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Perspectives for the Use of Hydrogen Energy in European Countries

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ABSTRACT

The most actual environmental problems in the XXI century are the following: global warming due to greenhouse gas emissions, energy production at coal, oil and power plants, air pollution, water pollution and waste recycling. Other environmental problems can be added to this short list, but the authors solve a specific task of promoting the idea of a promising "green" energy that will help humanity in conservation and development. European Union (EU) countries are planning to solve the main environmental challenges for the transition to low-carbon electricity by 2050. In many countries in the world every year there are more and more supporters of reducing emissions of carbon dioxide CO_2, nitrogen oxides NO and NO_2 and other greenhouse gases into the atmosphere. In recent years, EU has been consistently pursuing its own policy in the field of environmental protection, carrying out large-scale environmental measures. In Germany, United Kingdom (UK) and other European countries, a number of environmental initiatives are already gaining the status of state policy, which is being formalized in laws and regulations. Russian Federation acts on the world market as a leading country that produces and supplies significant energy resources not only to Europe, but also to many countries in the Asia-Pacific region. It is clear that the competitive stability of Russian energy companies significantly depends on the situation on the world energy market, but with the right strategy, Russia can actively influence the state of the entire energy market. With a confident leadership position, provided with significant natural, technological and human resources, Russian Federation has undeniable advantages over other energy-producing countries. It is Russia that can become the main supplier of clean energy for all other countries of the world, where tougher environmental requirements for energy generation are being cultivated. The authors of the study are considering the possibility of producing environmentally friendly hydrogen in Russia based on renewable energy sources (RES). The performed analysis shows the undeniable advantages of Russia in the export of hydrogen to other European countries.

INTRODUCTION

Despite the ongoing economic sanctions policy on the part of some states of the world, Russia remains a reliable and stable energy partner for most European countries. For all countries of the EU, there are uniform coordinated documents at the interstate level. Active work is constantly being carried out to unify and improve environmental requirements in the field of energy for all EU member states, which is reflected in a number of regulatory documents. In 2005, the "Energy Policy of EU" was approved. It is aimed at achieving three main goals, which are outlined in the "Energy Strategy of EU":

1. Ensuring reliable and safe power supply;
2. Creation of a competitive environment for energy suppliers to ensure affordable prices for energy resources;
3. Ensuring stable consumption of energy resources by increasing energy efficiency and reducing greenhouse gas emissions, reducing environmental pollution and dependence on the type of fuel (Isaeva 2019).

Currently, half of the energy needs of EU member states are met by external suppliers. In the future, this proportion may increase to 2/3 (Kaveshnikov 2014, Zuev 2007). EU countries are planning in the future to most effectively apply the principle according to which it is the "polluter" who pays. Each supplier of any resource will be considered a violator of the environment: raw materials, energy carriers or end product. Penalties provide for mandatory financial compensation for any environmental pollution. The amount of such financial compensation will depend on the degree of environmental friendliness of production processes.

It is considered to be free from such compensation, some ideal processes using RES. RES include those energy sources, the natural renewal of which occurs quickly enough for them in the short term. The most common RES are the

following types of energy: solar, hydraulic, geothermal, wind and biomass. When using RES, energy is generated through natural processes, while environmental pollution occurs on a minimal scale. It should be noted that environmental pollution can be minimal, but not equal to zero. This is explained by the fact that the creation of a technological process of energy conversion requires significant infrastructure and special equipment, the creation of which causes certain damage to the environment.

The existing strong dependence of the economies of many EU countries on non-RES has led to attempts to change the accepted classification of RES in order to include other sources in this list. An example is the nuclear power industry, where there are no massive harmful emissions of such non-environmentally friendly gases as CO_2, nitrogen oxides NO and $\underline{NO_2}$, etc. However, it can hardly be considered that fuel for nuclear power plants, formally, is a renewable type in real time human.

It should be noted that new processes in the field of regulation of energy resources impose special requirements on energy resources exported to European countries, for example, natural gas. Russian energy companies supply about 42% of all natural gas to European countries. It consists mainly of methane, although it is a non-RES source, nevertheless, it belongs to the most environmentally friendly form of energy due to the low CO_2 emissions during its production and combustion. The authors predict that the practical implementation of the "EU Energy Strategy" to reduce carbon emissions may, in the future, significantly reduce the level of natural gas supplies from Russia to Europe, or reduce profitability for Russian suppliers due to the implementation of the "polluter pays" principle. Another powerful factor in the implementation of the newest hydrogen strategy in Russia is the unique natural opportunities of the largest country in the world to obtain energy using RES.

PAST STUDIES

The authors of the study (Kaveshnikov 2014) review European energy policy and point out the significant cost of new reforms in the energy sector. Only a few European countries are relatively energy independent from external energy suppliers. Economically leading countries consume several times more energy than they produce energy themselves, and over time, this disproportion is increasing more and more. It is also necessary to note purely national differences in various sources of energy generation. For example, Germany is the leader among EU countries in the production of electricity from coal-fired power plants, and France is the leader in nuclear power plants.

As we know, the most environmentally friendly is the production of energy based on the oxidation of hydrogen, because as a result of a chemical reaction, the product of hydrogen combustion is water. The topic of hydrogen energy has found its place in the "Energy Strategy of EU", in which the countries of Western Europe have formed an environmental strategy for their development until 2050 (Gurkov 2014). "Action Plan for the Development of Hydrogen Energy in the Russian Federation until 2024" contains a roadmap that indicates that hydrogen can be used for the accumulation, storage and delivery of energy. Russian power engineers consider hydrogen as a promising energy carrier and a tool for solving new challenges to develop a low-carbon economy and reduce the anthropogenic impact on the climate. The uniqueness of hydrogen fuel lies not only in the complete absence of harmful emissions but also in its high calorific value. Another indisputable advantage is the technologically simple method of transporting hydrogen gas. "Action Plan for the Development of Hydrogen Energy" adopted in Russia was carefully and long prepared by leading power engineers and economists because they have been dealing with the problem of "decarbonization" for many years, said A. Belousov, First Deputy Prime Minister of the Russian Federation (Belousov 2021). He also noted that for the transportation of pure hydrogen, and as a part of a complex mixture, modern energy transport infrastructure can be used, for example, the new main gas pipeline from Russia to Germany through the Baltic Sea, Nord Stream 2 (Belousov 2021).

Currently, the cheapest way to produce hydrogen is the traditional method of steam reforming of methane, although it cannot be called environmentally friendly (Kraev 2020). Electrolysis is considered an alternative way to produce hydrogen, but it still cannot compete with the steam reforming of methane due to the significantly high cost, which is determined by the cost of electricity for this technology. Previous studies carried out by the authors comparing different methods of hydrogen production led to the conclusion that hydrogen produced using RES will be more than ten times more expensive than hydrogen produced by steam reforming from methane (Kraev 2020). So, existing RES do not allow the production of cost-competitive hydrogen. The Government of the Russian Federation is considering a modern technology of water electrolysis based on a nuclear power plant and a hydroelectric power plant, which will ensure the competitiveness of hydrogen produced by water electrolysis. Such a decision is justified and will allow minimizing daily fluctuations in the load of nuclear power plants due to the consumption of electricity for hydrogen production.

Not only in Russia, but also in other European countries, they show great interest in promising technologies for the

production of hydrogen. Avacon AG, a regional energy company from Germany, is already working on adapting the existing gas infrastructure to the practical use of hydrogen. Experimental studies are carried out on the existing gas distribution system of the city of Genthin (Saxony-Anhalt). The purpose of the measures is to increase the specific share of hydrogen in the main natural gas, which is supplied to German cities. To improve the environmental friendliness of energy systems, they began to replace up to 1/5 of the natural gas with hydrogen, although previously it was allowed to replace no more than 1/10. Stephan Tenge, one of the heads of Avacon AG, believes that since environmentally friendly "green" gas will play an increasingly important role in the future, it is necessary to re-equip the gas distribution network now so that it is adapted to receive the highest possible share of hydrogen.

METHODOLOGY

The study conducted by the authors is based on various methods of theoretical and scientific-practical study of environmental and economic approaches in obtaining promising types of fuel to meet the needs of the population. The work uses elements of functional cost analysis, methods of generalization, synthesis and abstraction. The research methodology included an economic analysis of data on various types of fuel used in modern energy. The authors used complex systems of methods in the field of management, which are used by Russian and foreign experts in the field of energy efficiency and ecology. In addition to theoretical ones, specific scientific and practical methods of socio-economic research are actively used in research work, primarily the analysis of documentary sources and the method of statistical analysis of statistical information. Information sources used in scientific work include documentary and statistical materials, special literature on the research topic and media materials.

RESULTS

The authors in their studies conducted an organizational and economic analysis of the feasibility of using hydrogen as a fuel in the aviation industry and noted that the first cargo transportation on hydrogen could be carried out as early in 2024 (Aslanov 2021). Our results showed a certain limitation of the use of hydrogen in aviation transport due to its specific physical properties, namely, very low density. For example, 1 m^3 of liquid hydrogen has a weight of 70 kg, while the density of liquefied natural gas ranges from 430 to 520 kg/m^3, and the specific gravity of kerosene is 780-850 kg/m^3. The use of aviation fuels with low density will require a significant increase in the volume of fuel tanks and a reduction in the usable volume on board the aircraft. However, for road and rail ground transport and stationary power plants, the use of hydrogen fuel is extremely promising.

After analyzing the energy plans of a number of European states, the authors believe that in the near future the demand for hydrogen in the developed countries of the world will grow by dozens, and perhaps even hundreds of times. Consulting firm Aurora Energy Research conducted in 2020 its study "Hydrogen for a net zero GB: an integrated energy market perspective" which notes that while it focuses on the UK, its results apply to other countries, including developing nations. The report says that the total capacity of electrolysis hydrogen projects to be completed by 2040 is a thousand times greater than all the electrolysis facilities currently operating in the world. The final power should be an impressive value of 213.5 GW. The report also presented a functional cost analysis of the process of hydrogen production by electrolysis and concluded that it is possible to reduce the cost of hydrogen in the future to below 2.5 Euro/kg. Analysts at Aurora Energy Research predict in their optimistic scenario a hydrogen price cap of 2 - 2.5 Euro/kg.

One of the world leaders in the energy sector, Shell, with the financial support of the EU, began construction in Germany in 2020 of the world's largest hydrogen production plant using water electrolysis. Until now, hydrogen at this enterprise was obtained only from natural gas. The volume of production will be 1.3 kilotons of hydrogen per year.

According to Bloomberg NEF experts, clean hydrogen could be used in the coming decades to cut up to 1/3 of global greenhouse gas emissions from fossil fuels and industry. At the same time, we are talking about acceptable costs in the transition to a new type of energy. This requires that at the level of the governments of the countries of the world, appropriate measures are taken to help expand the scale of modern technologies and reduce costs. The report notes the possibility of producing hydrogen in many countries before 2050, making it competitive with current natural gas prices in Brazil, China, India, Germany and Scandinavian countries on an energy equivalent basis. Experts from the Industrial Decarbonization department believe that hydrogen has sufficient potential to become a promising new fuel for the economy. In the coming years, it can be produced at a competitive price, stored underground for several months if necessary, and then transported through pipes. Bloomberg NEF analytical report on hydrogen price forecasts in various countries of the world provides the cost of producing sustainable "green" hydrogen, i.e. produced with the help of RES until 2050 (Table 1). We pay attention to the fact that hydrogen in European countries will not be the cheapest fuel: in Poland, 1 kg of hydrogen will cost 2.5 Euros, in Germany it will cost 2.25 Euros and in France, it will cost 2 Euros.

The cost of produced hydrogen depends significantly on the technology of its production. For example, hydrogen produced by electrolysis from solar and wind energy costs 5 to 10 times more than "conversion" hydrogen produced from natural gas. However, the cost of hydrogen depends on the energy source. For example, the price of "green" hydrogen from the energy of a nuclear power plant is 2 times cheaper than that from solar energy.

The cost of hydrogen, of course, depends on the producing country and the prices for energy carriers/raw materials in it. In Russia, hydrogen produced from methane costs about 1.1-1.6 Euro/kg, in the countries of the Middle East its cost drops to 0.9 Euro/kg, and in Europe, it reaches 2.23 Euro/kg. From an energy point of view, the thermal value of 1 kg of hydrogen is 2.5 times higher than that of methane or gasoline. It should be noted that the cost of hydrogen production in Russia is projected at the level of 1.5 Euro/kg if we use averaged data on the cost of electricity for hydrogen production in the calculations. A more detailed study of various energy sources and functional cost analysis confirm that the above data for Russia are approximate and do not reflect the real cost of electricity, and therefore do not demonstrate all the possibilities of the Russian energy sector.

We calculate in more detail the cost of electricity generation, as the main source of energy for the production of environmentally friendly hydrogen. The analysis below is based on official data on the cost of electricity, approved by the Federal Antimonopoly Service of the Russian Federation. The normative document under consideration contains selling wholesale prices for electricity for each electric power generation facility in Russia. We carry out a cost analysis in segmentation by types of generating processes: thermal, nuclear and hydropower plants. The significant difference in the cost of electricity depending on the type of power plant is impressive. The most expensive electricity is generated at the condenser-type thermal power plant, where the tariff rate for electricity per 1 kWh will be in the range of 0.01-0.02 Euro. The energy produced at nuclear power plants (NPP) is cheaper: 0.003-0.004 Euro/(kW/h). An additional effect is a new possibility of obtaining hydrogen to reduce daily fluctuations in the power of a nuclear power plant, i.e. elimination of an inefficient unloading mode (Aminov & Bairamov 2016; Fateev et al. 2018). However, in Russia, there are even cheaper sources of electricity. Their presence is associated with the unique natural features of a large Russian territory. We are talking about hydroelectric power plants (HPP). According to the order of the Federal Antimonopoly Service of the Russian Federation, the cost of electricity generation at hydroelectric power plants will be 0.0002-0.0004 Euro/(kWh) (Fig. 1).

Based on the data on the cost of electricity generation, we can say with confidence that hydropower has an undeniable advantage over other types. Another undoubted advantage of hydroelectric power plants is that they belong to truly RES, in contrast to nuclear and thermal energy.

The authors (Sinyak & Petrov 2008) analyzed the costs of hydrogen production and concluded that the electrolytic technology for hydrogen production would require about 60 kW/h of electricity per 1 kg. We consider how much it costs to produce 1 kg of gaseous hydrogen by electrolysis when generating electricity using various technologies (Table 2). It should be noted that a change in the cost of hydrocarbon fuels can significantly affect the cost of electricity generated by thermal power plants, while electricity produced by nuclear power plants and hydroelectric power plants practically does not depend on the global price situation in fuel markets.

As mentioned previously, thermal energy-producing companies or private households will be the main consumers of hydrogen. We then take into account the price of thermal energy generated by various technologies. The findings of estimating the cost of 1 MJ of thermal energy produced by gaseous fuel burning are shown in Table 3. Please note that these calculations are of an estimated nature and do not take

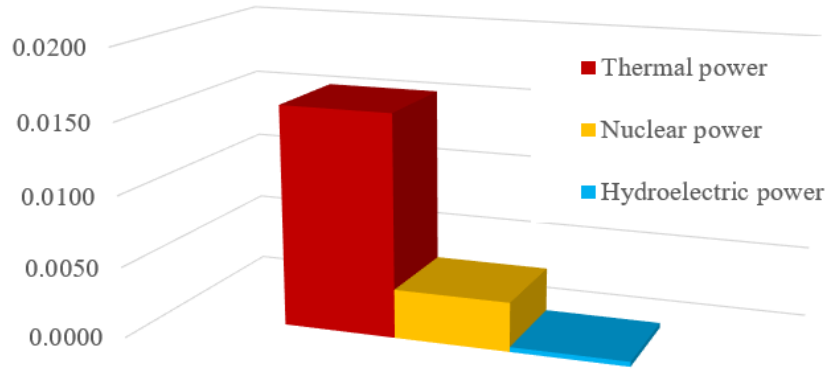

Fig. 1: Electrical power generation price in Russia for 1 kW/h, Euro.

into account capital investments in generation facilities, as well as transportation costs.

The estimated calculation given in Table 3 shows the undeniable advantage of hydroelectric power plants as a way to generate electricity for hydrogen production. It is fascinating to compare the costs of thermal energy produced from pure hydrogen and its mixing with natural gas, which is the primary energy source in the majority of European nations right now. The cost of the thermal energy received will be lower than the cost of thermal energy produced by burning natural gas with an equal mixture of hydrogen produced by electrolysis at hydroelectric power plants (50%) and natural gas (50%) (Fig. 2).

DISCUSSION

With a more accurate calculation, it is required to take into account the depreciation costs for electrolysis plants in the cost of the received energy (Sinyak & Petrov 2008). Within the framework of this research work, the authors do not talk about the process of gas transportation from the place of its production to the place of its consumption. Hydrogen can be transported in its gaseous or liquid state. The fundamental difference for determining costs lies in the significantly low temperature of liquid hydrogen: below 2600°C at atmospheric pressure, which is technically very difficult and expensive to make for mass consumption. By increasing the pressure in the line to 10 bar, we can slightly increase the boiling point by 100°C. By the way, the process of gas liquefaction is very energy-intensive and will require up to 1/3 of the growth in the cost of hydrogen (Kraev et al. 2018). When transporting liquid hydrogen, it will be necessary to additionally provide high-level thermal insulation for pipelines (Krenn & Desenberg 2020). Pumping liquid hydrogen will also require more additional energy to provide a cryogenic temperature level in the elements of pumping equipment. In the aggregate of the difficulties associated with the transportation of the liquid phase of hydrogen, this type of transportation at the level of modern technologies for industrial volumes of hydrogen production seems unacceptable.

The most optimal alternative to pipeline transportation of liquid hydrogen is its pumping in a gaseous state. Alternatively, the existing natural gas pipeline infrastructure in the world can be used (Belousov 2021). Modern gas pipelines, such as the Nord Stream, make it possible to transport any gas at high pressures up to 200 bar over remote distances of several thousand kilometers. Taking into account the significant differences in the physical properties of hydrogen and methane, as the main component of natural gas, the task of adapting compressor stations for pumping gaseous hydrogen may arise. The fact is that hydrogen is a gas with a low density (0.09 kg/m^3), and for comparison, the density of methane is an order of magnitude higher: 0.7 kg/m^3. With the existing high level of technological development, this problem is easily solved by certain engineering and technical methods. However, when transporting a gaseous mixture of natural gas and hydrogen in a ratio of 4:1, the change in the density of the mixture is not critical, and it is possible to use the existing gas transmission infrastructure in Europe.

CONCLUSION

The research project takes into account a new strategic focus on environmentally friendly hydrogen energy among several top European nations. Based on RES and the current gas transportation infrastructure, Russia has a unique chance to create the most promising and environmentally friendly hydrogen fuel for the export of gaseous hydrogen to EU nations. According to estimated calculations made by the authors, electrolytic hydrogen produced using existing hydroelectric power plants provides a significant (more than ten times) cost advantage. The environmental situation is improved at

Table 1: Producing green hydrogen prices in the countries of the world by 2050.

Country	Hydrogen price, Euro/kg
Japan	2.75
Poland	2.5
Germany	2.25
France	2
Argentina	1.5
Canada	1.5
Russia	1.5
Australia	1.25
Brazil	1.25
Chile	1.25
China	1.25
India	1.25
Morocco	1.25

Table 2: Comparison of hydrogen production cost depending on the method of generating electricity.

Generation source	Cost of 1 kWh of electricity, Euro	Cost of 1 kg of hydrogen, Euro
Thermal power	0.01 -0.02	0.60 – 1.25
Nuclear power	0.003 – 0.004	0.18 – 0.22
Hydroelectric power	0.0002 – 0.0004	0.015 – 0.025

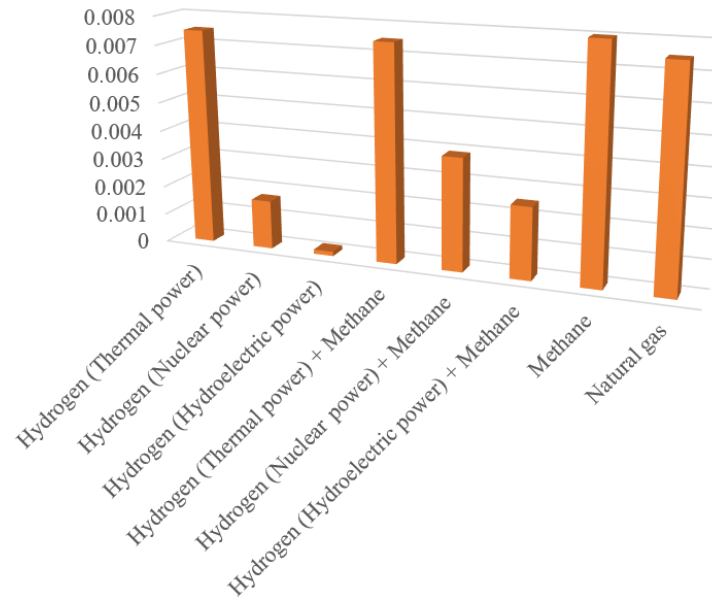

Fig. 2: Cost of generating 1 MJ of thermal electricity depending on the type of gas generation, Euro.

Table 3: Comparison of the cost of thermal energy depending on energy production technologies.

Energy carrier		Specific heat of combustion of gaseous fuel, MJ/kg	Cost of producing 1 kg of gaseous fuel, Euro	Cost of 1 MJ of thermal energy when burning gas, Euro
Hydrogen	Thermal power	120	0.60 – 1.25	0.005 – 0.01
	Nuclear power		0.18 – 0.22	0.0015 – 0.0019
	Hydroelectric power		0.015 – 0.025	0.0001 – 0.0002
Hydrogen + Methane (50% H_2 and 50% CH_4 by mass)	Thermal power	85	0.50 – 0.90	0.006 – 0.009
	Nuclear power		0.30 – 0.35	0.0038 – 0.004
	Hydroelectric power		0.24 – 0.25	0.0029 – 0.003
Methane		50	0.45	0.008
Natural gas		45	0.40	0.0075

the same time as the basic requirements for the production of "green" hydrogen using RES are met.

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