Hydrogen Technologies and Prospects for Their Use in the Asian Regions of Russia

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***Abstract* — The paper discusses the prerequisites for the development of hydrogen infrastructure and the scope of application of hydrogen technologies in the Asian regions of Russia (ARR). The previous approach to the creation of a hydrogen infrastructure in Russia may be revised due to economic sanctions and the impossibility of technology transfer. The available largest and most efficient resources of crude hydrocarbons and coal (nonrenewable energy resources – (NRER)), as well as the significant potential of renewable energy allow large-scale production of hydrogen in the Asian regions of Russia. There are also preconditions for the use of hydrogen technologies for energy end-users in this territory. The creation of large pilot testing grounds in isolated power systems of the Asian regions of Russia will make it possible to enhance and develop the hydrogen production, storage, and transport technologies to prepare them for delivery to export markets for energy equipment and services.**

***Index Terms*: development of hydrogen infrastructure, hydrogen technologies, ammonia, Asian regions of Russia.**

I. Introduction

The number of pilot and demonstration projects aimed at testing hydrogen technologies has been rapidly increasing in the world in the last decade. The growing social need to protect the environment from anthropogenic impact and the reduction in the cost of energy hydrogen technologies are reasons for their spread. Thus, according to the consulting company Lazard, at the moment, in the case of a large-scale hydrogen production, capital costs for electrolyzers, key components of electrochemical production of hydrogen, lie in the range of 310–920 $/kW for alkaline electrolyzers (AEL) and 460–1190 $/kW for polymer electrolyte membrane (PEM) electrolyzers. According to the forecasts published by the International energy agency (IEA), International renewable energy agency (IRENA) and DNV GL, the cost of all types of electrolyzers may further decrease by 20–70 percent in the period up to 2030–2050 (Table 1) [1–3].

Along with this, the number of mass-produced commercial models, for example, electric vehicles equipped with fuel cells (fuel cell electric vehicle, FCEV) increases. Currently, FCEVs are more expensive than other types of fuel systems of vehicles. However, the economic instruments used in some countries (subsidizing the purchase of zero emission vehicle, reducing transport tax, interest-free loans) and technological progress make it possible to reduce the cost of this technology [4, 5]. As a result, the number of FCEVs increased almost 5 times in the period from 2018 to 2021, and the share of hydrogen cars may reach 6% of the total number of passenger cars and light trucks sold in the world by 2030 [4–6].

The scalability of the fuel cell technology allows its use in other types of vehicles (trains, water and air transport), as well as in the energy supply systems of various scales and purposes – from households to large facilities of metallurgical, chemical, and other energy-intensive industries. Today, Panasonic Corporation produces “Ene-farm” fuel cells for the generation of heat and electricity [7], the “Sunfire” company develops and releases industrial solid oxide electrolyzers and fuel cells [8]. The energy production based on fuel cell can be organized for centralized and distributed isolated power supply. Fuel cells can also be used in mobile electricity generators. Combined cycle gas-turbine (CCGT) plants have become another area for hydrogen energy supply systems. Kawasaki Heavy Industries [9] and Mitsubishi Hitachi Power Systems (MHPS) [10] are leaders in the development of combined cycle and gas turbine plants using hydrogen as fuel. Currently, MHPS has created several gas turbine units operating on a methane-hydrogen mix (20% and 30% H_2), however, Mitsubishi has announced the release of the CCGT running entirely on hydrogen by 2027 [11].

Thus, in fact, the process of commercialization of hy-

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TABLE 1. Capital expenditure of electrolyzers, $/kW

The future of hydrogen			Green hydrogen cost reduction: scaling up electrolyzers to meet the 1.5°C climate goal			Hydrogen forecast to 2050 energy transition outlook 2022 (DNV)		
AEL	PEM	SOEC (Solid oxide electrolysis cells)	AEL	PEM	SOEC	AEL	PEM	SOEC
2019/2030			2020/2050			2022/2030		
500–1400/ 400–850	1100–1800/ 650-1500	2800–5600/ 800–2800	1000/ >750	>1500/ >1250	–	1000/ >750	>1500/ >1250	–

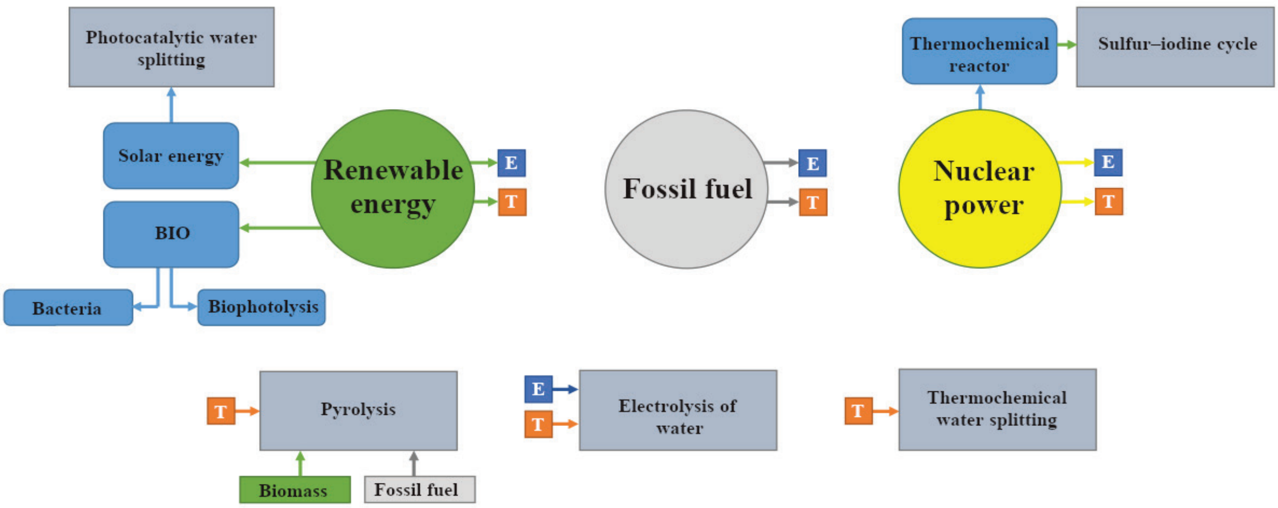

Fig. 1. Hydrogen production methods (T – thermal energy, E – electrical energy).

drogen technologies has begun in the world. Their spread will reduce carbon emissions in the transport sector of the economy, increase the efficiency of existing ones, and create low or carbon-free energy supply systems for different consumer groups, including industrial ones. As a result, the trend in the development of hydrogen technologies can solve several current problems facing the energy sector.

II. Hydrogen Energy Development in Russia

Russia has become the 6th country after Germany, Australia, Norway, Japan and the Republic of Korea, where the development of hydrogen energy is enshrined in program documents and is an integral part of the energy development. The Energy Strategy of the Russian Federation until 2035 and the Hydrogen Energy Development concept establish the creation of hydrogen energy; Russian hydrogen energy roadmap to 2024, The Strategy of Socioeconomic Development of the Russian Federation with a low level of greenhouse Gas Emissions until 2050, and the Transport Strategy of Russia until 2030 with forecast until 2035 touch upon the topic of the hydrogen energy in Russia [12–16]. The data presented in the listed documents show the export orientation of the hydrogen energy, the purpose of which is to build the facilities for the production, storage, and transportation of hydrogen and hydrogen-containing substances and to provide leadership of the Russian Federation as a world hydrogen producer and exporter. According to the Energy Strategy of Russia until 2035, the volume of production is up to 2 million tons by 2035, and the aim of the Hydrogen Energy Development Concept is to produce up to 12 million tons [13]. In the context of a low-carbon paradigm of global energy development, such export volumes have to rely on the hydrogen production by pyrolysis of biomass, methane and other fossil fuels, or by water electrolysis, when renewable energy and/or nuclear energy are used (Fig. 1).

To date, fossil fuel is the main source of hydrogen production, which involves the technologies for gas-steam methane reforming and coal gasification. Steam natural gas reforming will be the main method of producing hydrogen at the initial stage of the hydrogen energy development in the world. Probably, coal gasification will become the second most common method, because the cost of such production is comparable to the technologies of steam reforming in the presence of cheap and suitable quality coal. However, this technological process is characterized by significant energy losses. Both of the mentioned processes are exothermic, which can be used to produce thermal energy. These methods are also characterized by greenhouse gas emissions, which requires the use of carbon capture and storage technologies.

Any generating capacities (RES, thermal condensing and

Table 2. Hydrogen and ammonia production volumes in the Russian Federation, million tons per year

Production method	Asian regions of Russia	Europian regions of Russia	Total
“green” H_2	5.8	1.3	7.1
“non green” H_2	0.1	0.002	0.102
“non green” NH_3	13.4	0.2	13.6

nuclear power plants (NPPs)) can act as sources of electricity in the electrolysis-based hydrogen production. Some studies show that the hydrogen production at the off-peak load hours at hydroelectric power plants (HPPs) and NPPs can improve the efficiency of energy supply systems [17]. At NPP, hydrogen can be produced by low-temperature and high-temperature electrolysis (using solid oxide electrolyzers). In the first case, the operating temperature of the electrolyzers does not exceed 100°C. High-temperature electrolysis requires water preheating to 800–1000°C. In this case, the consumption of electrical energy goes down by about 30%, and the total efficiency can reach 45–50% [18].

The sulfur-iodine cycle of nuclear power plants is one of the most promising methods of large-scale hydrogen production [18]. The Institute of Nuclear and New Energy Technology (China) in 2005 named the research of such a technological path of hydrogen production as one of the priority studies and developed a pilot plant that produces 60 liters of hydrogen per hour. The Japan Atomic Energy Agency developed a laboratory plant for hydrogen production using a continuous closed sulfur-iodine cycle with a capacity of 30 liters of hydrogen per hour in 2019. The researchers aim to reach larger hydrogen production (100 l/h) and achieve a longer period of operability [18].

The electrolysis-based hydrogen production relying on renewable energy does not emit greenhouse gases and has a minimal negative impact on the environment in comparison with other methods of hydrogen production. Currently, the cost of the hydrogen production through electrolysis is higher due to renewable energy than the production of hydrogen by reforming natural gas. However, the trend towards reduction in the cost of equipment and the cost of electricity generated from photovoltaic (PV) and wind (WPP) power plants has been observed in the last decade. It offers the hope for the successful commercialization of green hydrogen production technologies in the future [1, 3, 19].

A wide range of possible methods for producing hydrogen (see Fig. 1) makes it possible to establish its production in various territories, regardless of natural and climatic conditions and the availability of fossil fuel (due to the existing gas, oil and coal infrastructure that allows transporting energy resources anywhere in the world). The resulting “yellow,” “green,” “grey” or hydrogen of another “color” (Yellow hydrogen is hydrogen produced using nuclear energy; green hydrogen is hydrogen produced without CO (electrochemical water splitting, biological hydrogen production, use of biomass); grey hydrogen is hydrogen produced through steam conversion of natural gas; black (brown) hydrogen is hydrogen produced from coal gasification.) will exclude any GHG emission at the stage of its use by end-users. In addition to these factors, hydrogen transportation over long distances is technically difficult due to chemical and physical properties of hydrogen, and the use of hydrogen-containing substances (ammonia, methylcyclohexane) leads to an even greater complication and lengthening of production and technological processes, and a decrease in the total energy efficiency of the energy supply chain - from primary energy resources to useful energy for the final energy consumer. As a result, a significant part of the hydrogen produced will be used near the place of its production in the way that is the cheapest for this area, and its “greening” technologies will be used for consumers who are critically sensitive to this indicator.

This idea can be implemented through the mechanisms to trade in “green” certificates. Similar to the “green” certificates confirming the fact of generating electricity based on renewable energy sources, hydrogen “green” certificates will provide a guarantee of low or zero carbon “origin” of hydrogen. By purchasing such a certificate, the buyer will be able to consume hydrogen produced by any method (see Fig. 1) as “green”. At the same time, the cost of the certificate will have to compensate for the difference in the cost of production between the “green” hydrogen and the hydrogen consumed by this final energy consumer, which is obtained with the carbon monoxide emission, given the transaction costs of the trading system for the “green” hydrogen certificates. As a result, international trade in carbon-free hydrogen will be carried out in the form of the sale of virtual digital “green” certificates, and “former” green hydrogen can be used near its production sites. In other words, the consumption of relatively cheap “green” hydrogen will be concentrated in places of hydrogen production, while “grey” or “blue” (but repainted in “green”) hydrogen will be used in large consumption centers [20].

According to the Ministry of Industry and Trade of the Russian Federation, the main export direction of hydrogen carriers [21] from Russia will be the countries of the European Union and the Asia-Pacific region. At the same time, it is planned that more than 80% of hydrogen and 98.5% of ammonia will be produced on the territory of the ARR (Table 2) [21]. Due to the new economic sanctions imposed in 2022, the estimated production volumes of hydrogen and ammonia may decrease and “green” hydrogen carriers may be consumed domestically.

At the same time, there are only a few projects in Russia aimed at using hydrogen technologies by end consumers:

- The government of the Sakhalin Region, State Atomic Energy Corporation Rosatom, Joint stock company (JSC) Russian Railways, and JSC Transmashholding signed the agreement on cooperation and interaction on the project for building railway communication using hydrogen fuel cell trains and systems to ensure their operation in September 2019 in Vladivostok [22]. Hydrogen passenger train is planned to be based on the railbus RA-3. Operational and financial models were prepared, a feasibility study of the passenger transportation project on Sakhalin Island was developed. The first train is expected by 2024, and their number on the suburban network will increase to 7 in 2025–2030 and to 30 in the more distant future;
- The JSC Rusatom Overseas, PJSC KAMAZ, JSC Development Corporation of Russian Far East and Arctic, and JSC Development Corporation of Sakhalin Region signed a memorandum of understanding, which suggests cooperation in the development and application of hydrogen technologies in the transport sector on Sakhalin Island in September 2021. The parties consider the possibility of joint participation in the project for the creation of a hydrogen fleet, and the organization of zero carbon transport on hydrogen fuel cells in the Sakhalin region [23];
- The PJSC Gazprom and JSC Russian Railways implement joint projects in the field of hydrogen energy. Natural gas extracted from the fields of the Yamalo-Nenets Autonomous District can become a feedstock for the production of hydrogen on site in order to use the produced hydrogen as fuel for locomotives on the "Ob–Karskaya" railway [24];
- The En+ Group company plans to develop and implement a project for building a hydrogen transport infrastructure in the Krasnoyarsk Territory: the first stage suggests the construction of liquefied natural gas refueling stations, and the second stage includes the construction of liquid hydrogen station. The company is also developing cryogenic tank containers for the liquid hydrogen transportation, which are designed to solve the problem of long-distance delivery of hydrogen [25];
- The leading manufacturer and supplier of iron ore products and hot-briquetted iron in Russia, the Metalloinvest company, is implementing a project for the construction of the "Mikhailovsky HBI" plant with the prospect of a full transition to hydrogen. The JSC Rusatom Overseas (a company of the State Corporation ROSATOM) and Air Liquide, a leading producer of industrial gases, signed a memorandum of understanding to explore the possibility of organizing the production of low-carbon hydrogen and introducing hydrogen into the production processes of Metalloinvest company [26, 27].

III. Hydrogen Technologies and Prospects for Their Adoption in the Asian Regions of Russia

Although the number of projects aimed at hydrogen production (33 projects in the Atlas of Hydrogen and Ammonia Projects [21]) is significantly larger than the number of projects related to the use of hydrogen technologies by domestic consumers, there are some prerequisites for their application in Russia:

- The possibility of large-scale production of "grey," "yellow," and "green" hydrogen based on the use of large and cost-effective natural gas and coal resources, which are unused for operational reasons of generating capacities in electric power systems, or idle due to dispatch restrictions on the release of power from nuclear power plants or renewable energy sources (HPPs, WPPs, and PVs);
- The availability of natural and climatic potential for the production of "green" hydrogen based on the creation of renewable energy sources in isolated areas, primarily in the Arctic zone of the country;
- The necessity to test the technologies for hydrogen production, storage, and transport to gain a strong position in the world markets for hydrogen technologies;
- The need to reduce GHG emissions in industry and transport, and to create low-carbon energy and fuel supply systems, primarily for consumers of off-grid energy systems using "green" electricity generation.

The last circumstance is especially important for the ARR, where due to natural and climatic conditions and poorly developed infrastructure, the implementation of energy and fuel supply is complicated. At the same time, the mining industry plays an important role in the territory of Siberia, the Far East, and the Arctic, which is as a rule represented by isolated industrial hubs. The energy supply systems in such decentralized and hard-to-reach places can be established by combining hydrogen technologies with renewable sources and/or small and medium-power nuclear reactors. The combination of these technologies will make it possible to create autonomous carbon-free energy supply systems, which will improve the quality of energy services provided and eliminate dependence on the import of energy carriers.

An example of such a power supply system is the project of the Arctic scientific station "Snezhinka," which is planned to be started in 2024. The station is a fully autonomous complex based on renewable energy and hydrogen technologies. Under the project, hydrogen produced based on renewable energy sources will be used for uninterrupted power supply to the complex together with batteries for seasonal storage of renewable energy [28].

Another possible direction of using hydrogen in the ARR is to reduce emissions in the transport sector of the economy. The continental, sharply continental, and Arctic climate prevails in this territory, which is characterized by a long period of low atmospheric temperature. In these conditions, the use of FCEV is more preferable compared to electric vehicles (battery electric vehicle, BEV). The fuel cell design allows the FCEV to be operated at temperatures up to –40°C. The study of the effect of low temperatures on electric buses revealed that the driving range of the battery electric bus is reduced by 38% at ambient temperatures from 0 °C to –5°C, whereas for FCEV, this indicator was only 23.1% [29, 30].

IV. Conclusions

The last decade has seen an active development of hydrogen technologies, which currently remain more expensive than conventional ones. However, technological progress and financial instruments used in the framework of environmental initiatives can reduce their cost and make them competitive. The rapid expansion of the global FCEV fleet and the use of fuel cells in energy supply will require an increase in hydrogen production, and the creation of the necessary infrastructure, i.e., the systems for hydrogen production, storage, transportation, and distribution.

The availability of enormous fossil energy sources, a large capacity of NPPs, a high potential of increase in the capacity of HPPs, and high technical potential of RES allow large-scale production of hydrogen in the ARR. At the same time, the produced hydrogen can be consumed near the production sites, whereas the export of "green" hydrogen, due to the high cost and technological complexity of hydrogen transport over long distances, will be carried out virtually using the mechanisms of trading in hydrogen "green" certificates that confirm the carbon-free "origin" of a certain amount of hydrogen.

The territory of Asian Russia has prerequisites for the creation of autonomous low or zero carbon energy systems based on hydrogen technologies, which will make it possible to provide testing grounds for the improvement of these technologies, and to decarbonize industrial production, buildings, and transport sector of the economy.

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References

[1] "Future of Hydrogen," International Energy Agency (IEA), Jun. 2019 [Online]. Available: https://www.iea.org/reports/the-future-of-hydrogen. Accessed on: Dec. 15, 2022.

[2] *Green hydrogen cost reduction scaling up electrolyzers to meet the 1.5°C climate goal*. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/. Accessed on: Dec. 15, 2022.

[3] "Hydrogen forecast to 2050 energy transition outlook 2022," Oslo, Norway, 2022. [Online]. Available: https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050.html

[4] *Global EV Outlook 2019* [Online]. Available: https://iea.blob.core.windows.net/assets/7d7e049e-ce64-4c3f-8f23-6e2f529f31a8/Global_EV_Outlook_2019.pdf. Accessed on: Dec. 15, 2022.

[5] *Global EV Outlook 2022* [Online]. Available: https://iea.blob.core.windows.net/assets/ad8fb04c-4f75-42fc-973a-6e54c8a4449a/GlobalElectricVehicleOutlook2022.pdf. Accessed on: Dec. 15, 2022.

[6] *Share of electric and fuel-cell vehicles in total cars and light trucks sales in the Sustainable Development Scenario and Net Zero Emissions by 2050 case* [Online]. Available: https://www.iea.org/data-and-statistics/charts/share-of-electric-and-fuel-cell-vehicles-in-total-cars-and-light-trucks-sales-in-the-sustainable-development-scenario-and-net-zero-emissions-by-2050-case-2019-2030. Accessed on: Dec. 15, 2022.

[7] *Panasonic Launches New "ENE-FARM" Product. A Fuel Cell for Condominiums* [Online]. Available: https://fuelcellsworks.com/news/panasonic-launches-new-ene-farm-product-a-fuel-cell-for-condominiums/. Accessed on: Dec. 15, 2022.

[8] *Sunfire liefert weltgrösste kommerzielle reversible elektrolyse (rsoc) an Boeing* [Online]. Available: https://www.sunfire.de/en/news/detail/sunfire-liefert-weltgroesste-kommerzielle-reversible-elektrolyse-rsoc-an-boeing. Accessed on: Dec. 15, 2022.

[9] *Hydrogen Only Dry Low NOx Combustion Technology* [Online]. Available: https://global.kawasaki.com/en/hydrogen/. Accessed on: Dec. 15, 2022.

[10] *Hydrogen-fired Gas Turbine Targeting Realization of CO_2-free Society* [Online]. Available: https://www.mhi.co.jp/technology/review/pdf/e554/e554180.pdf. Accessed on: Dec. 15, 2022.

[11] *All eyes are on Hydrogen Energy* [Online]. Available: https://power.mhi.com/special/hydrogen/article_2. Accessed on: Dec. 15, 2022.

[12] Government Decree (2020, Jun. 09). *No. 1523-r*. [Online]. Available: http://publication.pravo.gov.ru/Document/View/0001202006110003. Accessed on: Dec. 15, 2022. (In Russian)

[13] Government Decree (2021, Aug. 05). *No. 2162-r*. [Online]. Available: http://publication.pravo.gov.ru/Document/View/0001202108100014. Accessed on: Dec. 15, 2022. (In Russian)

[14] Government Decree (2020, Oct. 12). *No. 2634-r*. [Online]. Available: https://minenergo.gov.ru/node/19194. Accessed on: Dec. 15, 2022. (In Russian)

[15] Government Decree (2021, Oct. 29). *No. 3052-r*. [Online].Available:http://static.government.ru/media/files/ADKkCzp3fWO32e2yA0BhtIpyzWfHaiUa.pdf. Accessed on: Dec. 15, 2022. (In Russian)

[16] Government Decree (2021, Nov. 27). *No. 3363-r*. [Online]. Available: https://mintrans.gov.ru/documents/2/11577. Accessed on: Dec. 15, 2022. (In Russian)

[17] *Could Hydrogen Open New Markets for Nuclear?* [Online]. Available: https://www.energy.gov/ne/articles/could-hydrogen-help-save-nuclear. Accessed on: Dec. 15, 2022.

[18] *The Role of Nuclear Power in the Hydrogen Economy: Cost and Competitiveness. – Paris: Organisation for Economic Co-operation and Development (OECD)* [Online]. Available: https://www.oecd-nea.org/upload/docs/application/pdf/2022-09/7630_the_role_of_nuclear_power_in_the_hydrogen_economy.pdf. Accessed on: Dec. 15, 2022.

[19] *Hydrogen: a renewable energy perspective* [Online]. Available: https://www.irena.org/-/media/ Files/IRENA/Agency/ Publication/2019/ Sep/IRENA_Hydrogen_2019.pdf. Accessed on: Dec. 15, 2022.

[20] S. P. Popov, D. V. Maksakova, O. A. Baldynov, "Prospects for electro-hydrogen infrastructure creation in northeast Asia," *Geoeconomics of Energetics*, no. 1 (17), pp. 132–155, 2022. DOI: 10.48137/2687-0703_2022_17_1_132.

[21] *Russian Atlas of Low-Carbon and Carbon-Free Hydrogen and Ammonia Production Projects* [Online]. Available: https://www.rohstoff-forum.org/wp-content/uploads/sites/2/2022/01/russian_atlas_of_low_carbon_and_carbon_free_hydrogen_and_ammonia.pdf. Accessed on: Dec. 15, 2022. (In Russian)

[22] *A decision was made to move to the implementation stage of the project to launch hydrogen fuel cell trains on Sakhalin* [Online]. Available: https://rosatom.ru/journalist/news/prinyato-reshenie-o-perekhode-k-etapu-realizatsii-proekta-zapuska-na-sakhaline-poezdov-na-vodorodnykh/. Accessed on: Dec. 15, 2022. (In Russian)

[23] *Development of the Sakhalin Region are joining forces in the development of environmentally friendly transport on Sakhalin Island* [Online]. Available: https://rosatom.ru/journalist/news/rosatom-kamaz-korporatsiya-razvitiya-dalnego-vostoka-i-arktiki-i-korporatsiya-razvitiya-sakhalinskoy/. Accessed on: Dec. 15, 2022. (In Russian)

[24] *Hydrogen will accelerate trains* [Online]. Available: https://gudok.ru/newspaper/?ID=1554543&archive=2021.02.26. Accessed on: Dec. 15, 2022. (In Russian)

[25] *En+ Group presented the results of the first year of the transition to carbon neutrality* [Online]. Available: https://www.enplusgroup.com/ru/media/news/esg/en-group-predstavila-rezultaty-pervogo-goda-perekhoda-k-uglerodnoy-neytralnosti/?sphrase_id=33610. Accessed on: Dec. 15, 2022. (In Russian)

[26] *Metalloinvest shares plans to decarbonize production and introduce hydrogen technology* [Online]. Available: https://www.metalloinvest.com/en/media/press-releases/560365/. Accessed on: Dec. 15, 2022. (In Russian)

[27] *Metalloinvest. ROSATOM and Air Liquide agreed to prepare a joint project for the production of low-carbon hydrogen* [Online]. Available: https://www.metalloinvest.com/en/media/press-releases/560285/. Accessed on: Dec. 15, 2022.

[28] *Snezhinka Station: the ISS beyond the Arctic Circle* [Online]. Available: https://arctic-russia.ru/en/project/snezhinka-station-the-iss-beyond-the-arctic-circle/. Accessed on: Dec. 15, 2022. (In Russian)

[29] *Technical note fuel cell electric buses cold weather operation* [Online]. Available: https://www.ballard.com/docs/default-source/motive-modules-documents/technical-note---bus-cold-weather-operation---final.pdf?sfvrsn=4&sfvrsn=4. Accessed on: Dec. 15, 2022.

[30] *Study by CTE: Cold weather effects range loss in winter fuel cell beats battery* [Online]. Available: https://fuelcellsworks.com/news/study-by-cte-cold-weather-effects-range-loss-in-winter-fuel-cell-beats-battery/. Accessed on: Dec. 15, 2022.

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