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Economic Analysis of Recently Announced Green Hydrogen Projects in Russia: A Multiple Case Study

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Abstract: Nowadays, transitioning to hydrogen energy is considered one of the most promising ways for decoupling economic growth and increasing carbon emissions. Hydrogen demand worldwide is expected to increase in the upcoming decades. However, large-scale development of hydrogen energy still lacks economic efficiency. The economic efficiency of hydrogen production can be increased due to country-specific factors, such as energy and raw materials costs or developed infrastructure for storage and transportation. This study aims to forecast the economic parameters and competitiveness of Russian green hydrogen projects and their future impact on the global hydrogen market. This study forecasts the levelized cost of hydrogen for Russian projects from 1.2 to 11.7 USD/kg with a median value of 4.94 USD/kg. The total capacity of Russian hydrogen production projects may contribute to a slight reduction in the price of hydrogen on the global market. However, Russian hydrogen projects are still in their early stages of development with limited geographical coverage. Russian hydrogen export capacity is nearly halved as a result of sanctions. The anticipated comparative advantages and favorable global impact may be eliminated by these factors.

Keywords: economic efficiency; economic competitiveness; hydrogen projects; levelized cost of hydrogen

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1. Introduction

In the modern world, the energy sector based on fossil fuels is the predominant source of greenhouse gas emissions and environmental pollution [1]. Hydrogen is being explored as a potential substitute for fossil fuels, as suggested by authorities and scientists [2]. Its utilization is expected to address several environmental and social issues, such as air pollution, global warming, and climate change, as hydrogen fuel does not generate harmful emissions due to its carbon-free nature [3–5]. Ongoing research and advancements highlight the potential of hydrogen as an energy carrier.

Globally, 522 hydrogen projects have been announced for 2021–2030, of which 43 are giga-scale clean hydrogen projects (Figure 1). Most of the hydrogen activity will be carried out in Europe through 261 hydrogen projects. Many European countries are investing in finding non-carbon-intensive alternatives for industrial and transport use in line with the European Green Deal and efforts to strengthen the local value chain.

According to recent research by the Hydrogen Council [6] (p. 18), hydrogen demand worldwide is expected to increase in the upcoming decades. It is projected to reach 145 million metric tons in 2030 and 660 million in 2050. In Europe, it is projected to account for approximately 14 percent of global demand in 2030 and reach up to 95 million tons annually in 2050 (Figure 2).

Despite the positive prospects for hydrogen, there are still multiple barriers of a social, economic, and technological nature, which impede the large-scale development of hydrogen energy [7–11]. The main barrier is the high cost of hydrogen, which makes it less competitive than fossil fuels [12]. Therefore, a considerable amount of literature has been published recently on measurements of the economic efficiency of hydrogen. Most studies highlight that the economic efficiency of hydrogen production depends on country-specific factors and is complexly influenced by CAPEX, capacity factors, and energy cost [13–15]. Due to regional differences, hydrogen may be more competitive in one country than another.

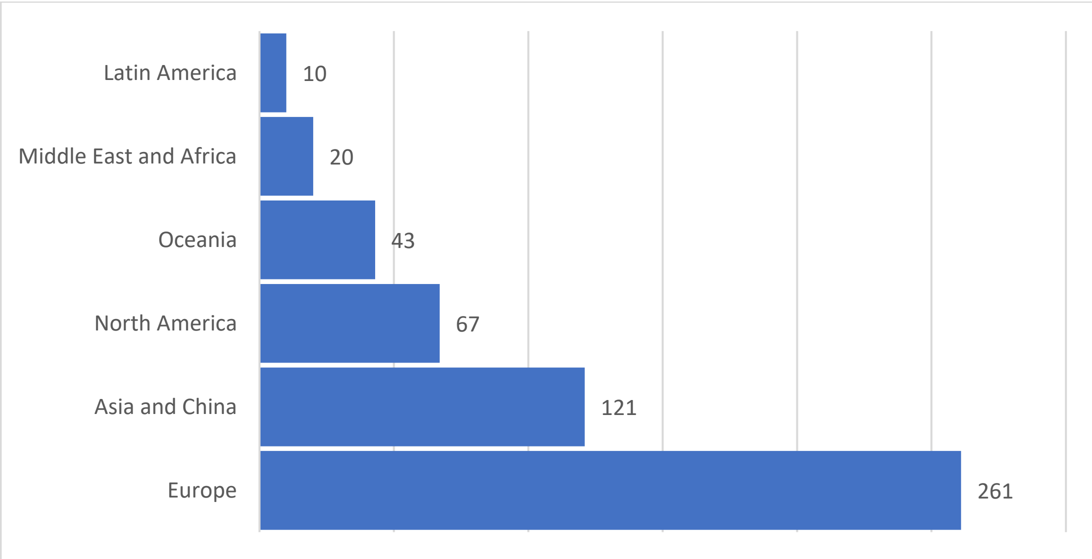

Figure 1. Quantity of global hydrogen projects announced (by region, 2021). Source: based on [6] (p. 36).

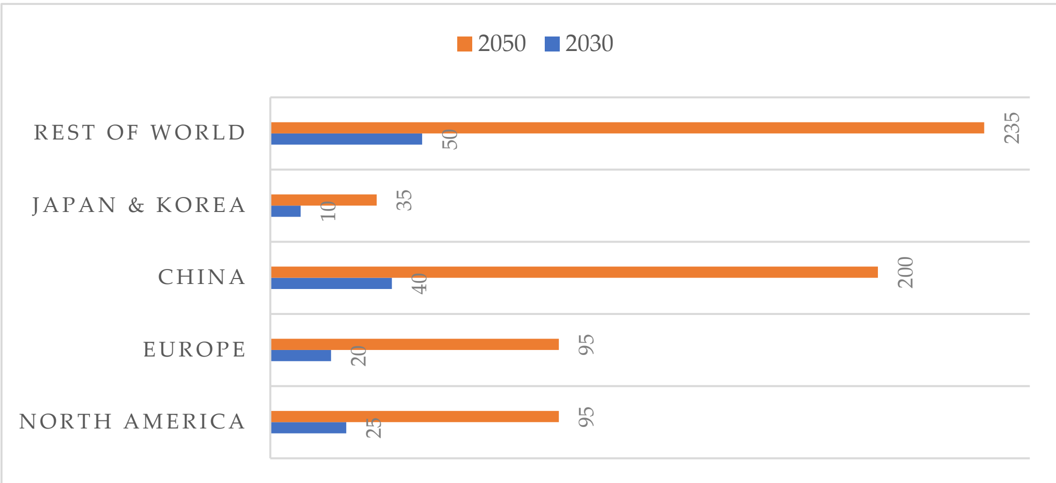

Figure 2. Forecast hydrogen demand worldwide in 2030 and 2050 by region (in a million metric tons) [6] (p. 18).

Recently, 54 hydrogen projects were announced in Russia. Currently, these projects are at various stages of development, ranging from early planning phases to those that are already operational. All projects are divided into five geographical clusters: Sakhalin (Rosatom's project to deliver "blue" hydrogen by sea to China), Yakutia (the project of the North-Eastern Alliance to deliver "blue" hydrogen to China by rail), Yamal (NOVATEK's project to export "blue" hydrogen by sea to Germany), Eastern Siberia (supplies of En+ "green" hydrogen to China by rail) and the North-West (projects of "green" hydrogen "Rosatom", "Rosnano", "H2 Pure energy").

Some experts argue that Russian projects have clear competitive advantages in the global hydrogen market, such as significant production capacity reserves [16], low production costs [17], good accessibility to potential consumers (EU, China, and Japan) [18], and well-developed infrastructure for the transportation of natural gas and liquefied natural gas [19]. However, there is no information about the expected economic efficiency of these projects in official documents or academic literature.

This study aims to forecast the economic efficiency and competitiveness of Russian hydrogen projects and their future impact on the global hydrogen market. The research seeks to address the following questions: (i) what is the projected economic efficiency in main Russian hydrogen clusters; (ii) what are potential factors for decreasing the projected cost of hydrogen; (iii) what are the main risks for the implementation of Russian hydrogen projects in the current geopolitical conditions and how they can be eliminated. The levelized cost of hydrogen (LCOH) is used in this study as the key economic metric.

The rest of this paper is organized as follows: Section 2 reviews existing literature on barriers and the future perspective of the development of hydrogen energy. Section 3 describes the methodology and data for analysis and evaluation of the economic efficiency of Russian hydrogen clusters. Section 4 reports the results of the calculations and compares them with results from other countries. Section 5 discusses the risks and prospects of the global hydrogen market. Section 6 concludes the research.

2. Literature Review

Several studies investigating barriers to the development of hydrogen energy propose to classify them according to three groups: production barriers, storage barriers, and barriers to hydrogen delivery [10,20,21]. Economic, environmental and technological barriers are closely intertwined at each stage of the hydrogen supply chain. Today, the most significant fraction of hydrogen in the world is produced by its release from fossil energy sources (technology of steam reforming of natural gas and coal gasification). Economically, these methods are more profitable, although they are more expensive than using fossil sources "directly" [12]. However, environmentally, they are considered unpromising due to (1) their contribution to the planetary "link" to non-renewable energy and (2) "dirty" production technologies—a high degree of negative impact on the environment [22,23]. It should be noted that international organizations, authors of the latest supranational hydrogen strategies and researchers are increasingly abandoning color recognition in analyzing energy, environmental, social and economic benefits of introducing a particular hydrogen production technology [24,25]. The reason for revising existing classifications was that the color typology does not allow us to obtain a holistic idea of the nature and prospect of production technology. Several green technologies, traditionally related to recommended, have shallow indicators regarding social and economic advantages, and grey hydrogen, despite seeming non-ecologically, in actual practice, is more effective in several criteria [26]. The most promising method of hydrogen production is electrolysis from renewable energy sources [27]. This method is much more environmentally friendly in comparison with other methods. Unfortunately, from an economic point of view, this method is the most commercially inappropriate. In this regard, this method has not yet received widespread distribution [28].

Analysis of their advantages and disadvantages reveals a similar paradox: with high environmental friendliness parameters, the cost of hydrogen production increases, and when following the methods that are most economically feasible, the environmental friendliness parameter decreases [29]. In this regard, researchers are attempting to develop a holistic methodology for quantitative and qualitative assessment of production technologies feasibility, which would reduce all indicators to a single matrix or rating system [30]. Experts say that in evaluating the effectiveness of a particular technology, many additional factors must be considered—not only indicators of the cumulative environmental impact and total consumption of primary energy resources [31]. Valente [32], for example, points to the feasibility of using the "life cycle" category in hydrogen production, which makes it possible to assess the rationality of technologies and the production routes resulting from their implementation.

The problems of its storage make the switch to hydrogen energy difficult [33]; it is not yet possible to achieve adequate indicators in terms of compactness and economic feasibility [34].

To date, there are two groups of solutions for the intermediate storage of hydrogen—physical methods and chemical methods. These methods are implemented in the following varieties: adsorption method of hydrogen storage, storage in liquid organic hydrides, storage in ammonia, sponge iron, or silicon alloys [8,10,35].

Storage thus remains a problematic aspect of hydrogen energy. The efficiency of hydrogen energy carrier systems does not exceed 60%, which is significantly lower than storage systems for other energy carriers. On the other hand, Tarhan, C. and Çil, M.A. [36] suggest that in storage, hydrogen loses only to exhaustible energy carriers, and if the efficiency of hydrogen storage systems is compared with other energy storage systems coming from renewable sources, then it turns out to be more efficient. According to existing calculations and estimates, hydrogen storage systems are characterized by high-energy storage density and low capital costs when compared with pumped storage power plants or, for example, with floating nuclear power plants.

The quick depreciation of such systems is a significant cost-effectiveness concern in the adoption of hydrogen storage systems as pointed out by Elberry et al. [37].

Aziz, M., Wijayanta, A.T., and Nandiyanto, A.B.D. argue that the technology of hydrogen storage in the form of ammonia is up-and-coming [38]. In 2020, Japan, in the context of the resource strategy of the Ministry of Economy, Trade and Industry, established the Ammonia Energy Council, which operates based on public–private partnership mechanisms [39].

Hydrogen is delivered to the places of its final consumption in gaseous or liquid states or in the form of solid or liquid carriers that bind hydrogen. Delivering hydrogen to the final consumption location is necessary to utilize it as an energy carrier. In this regard, transport systems for hydrogen are an actual vector of research and development.

The most significant amount of hydrogen globally is transported by pipelines or trailers with pressurized container pipes in a gaseous form. In liquefied form, hydrogen is transported in cryogenic tanks by road or rail. Each of the above methods has its range of rational applications. Leading companies in hydrogen production—Air Products, Praxair, Air Liquide, BOC Group (USA), supply hydrogen in pipelines and to places without access to pipeline systems—by road. However, the metal's " hydrogenation " problem still cannot be dismissed—monitoring the pipeline's condition is, according to Ohaeri et al., a necessary measure which also affects the rise in the cost of transportation. In general, it can be said that today all methods of hydrogen delivery are used to varying degrees. Hydrogen delivery in cryogenic tank trucks is the most economical for medium-sized consumers [40].

Pipeline systems are of great social importance and are economically viable for delivering hydrogen to regions with high-energy needs [41]. In this regard, let us dwell in more detail on the social aspect of hydrogen transportation.

Moradi, R. and Groth, K.M. [10] rightly highlight the need for pipeline patrols, new earthwork regulations, and underground pipe laying. The social aspect thus becomes prevalent when evaluating a particular hydrogen delivery technology.

Thus, the pace of development of hydrogen energy is directly related to solving problems in three dimensions—production, storage and delivery. To date, researchers are trying to improve each of the three links in this chain, but the most challenging thing is to achieve a delicate balance between social good, economic efficiency and concern for the environment.

Regarding indicators to measure the economic efficiency of the hydrogen supply chain, the levelized cost of hydrogen is commonly used in the literature. Thus, Correa et al. [42] examine the technical and economic viability of producing green hydrogen in Argentine Patagonia and transporting it to Italy via ships. Through the utilization of liquid organic hydrogen carriers for hydrogen storage and transport, the minimum levelized cost of hydrogen (LCOH) was determined. The results showed a final cost of 8.60 €/kgH2 and 11.17 €/kgH2 for the Argentine and Italian production scenarios, respectively.

Fan et al. [43] examined the production cost, cost structure, and regional variations of the traditional coal-to-hydrogen (C2H) process, compared to coal-to-hydrogen coupled with CCS (C2HCCS), alkaline electrolysis (ALK), and proton exchange membrane electrolysis (PEM) in China. The preliminary results revealed that (1) the LCOH of C2HCCS was 13.1–19.4 RMB/kg, which was 57.6–128.3% higher than C2H (7.2–10.1 RMB/kg) and 20.5–61.0% lower than hydrogen production via water electrolysis powered by renewable energy (16.4–51.8 RMB/kg); and (2) C2HCCS could be a cost-effective option for the blue hydrogen energy industry in northwestern regions of China, particularly in the provinces of Inner Mongolia, Xinjiang, and Gansu.

Yang et al. [44] compare the main types of hydrogen production cells, namely alkaline (ALK), anion exchange membrane (AEM), and proton exchange membrane (PEM) The ALK technology is predicted to have 23.85% and 51.59% lower hydrogen production costs in the short term than AEM and PEM, respectively. However, with technological advancements or breakthroughs, AEM and PEM costs are expected to decrease by 24% and 56.5% in the medium and long term.

Steam-methane reforming (SMR) is widely employed for large-scale hydrogen production due to its favorable economics [45]. The LCOH of grey hydrogen produced through SMR ranges from USD 0.7 to USD 2.1/kg [46]. At the same time, the addition of CCS technology to grey hydrogen production facilities increases the LCOH of blue hydrogen, typically costing approximately USD 0.5 to USD 1/kg, ultimately resulting in an overall levelized cost of blue hydrogen ranging between USD 1.2 and USD 2.3/kg [47,48]. The cost of coal-based hydrogen production without CCUS is USD 1.3 to USD 2.5/kg, whereas with CCUS (blue hydrogen), the cost ranges between USD 1.6 and USD 2.6/kg [46].

Country-specific factors in the economic efficiency of hydrogen production also play a significant role. China's economy benefits from its vast coal mining infrastructure, as it produces low-cost coal-based hydrogen, costing USD 1/kg [49,50]. Methane pyrolysis hydrogen is estimated to cost between USD 1.6 and USD 3.4/kg in the market [46].

Nuclear-based hydrogen, or purple hydrogen, is another sustainable source of producing low-carbon hydrogen through electrolysis and thermochemical cycles. The market price of nuclear LCOH produced through electrolysis is approximately USD 4.2 to USD 7.0/kg, whereas through thermochemical cycles, the cost ranges between USD 2.2 and USD 2.6/kg, respectively [46,50].

Vom Scheidt et al. examined locational energy prices in producing hydrogen in Germany. Their study shows that considering current uniform single prices, congestion costs in the power grid increased by 17%. The study also found that locational prices play a crucial role in determining the optimal placement of hydrogen plants, enhancing the economics of the German power system [51].

Mansilla et al. and Li Y et al. evaluated the cost competitiveness of hydrogen produced using off-peak energy prices in Europe and China, respectively. According to Mansilla et al., the reduction in the "levelized cost of hydrogen" (LCOH) was modest at only 3% [52]. On the other hand, Li Y et al. determined that hydrogen's most economically viable application of off-peak prices is as a chemical material [53].

Tang O. and colleagues highlighted the significance of grid energy in hydrogen production, and the authors concluded that wind speed plays a crucial role in reducing costs, whereas solar radiation has a relatively minor impact [54].

Minutillo et al. estimated the LCOH in Italy using three fixed energy prices applied to different energy consumption levels. The study revealed that hydrogen costs rise as grid energy usage for electrolysis decreases from 100% to 25% [55].

The competitiveness of hydrogen production has been examined in other regions worldwide. In Texas and Germany, small- and medium-sized users can already obtain cost-competitive green hydrogen produced from wind energy. According to Glenk G. et al. [13], this is due to the decreasing cost of wind energy and electrolysis technology. In Chile, the LCOH has been investigated by Gallardo et al. [56] and Armijo et al. [14] Gallardo et al. evaluated the LCOH from solar generation in the Atacama Desert, utilizing energy data from real-life solar PV plants and simulated solar concentrator facilities with thermal storage, as well as fixed power purchase contract pricing. They discovered that the hybridization of solar and wind energy could reduce hydrogen production costs depending on the electrolyzer capacity factor increase. Armijo et al. estimated that the cost of green hydrogen shortly would be rough USD 2/kg.

Additionally, Macedo and colleagues researched the feasibility of using hybrid solar–wind systems for hydrogen production and storage in Brazil [15]. Their investigation revealed that these systems are currently not economically practical in the country. Conversely, Qolipour and his team analyzed the economics of generating electricity and hydrogen in Iran and determined that a hybrid solar–wind system is financially viable [57]. Jahangiri and colleagues combined a hybrid solar–wind system with Qatar's power grid to meet the electricity and hydrogen demands, ultimately achieving a hydrogen price as low as USD 2.1/kg [58].

Lei G. and colleagues found that the hybrid system is more practical than relying solely on grid energy [59]. Benalcazar and the team assessed the economic performance of electrolyzers powered by hybrid solar–wind energy in Poland, using a Monte Carlo-based approach to estimate the levelized cost of hydrogen (LCOH). They discovered that as the capacity of the electrolyzer increased over time, the LCOH became more competitive [60]. Touili et al. found that, for most locations in Morocco, the optimal technology is the 1-axis tracking PV system [61].

Together these studies provide important insights into the economic and technological problems of developing hydrogen energy. However, there has been little discussion about the cross-country competitiveness of hydrogen supply chains and the potential role of new projects entering the market.

3. Methodology and Data

This study uses the levelized cost of hydrogen (LCOH) as the key economic metric of hydrogen production. The levelized cost of a hydrogen production is the ratio of the total costs of a generic/illustrative plant to the total amount of hydrogen expected to be produced over the plant's lifetime. The calculation of LCOH (2) is similar to levelized cost of energy (LCOE) calculation (1), where the total amount of energy produced is substituted for the total amount of hydrogen produced during lifetime of the production plant:

$$LCOE = \sum_{t=0}^{T} \frac{C_{CAPEX} + C_{OPEX}}{(1+r)^t} \Big/ \sum_{t=1}^{T} \frac{E}{(1+r)^t} \quad (1)$$

$$LCOH = \sum_{t=0}^{T} \frac{C_{CAPEX} + C_{FOM} + C_{VOM}}{(1+r)^t} \Big/ \sum_{t=1}^{T} \frac{H}{(1+r)^t} \quad (2)$$

where

- C_{FOM}—fixed *OPEX*, including maintenance of production equipment costs;
- C_{VOM}—variable *OPEX*, including fuel/electricity and CCS/water costs;
- H—the total amount of hydrogen produced;
- r—the discount rate.

LCOH, which measures production costs, does not account for expenses related to delivering or storing hydrogen or adapting it for end use. These expenses could be significant, and future research should examine the potential costs that producers may incur when using a hydrogen distribution, transmission, and storage network. Additionally, there is limited information on the amount and timing of pre-development and decommissioning expenses. While our research covers the capital and operational costs of hydrogen compression, we have not factored these costs into our *LCOH*, as they vary depending on the type of network a plant is connected to (transmission or distribution) or if it necessitates storage [42,62].

The data for calculating *LCOH* of Russian projects were gathered from various open sources, including government reports, industry publications, and news articles. In total, it was collected information on 54 hydrogen projects in Russia. Since there is no accessible information about both Capital Expenditures (CAPEX) and Operating Expenditures (OPEX) in Russian projects, LCOH calculation was based on analogy approach. This study conducted a thorough analysis of international projects with similar methods and scales of production.

The exploratory data analysis (EDA) introduced in the Python Sweetviz tool [63] was used to understand the key features and patterns in the data. One of the critical advantages of Sweetviz is that it can generate reports automatically, allowing analysts to quickly gain insights into the data without spending significant amounts of time on manual analysis. The Sweetviz reports providing detailed information on various aspects of the data, including distributions, correlations, and missing values. The tool also allowed us to explore the relationships between different data variables, helping us identify potential patterns and trends.

Both Capital Expenditures (CAPEX) and Operating Expenditures (OPEX) over 25 years from 2025 to 2050 were examined for calculation of LCOH for 11 projects. As a result, 11 projects were chosen as analogues (Table 1).

The analysis of CAPEX and OPEX for two periods, namely 2025 and 2050, provides an insight into the future costs of the project. Using a report [62] as a starting point for these indicators allows for a consistent and accurate project analysis. Using average values of the indicators ensures that extreme values do not skew the calculations.

Table 1. Similar international hydrogen projects.

№	Project	Technology	Projected Production Volume of Hydrogen, kg of Hydrogen/Year	LCOH	Equivalent International Project	Technology	Projected Production Volume of Hydrogen, kg of Hydrogen/Year	LCOH
1	Production of “green” hydrogen by water electrolysis using the electric power of the Nizhnekamsk HPS	Electrolysis	2,500,000	4.94	Ari Products Arizona	Alkaline electrolysis	4,000,000	5.86
2	Production of “green” hydrogen/ammonia by water electrolysis using the electric power of the Ust-Ilimsk HPS	Electrolysis	5,400,000	4.94	Bad Lauchstädt energy park	Alkaline electrolysis	5,000,000	5.86
3	Production of “green” hydrogen by water electrolysis using the electric power of the Mamakan HPS	Electrolysis	6,000,000	4.94	Candem County (GA), green power plant	Proton exchange membrane electrolysis	5,000,000	5.86
4	Production of “green” hydrogen by water electrolysis using the electric power of the WPS	Electrolysis	3,500,000	5.86	Energía Los Cabos	Proton exchange membrane electrolysis	4,000,000	5.86
5	Production of “green” hydrogen by water electrolysis using the electric power of the Tugur tidal power plant	Electrolysis	350,000,000	4.94	Helios Green Fuels—Neom	Alkaline electrolysis	483,000,000	5.86
6	Production of “green” hydrogen by water electrolysis using the electric power of the WPS	Electrolysis	16,000,000	1.15	Huadian Baotou City Damaoqi Hydrogen Production Electrolysis Project	Alkaline electrolysis	17,000,000	5.86
7	Production of “green” hydrogen/ammonia by water electrolysis using the electric power of the Irkutsk HPS	Electrolysis	4,200,000	4.94	Linde Leuna Chemical Complex	Proton exchange membrane electrolysis	4,000,000	5.86

Table 1. *Cont.*

№	Project	Technology	Projected Production Volume of Hydrogen, kg of Hydrogen/Year	LCOH	Equivalent International Project	Technology	Projected Production Volume of Hydrogen, kg of Hydrogen/Year	LCOH
8	Production of "green" hydrogen by water electrolysis using the electric power of the Mezen tidal power plant with a capacity of up to 12 GW	Electrolysis	500,000,000	4.94	Murchison	Proton exchange membrane electrolysis	749,700,000	5.86
9	Production of "green" hydrogen/ammonia by water electrolysis using the electric power of the Onda HPS	Electrolysis	5,200,000	1.15	Ningxia Solar Hydrogen Project, Phase 1	Proton exchange membrane electrolysis	5,000,000	5.86
10	Production of "green" hydrogen by water electrolysis using the electric power of the Ust-Srednekansk HPS	Electrolysis	16,000,000	4.94	RWE-Thyssenkrupp Duisburg steel plant (HydrOxy Hub Walsum)	Alkaline electrolysis	17,000,000	5.86
11	"Production of "green" hydrogen by water electrolysis using the electric power of a 1 GW WPS	Electrolysis	50,000,000	5.86	Steag-Thyssenkrupp Duisburg steel plant (HydrOxy Hub Walsum)	Alkaline electrolysis	69,000,000	5.86

Source: compiled by the authors based on [64].

The selection of a 25-year project implementation period is based on an analysis of scientific literature and official sources. This period is optimal for large-scale projects requiring significant investment and long-term impact. The discount rate of 15% reflects the cost of capital and the risk associated with the project. This rate is commonly used in financial analyses and is based on prevailing market conditions [65,66].

Since all chosen projects use electrolysis as a production technology variable OPEX consists of energy and water costs, where water cost can be neglected. Annual hydrogen production H was taken from the projects' information, hence the degradation rate of electrolyzer was not included in the calculations.

Using US dollars as the currency for calculations is common in international business transactions and financial analyses. The conversion of rubles and pounds to dollars using the weighted average exchange rates for 2020 ensures the calculations are accurate and reflect the actual values.

4. Results

Our multiple case studies of open-access sources have revealed that most Russian-announced projects (53%) are focused on producing green hydrogen. Regarding the specific power sources used to generate the electricity needed for hydrogen production, our research found that hydroelectric power plants were the most common, accounting for 15% of projects. This is likely because Russia has a number of large rivers and hydropower facilities already in place.

Wind power was the second most common source, used in 13% of projects. This reflects the fact that wind energy is becoming increasingly cost-competitive with traditional fossil fuels. Solar power was also used in 13% of projects, suggesting that solar technology is also becoming more viable for large-scale energy production. Nuclear and tidal power plants are used in 26% of the projects (Table 2). Overall, using renewable energy sources such as hydroelectric and wind power plants in these projects is a positive step towards reducing the carbon footprint of the hydrogen production process. It also highlights the growing importance of renewable energy sources in meeting the world's energy needs in a sustainable and environmentally friendly way.

The region where hydrogen projects are located has been identified in 42 cases, with the main locations in Murmansk region, Sakhalin region, Yamalo-Nenets Autonomous Okrug (YANAO), and Irkutsk region. The Murmansk region in the far north is essential due to its strategic position as a gateway to the Arctic and its potential for producing green hydrogen using renewable energy sources such as wind and hydropower. The Sakhalin region in the Far East has also shown promise in developing hydrogen projects, particularly in hydrogen transportation. This is due to the region's abundant natural gas resources, which can be used to produce blue hydrogen through steam methane reforming (SMR) and other processes.

Table 2. Distribution of project types.

Number of Projects	Percentage of All Projects	Type of Project
8	14.81%	Production of "green" hydrogen by water electrolysis using the electric power of HPS
7	12.96%	Production of "green" hydrogen by water electrolysis using the electric power of WPS
7	12.96%	Production of "green" hydrogen/ammonia by water electrolysis using the electric power of HPS
3	5.56%	Production of "green" hydrogen by water electrolysis using the electric power of the tidal power plant
3	5.56%	Production of "green" hydrogen by water electrolysis using the electric power of a solar power plant
2	3.70%	Production of "blue" ammonia by steam methane reforming with carbon capture and long-term underground storage technology
2	3.70%	Production of "blue" hydrogen/ammonia by steam methane reforming with CO_2 capture
2	3.70%	Production of "green" hydrogen by water electrolysis using the electric power of hydropower plants
1	1.85%	Production and supply of hydrogen for the Nord Stream 2 project
1	1.85%	Supply of hydrogen from Russia to Japan
1	1.85%	Production and supply of hydrogen
1	1.85%	Conversion of turbines to operate on hydrogen-containing fuel gas mixtures
1	1.85%	Project for hydrogen generation at Yamal LNG plant
1	1.85%	Establishment of railway transportation using hydrogen fuel cell trains
1	1.85%	Reduction in greenhouse gas emissions through the use of hydrogen
1	1.85%	Production of methane-hydrogen mixtures and creation of transportation infrastructure
1	1.85%	Fund for participation in selection processes for new green energy generation programs in Russia
1	1.85%	Complex processing of natural gas with production of hydrogen, ammonia, and other low-carbon products using carbon capture and long-term underground storage technology
1	1.85%	Creating and using autonomous modules for hydrogen production and storage at individual nuclear power plants
1	1.85%	Industrial production of hydrogen using advanced energy technologies
1	1.85%	Production of "blue" ammonia by steam methane reforming with CO_2 capture
1	1.85%	Production of "blue" ammonia based on gas fields with CO_2 capture technology
1	1.85%	Hydrogen Energy Scientific and Technical Center
1	1.85%	Production of "blue" ammonia by gasification of brown coal with CO_2 capture and storage technology
1	1.85%	Production of low-carbon hydrogen by water electrolysis using the electric power of WPS
1	1.85%	Production of "turquoise" hydrogen by methane pyrolysis at the Sosnogorsk GPP
1	1.85%	Production of low-carbon hydrogen by water electrolysis using the electric power of NPS
1	1.85%	Investment in Russian developments in the field of hydrogen energy

Source: compiled by the authors.

The Yamalo-Nenets Autonomous Okrug (YANAO) in northern Siberia is another region that has emerged as a potential location for hydrogen projects. The region's vast reserves of natural gas and oil provide a significant advantage in producing blue hydrogen, which can be used for various applications including transportation, industrial processes, and power generation. Finally, the Irkutsk region in Siberia has also been identified as a potential location for hydrogen projects, thanks to its abundance of renewable energy sources such as hydropower and geothermal energy. The region has already seen some success in developing green hydrogen projects, including a pilot project to produce hydrogen from hydropower at the Irkutsk hydroelectric power plant.

In a broad context, regarding clusters, the primary location for hydrogen projects is the North-west cluster—44%, followed by Eastern Siberia—17%, Sakhalin—17%, Yamal—12%, and Yakutia—10% (Figure 3).

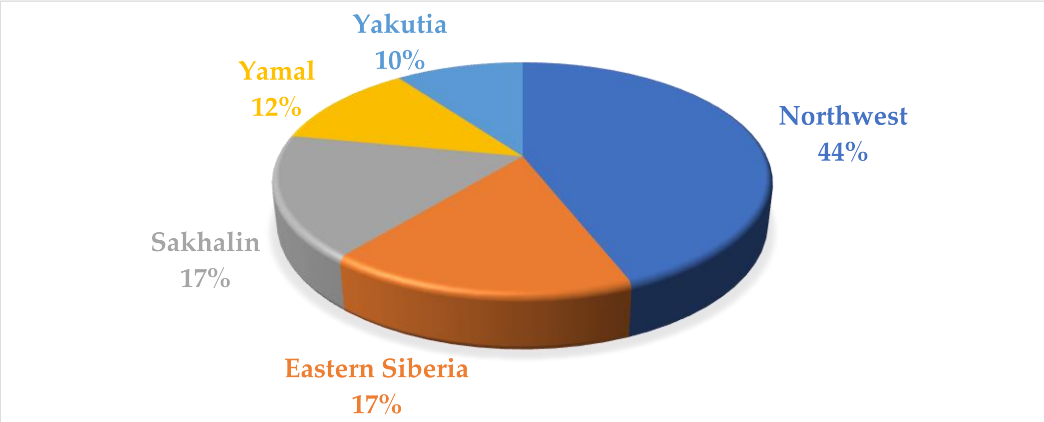

Figure 3. Location for hydrogen projects. Source: compiled by the authors.

The production type of hydrogen has been revealed in 43 projects. The distribution is as follows: green hydrogen is produced in 24 projects (56%); green hydrogen/ammonia is produced in 8 projects (19%); another 8 projects (19%) are focused on the production of blue hydrogen/ammonia; low-carbon hydrogen is produced in 2 projects (5%). Finally, Turquoise hydrogen was produced in 1 project (2%). A total of 72% of the hydrogen production in these projects is done through electrolysis, while the remaining 28% is produced through steam methane reforming (Figure 4).

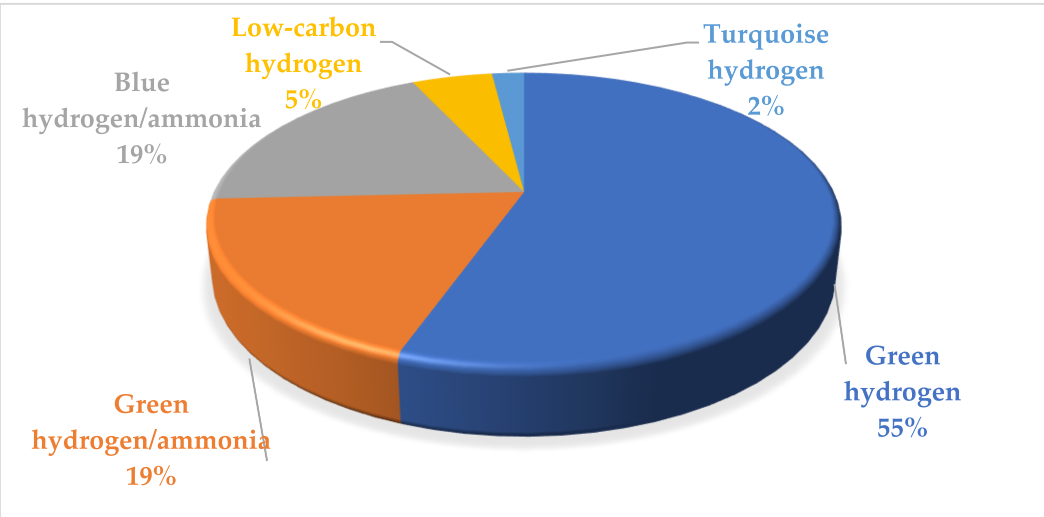

Figure 4. Type of production. Source: compiled by the authors.

Our calculations revealed that foreign projects had an LCOH of USD 5.89 per kilogram. Upon analyzing the projects in detail, it was found that the cost of electricity used during electrolysis was the primary factor influencing the final LCOH. The paper observed that for projects utilizing the same energy source but with varying production volumes, the LCOH remained consistent. This finding suggests that production volume alone does not significantly affect the cost of hydrogen production when the energy source remains constant.

LCOH in Russian green hydrogen projects ranges from 1.2 to 11.7 dollars per kilogram of hydrogen (Figure 5). It indicates significant variability in the cost of hydrogen depending on the type of electricity generation. The median value of 4.9 dollars per kilogram of hydrogen.

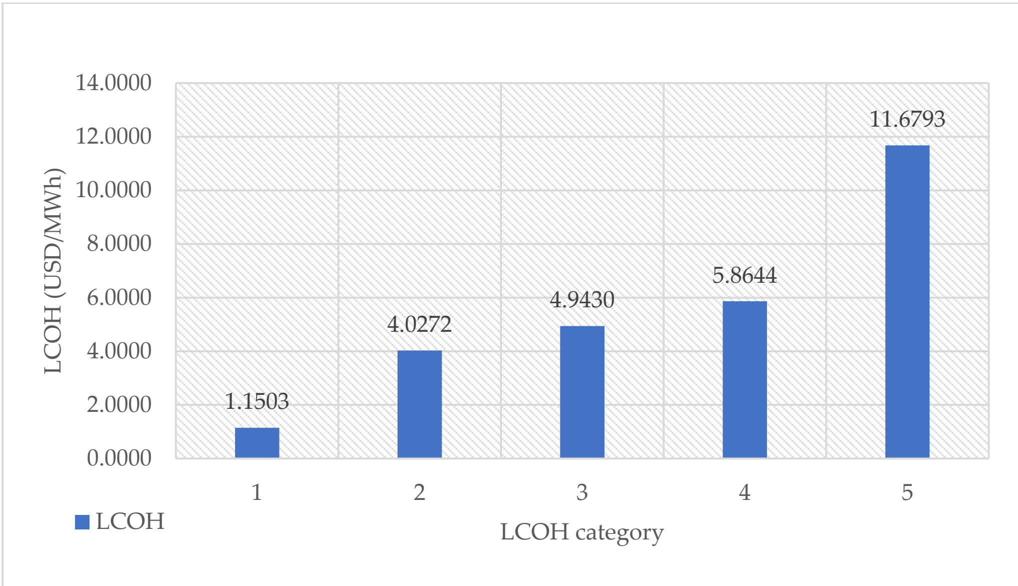

Figure 5. LCOH of Russian green hydrogen projects Source: compiled by the authors.

The statement that production capacity does not affect the cost of hydrogen production at the initial stage is noteworthy. This means that regardless of the size of the production facility, the cost of producing hydrogen remains relatively constant. In other words, the cost of hydrogen production is not affected by economies of scale at the initial production stage. Overall, this information helps assess the economic viability of hydrogen production, as it indicates the range of costs that must be considered when evaluating different production methods. It also highlights the importance of considering the effect of the production scale on cost when developing long-term production strategies.

5. Discussion

The market for hydrogen energy in Russia is expected to multiply in the future and might reach USD 2.2–3.9 billion in 2025–2035 (the global market will be USD 26 billion in 2025) [67]. Our study reveals that a significant share of Russian hydrogen projects (56%) focuses on producing green hydrogen, the preferable type of hydrogen from an environmental point of view. The median value of expected LCOH in Russian green hydrogen projects is a little less than average in the world [68]. The main competitive advantage of these projects is cheap hydro energy that can be used for electrolyzing. Another significant competitive advantage is the developed hydrogen transportation infrastructure built earlier for natural gas transportation. The delivery cost can be decreased if Russia exports hydrogen to South Korea or Japan, both of which have sizable ports on the Pacific coast. In the future, the critical areas for the use of hydrogen may be export, decarbonization of industry, transport and the housing and communal services sector, and the development of robotics [11].

However, due to sanctions, Russia is currently cut off from the world's primary consumers of "blue" and "green" hydrogen, and the sales market can eventually shrink only to China. As a result, Germany, Japan, and South Korea were taken off the list of the top importers, and the valuation for the Russian Federation's hydrogen export potential was almost cut in half, from 9.5 million to 4.5 million tons. Actual exports from Russia may decrease from the previously forecasted 2.2 to 1.4 million tons per year by 2030 [18].

Without government support measures, in the new market situation, only projects in Sakhalin and Yakutia will have a positive IRR, but the NPV will be negative (indicators are calculated for 20 years at the cost of capital of 15%).

To raise the economic effectiveness of projects, it is proposed to expand existing support measures for ten years—subsidizing loan rates, CAPEX, OPEX, tax incentives, compensation of 50% of transport costs, reducing electricity costs, etc. The cost of state support measures in the new presentation of the Russian ministry of energy has increased to USD 7.6 billion instead of USD 2.3 billion [69].

It is not entirely clear how the risks of recent months can develop soon. Among them are the liquidation of hydrogen projects or the fall of their investors under sanctions, violations of supply chains, and the departure of hydrogen solution providers (Siemens, Enel, Uniper, RWE, Total Energies).

With the world's rising gas prices, the prospects for exporting "blue" hydrogen from countries with low gas prices, such as the Russian Federation, look optimistic. However, it is not clear whether Russia will be able to win a place in the market of countries with the most significant prospective demand for hydrogen—the EU, Japan, and South Korea. With access to "green financing", considering low gas prices and the availability of a support system for such projects in the Russian Federation, the Russian "product" is economically quite competitive. Nevertheless, political motives might prevent the signing of long-term contracts, and without them, hydrogen projects in the Russian Federation will be financially too risky.

6. Conclusions

This study is devoted to analysis of economic competitiveness the potential impact of announced Russian hydrogen projects on the hydrogen market. Multiple case studies have revealed that most Russian-announced projects (53%) are focused on producing green hydrogen, from which 15% are based on the use of hydro energy.

The study contributes to the literature by forecasting the main economic metrics of green hydrogen projects in Russia based on an analogy approach. The results of the study forecast the levelized cost of hydrogen for Russian green hydrogen projects in the range from 1.2 to 11.7 USD per kilogram of green hydrogen with a median value of 4.9 USD per kilogram, which is slightly less than the world average. Therefore, the total capacity of Russian hydrogen production projects may contribute to a slight reduction in the price of hydrogen on the global market. However, Russian hydrogen projects are still in their early stages of development with limited geographical coverage. Due to sanctions, Russian hydrogen export potential is almost cut in half. These factors can eliminate the expected comparative advantages and positive global impact.

Our work has some limitations. The most important limitation lies in restricted data availability. For this reason, the analogy method was used to calculate LCOH. Despite this, our work could be a starting point for a more thorough investigation of the possible ways for LCOH to decrease in different Russian hydrogen clusters. Future research will calculate comparable economic indicators for hydrogen storage and transportation.

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