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Carbon Capture and Storage in Hydrogen Production: World Experience and Growth of Export Opportunities of the Russian Hydrogen Sector

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ABSTRACT

The purpose of this paper is a review of the commercialization and demonstration of CCS projects and an analysis of the commercial prospects for CCS industrial application in the production of low-carbon hydrogen in Russia and globally. The research was carried out using the methods of literature review, detailed analysis of regulatory documents, descriptive statistics, meta-analysis, and case studies. The results of the study clearly show that the widespread introduction of carbon capture and storage technologies can significantly affect the future development of the global energy market and the share of the Russian Federation in it. Despite the growing share of renewable energy in the global energy balance and the production of innovative energy products, the prospects for completely ousting hydrocarbon fuels from the market currently seem unattainable. Therefore, decarbonization of the global economy is impossible without the development of CCS in the coming decades.

Keywords: Decarbonization, Carbon Capture and Storage, Hydrogen Production, CAPEX, OPEX, LCOH
JEL Classifications: Q20, Q42, Q55, O32

1. INTRODUCTION

In the last several years, the government of the Russian Federation has been taking active measures to create a highly productive export-oriented hydrogen energy sector in the country. It is crucial for the Russian economy to maintain a leading position in the global energy market and maintain competitiveness in the context of the global energy transition. According to the Russian Ministry of Energy, the potential volumes of hydrogen exports from the country to the world market could reach up to 0.2 million tons next year, and from 2 to 12 million tons by 2035. In the long term (by 2050), exports can grow up to 15-50 million tons, depending on the pace of development of the global low-carbon economy and the growth in demand for hydrogen in the global market (Vechkinzova et al., 2022; Bazhenov et al., 2022).

However, today, the main consumers of hydrogen place high demands on technologies for hydrogen production due to the need to decarbonize the global economy. Developed countries, primarily the countries of the European Union, give preference to “green” hydrogen, which uses renewable energy sources for hydrogen production. This leads to a decrease in demand for hydrogen produced from hydrocarbon fuels. In an attempt to meet the growing demand for green hydrogen, more than half of the fifty-four announced in 2020-2022 Russia’s new hydrogen projects involve the use of renewable energy sources (RES), including hydro, solar, and wind energy (Gomonov et al., 2023).

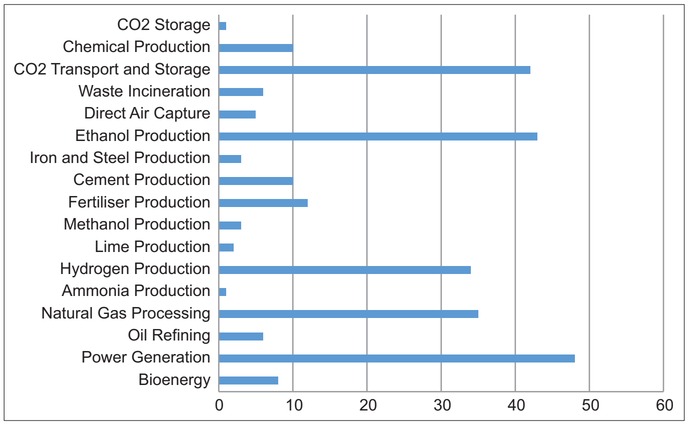
At the same time, it is widely known that modern electrolyze technologies with the use of renewable energy sources are uncompetitive in comparison with the traditional method of steam methane reforming (SMR) from a commercial point of view. Experts of the World Hydrogen Council believe that in the future, the costs of producing hydrogen by SMR technology will increase due to the introduction of various types of carbon taxes, and the costs of producing hydrogen by electrolysis, on the contrary, will decrease as technology develops and benefits economies of scale and learning-by-doing effects (Revinova et al., 2023). However, the future of the technological development of hydrogen production is not yet clear. One of the most promising alternatives to the development of low-carbon hydrogen production based on renewable energy sources by water electrolysis is the use of traditional steam methane reforming and coal gasification but using CO_2 capture and storage technologies (Qureshi et al., 2023).

It is important to note that the prospects for widespread use of carbon capture and storage (CCS) technologies today are not limited to the hydrogen production sector. This cluster of technologies is applied to modernize existing power-generating facilities to reduce emissions in ethanol production and natural gas processing, as well as in many other industrial sectors (Figure 1). In addition, in the future, captured CO_2 can be used in various technological processes to produce environmentally friendly synthetic fuels, which, together with the above-mentioned areas of CCS use, can create significant demand for their development and the manifestation of scale and learning-by-doing effects (Young, 1993; Sagar et al., 2006; Ratner and Zaretskaya, 2018).

The purpose of this paper is a review of commercial and demonstration CCS projects and an analysis of the commercial prospects for CCS industrial application in the production of low-carbon hydrogen in Russia and globally. The research was carried out using the methods of literature review, detailed analysis of regulatory documents, descriptive statistics, meta-analysis, and case studies.

The remainder of the paper is organized as follows: Section 2 provides a short literature review of the topic of the technical and economic parameters of modern CCS technologies. Section 3 analyzes the statistics of commercial and demonstration CCS projects. Section 4 presents the results of the meta-analysis of data on the economic parameters of hydrogen products with CCS. Section 5 concludes and discusses some policy applications of the main results of the study.

Figure 1: The number of CCS commercial projects by industry



Source: Authoring based on https://co2re.co/FacilityData

2. LITERATURE REVIEW

Nowadays, the development and widespread practical application of Carbon Capture, Utilization, and Storage (CCUS) technologies is considered as a necessary condition for achieving the goals of decarbonization of the global economy (IEA, 2020). Presently, this is the only group of technologies that contributes both to the direct reduction of emissions in key sectors of the economy and to the removal of CO_2 from already produced emissions, which are technologically impossible to avoid (Wang et al., 2021). Another important factor in the attractiveness of CCUS technologies is that they provide the opportunity to modernize energy facilities that were built without climate targets relatively recently and could still operate for decades if it were possible to reduce their CO_2 emissions (Ratner and Ratner, 2017; Han et al., 2023). In addition, CCUS technologies can enable the production of low-carbon hydrogen from natural gas or coal in countries with low-cost resources in a cost-effective manner (Yu er al., 2021). An additional advantage of this cluster of technologies is that the captured CO_2 can be used in various technological processes, including to produce environmentally friendly aviation fuel, which increases the commercial attractiveness of the technology (Ratner et al., 2019; Berger et al., 2021).

However, the level of development of CCUS technologies is currently significantly slower than previously expected. Back in 2009, the International Energy Agency (IEA) roadmap for promoting CCUS set a goal of developing 100 large-scale projects between 2010 and 2020 with a total storage capacity of about 300 million tons of CO_2 per year (IEA, 2009). Nevertheless, according to the end of 2020, the actual capacity of CCUS storage devices is only about 40 million tons, i.e., 13% of the target (IEA, 2020).

Investments in CCUS lag significantly behind investments in other so-called “clean” energy technologies and amount to approximately 0.5% of the total global investment in renewable energy and energy-efficient technologies (IEA, 2020). Scholars agree that the lack of a consistent policy is the main reason for such restrained investor interest in CCUS technologies (Yang et al., 2019; Zhang et al., 2021; Chen et al., 2022). In the absence of carbon penalties/taxes, investments in CCUS may not be commercially justifiable, especially in regions and industries where CO_2 is not used as an industrial feedstock. The high cost of installing infrastructure and difficulties in integrating different elements of the CO_2 supply chain, technical risks associated with installing or expanding CCUS capacity in some application areas, difficulties in sharing business risks among project partners, and problems in securing financing have also hampered investments (Lin and Tan, 2021). Public resistance to carbon geological storage, especially on land, has also played a role in some cases, especially in Europe (Singleton et al., 2009; Selosse and Ricci, 2017). In addition, CCUS is often classified as a fossil fuel technology that competes for public and private investment with renewables, although in practice, using these technologies in parallel with renewable energy provides significant synergies to achieve climate goals (IEA, 2020).

Tighter climate targets announced under the 2015 Paris Climate Agreement and the goal of keeping average annual temperatures below 1.5°C, in particular, have fueled increased interest in carbon mitigation options that go beyond renewable development energy, including CCUS technologies (Warren, 2019; Vishal et al., 2021). An increasing number of countries and organizations are adopting net-zero emissions targets and incorporating CCUS into their energy strategies and roadmaps. By August 2020, 14 countries and the European Union (EU), which jointly account for about 10% of global energy-related CO_2 emissions, had adopted formal net-zero emissions targets in national legislation by 2045, 2050, or later (Global CCS Institute, 2022). Similar targets are being discussed in about 100 other countries. Of the 16 national climate strategies submitted by August 2020, nine mention the important role of CCUS; these include Canada, France, Germany, Japan, Mexico, Portugal, Singapore, the UK, and the US. Collectively, these countries account for 96% of total energy-related CO_2 emissions in countries that have introduced decarbonization strategies by 2050 (Ratner and Zaretskaya, 2020; Van Coppenolle et al., 2023).

CCUS can help decarbonize long-distance transport by storing CO_2 as a source of synthetic hydrocarbon fuels. The captured CO_2 can be used to convert low-carbon hydrogen into synthetic hydrocarbon fuels (diesel, gasoline, and kerosene), which are easier to store, transport, and use but have potentially lower life-cycle CO_2 emissions than conventional fossil fuels. However, the production of synthetic hydrocarbons is energy-intensive and requires large amounts of hydrogen, making them relatively expensive (Rubin et al., 2015; Bui et al., 2018). As CO_2 emissions limits increase over time, CO_2 feedstock increasingly has to be obtained from biomass or air (DAC technology) (Titova and Ratner, 2019; Ahlström et al., 2022; Chen and Wu, 2022; Atassi and Yang, 2022).

In heavy industry, CCUS technologies can be applied directly at production facilities (in industrial processes) and at energy facilities. In general, emissions from industrial processes that rely on chemical reactions (such as the production of certain bulk materials) are virtually impossible to reduce without capturing CO_2. A prime example here is the production of clinker, the key active ingredient in cement (Zajac et al., 2021; Sanjuán et al., 2020; Guo et al., 2023). Process emissions account for about two-thirds of emissions from a cement kiln. Even if the furnace in which it is produced were electrified or powered by bioenergy fuel, these emissions would persist. Alternative binders that could replace cement in construction (such as magnesium oxide derived from magnesium silicates) are still in the research and development (R&D) stage today (Global CCS Institute, 2022).

Currently, there are also limited alternatives to CCUS to reduce emissions from steel and chemical production (Lau et al., 2021; Fasihi et al, 2019). CCUS technologies in the steel and chemicals sectors also tend to be at a higher level of technological maturity than their hydrogen-based alternatives. A hydrogen-based direct reduction iron (DRI) steelmaking process that significantly reduces emissions could provide an economically viable alternative to CCUS-equipped plants, but likely only in regions with access to very low-cost renewable electricity to produce hydrogen from water electrolysis (Ratner et al., 2018; Zakeri et al., 2023; Wang et al., 2021). Based on current estimates of average industrial production costs, producing one ton of steel using CCUS-equipped DRI technology and innovative smelt recovery processes is typically 8-9% more expensive than current mainstream commercial production methods, but the use of hydrogen-based DRI typically increases costs by about 35-70% (Rosner et al., 2023; Tang et al., 2020). A similar problem is observed in the chemical sector. Hydrogen produced through electrolysis and used as a feedstock for the production of ammonia and methanol could be an important alternative to CCUS, but in most regions today, it is more expensive than using CCUS in existing or new plants. The cost of producing CCUS-equipped ammonia and methanol is typically about 20-40% higher than their cost-neutral counterparts, while the cost of electrolytic hydrogen plants is 50-115% higher (Lau et al., 2021).

In summary, the literature review concludes that carbon capture and storage technologies are a cost-effective way to reduce emissions in many industries compared to other options. Many studies by scientists from various fields of knowledge are focused on assessing the technical and economic parameters of production processes using CCUS. However, in the scientific literature, little attention is paid to forecasting the improvement of these parameters with the development and wider practical application of CCUS.

3. METHODOLOGY AND DATA

The research was carried out using the methods of literature review, content analysis of regulatory documents, case studies, meta-analysis, and descriptive statistics. The information base for the study was the analytical reviews of the International Energy Agency and the CCUS project database of the CCUS World Institute (https://co2re.co/FacilityData).

Meta-analysis is used to integrate and summarize previous empirical estimations of the cost of hydrogen production using different technologies. Generally, meta-analytical studies report the mean values and estimated standard deviations of the considered effect size, which allow for explaining the heterogeneity of the results of several different empirical study (Erauskin-Tolosa et al., 2020).

As the key economic metric for hydrogen production, this study uses the levelized cost of hydrogen (LCOH). The levelized cost of 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 standard formula for calculation is as follows (Ratner and Klochkov. 2017; Li et al., 2017; Gomonov et al., 2023; Yang et al., 2023)

$$LCOH = \frac{I_0 + \sum_{t=1}^{T} A_t \cdot F_t \cdot (1+r)^{-t}}{\sum_{t=1}^{T} H_t \cdot (1+r)^{-t}} \tag{1}$$

Where

I_0 - unit cost of production equipment, taking into account installation (for production processes using CCS, it consists of

the cost of equipment for hydrogen production, the cost of a CO_2 capture installation, and the cost of building storage facilities);
A_t- Cost of equipment maintenance per year t;
F_t – Cost of fuel (natural gas, coal) per year t;
H_t – Amount of hydrogen produced per year t;
T – Duration of operation of production equipment (years);
r – Discount coefficient.

4. RESULTS

4.1. Geography and Dynamics of CCUS Technologies Development

Currently, 31 countries have commercial hydrogen capture and storage projects at various stages of development (Figure 2). The largest number of projects are being implemented in the USA and Great Britain, and a significant number of projects are being implemented in Canada, Norway, the Netherlands, Australia, and China.

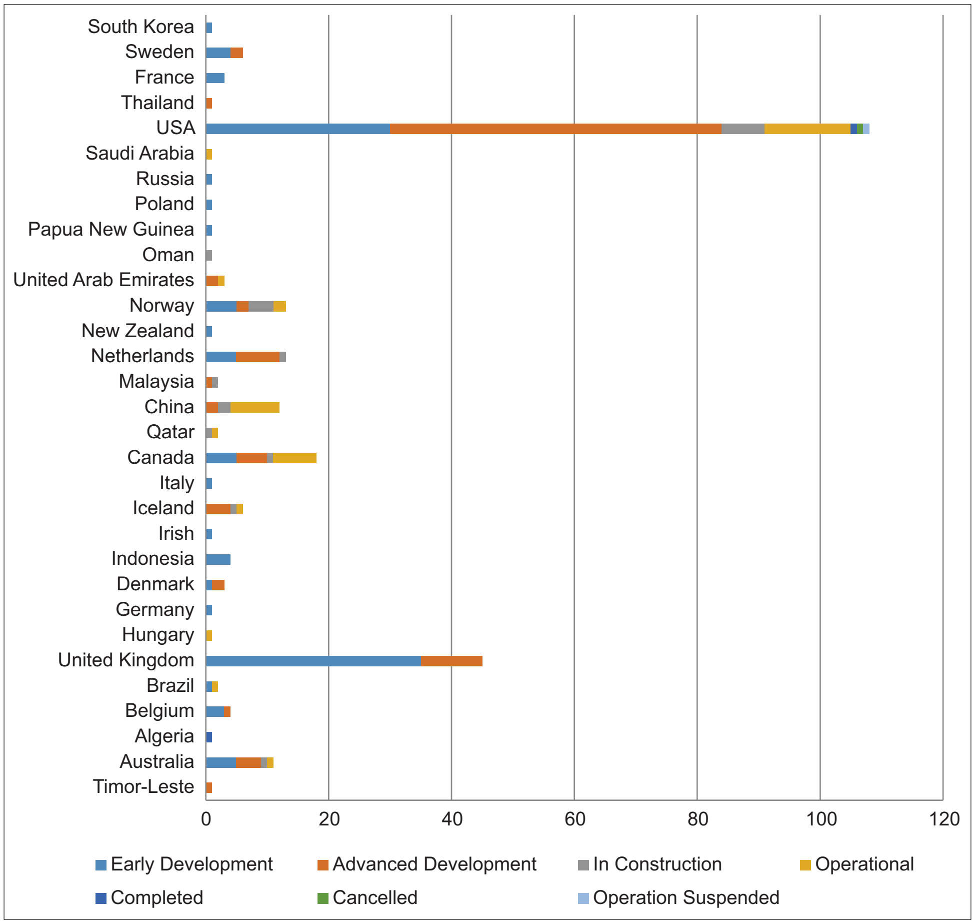
The United States is a world leader in promoting CCS technology and is currently implementing more than 100 projects, of which 14 are active and 54 are in the final stages and will be brought into the active phase soon. As for the UK, there are no active commercial CCS projects in the country yet, but 10 projects are already in the final stages of development and another 35 are in the early stages of development.

Globally, more than 150 CCS projects are expected to be launched in the coming years (Figure 3). This assumes that the necessary conditions have been created for the effects of scale and learning to occur and the unit cost of CCS capacity is likely to decrease in the medium term.

In addition to commercial projects, pilot CCS demonstration projects are currently being implemented in many countries to address the weaknesses of the technology and attract the attention of investors to it. The majority of such projects are being implemented in the USA, China, Japan, Australia, and the UK (Figure 4). Thus, the cluster of leading countries in the development of CCS technology is now well-defined. Basically, these are countries with a developed energy system based on the use of hydrocarbon fuels and with developed industries.

Unfortunately, to date, Russia is not among the countries actively developing CCS technologies. There is only one commercial project being implemented in the Russian Federation, Novatek Yamal LNG CCS, the launch of which is scheduled for 2027. Novatek is evaluating options for pumping carbon dioxide into the South Tambey deposit on the Yamal Peninsula. CO_2 can be captured at the Yamal liquefied natural gas plant, which produces about 2.6 tons of CO_2 per ton of LNG. The capacity of the Yamal LNG plant is 16.5 million tons of LNG per year. There are no demonstration or pilot projects in Russia.

Figure 2: The number of commercial CCS projects: breakdown of projects by stages and countries



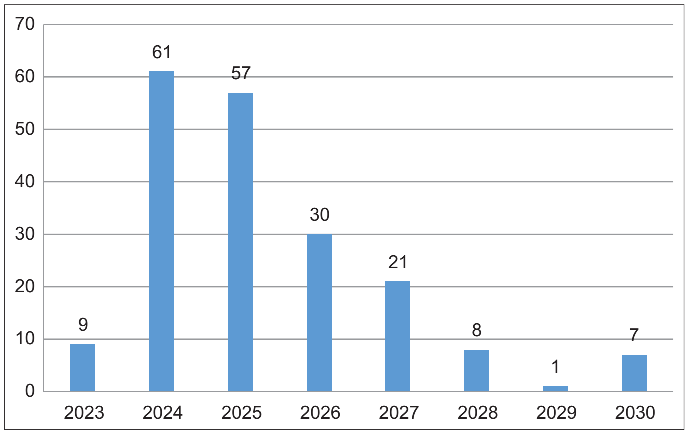
Source: Authoring based on data from https://co2re.co/FacilityData

Nevertheless, the prospects for the development of CCS technologies in Russia are assumed by the international expert community as quite high. According to the CCS Implementation Readiness Index, calculated using the methodology of the Global CCS Institute, Russia is among the countries with the highest scores on this index in recent years (Figure 5), although it is inferior to most BRICS partners.

The CCS Readiness Index is calculated based on four indicators that reflect the state of the following areas:

1. The country's objective interest in the development of this cluster of technologies, determined by the structure of the economy (dependence on hydrocarbon fuels or export of hydrocarbon resources);
2. The presence of government policies in the field of CCS development (strategies for the development and support of the development of CCS technologies, including both measures to directly support CCS (subsidies, grants) and implicit support through measures such as carbon pricing, funding for research, or initiative projects);
3. Readiness of the regulatory and legal environment (including environmental legislation);
4. Availability of carbon storage infrastructure (geological and technical aspects).

Figure 3: The number of expected projects of CCS to launch up to 2030

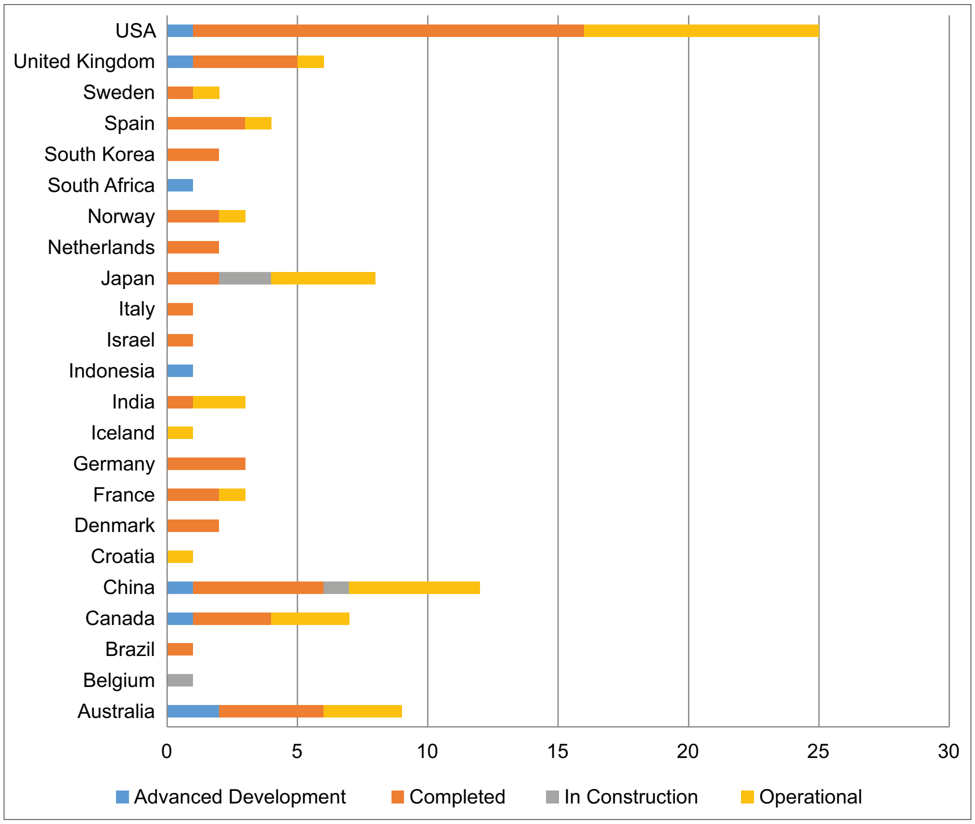


Source: Authoring based on data from https://co2re.co/FacilityData

Hydrogen production using CCS technologies for commercial purposes is currently carried out at three industrial facilities, two of which are in the United States and the third in Canada (Table 1). In the United States, captured carbon dioxide is used in the oil and gas industry to enhance oil recovery. In Canada, captured carbon dioxide is pumped into geological storage and simply stored there.

In the coming years (until 2030), it is planned to launch another 23 industrial facilities for the production of hydrogen using CCS technologies in the world (Table 2): 7 projects in the UK, 5 projects in the USA, 4 projects in the Netherlands, 3 projects in Canada, 2 in Australia, and one each in New Zealand and Sweden. Most projects plan to use natural gas as a source of hydrogen production through steam and autothermal reforming.

Figure 4: The number of pilot and demonstration CCS projects: breakdown of projects by stages and countries



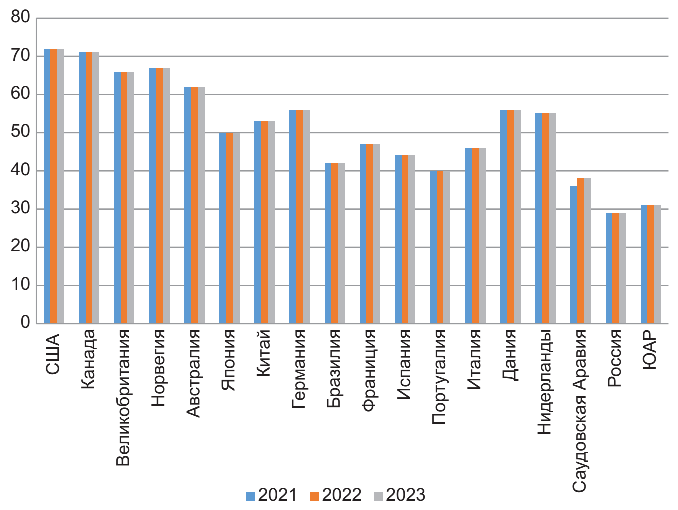
Source: Authoring based on data from https://co2re.co/FacilityData

In addition, three demonstration projects for the use of CCS in hydrogen production are at various stages of implementation - one project in Australia and two in Japan. Current ones include the Japanese Ministry of Economy, Trade, and Industry (METI)-approved Tomakomai CCS demonstration project, which captures CO_2 from a hydrogen production facility at the Idemitsu Kosan refinery on the island of Hokkaido at Tomakomai Port. Approximately 100,000 tons of CO_2 per year were injected into two offshore storage facilities between fiscal years 2016 and 2018, and post-injection monitoring will continue for several years.

Another Japanese demonstration project is due to start in 2024. INPEX is constructing a blue hydrogen and ammonia production plant at the Higashi-Kashiwazaki gas field in Niigata Prefecture. The project involves producing 700 tons of blue hydrogen per year and injecting CO_2 generated during the production of hydrogen and ammonia into depleted oil and gas fields. INPEX is collaborating with the Japan Organization for the Security of Metals and Energy Supply (JOGMEC) to assess underground CO_2 storage facilities, as well as the Japan New Energy and Industrial Technology Development Organization (NEDO) to secure financing for the project.

Australia's pilot Hydrogen Energy Supply Chain (HESC) project aims to establish full-scale commercial supplies of low-carbon hydrogen to Japan. The launch of the pilot stage of the project is planned for 2028; after 2 years, it is planned to move to the commercial stage.

Figure 5: CCS Readiness Index for chosen countries in 2021-2023



Source: authoring based on Global CCS Institute data

4.2. Economic Aspects of CCS Technologies in Hydrogen Production

The cost of producing hydrogen from fossil fuels is mainly determined by two factors: Capital costs (CAPEX) and operating costs (OPEX), in which the main share is the cost of raw materials (Gomonov et al., 2023; Revinova et al., 2023). Coal gasification facilities have higher capital costs (average $2,670/kW) than steam methane reforming (average CAPEX estimates $910/kW). However, lower coal prices offset these advantages, and the cost of hydrogen produced using two different technologies is almost the same at the end. According to (Global Status of CCS, 2019), the share of capital costs in the total cost of hydrogen produced by coal gasification is 50%, and operating costs and fuel are 15-20%, depending on the price of coal. For steam methane reforming processes, fuel costs are 45-75%. The IEA estimates that equipping a coal gasification production facility with CSS technology will increase capital costs by 5% and OPEX by 130%. Equipping the first conversion unit with CCS will increase CAPEX by an average of 50%, and OPEX by only 10% (IEA, 2019).

In addition to the cost of carbon capture equipment, the cost of constructing CO_2 storage sites is also an important factor in the overall cost-effectiveness of CCS applications, although storage costs are generally considered to be low compared to CO_2 capture costs. Estimates of CO_2 storage costs in the literature vary widely depending on the CO_2 injection rate and the characteristics of the storage tanks, as well as the location of the CO_2 storage sites. The cost of developing new sites, particularly where CO_2 storage has not previously been undertaken, is highly uncertain, particularly concerning the influence of reservoir properties and characteristics. The cost of storing CO_2 in more than half of US land-based storage facilities is <$10 per ton (Global Status of CCS, 2022). Depleted oil and gas fields using existing wells are expected to be the cheapest storage option.

To estimate the cost of hydrogen as a final product, the literature typically uses the LCOH indicator, similar to the LCOE indicator used to calculate the cost of electricity. Data for different hydrogen projects vary significantly, so meta-analysis of data is typically used to obtain reasonable estimates.

Table 1: Active commercial hydrogen with CCUS projects

Project name	Country	Year of commissioning	Technology, capacity, carbon use/storage methods
Great Plains Synfuels Plant and Weyburn-Midale	USA	2000	Coal gasification, 3 billion ton/year The captured CO_2 is transported by pipeline to the Weyburn and Midale oil installations in Saskatchewan, (Canada) for use in enhanced oil recovery.
Valero Port Arthur Refinery	USA	2013	Steam methane reforming (SMR), 1 billion ton/year The captured CO_2 is transported to oil fields in Texas to enhance oil recovery.
Quest	Canada	2015	Steam methane reforming (SMR), 1 billion ton/year The captured CO_2 is transported via pipeline to a storage site for dedicated geological storage.

Source: Authoring based on data from https://co2re.co/FacilityData

Table 2: Commercial CO_2 capture and storage projects planned for commissioning for hydrogen production

Name of the project	Country	Year of commissioning	Technology, capacity, carbon use/storage methods
Acorn	Great Britain	2024	Technology – n/a Capacity – n/a The captured CO_2 is transported via existing oil and gas pipelines to a storage site for dedicated geological storage.
Air Liquide Refinery Rotterdam CCS	Netherlands	2024	Technology – n/a Capacity – n/a Based on Air Liquide oil refinery
Air Products Net-Zero Hydrogen Energy Complex	Canada	2024	Autothermal reforming (ATR) with capture rate 95% Capacity – n/a Transportation via Alberta Carbon line (Wolf Carbon Solutions).
Blue But Better	Canada	2024	Steam methane reforming (SMR) Hydrogen production capacity 1,500 ton/day Carbon capture capacity 3 billion ton/year Transportation via Alberta Carbon line to Clive oil fields to enhance oil recovery.
ExxonMobil Benelux Refinery CCS	Netherlands	2024	Technology – n/a Capacity – n/a Based on ExxonMobil Benelux oil refinery
Project Pouakai Hydrogen Production with CCS	New Zealand	2024	Technology – n/a Capacity – 1 billion ton/year Carbon use/storage methods – n/a
Hydrogen to Humber Saltend	Great Britain	2025	Autothermal reforming (ATR) Carbon capture capacity 1.2 billion ton/year Carbon use/storage methods – n/a
Linde hydrogen plant for OCI fertilizer blue ammonia Beaumont	USA	2025	Technology – n/a Capacity – n/a Carbon use/storage methods – n/a
Lone Cypress Hydrogen Project	USA	2025	Technology – n/a Capacity – n/a Carbon use/storage methods – n/a
Louisiana Clean Energy Complex	USA	2025	Technology – n/a Capacity 5 billion ton/year with capture are 95% Carbon use/storage methods – n/a
Polaris CCS Project	Canada	2025	Technology – n/a Capacity 750,000 ton/year The captured CO_2 is transported via pipelines to a storage site for dedicated geological storage
Preem Refinery CCS	Sweden	2025	Technology – n/a Capacity 500,000 ton/year Carbon use/storage methods – n/a
Acorn Direct Air Capture Facility	Great Britain	2026	Direct air capture (DAC) Capacity – n/a Carbon use/storage methods – n/a
L10 Carbon Capture and Storage	Netherlands	2026	Technology – n/a Capacity 4-5 billion ton/year Storage in depleted gas fields in North Sea
Northern Gas Network H21 North of England	Great Britain	2026	Technology – n/a Capacity 500,000 ton/year Carbon use/storage methods – n/a
Zeeland Refinery Azur	Netherlands	2026	Technology – Cryocap Capacity 800,000 ton/year Carbon use/storage methods – n/a Storage in depleted gas fields in North Sea
Ascension Clean Energy (Louisiana)	USA	2027	Technology – n/a Capacity of hydrogen production 7.2 billion ton/year Geological storage
Baytown Low Carbon Hydrogen	USA	2027	Technology – n/a Capacity of hydrogen production 1,000 billion cbft/year Capacity of CO_2 capture 7 billion ton/year Carbon use/storage methods – n/a
H2NorthEast	Great Britain	2027	Technology – n/a Capacity 355 MW (fist stage by 2027) Capacity 1,000 MW (second stage by 2030) Carbon use/storage methods – n/a

(Contd...)

Table 2: ***(Continued)***

Name of the project	Country	Year of commissioning	Technology, capacity, carbon use/storage methods
Net Zero Teesside – BP H2Teesside	Great Britain	2027	Technology – n/a Hydrogen production capacity 500 MW Carbon capture capacity 1 billion ton/year Carbon use/storage methods – n/a
Phillips 66 Humber Refinery CCS	Great Britain	2027	Technology – n/a Capacity – n/a Carbon use/storage methods – n/a
Mid West Modern Energy Hub	Australia	n/a	Technology – n/a Capacity – n/a Carbon use/storage methods - Storage in depleted gas fields in Perta
Hydrogen Energy Supply Chain (HESC) project	Australia	n/a	Technology – n/a Capacity of hydrogen production 30,000-40,000 ton/year on early stage and 225,000 ton/year later Carbon use/storage methods – n/a

Source: Compiled by the authors based on data (https://co2re.co/FacilityData)

In (Kaplan and Kopacz, 2020), as a result of a meta-analysis of data from various sources, median estimates of the cost of hydrogen production from hydrocarbon sources using CCS technologies are presented in comparison with median estimates of the cost of "green" hydrogen. The median cost estimate for 1 kg of hydrogen produced using steam methane reforming technology using CCS is US$2.09 (based on 33 sources), while the median cost estimate for hydrogen produced without CCS is US$1.66 (based on 18 sources). Thus, the use of CSS in the reforming process increases the cost of production by more than a quarter. In addition, it should be noted that modern technologies do not capture all CO_2, but approximately 90% of all emissions occur during the steam reforming process.

The median estimate of the cost of hydrogen produced using coal gasification technology is US $1.84 without the use of CCS (obtained from 11 sources), and with the use of CCS is US $2.23, that is, CO_2 capture increases the cost of the final product by more than 20%. At the same time, more than 85% of CO_2 emissions are captured. For comparison, the median cost estimate for hydrogen produced through electrolysis is US$3.64 (based on 40 sources), which is 63-74% more than the cost of hydrogen produced from hydrocarbon sources, capturing about 90% of the total CO_2 emissions.

Thus, the economic feasibility of developing CCS technologies to decarbonize hydrogen production is high. Even taking into account the fact that the remaining volumes of CO_2 emissions may be subject to taxation in the future (in the event of a large-scale implementation of a carbon tax), their economic attractiveness remains higher than that of electrolysis technologies at the current level of development (US $ 2.24-2.7 versus US $3.64).

It should be noted that in recent years, many works have appeared in the scientific literature on energy economics that predict a reduction in the cost of hydrogen production through electrolysis due to the implementation of economies of scale and the learning curve effect in the production of electrolyzes themselves, which should ultimately lead to a decrease in the cost of "green" hydrogen to values comparable to the cost of traditional production based on hydrocarbon fuels (Ceran, 2020; Rubin et al., 2015). However, the same processes are elements of the development of any knowledge-intensive technologies, including carbon capture and storage technologies. The main potential areas for reducing both capital and operating costs are the use of innovative solvents, standardization of capturing devices, modularization, reduction of incidental costs, and better integration with the process plant, as well as increasing the size of capturing facilities (Ratner and Nizhegorodtsev, 2018; Winskel et al., 2014). In addition, operating costs can be reduced through optimized maintenance strategies, optimized use of thermal energy and water, improved compression efficiency, and digitalization. Experts believe that the introduction of new digital technologies such as new sensors, artificial intelligence, and the Internet of Things can make a significant contribution to the development of predictive maintenance and automation of carbon storage equipment (IEAGHG, 2020a). The cost reduction potential of carbon capture and storage technologies is estimated to range from 25% to 70% (Bui et al., 2018; Lau et al., 2021).

Therefore, over time, we can expect both a reduction in the cost of hydrogen produced using CCS technologies and an increase in the percentage of CO_2 capture due to the improvement of this cluster of technologies. In addition, the use of captured CO_2 is also considered potentially economically attractive and could create an additional revenue stream for CCS projects.

5. CONCLUSION

The widespread introduction of carbon capture and storage technologies can significantly affect the future development of the global energy market and the Russian Federation's share in this market. Despite the growing share of renewable energy in the global energy balance and the production of innovative energy products, the prospects for completely ousting hydrocarbon fuels from the market currently seem unattainable. Therefore, decarbonization of the global economy is impossible without the development of CCS in the coming decades.

The highly likely reduction in the cost of CCS technologies due to the manifestation of scale and learning effects may be a factor in the revival of interest in hydrogen production projects based on hydrocarbon sources such as natural gas and coal. Even taking into account the potential increase in the carbon tax, the final cost of hydrogen derived in this way is significantly lower than that produced using electrolysis technology. Therefore, it can be recommended to adjust the Russian hydrogen energy development strategy towards expanding the share of hydrogen production projects using traditional coal gasification technologies and steam methane reforming using carbon capture and storage technologies. Taking into account the high level of development of the gas and coal industries in Russia and the current price discrimination of traditional Russian export energy products on the world market, such an adjustment to the strategy may make it possible to increase the competitiveness of Russian hydrogen in terms of cost.

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