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Development of "green" hydrogen energy in the European part of the Russian Federation

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Abstract. The development of hydrogen energy in the Russian Federation has been interfered by a number of serious problems and issues connected with the innovative nature of this sector of economics. The problems include lack of experience in production, storage and transportation of "green" hydrogen. The development results within the Concept for the development of hydrogen energy present the Russian Federation as the largest exporter of hydrogen by 2050. The Concept estimates the future hydrogen production volumes to be as high as 200,000 tons by 2024, from 2 to 12 million ton by 2035 and from 15 to 50 million ton by 2050. Currently, there are projects on producing "green" hydrogen through electrolysis of water at hydroelectric stations. Moreover, there are different methods of hydrogen storage used in the Russian Federation. However, there is no transportation infrastructure for "green" hydrogen. Therefore, in order to build up transportation infrastructure the authors use economic calculations to consider and actualize the routes for transportation of the "green" hydrogen. To evaluate the profitability the infrastructure and the routes were created for transporting the "green" hydrogen as the export raw material produced in the Niznekamskya HES (Naberezhnye Chelny, Republic of Tatarstan, Russia) to the EU countries. The authors consider waterways, land routes and pipelines for delivering the "green hydrogen" as the transportation facilities and the cargo routes. They evaluate the indicators which characterize the "green" hydrogen transportation by means of waterway, railway and automobile transport and pipelines. The authors estimate the comparative payback periods for the hydrogen transportation by means of waterway, railway and automobile transport and pipelines along their main routes according to the hydrogen market price.

Keywords: hydrogen, production, transportation, cost, payback period, technology, hydroelectric station

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Развитие «зеленой» водородной энергетики в европейской части Российской Федерации

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Аннотация. На пути развития водородной энергетики в Российской Федерации возник ряд серьезных проблем и вопросов в связи с инновационностью данной отрасли экономики. Эти проблемы включают в себя отсутствие опыта производства, хранения и транспортировки «зеленого» водорода. В результате внедрения «Концепции развития водородной энергетики» Российская Федерация должна стать крупнейшим экспортером водорода к 2050 г. Данная концепция оценивает объемы будущего производства водорода к 2024 г. – 200 тыс. т, 2035 г. – от 2 до 12 млн т и 2050 г. – от 15 до 50 млн т. На данный момент существуют проекты создания «зеленого» водорода электролизом воды на гидроэлектростанциях, также в Российской Федерации уже существуют и используются отдельные способы хранения водорода, но полностью отсутствует транспортная инфраструктура. В связи с этим для создания транспортной инфраструктуры рассмотрены и актуализированы пути транспортировки «зеленого» водорода с использованием экономических расчетов. Для оценки рентабельности создана инфраструктура и маршруты для транспортировки «зеленого» водорода как экспортного сырья, производимого на Нижнекамской ГЭС (г. Набережные Челны, республика Татарстан, Россия) в страны Евросоюза. В качестве транспортной инфраструктуры рассмотрены водные, наземные и трубопроводные пути, а также трассы следования груза. Произведена оценка показателей, характеризующих экономическую эффективность транспортировки «зеленого» водорода водным, железнодорожным и автомобильным транспортом, трубопроводными путями. Рассчитаны сравнительные сроки окупаемости транспортировки водорода различными видами транспорта по их основным трассам в зависимости от рыночной стоимости водорода.

Ключевые слова: «зеленый» водород, производство, транспортировка, стоимость, срок окупаемости, технология, гидроэлектростанция

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俄罗斯联邦欧洲部分”绿色 “氢能源的发展

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摘要：在俄罗斯联邦发展氢能源的道路上，出现了一些与这一经济分支的创新性有关的严重问题和困难。这些问题包括缺乏生产、储存和运输 «绿色 «氢气的经验。氢能源发展构想所拟定的发展结果是，到2050年俄罗斯联邦将成为最大的氢气出口国。该构想还预计未来的氢气产量到2024年为20万吨，2035年为200万至1200万吨，2050年为1500万至5000万吨。目前，有通过水力发电站的水电解来制造»绿色 «氢气的项目，在俄罗斯联邦也已经存在并使用一些氢气储存方法。但»绿色 «氢气的运输基础设施却完全没有。因此，为了建设»绿色 «氢气运输基础设施，作者使用经济价值计算方法研究和更新了的»绿色 «氢气运输方式。为了评估盈利能力，创建了将下贝列日涅切尔尼水电站（俄罗斯鞑靼斯坦共和国下贝列日涅切尔尼）生产的 «绿色 «氢气作为出口原料运往欧盟国家的基础设施和路线。作为运输基础设施，考虑了运输 "绿色" 氢气的水路、陆路和管道路线以及货运路线。评估了通过水路、铁路、公路运输和管道运输 «绿色 «氢气的特征指标。根据氢气的市场价值，计算了铁路和公路运输、氢气管道、水路等主要路线的氢气运输的比较投资回报期。

关键词：氢气、生产、运输、成本、投资回收期、技术、水力发电站

Introduction

In 2021, "The Concept for the Development of Hydrogen Energy in Russia" was adopted by the Order of the Russian Government[1]. Its implementation raises a number of serious issues and problems. The development directions established and the results expected from its implementation are expected to make the Russian Federation the largest exporter of hydrogen by 2050. Future volumes of hydrogen production in Russia are estimated at 200 thousand tons by 2024, from 2 to 12 million tons by 2035, and from 15 to 50 million tons by 2050 [1]. A number of serious problems and challenging issues arise on the way

[1] Website of the Russian Government Concept for the Development of Hydrogen Energy in Russia URL: http://static.government.ru/media/files/ 5JFns1CDAKqYKzZ0mnRADAw2NqcVsexl.pdf

to the development of hydrogen energy in Russia. These problems include: a lack of experience in the production of hydrogen, more specifically, green hydrogen, which will have the greatest demand in the future; issues related to green hydrogen storage in the simplest possible way, such as bounding it, as well as the lack of experience in transporting pure hydrogen and, as a result of the above, the lack of understanding of the feasibility of producing, transporting, storing, and using green hydrogen.

At present, there are several categories of hydrogen [2, 3]:

– grey, which results in the emission of CO_2 into the atmosphere, the main production method of which in this case is the conversion of methane;

– brown hydrogen, separated from grey hydrogen, produced from coal;

– black hydrogen, obtained from petroleum products;

– yellow hydrogen, produced using atomic energy;

– blue hydrogen, produced from natural gas, in this case, carbon dioxide is stored in special facilities;

– green hydrogen, produced by water electrolysis, using renewable energy sources.

The most promising areas for the use of hydrogen technologies are [4]:

– the development and organization of serial production of autonomous power and heat supply sources, emergency (backup) power supply systems, and power plant energy utilization systems during slack hours based on renewable energy sources with hydrogen storage;

– the development and organization of serial production of a new generation of equipment for gasification (processing) of biomass, organic household and industrial waste to obtain synthesis gas (hydrogen), thermal and electric energy;

– the organization of production of new environmentally friendly universal fuel based on hydrogen-methane blends (for transport and fixed power plants, including the systems for distributed energy generation);

– the establishment of a testing and demonstration facility and a certification centre for hydrogen technology and equipment;

– the development and organization of production of power plants based on solid polymer and solid oxide fuel cells for special purposes, etc.

Intended Use of Hydrogen in Russia

According to the adopted "Concept for the Development of Hydrogen Energy", transporting of green hydrogen to the countries of the European Union (EU) is a relevant, promising, and economically feasible issue.

Among the major potential consumers of green hydrogen are the EU countries [5], which have adopted the zero CO_2 emissions target, as well as China, which is the main consumer of hydrogen in the world both currently and in the predictable future. This is related to the growth of production capacities requiring huge amounts of energy from various sources, including green hydrogen [6]. Given the problems associated with the transportation of green hydrogen, the most reasonable place for the production of hydrogen to be exported to the EU countries is the European Russia, whereas for export to China and the Asian region, it is Eastern Siberia.

Profitability Assessment of Green Hydrogen Produced in European Russia

Due to the unique property of hydrogen – its high permeability, associated with the smallest molecular sizes, and complexity of transportation methods, the key factors affecting its cost are [7]:

1. Its production cost. At present, companies that own green hydrogen production projects estimate that its production cost is around 3 USD/kg.

2. The proposed way to reduce losses during hydrogen storage is a constant and uninterrupted transportation of hydrogen to the consumer.

3. The purchase costs of special vehicles or transport containers.

4. The transportation costs of hydrogen, such as losses in hydrogen volumes, fuel costs for transporting hydrogen.

At the moment, Russia does not have the infrastructure for transporting hydrogen neither within the country nor to other countries [8], therefore for the sake of example, it is proposed to consider the development of transporting infrastructure and routes for green hydrogen as an export raw material produced at the Nizhnekamsk HPS (city of Naberezhnye Chelny, the Republic of Tatarstan, Russia), to EU countries, namely to Germany. The transport infrastructure considered are water, land and pipeline hydrogen transporting routes:

1. Transportation of hydrogen by river from the city of Naberezhnye Chelny to the ports of

Germany or by sea from St. Petersburg to the port cities of Germany.

2. Transportation of hydrogen by rail and road from Naberezhnye Chelny to Germany (the city of Dresden).

3. Transportation by hydrogen pipeline from the city of Naberezhnye Chelny to Germany or St. Petersburg.

However, it should be noted that the sea route from St. Petersburg is only possible in combination with other methods of hydrogen transportation described above (river, road, and rail transport).

The payback calculation for these transportation routes assumes a production cost of 3 USD/kg of hydrogen and a variable market price of 5 to 10 USD/kg. This range of hydrogen prices was chosen with a reference to a study conducted by the International Council on Clean Transportation under a direct connection scenario: the electrolyzer receives electricity directly from renewable energy sources (RES). In this case, the estimated price of hydrogen by 2050 will be 6 USD/kg for the USA and 10 USD/kg for the EU countries [9].

The payback period for the above types of transportation is calculated using the equation

$$T = \frac{P_{eq} \cdot n}{Q \cdot L \cdot (P_m^{H_2} - P_p^{H_2} - C_t)}, \qquad (1)$$

where P_{eq} is transportation equipment costs, USD; n – number of the equipment for continuous supply, pcs.; Q – annual hydrogen production, kg; L – hydrogen transportation losses, %; $P_m^{H_2}$ – market price for 1 kg of hydrogen, USD; $P_p^{H_2}$ – production costs for 1 kg of hydrogen, USD; C_t – transportation costs, USD.

Among the main costs of transporting hydrogen are the taxes, maintenance and fuel consumption for the different routes that will create a more complete economic picture of hydrogen transportation. For this purpose, equation (2) was defined for calculating the annual costs associated with fuel consumption for water and road routes, and equation (3) for estimating the cost of transporting 1 kg of hydrogen:

$$C_o = Q_f \cdot P_f, \qquad (2)$$

where C_o is the overall cost of fuel used for transportation, USD; Q_f – fuel consumption on a route, t; P_f – fuel market price, USD;

$$C_t = \frac{C_o}{M}, \qquad (3)$$

M is the hydrogen carrying capacity of transport, kg.

The equation for calculating the payback period includes an assumption of the continuity of hydrogen transportation. For this purpose, equation (4) was developed, which allows estimating the number of vehicles required for continuous transportation to the consumer:

$$n = \frac{Q_{H_2}}{(365/t) \cdot M},$$

where Q_{H_2} are annual volumes of hydrogen consumption, t; t is route time, days.

Hydrogen Transportation by Rail and Road

The Nizhnekamsk HPS produces only a small volume of hydrogen, therefore, it is advisable to transport hydrogen by rail or road. Both routes cover approximately the same length and travel time, about 2–3 days.

One of the negative factors are the losses during the transportation of liquefied hydrogen. For instance, the losses of hydrogen during transportation by rail in tanks are constant and associated with the continuous evaporation of hydrogen due to the necessary technological operations. During a chilldown of a tanker, which needs to be carried out at least twice a year, up to 30 % of hydrogen from the volume of the tank is lost. Losses from the flaws of the vacuum thermal insulation of the tank are 0.5 %/day of volume. At each refueling of tanks, there are losses associated with the evaporation of the first portion of hydrogen; according to experts, these losses amount to about 4 %. Losses to create a pressure drop between the liquefaction unit and the tank are approximately 1.5 % [10].

At present, truck tankers and rail tank cars for liquefied hydrogen, presented by Cryogenmash OJSC, are already available on the Russian market. Also ISO containers with built-in hydrogen storage tanks are offered for the transportation of hydrogen by rail. The volume of tank cars from Cryogenmash OJSC is 100 m^3 that allows transporting about 4 tons of hydrogen in each. The price of these tank cars is 200,000 USD, the duration of the route is 6 days. To calculate the costs, the tax charge for the delivery of goods by rail should be also taken into account. For instance, let us choose suitable similar tax charges for the delivery of liquefied gas for a 2,400 km long route, e.g. the Surgut-Saransk route (2,300 km). The tax charge for this route is 7,755 RUB/t (103.4 USD/t) [11]. Thus, the cost of transportation will be 0.103 USD/1 kg of hydrogen. The number of tank cars for continuous transportation can be calculated using the equation (4):

$$n = \frac{2,500}{(365/6) \cdot 4} = 10.27 \text{ units.}$$

Hence, 10 tank cars are required.

The payback period for this type of transportation at a hydrogen price of 10 USD/kg is calculated using the equation (1):

$$T = \frac{200,000 \cdot 10}{2,500 \cdot 0.9 \cdot (10 - 3 - 0.103)} = 0.128 \text{ years} = 47 \text{ days.}$$

Thus, the payback period will be 47 days (see **Table 1**).

Table 1

Payback period of the railway and road transport route

Value, day	Hydrogen market price, USD/kg					
	5	6	7	8	9	10
Payback period of the railroad route	171	112	83	66	55	47
Payback period of the road transport route	516	284	213	170	142	122

The PPC-45 (ППЦ-45) tank trucks presented by Cryogenmash OJSC have a volume of 45 m^3 and are able to carry 2.7 tons of hydrogen [12]. Their market price, together with a prime-mover truck, will be approximately 350,000 USD. Let's assume the duration of the road equal to 6 days. Transportation costs in this case, excluding various tax charges, will comprise the fuel consumption. Thus, a Mercedes brand prime-mover truck consumes about 22 liters of diesel fuel per 100 km, hence, the entire route will require approximately 1,050 liters of diesel fuel. Using the equations (2) and (3) and assuming the diesel fuel price 0.9 USD/liter, the cost of delivering 1 kg of hydrogen will be 0.35 USD:

$$C_o = 1,050 \cdot 0.9 = 945 \text{ USD;}$$

$$C_t = \frac{945}{2,700} = 0.35 \text{ USD/kg } H_2;$$

The number of tank trucks is calculated using the equation (4):

$$n = \frac{2,500}{(365/6) \cdot 2.7} = 15.22 \text{ units.}$$

Therefore, the number of tank trucks is 15.

The payback period for this type of transportation at a hydrogen price of 10 USD/kg is calculated using the equation (1):

$$T = \frac{350,000 \cdot 15}{2,500 \cdot 0.9 \cdot (10 - 3 - 0.35)} = 0.333 \text{ years} = 122 \text{ days.}$$

Thus, the payback period will be 122 days (see Table 1).

The calculation of the breakdown of prices for 1 kg of hydrogen from 5 to 10 USD clearly shows that the rail and road transportation methods turned out to be the cheapest. However, it should be noted that with an increase in the time of delivery to the destination, the losses will increase, and, consequently, the payback period of these methods will also increase. It should also be noted that 30 % losses from the volume of the tank truck per year due to its chilldown were not taken into account.

Transportation of Hydrogen by Pipeline

The gas velocity in low-pressure pipelines (0.1 MPa and below) is 10 m/s, and in main pipelines (68 MPa) this value is twice as high. With the same pipe diameters and pressure drop, the hydrogen flow rate is almost 3 times higher than that of methane. The unit cost of transporting hydrogen decreases with distance, although the increase in flow resistance is partly offset by the difference in viscosity. To transfer an equal amount of gas through a pipeline, hydrogen requires approximately 4.6 times more energy than natural gas, and during transportation over a distance of 2.54 thousand km, only 80.70 % of the initial hydrogen will be transferred (**Fig. 1**) [13].

The establishment of a new hydrocarbon pipeline duplicating the gas main from Naberezhnye Chelny to St. Petersburg, which is about 1,250 km long, will have a loss of approx. 10 %. A rough estimate of the establishment of this pipeline can be made using the Nord Stream gas pipeline system, where the cost of 1 km of the gas pipeline was 3.9 million USD. Therefore, the estimated cost of the hydrogen pipeline will be almost 5 billion USD. A similar estimate of the cost of a 2,500 km long hydrogen pipeline to Germany with an expected loss during transportation of about 20 % is 10 billion USD.

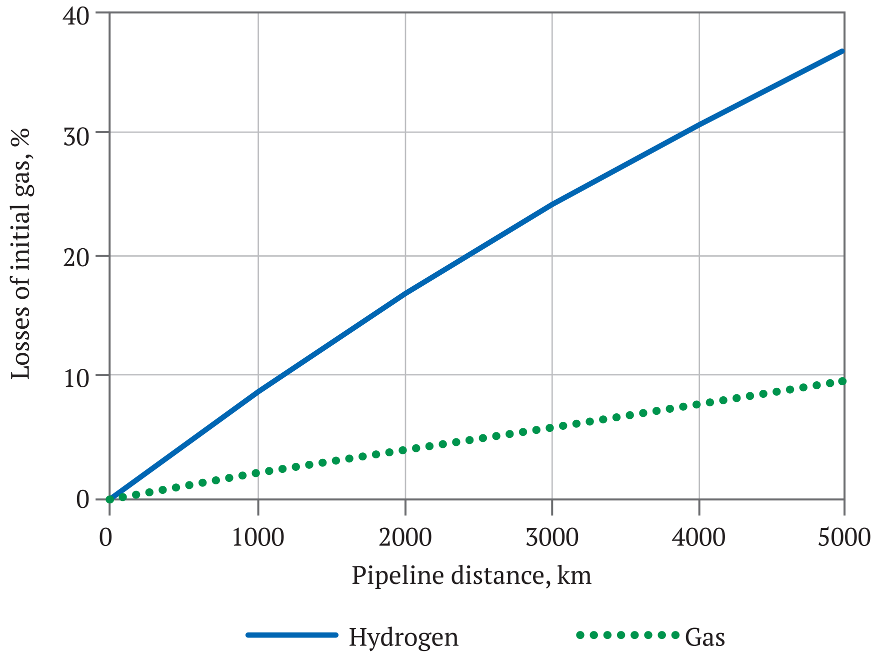

Fig. 1. Dependence of initial gas losses during pumping on the distance of the pipeline

These calculations show that the payback period for these hydrogen pipelines at a hydrogen price 10 USD/kg is much longer compared to other hydrogen transportation routes (see **Table 2**).

Table 2

Payback period for pipelines

Value, year	Hydrogen market price, USD/kg					
	5	6	7	8	9	10
Payback period for pipeline from Naberezhnye Chelny to Germany	2535	1682	1258	1005	837	717
Payback period for pipeline from Naberezhnye Chelny to Saint Petersburg	1118	744	557	445	371	318

The formation of a unified hydrogen energy system of HPSs located in the European Russia (Zagorsk, Nizhny Novgorod, Cheboksary, Kamsk, Zhigulevskaya, Saratov, Volzhskaya, Chirkeyskaya, Votkinsk, and Nizhnekamsk HPSs) (**Fig. 2**), creating green hydrogen production facilities at each HPS would increase the annual production to 25 thousand tons, which in turn will increase the payback period (**Table 3**).

Table 3

Payback period of a hydrogen pipeline connecting HPSs in the European part of Russia

Value, year	Hydrogen market price, USD/kg						
	5	6	7	8	9	10	20
Payback period of a hydrogen pipeline connecting HPSs in European Russia	436	289	216	173	144	123	51

The total length of the Russian part of the pipeline will be about 2,800 km. The project cost is approx. 15 billion USD.

The creation of a state program to subsidize the production and transportation of hydrogen would significantly reduce the payback period of the project [14].

Transportation of Hydrogen by Water Route

At present, there is already a marine vessel in the world that is designed to transport liquefied hydrogen. It is a Japanese vessel Suiso Frontier by Kawasaki Heavy Industries, which was launched in 2020 [15]. The particulars of this vessel are as follows: displacement – 9,000 tons, maximum capacity of liquefied hydrogen – 75 tons. The cost

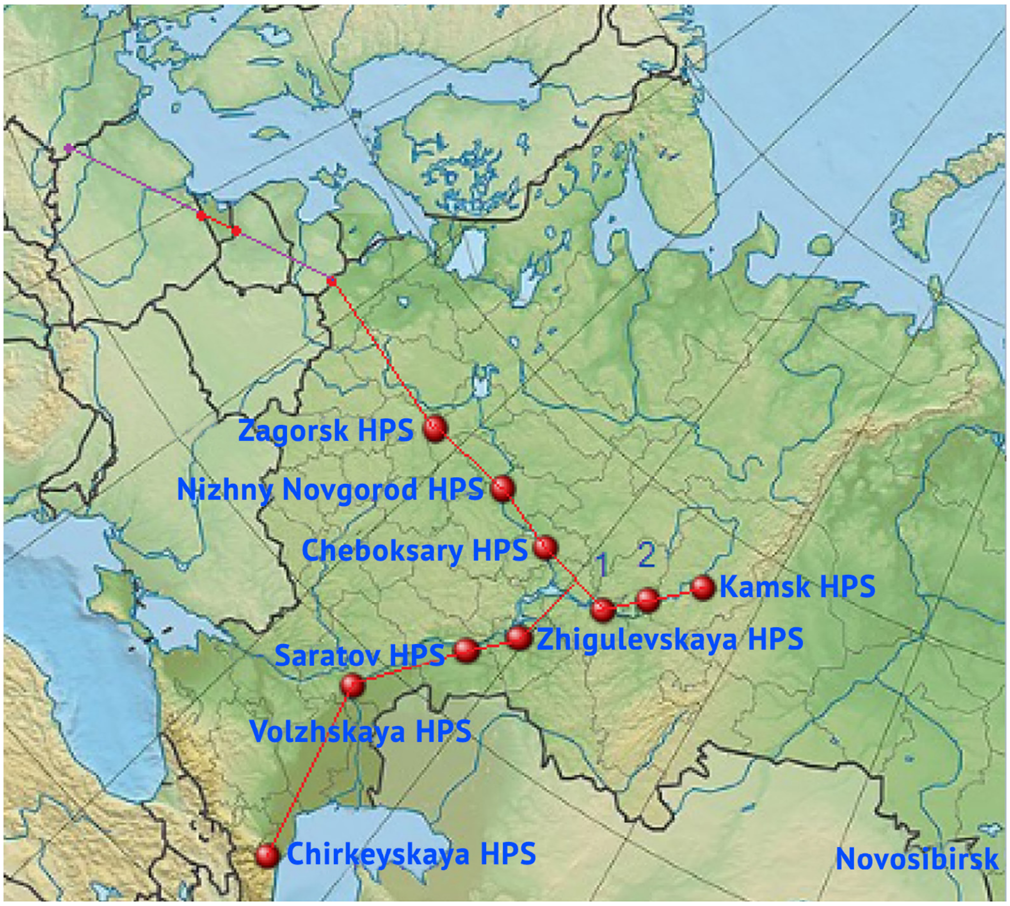

Fig. 2. Proposed shared hydrogen energy system European part of Russia

of this project was 350 million USD. According to the Kawasaki Group, losses during the transportation of hydrogen by this vessel are reduced down to zero [16].

A vessel of this type, intended for river navigation for hydrogen transportation, should have no more than 5000 tons of displacement. An estimate shipbuilding cost of such vessel is 200 million USD, and its transport capacity is 30 tons of liquid hydrogen.

At the moment, the average duration of maritime navigation from the port of St. Petersburg to the port cities of Germany is 7 days, hence, the time of one route is 14 days. During this time, the ship will need 400 tons of marine fuel – admiralty fuel oil. River navigation from Naberezhnye Chelny to St. Petersburg is 10 days, together with sea navigation, the duration would be 17 days, therefore, the time of one route is approximately 34 days. During such time, similar vessels consume about 600 tons of admiralty fuel oil [17]. One ton of F-5 (Ф-5) admiralty fuel oil currently costs about 20 thousand rubles, which, at a dollar rate of 104 rubles (USD exchange rate as of March 23, 2022) is 192 USD/t.

Thus, the cost of delivery of 1 kg of hydrogen will be (equations (2) and (3)) 1.41 USD for the sea route from St. Petersburg to Germany and 5.32 USD for the combined route (river and sea from Naberezhnye Chelny to Germany):

$$C_o = 400 \cdot 266 = 106,400 \text{ USD};$$

$$C_o = 600 \cdot 266 = 159,600 \text{ USD};$$

$$C_t = \frac{106,400}{75,000} = 1.41 \text{ USD/kg } H_2;$$

$$C_t = \frac{159,600}{30,000} = 5.32 \text{ USD/kg } H_2.$$

Let’s calculate the required number of vessels for a continuous cycle of transportation from St. Petersburg to Germany by sea and river, respectively:

$$n = \frac{2,500}{(365/14)\cdot 75} = 1.27 \text{ units};$$

$$n = \frac{2,500}{(365/34)\cdot 30} = 7.76 \text{ units}.$$

Thus, 1 vessel of the Suiso Frontier class will be required, as well as 8 river vessels similar to the Suiso Frontier, for the route from Naberezhnye Chelny to Germany.

Using the obtained data, the payback of these types of transportation can be calculated. In the case of transportation by sea and river, excluding the transportation to St. Petersburg, based on equation (1), the payback period at a market price of hydrogen 10 USD/1 kg would be respectively:

$$T = \frac{350\cdot 10^6 \cdot 1}{2,500\cdot 1\cdot (10-3-1.41)} = 25.044 \text{ years};$$

$$T = \frac{200\cdot 10^6 \cdot 8}{2,500\cdot 1\cdot (10-3-5.32)} = 380.9 \text{ years}.$$

Based on the calculations, at a market price of 10 USD per kilogram of hydrogen, the sea route, with some exceptions, will pay off in about 25 years, and the river route only after 381 years. However, after calculating the breakdown of prices for 1 kg of hydrogen from 5 to 10 USD, it can be demonstrated that the river transportation type has negative payback values at the market price of hydrogen per kilogram from 5 to 8 USD, which actually makes this type of hydrogen transportation unprofitable and unfeasible (see **Table 4**).

Table 4

Payback period of water routes

Value, year	Hydrogen market price, USD/kg					
	5	6	7	8	9	10
Payback period of the river route	−193	−276	−485	−2000	941	381
Payback period of the sea route	237	88	54	39	31	25

Given the lack of investment attractiveness of the river route using the Suiso Frontier river analogues, it is proposed to investigate and consider the transportation of green hydrogen by river container transportation, loading it into ISO containers. This method allows accumulating green hydrogen from the facilities of the Volga-Kama cascade and updating the general hydrogen energy system of HPPs (see Fig. 2) by changing transportation from pipeline to river. As a result, it will reduce the losses associated with transporting hydrogen over long distances and make it possible to use vessels with a more straightforward design.

Conclusion

At present, the production of green hydrogen is at the initial stage of development. Technological progress in this field would allow reducing the cost of hydrogen production by reducing the cost of its transportation and storage.

Based on the assessments of the proposed transportation routes, the cheapest and most accessible, in terms of technology, are railway routes. However, this transportation method is only partially available for transporting hydrogen, since the required rail infrastructure does not always exist.

Road transport is also a cheap and accessible option for hydrogen transportation and is just slightly inferior in terms of economic efficiency to rail transport.

Based on the estimates made, hydrogen transportation by hydrogen pipelines is of little use for small hydrogen production volumes. However, the economic efficiency of the hydrogen pipeline increases if it is used on a larger scale. The creation of a unified hydrogen energy system for the European Russia will increase the production of green hydrogen in the country, allowing considering this type of transportation as the main option in the future.

Water transportation routes are considerably inferior to other methods of transportation: the river routes seem not at all feasible, whereas the sea route appears excessively expensive. However, these methods of transportation also have certain prospects. For instance, the creation of river container transportation of green hydrogen loaded into more advanced ISO containers at the facilities of the Volga-Kama cascade would allow switching the unified hydrogen energy system of HPSs from the use of pipelines to river transportation. Such an approach reduces losses from the length of the pipeline and also allows using vessels with a more straightforward design, i.e. container ships, thereby reducing the cost of the vessel, and its respective payback.

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