as the use of power plants in urban environmentally friendly transport. More on this, in our opinion, the most popular in the near future will be an eco -tram and an eco-train running on hydrogen fuel, which is stored in special containers placed on the roof of a tram car or train. At the same time, two technologies for storing hydrogen fuel have been developed:

1. Intermetallic-storage of hydrogen fuel is carried out inside refillable metal cartridges under low pressure, which meets the highest safety standards. At the same time, the storage tanks for hydrogen fuel are filled with a calibrated mixture of metals (powders), which are capable of absorbing hydrogen with hybrid transformation, and, if necessary, releasing gas;
2. Bottled - a method of storing hydrogen, in which fuel is pumped into cylinders under high pressure, however, with this method, a high volume content of gas cannot be achieved.

Electricity generation is carried out in fuel cells using a direct chemical reaction as a result of the interaction of hydrogen fuel with air mass. The main significant advantages of using this eco -transport are absolute ecological cleanliness of this type of public urban transport; no need for a contact electrical network and traction substations; high indicators of safety and reliability of work; and high level of energy efficiency. Tests of a model sample of an eco -tram in the urban traffic cycle without connecting electricity storage devices showed the efficiency of an electrochemical generator equal to 56%. Table 1 presents the comparative technical and economic indicators of the use of trams from the mains and from the on-board power source.

When using hydrogen fuel, the cost of laying cable networks is reduced (the savings are 12 million rubles/1 km of travel), as well as contact networks (14 million rubles/1 km). In addition, the costs for the construction of a traction substation, the cost of which is 100-150 million rubles, are excluded for every 2.0-2.5 km of the tram line. All of the above results in a significant reduction in the cost of operating eco-trams. Calculations show that the cost per 1 km of a tram running on a hydrogen fuel cell is 20-20% lower than that of traditional tram models (Pavlenko and Danielyan, 2019). Table 2 shows the expected results of using hydrogen fuel on the Russian Railways.

Equipping a fuel cell power plant for marine and river equipment will also have similar expected characteristics. Of particular

Table 1: Comparative technical and economic characteristics of the use of trams based on fuel cells and hydrogen fuel in the urban cycle according to the state

No. p/p	Name indicator	Unit rev.	Traditional tram model	Ecotram on hydrogen fuel
1	Tram Unit cost	Million rub.	100	126
2	Income from the operation of 1 tram per year	Million rub.	7.2	7.2
3	Electricity cost	RUB/kW* h	6.95	1.5
4	Operating costs of 1 tram including depreciation and repair	Million rub.	17.0	7.0
5	Balance of operation of 1 tram, taking into account depreciation, excluding wages per year	Million rub.	-10.8	-0.73

Source: Developed by authors based on characteristics of tram LM-68M2 and Hydrogen tram in Saint Petersburg

Table 2: Forecast of the effects of using hydrogen fuel on the railway of the Russian Federation

No. p/p	Type of railway transport	Expected results	Note
1	Shunting locomotives	Absolute environmental efficiency	Replacement of heat engines
2	Special equipment for working in tunnels		
3	Passenger trains of regional directions		
4	Railcars	Improving environmental performance, increasing the level of equipment autonomy	
5	Lubricators	Expansion of functionality, heating of arrows	Replacing lithium-ion batteries
6	Stationary railway facilities	Independence from electrical networks, high energy efficiency, resource saving	Electricity and heat supply

Table 3: Comparison of options for providing refuelling with hydrogen[7]

No. p/p	Technical and economic characteristics	Unit rev	Natural gas conversion	Electrolysis
1	Electrical energy costs	kWh/kg (H_2)	2	42
2	Natural gas costs	m^3/kg (H_2)	4.2	-
3	The cost of produced hydrogen fuel	RUB/kg (H_2)	39	251

Source: Kasatkin M.A., Landgraf I.K. Prospects for hydrogen power plants on fuel cells for the development of electric transport//Transport of the Russian Federation. 2019. No. 6 (85). pp. 46-49

economic and technological interest is the process of providing transport with fuel cell power unit. Fuel Cell Power Unit is a complex set of technological systems in which the energy source is an electrochemical generator [6]. Hydrogen gas stations based on the conversion of fossil fuels have the following obvious advantages compared to the traditional gas station option:

- Reduction of electric energy costs
- Reduction of the physical volume of the system from 36 to 7 m^3
- Increasing the system reliability and equipment service life
- The station for refuelling vehicles with hydrogen based on the principle of water electrolysis consists of the following main elements: Electrolyser; compressor; hydrogen storage tank; filling columns.

Comparison of technical and economic characteristics of electrolysis and natural gas conversion technologies is presented in Table 3.

It can be seen from the data in the table that the natural gas conversion technology reduces the cost of electrical energy by 21 times. This technology, unlike electrolysis, requires natural gas. At the same time, the integral cost of the resulting hydrogen fuel is 6.4 times lower than when using the electrolysis technology.

3.1.2. Economic aspect

As a critical component of the energy transformation, hydrogen is gaining significant traction. Hydrogen (H_2) is attracting extraordinary attention and funding, owing to a worldwide change toward decarbonization by governments, investors, and customers. More than 40 countries had published hydrogen roadmaps by 2022. This momentum is present throughout the value chain and is hastening cost decreases for hydrogen manufacturing, transmission, delivery, retail, and end uses. There are currently over 680 hydrogen initiatives across the value chain, with 85% of worldwide projects coming from Europe, Asia, and Australia. Activity in the Americas, the Middle East, and North Africa is also accelerating. If all projects are completed, total expenditures in hydrogen spending will surpass USD 240 billion by 2030. However, only USD 22 billion (approximately 10% of proposals) have received a final investment decision (FID), are under construction, or are operational (Hydrogen Council - McKinsey Company, 2022).

The expense of producing hydrogen energy is divided into two primary components: Capital and electricity. The study discovered that the practical cost of grey hydrogen energy is USD 1.25/kg, whereas the cost of green hydrogen energy is comparatively high (Boretti, 2020). By 2030, the typical expense of green hydrogen energy is expected to exceed USD 2/kg (Boretti, 2021). According to the reference, grey hydrogen energy (EUR 1.3/kg) and blue hydrogen energy (EUR 1.68/kg) are still the main hydrogen energy sources especially in Portugal, compared to green hydrogen energy (EUR 4.65/kg and EUR 3.54/kg) from grid electricity and solar power using the Polymer Electrolyte Membrane (PEM) (Khatiwada et al., 2022). By 2030, the leveled cost of hydrogen (LCOH) of green hydrogen energy will decline to EUR 4.03/kg (grid electricity) and EUR 2.49/kg (solar electricity). Several investigations have shown that green hydrogen energy generation costs will keep on decreasing. Dark fermentation of biomass for renewable hydrogen energy generation costs up to USD 51/kg in the United States but is anticipated to decline to USD 5.65/kg by 2025 (James et al., 2016). According to the Hydrogen Council, the expense of wind-based electrolysis linked to PEM electrolysers in Germany is the lowest at USD 6/kg. This is anticipated to fall to USD 2.60/kg by 2030, which is significantly less than the cost of producing green hydrogen energy via on-site electrolysis in Canada (Hydrogen Council - McKinsey Company, 2020).

Infrastructure like hydrogen transport and distribution systems, storage, and hydrogen refilling stations also play a big role in determining how much hydrogen energy costs. The U. S. Department of Energy computed the costs of hydrogen transport, distribution, and refilling using the HDSAM instrument created by the Argonne National Laboratory: (a). The cost of piping system (100 km) is USD 4.85/kg; (b). Compressed hydrogen vessel (283 km) costs USD 3.30/kg; (c). Liquid hydrogen (283 km) costs USD 3.25/kg (The U.S. Department of Energy, 2015).

Even though the costs of producing, storing, and transporting hydrogen energy are comparatively expensive, many studies have found both scientific and commercial grounds for believing that they will decline significantly in the future. This is because of the economies of scale and the learning effect of hydrogen-related technologies, as well as the fact that the cost of making electricity from renewable sources is expected to go down. This is because of the economies of scale and the learning effect of hydrogen-related

6. Kasatkin M.A., Landgraf I.K. Prospects for hydrogen power plants on fuel cells for the development of electric transport // Transport of the Russian Federation. 2019. No. 6 (85). pp. 46-49. - [Electronic resource]. – Access mode: https://cyberleninka.ru/article/n/perspektivy-vodorodnyh-energoustanovok-na-toplivnyh-elementah-dlya-razvitiya-elektrotransporta/viewer (Accessed 08/19/2022)

7. Kasatkin M.A., Landgraf I.K. Prospects for hydrogen power plants on fuel cells for the development of electric transport // Transport of the Russian Federation. 2019. No. 6 (85). pp. 46-49. - [Electronic resource]. – Access mode: https://cyberleninka.ru/article/n/perspektivy-vodorodnyh-energoustanovok-na-toplivnyh-elementah-dlya-razvitiya-elektrotransporta/viewer (Accessed 08/19/2022)

technologies, as well as the fact that the cost of making electricity from renewable sources is expected to go down.

The important question in the downstream application of hydrogen energy, which includes the electricity sector, heat supply, and transportation sector, is whether hydrogen energy uses can contend with fossil energy in these sectors. The hydrogen energy will become competitive once the following pricing goals are reached (Li et al., 2023).

a. The overall supply cost, including manufacturing costs and shipping and distribution costs, should be <USD 4.0/kg, with shipping and distribution costs <USD 2.0/kg.
b. The electrolyzer system's initial cost is <USD 300/kW, and its conversion effectiveness is 77%.
c. The fuel cell device will cost <USD 40/kW, have a high efficacy of 65%, and a life expectancy of 5000 h. The device eventually costs USD 30/kW and has a life span of 8000 h.
d. Vehicle internal hydrogen storage costs as little as USD 10/kWh and will ultimately fall to USD 8/kWh.

Furthermore, The Hydrogen Council expected that hydrogen production costs are decline more than 60% for renewable (green hydrogen) by 2030 compared to 2020 baseline (Figure 1). Three reasons are causing this acceleration. First, capital expenditures are decreasing. By 2030, the electrolyzer capex are estimated to fall significantly, to around USD 200-250/kW at the system level (including electrolyzer stack, power supplies and rectifier, purification, and compression to 30 bar). Due to accelerated cost roadmaps and faster scale-up of electrolyzer supply networks, this amount is 30-50% cheaper than in 2020.

Second, the levelized cost of energy (LCOE) is also decreasing. The implementation of at-scale renewables, particularly in areas with high solar irradiation, is resulting in ongoing cost decreases of renewables that are up to 15% lower than originally anticipated (where renewables auctions continue to break record lows).

Finally, usage is continuing to rise. Higher electrolyzer utilization levels are being achieved in large-scale, combined renewable hydrogen initiatives. This success is mainly due to manufacturing centralization, a superior blend of renewables, and system engineering optimization.

4. FINDINGS AND RESULTS

4.1. Economic and Technological Potential and Challenges

The Russian Federation continues development and testing of advanced fuel cell stacks using hydrogen. For example, the first fuel cell battery based on the BTE-5 kW solid polymer electrolyte was developed in the Russian Federation, based entirely on domestic technologies, and intended for transport infrastructure facilities of Gazprom PJSC. The undoubted advantages of this battery include obtaining uninterrupted power sources for transport installations and aviation, as well as the possibility of equipping electric heat generators in order to provide energy, heat, hot water supply to housing and communal services.

Hydrogen-air battery BTE-P with a solid fuel electrolyte of kilowatt class has the following technical characteristics:

- Electrical efficiency-50%
- Rated output electric power- 5 kW
- Output voltage of direct electric current- 50-80 V
- Used fuel-hydrogen with a purity of at least 99.999%
- Used oxidizing agent-atmospheric air[8].

In Russia, the most powerful BTE-50/kW battery has also been designed and is already in use, designed to complete megawatt -class power plants based on fuel cells for transport and stationary purposes, as well as in the BTE-50V hydrogen-air battery with a solid polymer electrolyte with a power of 50/kW megawatt class. The main technical characteristics of the latter are as follows:

- Electrical efficiency- 50%
- Rated output electric power- 50 kW
- Output voltage of direct electric current- 115-180 V
- Used fuel-hydrogen with a purity of at least 99.999%
- Used oxidizing agent-atmospheric air[9].

Russian specialists are working on a qualitative improvement in the current-voltage characteristics of fuel cell batteries. Tests show that the use of antioxidant coating technologies makes it possible to obtain the following current-voltage characteristics: DC output voltage 114 V, nominal output electric power in coated batteries-98 kW, current strength-853 A. The test results demonstrate an improvement in the current-voltage characteristics of a promising sample compared to the prototype (experimental) sample by at least 26-39%. Table 4 presents the technical parameters of the experimental and prospective samples of the fuel cell stack.

Table 4 shows that a promising battery of a hydrogen fuel cell with the same efficiency factor = 60% is significantly ahead of the prototype in terms of such parameters as rated power (1.5 times higher), the life time before factory repair is 2.5 times more, a decrease in the total mass by 3.7 times, a significant decrease in overall dimensions and specific mass (by 5.6 times) and volume (by 2.3 times) indicators.

4.2. The Prospect of Hydrogen Energy in Russia

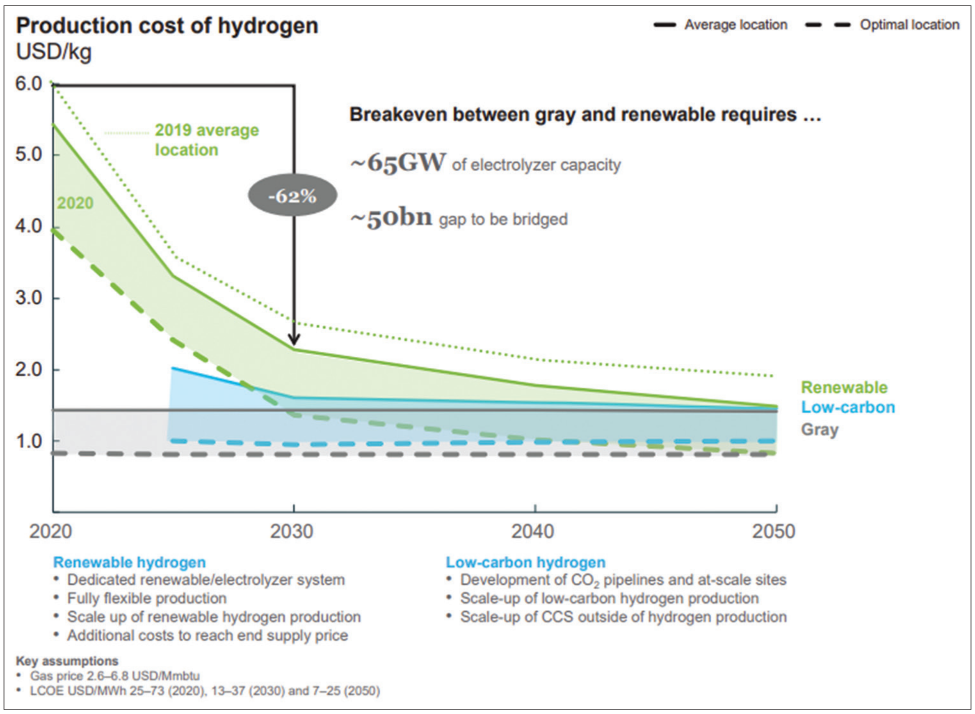
The draft Concept for the Development of Hydrogen Energy assumes that by 2050 Russia will export from 7.9 to 33.4 million tons of hydrogen per 11 year, while receiving an annual income of 100 billion US dollars.[10] This will become possible when a balance is established between export volumes, satisfaction of

8. Federal State Unitary Enterprise "Krylovsky State Research Center" Yekaterinburg. Ship electrical engineering and technology, fuel cells and hydrogen energy. - [Electronic resource]. – Access mode: https://krylov-centre.ru/activities/ship-electrical-engineering-and-technology/ (accessed 24.08.2022).
9. Federal State Unitary Enterprise " Krylovsky State Research Center " Yekaterinburg. Ship electrical engineering and technology, fuel cells and hydrogen energy. - [Electronic resource]. – Access mode: https://krylov-centre.ru/activities/ship-electrical-engineering-and-technology/ (accessed 25.08.2022).
10. Russia has planned to export hydrogen up to $100 billion a year. - [Electronic resource]. – Access mode: https :// www . rbc . ru / business /15/04/2021/6075 ff 5 b 9 a 79472446 f 75 b 01 (accessed May 16, 2022).

Table 4: Technical characteristics of experimental and advanced samples of the battery and fuel cell[12]

No. p/p	Name indicator	Unit rev.	Prototype BTE-50K	A promising sample with hydrogen fuel
1	Rated battery power	kW	50	75
2	Efficiency	%	60	60
3	The period of resource work before factory repair	h	8000	20 000
4	Weight	kg	710	190
5	Dimensions			
	Length	m	1.18	0.83
	Width	m	0.54	0.56
	Height	M	0.54	0.45
6	Specific indicators			
	Mass	kg/kW_{nom}	fourteen	2.5
	Voluminous	l/kW_{nom}	7	3

Figure 1: Estimated cost of producing hydrogen from various sources between 2020 and 2050 (Hydrogen Council - McKinsey and Company, 2021)



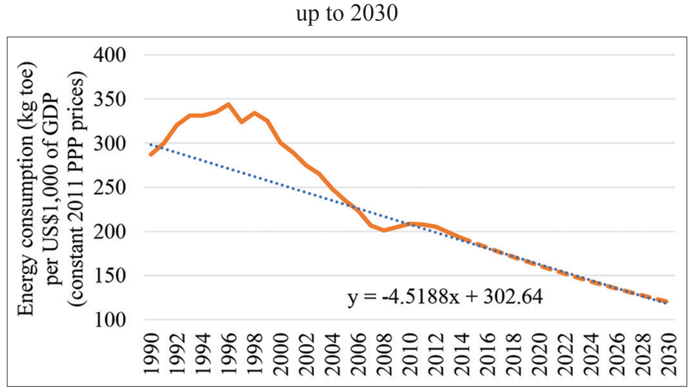
domestic demand and the development of hydrogen technologies that reduce the carbon footprint [5].

It should be noted that at present Russia is inferior to almost all leading countries in terms of energy efficiency. With an almost twofold increase in the GDP of the Russian Federation in the period 2000-2018. (181% of the 2000 level), the energy intensity of GDP over the same period decreased by more than 40%.

At the end of 2018, the energy intensity of Russia's GDP decreased by 12% compared to 2007, which indicates a significant lag in the actual rate of its decline from the target value. While maintaining the average rate of decline in the energy intensity of GDP, equal to 1.1% per year, the achievement of the target value of 40% will become possible by 2043-2045. Figure 2 shows the dynamics of the energy intensity indicator of the RF GDP, the forecast for a decrease in this indicator, as well as the trend line in the period up to 2030.

Today, the energy intensity of the Russian economy exceeds the energy intensity level of the EU by 2 times, the US - by 1.5 times,

Figure 2: The level of energy intensity of Russia's GDP for the period up to 2030



Source: Built by the authors based on (Bashmakov, 2018; 2022)

China - by 1.1 times. Thanks to the active state policy of energy efficiency in China, the EU and the USA, the gap between the energy intensity of Russia's GDP and the indicators of these countries in 2030 may be 9%, 50% and 30%, respectively (Figure 3).

According to the forecast made by the Ministry of Economic Development of Russia[11], the reduction in the energy intensity of the GDP of the Russian Federation and the achievement of its average world level is possible no earlier than 2035, subject to accelerated modernization of the technological base. To do this, the Russian economy must completely switch to the use of the best available energy technologies. This forecast contains four scenarios for changing the energy efficiency of the economy of the Russian Federation, depending on the state policy in the field of energy conservation and energy efficiency.

Scenario 1. Energy efficiency remains at the level of 2016-2018. For the entire period until 2035 (the technological factor does not change). This scenario makes it possible to evaluate the contribution of the structural factor, which shows how much the energy intensity of GDP will change if its structure changes while maintaining the technologies used.

Scenario 2. Extrapolation of the rate of decline in the energy intensity of GDP in all areas of energy use due to the technological factor determined for the period 2000-2018 in the horizon until 2035. This scenario shows how much the energy intensity of the RF GDP will decrease due to the influence of the technological factor in the absence of additional state policy measures to stimulate the modernization of the economy of the Russian Federation.

Scenario 3. Achievement of energy efficiency parameters at the level of the best available technologies in the world by 2050 due to the modernization of the technological base on an energy efficient basis.

Scenario 4. Achievement of energy efficiency parameters at the level of the best world technologies by 2035 due to the accelerated modernization of the technological base on an energy efficient basis.

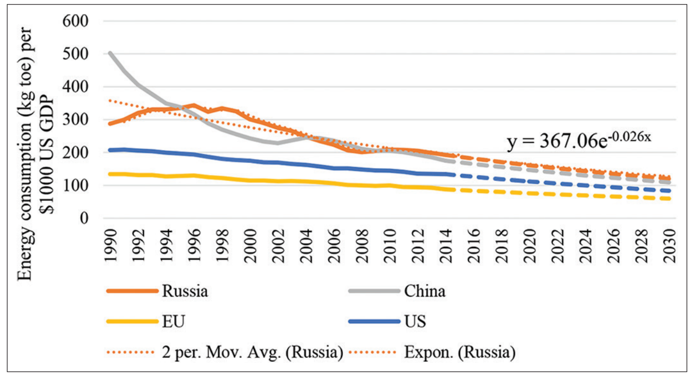
Figure 4 shows a forecast for a decrease in the energy intensity of GDP by 2035, which will be 21% (scenario 1), 31% (scenario 2), 36% (scenario 3), 46% (scenario 4).

According to the author's scenario (Figure 5), by 2030 Russia will be able to outstrip China in terms of energy intensity by 11%, subject to government support and funding in the required amount of areas of technological modernization of the economy. However, there will be a lag of 14% from that of the United States.

An analysis of the Russian practice of implementing energy policy makes it possible to identify the following problems that impede the improvement of the energy efficiency of the domestic economy:

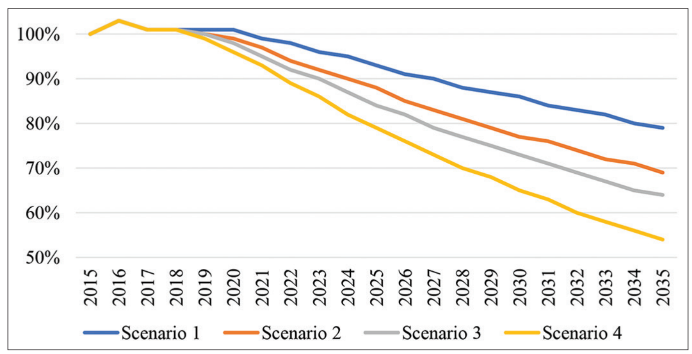
1. The absence of a focus on energy efficiency of the state economic policy in the period from 1990 to 1998 and, as a result, the imperfection of the regulatory and legal framework of the specified period for energy saving and energy efficiency.
2. Lack of sufficient investment and bank lending to energy efficiency programs due to high risks, and, as a result, insufficient financing of energy projects and programs.

Figure 3: The level of energy intensity of the GDP of Russia, China, the EU and the USA in the period up to 2030



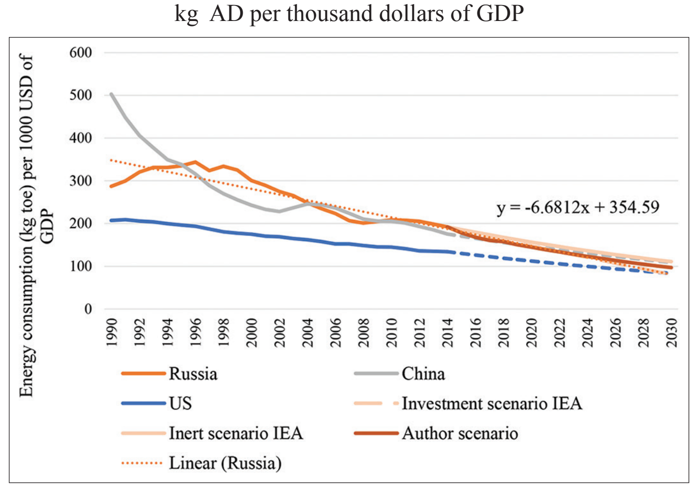
Source: Compiled by the authors based on World Bank data [Electronic resource]. – Access mode: https://data.worldbank.org/indicator/EG.USE.COMM.G.D._PP.KD (accessed 14.05.2022)

Figure 4: Dynamics of the energy intensity of the GDP of the Russian Federation from 2015 to 2035



Source: State report on the state of energy saving and energy efficiency improvement in the Russian federation for 2019" by the ministry of economic development of the Russian federation

Figure 5: Dynamics of the energy intensity of the GDP of the Russian Federation from 1990 to 2017 and forecast scenarios up to 2030, kg AD per thousand dollars of GDP



Source: Compiled by the authors based on World Bank data

11. State report on the state of energy conservation and energy efficiency in the Russian Federation. Ministry of Economic Development of the Russian Federation. - [Electronic resource]. – Access mode: economy . gov . ru (accessed May 14, 2022).
12. Landgraf I.K., Kasatkin M.A. Experience in the development of key hydrogen energy technologies of the Federal State Unitary Enterprise " Krylov State Research Center", Yekaterinburg, 2021 - [Electronic resource]. - Access mode: https://rus-shipping.ru/ru/shipbuilding/news/?id=28443 (08/25/2022).

3. The priority is the construction of new generating capacities, and, as a result, the lack of goals for the modernization of existing capacities.
4. The presence of systemic inertia in energy consumption, the lack of desire of private companies and households to take energy efficient measures, despite their advantages and practical evidence of effectiveness.
5. Lack of statistics on energy efficiency at the local, regional, national and sectoral level, and, as a result, underestimation of the energy efficiency potential.
6. Lack of awareness and awareness of the energy efficiency of all participants in the generation and consumption of energy, and, as a result, the presence of behavioral barriers.
7. Lack of an effective system for separating the incentives of all stakeholders, as well as the interest and motivation in building energy-efficient behavior.
8. High transaction costs of energy efficiency projects and, as a result, a serious problem of overall energy efficiency among all end users.
9. The presence of exclusive supply rights granted to large energy suppliers and, as a result, the presence of weak competition.
10. The presence of a monopoly or oligopoly in the oil and gas industry and the electric power industry, and, as a result, a sharp limitation in the ability to use the energy efficiency potential.
11. The absence of an independent, objective assessment of the general actual state of the power equipment of power facilities, and, as a result, the absence of state monitoring of the reliability of the energy system, analysis and forecast of energy consumption for a period of 5-15 years, state support for combined heat and power generation.
12. Lack of effective control of depreciation of equipment and residual resources, debugged, sufficiently equipped, repair base, as well as highly qualified technical personnel.
13. Lack of effective interaction between scientific and design institutes, as well as energy structures.
14. Untimely updating of the technical and regulatory framework.
15. Lack of strategic research plans that determine the future development of the energy sector.

In order to solve the above problems, in our opinion, concentrated and coordinated actions are required on the part of Russian regulators to realize the potential of energy efficiency and energy saving. An analysis of world experience shows the importance of having political will and coordination of actions in creating a national production and consumer culture focused on energy saving. For these purposes, Russia developed and adopted in October 2020 the Roadmap for the Development of Hydrogen Energy until 2024[13].

In this document, a special role in solving the tasks set in the Energy Strategy of Russia is assigned to such locomotives of the Russian economy as PJSC Gazprom and the State Atomic Energy Corporation Rosatom. The Roadmap highlights Russia's existing competitive advantages in the field of hydrogen fuel production, such as the presence of special technological know-how and R&D, a resource base, significant reserve capacities in the power generation system, developed transport infrastructure, geographical accessibility of large consumers, etc. This map outlines the first steps in the formation of a pool of industrial enterprises that support the development of hydrogen energy in the Russian Federation, and state authorities, which implies the further implementation of the planned actions within the framework of the institution of public-private partnership.

According to the authors of the study, one of the ways to solve these problems is to create a specialized energy efficiency agent in the form of a public-private partnership. The main activities of this agent include the following functions:
- Conducting technical expertise and economic assessment of the introduction of energy efficient technologies for the Government of the Russian Federation and consumers by creating and monitoring a system for certification of equipment quality, updating technological regulations and services to improve energy efficiency. This function will allow to overcome the heterogeneity of legal norms and technological regulations.
- Advising the Government of the Russian Federation and industry regulators on legal and regulatory policy to improve energy efficiency in order to form the necessary legal framework, which will significantly reduce the risks for private investors in energy efficiency projects.
- Coordinating initiatives of the Government of the Russian Federation in the field of energy efficiency and monitoring the achievement of established targets for energy efficiency in the system for identifying adverse selection factors.
- Negotiate energy efficiency financing with international financial institutions to facilitate access to capital for commercial banks.
- Creation of standard forms of contracts for special credit lines, risk sharing mechanism and energy services for the purpose of information and legal support.
- Creation of a database on energy efficient technologies with a description of the technical and economic characteristics and implementation experience within the energy system.
- Creation of a transaction cost accounting center to reduce the costs of enterprises on projects aimed at improving energy efficiency.

The agent can also act as an arbitrator between international financial organizations and the Government of the Russian Federation in order to provide financial assistance and develop new models for financing the energy efficiency system[14]. In addition, the agent may be the initiator of revising the principles of accounting for the life cycle costs of infrastructure construction projects through long-term planning, which will allow assessing the effect of energy efficiency measures with a high capital intensity.

13. Decree of the Government of the Russian Federation of October 12, 2020 No. 2634-r "On approval of the action plan "Development of hydrogen energy in the Russian Federation until 2024 ". - [Electronic resource]. – Access mode: https://demo.garant.ru/#/document/74788808/paragraph/1/doclist/571/showentries/0/highlight/concept%20development%20hydrogen%20energy:3 (accessed 15.05.2022 .).

14. Energy Efficiency Policies around the World: Review and Evaluation // World Energy Council. 2008 No. 38-40. 13 p . - [Electronic resource]. – Access mode: worldenergy . org (accessed May 15, 2022).

It should be noted that at present, when using the traditional scheme for planning and operating infrastructure facilities with the division into design, construction and operating phases of the costs of the entire life cycle of the facility, there is no possibility of optimizing them, since each participant applies solutions that lead to cost reduction at one stage of the life cycle cycle and its increase at other stages. In order to solve this problem in world practice, the so-called EPC contracts (turnkey project contracts) are used, the essence of which is to combine the design, construction and operation processes within the competence of a single responsibility center. In conclusion, most innovative solutions aimed at reducing energy intensity generally have a high return in terms of energy savings and can increase the financial potential of energy efficiency investments that are not currently profitable in Russia.

4.3. Potential Support from Multi Stakeholder Collaboration towards PPP

Hydrogen production is already ramping up, and significant investments are being done around the world. It will be an essential low-carbon option in a variety of industries. However, the growth of hydrogen still needs adequate financial, infrastructure, and governmental support in order to accomplish widespread implementation and scale-up through business initiatives. Therefore, the government takes a strategic role in developing hydrogen in each country. At least there are several steps taken by the government in accelerating the development of hydrogen

a. National strategies.
   40 national hydrogen strategies have been announced on a global scale as countries establish pathways to utilize hydrogen's potential to decarbonize, ensure energy security, and stimulate sustainable economic development from stranded energy resources. Stakeholders ranging from governments to sectors to customers themselves are increasingly realizing that hydrogen is required to reach net-zero emissions.
b. Regulatory certainty
   The main challenge that hydrogen project developers currently face is a lack of demand visibility; many are waiting for judgments on the enabling legal regulations and financing that will encourage offtakers to sign long-term hydrogen trade agreements. Creating demand visibility within a strong regulation framework overcomes the cost-competitiveness gap, boosts investor interest, and has a knock-on impact throughout the value chain, allowing investments in hydrogen supply, equipment production, and infrastructure.
c. Public funding
   In addition to financing support schemes based on competitive tendering, policymakers have access to grants, loans, and tax credits. The cost of hydrogen will go down even more if support programs for it are rolled out quickly. This will help mature projects get off the ground and speed up the use of hydrogen to help meet global climate goals within this decade.
d. Incentives
   To promote the early acceleration of hydrogen, governments may decide to implement incentives such as tax breaks or subsidies.

On the other hand, the industry is also encouraged to make efforts, especially in the development of large-scale hydrogen projects applying the PPP after regulatory certainty and public funding are established. The following are amongst key considerations in promoting PPP for the project:

a. Advancing project proposals to FID through resources and financial deployment commitments; Industry should commit to employing resources to develop projects toward FID by undertaking feasibility and FEED studies as regulatory assurance is reinforced and financial support begins to flow. Project developers should concentrate on developing long-term partnerships with hydrogen suppliers and offtakers, as well as actively reducing the perceived risk of engaging in hydrogen projects through project staging and collaboration with established partners with proven track records.
b. Increase the potential and capacity of the hydrogen supply network; Commit to growing supply chain capability and capacity as government goals transform into regulation action and trust in a prolonged demand forecast. The business should begin building up capability to allow large-scale implementation. Policy, technology, and end-user apps must all be aligned and synchronized. As the business grows, it must guarantee that project ideas and tools (such as electrolyzers) are accessible. Distribution networks must be prepared, which only business can do. Scaling up green hydrogen usage requires increasing renewable electricity capability at a large scale.
c. Develop cross-border trade networks; worldwide commerce unleashes the full potential of hydrogen as a movable, renewable energy source. However, project ideas to create hydrogen infrastructure are scarce, and industry should focus its efforts on creating infrastructure to allow cross-border commerce (through building out terminals, large-scale storage, and hydrogen conversion technologies). As international collaboration among states grows, the industry should actively participate in prioritizing actions to ensure that international commerce movements efficiently meet supply and demand.

The analysis of the world experience and Russian practice in the field of application of innovations in the fuel and energy complex in the conditions of the energy crisis and the transition to green energy allows us to draw the following discourses:

- Stimulation of the implementation of innovative energy projects is carried out within the framework of contractual and institutional forms of PPP, aimed primarily at improving energy efficiency and decarbonization of industry, transport, capital facilities and transport.
- The energy transition to a carbon neutral economy is carried out by attracting large private businesses and providing government guarantees through PPPs.
- In order to increase the competitiveness of the domestic economy in the global energy market in the Russian Federation, it is necessary to develop hydrogen energy in the context of the implementation of public-private partnership mechanisms.
- It is essential that the Government of Russia take certain measures, first of all, to initiate coordinated and systematic actions to improve energy efficiency, aimed at increasing the competitiveness of the Russian Federation in connection with the energy transition to a carbon neutral economy.

- Scientific hypotheses that the development of the hydrogen fuel industry within the framework of the created economic agent in the form of a public-private partnership, which will allow the transition to green energy, achieve carbon neutrality of the industry, and increase the competitiveness of private sector companies, were confirmed in the course of this work.

5. CONCLUSION

It should be emphasized that the program for the transition to hydrogen fuel is not an integral part of a large-scale strategy for the decarbonization of the Russian economy (Garmston, 2012; Potashnikov et al., 2022). At the moment, the Russian Federation, within the framework of our country's obligations under the Paris Agreement, does not implement carbon regulation.

6. FINDINGS

- The transition to hydrogen energy is a phase, leading to fundamental changes without the possibility of returning to the bifurcation point;
- The creation of hydrogen energy in the US and the EU, according to experts, will lead to a significant rise in prices due to the introduction of a "carbon tax" and the isolation of the economies of these countries;
- The conditions of anti-Russian sanctions and the closure of the European market for Russia create a paradoxical situation: on the one hand, a decrease in Russian exports in the potential hydrogen market, on the other hand, the strategy of Europe's transition to hydrogen fuel creates an acute shortage of hydrogen, which will undoubtedly lead to a severe energy crisis;
- Adaptation of the Russian economy in the context of the "hydrogen agenda" is a necessary measure;
- The transition to hydrogen fuel in Europe and, mainly, China, will lead to a guaranteed, exponential growth in demand for copper and rare earth metals, the reserves of which are very limited. This, in turn, will lead to a sharp increase in prices for metals and toughen competition and control over deposits;

The authors of the study emphasize that the relevance of the above conclusions for the Russian Federation is confirmed by the "road map" for the development of hydrogen energy and the Concept for the Development of Hydrogen Energy in the Russian Federation. Concepts and programs of this kind were adopted by such leading world economies at the end of the 20th century as the USA, the EU, China, etc.

In this concept, the introduction of eco-transport is defined as one of the promising areas for the use of hydrogen technologies. For this, it is planned to develop hydrogen power plants for electric transport, filling stations, as well as systems for storing and transporting hydrogen fuel. We emphasize that hydrogen within the framework of this Concept is considered not as a fuel, but as an energy carrier.

7. ACKNOWLEDGMENT

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