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Key challenges for the development of the hydrogen industry in the Russian Federation

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ABSTRACT

The Russian Federation is one of the five largest emitters of carbon dioxide. The carbon intensity of the Russian economy is one of the highest in the world. The development of the hydrogen industry in Russia is of crucial importance because it will allow reducing the carbon footprint of the economy, reducing the impact on the environment and reaching a new level of the fuel production basis and energy complex of the country. The paper presents the development prospects of hydrogen technologies in the Russian Federation, identifies the features of resource constraints in the H_2 production and aspects of H_2 transportation. Several hydrogen technologies of highest priority are identified, and technological barriers that must be overcome for their wide dissemination are described. Advanced solutions developed by Russian scientific, educational and industrial organizations for hydrogen energy infrastructure are presented. Special attention is paid to the standardization aspects of hydrogen technologies and the educational issues for the hydrogen industry development in the Russian Federation. The actions/targets set by Russian Federation are highlighted in the framework of Sustainable Development Goals system introduced by United Nations.

Introduction

The potential for reducing emissions from the use of low-carbon hydrogen is estimated at 5–6 Gt of CO_2-eq. per year, which is ~20 % of the required reduction (to keep global warming within 1.5° C). The development of the hydrogen industry as a base for building a low-carbon economy in the Russian Federation is of crucial importance since the Russian Federation is one of the five largest emitters of carbon dioxide (CO_2). In the pre-pandemic 2019, CO_2 emissions in the Russian Federation amounted to 1.8 billion metric tons (~5% of the global total) [1]. At the same time, the carbon intensity of the Russian economy is one of the highest in the world and amounts to 445 kg of CO_2/$1000 GDP, which is higher than the values of the European Union (148 kg CO_2/$1000 GDP) and the USA (245 kg of CO_2/$1000 GDP), and close to that of China (511 kg CO_2/$1000 GDP), which is the leader among CO_2 emitters (2019 data) [1].

Alternative resources are essential in the substitution of the non-renewable fossil fuels to reduce carbon footprint. Amongst the others, hydrogen is very promising alternative as the near-term green energy basis by virtue of its clean combustion product: water. Ever-growing number of state-of-the-art review and overview articles highlight the fast development of different areas of hydrogen technologies (see further). Hydrogen energy systems are regarded as the prospective replacement of the present fossil fuel energy systems, which concurrently supporting the long-term energy and environmental sustainability [2]. Hydrogen can be extracted from an extensive range of substances, such as fossil fuels (natural gas, oil, coal) [3,4], water [5–7], biomasses [8,9], wastes (i.e. sewage sludge) [10,11], etc. A wide spectrum of H_2-fuel application is available, including fuel cells [12], direct-combustion [13,14], and co-combustion with other fuels [15,16]. The fuel cells are considered as a novel green and sustainable energy strategy for automobiles [17], maritime [18], aviation and aerospace [19] applications due to their high efficiency, flexibility, modular structure, and noiseless operation [20,21]. In terms of power management and stability, fuel cells can significantly improve the performance of grid utility when compared to the intermittent nature of solar and wind resources [22,23]. Fuel cell energy generation devices for power network interfaces have recently been utilized in grid-connected applications [22,24,25].

Novel hydrogen technologies can help to reduce the carbon intensity of the economy and the environmental impact, and achieve a new level

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Nomenclature

Abbreviations

AEM anion exchange membrane
CGH_2 compressed gaseous hydrogen
CCUS carbon capture, utilization, and storage
CO_2-eq CO_2-equivalent
DRI direct reduced iron
GDP gross domestic product
HTGR high-temperature gas-cooled nuclear reactors
Hythane hydrohen-methane mixture
IEA International Energy Agency
ISO International Organization for Standardization
IEC International Electrotechnical Commission
JSC joint stock company
LH_2 liquefied hydrogen
LLC limited liability company
LOHC liquid organic hydrogen carrier
MDEA methyl diethanolamine
PEM proton-exchange membrane
PEMFC proton-exchange membrane fuel cell
RES renewable energy sources
SMR steam methane reforming
SOE solid oxide electrolyzer
SOFC solid oxide fuel cell
SDGs Sustainable Development Goals
TC Technical Committee
TRL technology readiness level
UN United Nations

Units

Bcm billion cubic meters
Gt gigatons
GW gigawatt
MW megawatt
Mt megaton
Mtce Million Ton Of Coal Equivalent

Organizations Acronyms

IC SB RAS Federal Research Center Boreskov Institute of Catalysis, Siberian Branch Russian Academy of Sciences
IGIC RAS N.S.Kurnakov Institute of General and Inorganic Chemistry Russian Academy of Sciences
IHTE UB RAS Institute of High-Temperature Electrochemistry, Ural Branch Russian Academy of Sciences
IPCP RAS Institute of Problems of Chemical Physics Russian Academy of Sciences
ISSP RAS Institute of Solid State Physics Russian Academy of Sciences
ISSC UB RAS Institute of Solid State Chemistry, Ural Branch Russian Academy of Sciences
ISSCM SB RAS Institute of Solid State Chemistry and Mechanics, Siberian Branch Russian Academy of Sciences
JIHT RAS Joint Institute for High Temperatures Russian Academy of Sciences
JINR Joint Institute for Nuclear Research
Kurchatov Institute National Research Centre Kurchatov Institute
MSU Moscow State University
MIPT Moscow Institute of Physics and Technology
Niigrafit State Research Institute of Graphite – Based Structural Materials
Samara Polytech Samara State Technical University
SDEBE Special Design Engineering Bureau in Electrochemistry with Experimental Factory
TIPS RAS A.V.Topchiev Institute of petrochemical synthesis Russian Academy of Sciences
TPU National Research Tomsk Polytechnic University
TRINITI JSC JSC State Research Center of the Russian Federation Troitsk Institute for Innovation and Fusion Research
TSTU Tambov State Technical University
ZIOC RAS N.D.Zelinsky Institute of Organic Chemistry Russian academy of Sciences

of the fuel production basis and energy complex of the Russian Federation to ensure its competitiveness and sustainability in the long term [26]. They are important for ensuring the connectivity of the Russian Federation territory due to the development of remote (e.g. the Arctic) regions and autonomous energy supply systems [27,28]. The effect of creating high-tech jobs for the development of a new industry is also important [29].

The possibilities of intensive development of the national market and the entry of the Russian Federation into a leading position in the emerging global hydrogen markets are based on the following premises:

a) Availability of low-carbon energy potential (electricity with low specific CO_2 [30] emissions, solar [31] and wind [32] potential) and significant reserves of hydrocarbon resources for large-scale hydrogen production. According to forecasts of the IEA [33] and the Ministry of Energy of the Russian Federation, [34] natural gas, whose production volumes in the Russian Federation in 2019 alone amounted to 737.8 billion m^3 [35], will remain the main raw material for hydrogen production over the next 10–15 years.
b) Significant experience in the use of methane steam conversion and electrolysis technologies, and the availability of developments and competencies in a wide range of hydrogen [36–38] and CCUS [39–41] technologies. The current world level of 2/3 of the infrastructure technologies necessary for the production, transportation and use of low-carbon hydrogen corresponds to the pre-commercial stage – the “large prototype” or “demonstration” levels (TRL 5–7) [42]. The Russian Federation can act as a testing ground for new technological solutions and their exporter.
c) Favorable geographical location, which opens the possibility for the formation of supply chains of hydrogen to the largest projected centers of its consumption in Europe and the Asia-Pacific region with a relatively short logistics leg [43], as well as the presence of a developed oil and gas transportation infrastructure, promising for the transportation and export of hydrogen. For example, the total length of gas pipelines in Russia is 172.6 thousand km with 254 compressor stations. At the same time, the bulk of hydrogen (~5.2 million tons in 2020) is produced at enterprises that use it further in their technological processes (the so-called captive hydrogen) of oil refining (~37 %) and chemical industry (~48 % – ammonia production, ~13 % – methanol production) [44]. The situation in the world is similar – there is practically no market for non-captive export hydrogen, and with proper efforts, the Russian Federation can take a leading position in it.

However, to realize these advantages and build an economically self-sufficient hydrogen industry in the Russian Federation, it is necessary to adopt a set of measures set out in the Energy Strategy of the Russian Federation for the period up to 2035 [34], the Hydrogen Energy Development Concept [45], the Roadmap “Development of Hydrogen Energy in the Russian Federation until 2024″ [46], the Technological Strategy for the Development of hydrogen Energy in the Russian Federation until 2035 and the Comprehensive program for the development of the low-carbon hydrogen energy industry in the Russian Federation. One of the key tasks is to create an infrastructure for the transportation and consumption of hydrogen and energy mixtures based on it and the development of domestic low-carbon technologies for the production, storage, transportation, and use of hydrogen. For the successful implementation of this measure, it is necessary to analyze technological and economic opportunities and barriers for Russia, to determine the most appropriate directions for the development of technologies to unlock the economic potential of the hydrogen industry. This work is devoted to these tasks.

Prospects for the development of hydrogen technologies

Turning directly to hydrogen technologies, it is important to note that the potential market for hydrogen technologies exceeds the hydrogen market by an order of magnitude. And if the Russian Federation occupies 10 % of the hydrogen technology market, the country will be able to receive up to several billion dollars ($4.1–4.3 billion) a year in tax revenues from technology companies. The potential volumes of hydrogen exports, according to the Hydrogen Energy Development Concept, from the Russian Federation to the world market may amount to 0.2 million tons in 2024, 2–12 million tons in 2035, and 15–50 million tons in 2050, depending on the pace of development of the global low-carbon economy and the hydrogen demand growth in the world market.

The main goal of the development of the hydrogen industry in the Russian Federation is to reduce the cost of producing low–carbon hydrogen **to $2 per 1 kg**, which can be achieved by improving elements of existing technologies and developing new ones. There are two main routes to produce large-scale hydrogen – hydrocarbon reforming and water electrolysis. For hydrogen produced from natural gas, the achievement of the target indicator is possible if CO_2 capture, utilization and storage processes are widely developed and implemented (including CO_2 capture with new variations of high-efficiency amine purification [47] and pressure swing adsorption [48]); the development of membrane technologies and materials for hydrogen production are also necessary [49,50]. The second route is an environmentally friendly energy strategy to produce high-purity hydrogen (99.999 %) from renewable water via water electrolysis. However, hydrogen production efficiency in this case is low to be economically competitive with fossil fuel based H_2 due to the high energy consumption and low hydrogen evolution rate. Therefore, to increase the efficiency and reduce the energy consumption, it is necessary to increase the activities within alternative low cost electrocatalysts, efficiency and energy reduction. The target $2/kg H_2 value can be provided by the 85–90 % reduction in the cost of electrolyzers due to the development of new corrosion-resistant materials and coatings for alkaline electrolyzers [51], which are well established technology up to the megawatt range for commercial level in worldwide [52]. The development of new proton-conductive membranes with an increased resource for PEM electrolyzers [52], and new multilayer ceramic materials for SOE (the electrical energy in SOE converts into the chemical energy along with producing the ultra-pure hydrogen with greater efficiency) [53] are also perspective.

Considering the stated ambitious plans, the envisaged state investments in hydrogen technologies in the Russian Federation amounted to only 9 billion rubles until 2024.

Hydrogen production: Resource constraints

In the world, hydrogen production is growing by about 3–4 % per year. Currently, taking into account ammonia, more than 100 (116) million tons of hydrogen are produced and consumed in the world. More than 90 % of hydrogen is captive and produced at the place of its consumption, and less than 10 % is supplied by specialized companies operating in the industrial gas market (Air Liquide, Linde, Praxair Inc., etc.). The total average annual volume of hydrogen production in Russia is about 5 million tons, more than 95 % of which is captive (the rest of the hydrogen is consumed almost entirely in the rocket and space industry).

At the same time, covering demand with low-carbon hydrogen is associated with resource, technological and production constraints. Table 1 shows the *linear upscaling factors* of the *existing* resources for the production of 60 million tons of low-carbon “green” non-captive hydrogen in the world per year. The assessment of the installed capacity of RES was carried out based on solar power plant; capacity factor of solar power plant and wind power plant in Russia are close on average, so it is possible to generalize the result for wind power plant and other RES.

These coefficients are several times higher and range from 16 to 21.6 (see Table 2) to produce 2.4 million tons of electrolytic hydrogen in the Russian Federation.

Today, the average capacity of groups of industrial alkaline electrolyzers in the world (one of the most common nowadays) is about 250 MW (with a production of 6 million m^3 per year). In Russia, to produce 2.2 million tons for export and 0.2 million tons per year for domestic consumption, which are required by 2030 in the sustainable development scenario (about 26,705 million m^3 per year), about 1.08 GW of electrolyzers are needed. It is estimated that the current power of operating electrolyzers in Russia is about 0.05 GW. There are no restrictions on the consumption of freshwater. The production of hydrogen by electrolysis, as well as steam conversion of methane requires 9.4 million tons/year, which is less than 1 % of the volume of water in Lake Baikal. There are no resource (methane) restrictions to produce low-carbon hydrogen from hydrocarbon raw materials in the required volumes.

At the same time, there is a high level of dependence on imports of low-carbon hydrogen production technologies from hydrocarbons. Most of the existing methane steam conversion plants and all new plants are supplied by foreign companies. One of the critical areas in the domestic industry is catalysts. However, Rosneft produces more than 70 % of hydrogen using its own catalysts [54]. The same catalysts are operated by Russian enterprises of other oil companies.

As stated in IEA report [55], global hydrogen demand of 90 Mt in 2020 was met almost entirely by fossil fuel-based hydrogen, with 72 Mt H_2 (79 %) coming from dedicated hydrogen production plants. The remainder (21 %) was byproduct hydrogen produced in facilities designed primarily for other products, mainly refineries in which the reformation of naphtha into gasoline results in hydrogen. Pure hydrogen demand, mainly for ammonia production and oil refining, accounted for 72 Mt H_2, while 18 Mt H_2 was mixed with other gases and used for methanol production and DRI steel production. Natural gas is the main fuel for hydrogen production, with SMR being the dominant method in the ammonia and methanol industries, as well as in refineries. Using 240 bcm (6 % of global demand in 2020), natural gas accounted for 60 % of annual global hydrogen production, while 115 Mtce of coal (2 % of global demand) accounted for 19 % of hydrogen production, reflecting its dominant role in China. Oil and electricity fuelled the remainder of dedicated production. Various technology options exist to produce low-carbon hydrogen: from water and electricity via electrolysis; from fossil fuels CCUS; and from bioenergy via biomass gasification. However, they account for very small shares of global production: at 30 kt H_2, water

Table 1
The upscaling factors of the required resources for the production of 60 million tons of hydrogen per year in the world.

Resource	Upscaling factor
Electrolyzers production, GW per year	5.4
The volume of installed capacity based on renewable energy sources, GW	1.9
RES area, thousand km (RES area refers to the required area of land plots for the construction of RES)	5.8

Table 2
The upscaling factors of the required resources for the production of 2.4 million tons of hydrogen per year in the Russian Federation.

Resource	Upscaling factor
Electrolyzers production, GW per year	21.6
RES area, thousand km	16
The volume of installed capacity on the basis of RES, GW	16

electrolysis made up ~0.03 %, and 16 fossil fuel with CCUS plants produced just 0.7 Mt H_2 (0.7 %) [55].

Transportation of hydrogen

There is currently-one operational tanker from Kawasaki [56] to transport hydrogen. The company also announced a project for the construction of 80 tankers with a total transportation volume of about 9 million tons [57]. The cost of the prototype tanker for 75 tons was 368 million dollars.

For the transportation of LH_2 in a liquefied state, tanks with a volume of 4 tons are used today, about 1000 tanks are produced in the world per year. Accordingly, to transport 60 million tons of LH_2 in tanks, it is necessary to increase their number to 625,000 units.

In the Russian Federation, the production capacity of tanks for LH_2 is 10 pcs per year [58], about 21,000 tanks will be required to transport 2.4 million tons of low-carbon hydrogen (required by 2030 in a sustainable development scenario). Complex solutions of tanks for the transportation of CGH_2 in the Russian Federation are at a low level of technological readiness. Hydrogen transportation requires significant investments in the development of production facilities and infrastructure; in particular, a twofold increase in the volume of ammonia production, an increase in the volume of toluene production for the transportation of hydrogen in the LOHC form by 102 times.

Hydrogen technologies: Priorities of the Russian Federation

Today, there is a high dynamics of development of hydrogen technologies in the world. Since 2010, more than 15 thousand international patents have been registered on hydrogen technologies in the world, while in Russia patent activity in this area has been rapidly declining in recent years to the level of less than 20 new patents per year. Since 2010, 819 patents have been registered in the Russian Federation on hydrogen technologies.

The development of the hydrogen economy in the Russian Federation requires, first of all, the development of critical technologies. The criteria for choosing priority areas for the development of hydrogen technologies are the demand for the industry in the short-term (2030) and long-term (2050) period, criticality for import substitution, export potential.

Analysis of the technology readiness levels shows that an initial package of hydrogen technologies with a relatively high technology readiness level has already been formed in the world, and it is expected that by 2030 most hydrogen technologies will be ready for industrial use; today, in the Russian Federation TRL is 6 and lower for most technologies.

The current situation is due to the specifics of financing science and development in the Russian Federation. The main part of the budget of scientific organizations was/is targeted budget funds, the Russian Foundation for Basic Research, the Russian Science Foundation, and subsidies under Federal targeted programs. The specificity of the targeted nature of these funds determined the maximum level of readiness of the funded developments at about the level of TRL 4–5.

Considering the achieved level of technological readiness and importance for the implementation of the hydrogen program in Russia, **23 priority technologies** have been identified and presented in Fig. 1.

Following these criteria, priority technologies are divided into 3 groups:

1. Purchase and use of technological equipment necessary for the speedy creation of the industry from foreign suppliers. *4 technologies are assigned to this category:* SMR, autothermal reforming, hydrogen purification from CO_2 by amine absorption, hydrogen compression technologies (CGH_2).
2. Development of Russian technologies that are in demand in Russia in the long term to replace imported technologies. *8 technologies:* PEM electrolysis; AEM electrolysis; alkaline electrolysis; low-pressure vessels for hydrogen storage, H_2 storage in methanol technologies; ammonia technologies (ammonia synthesis); steam-gas power generators based on methane-hydrogen mixtures; the use of hydrogen to produce hot briquetted iron.
3. Development of Russian technologies with advanced technical and economic indicators for use in Russia and for export. This category

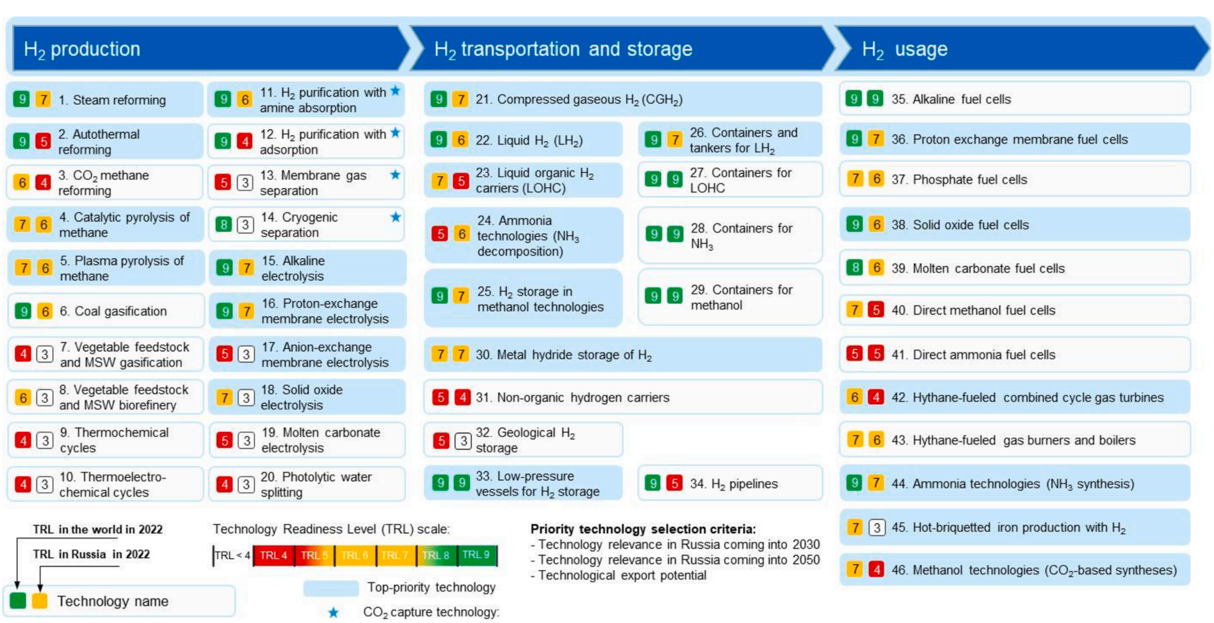

Fig. 1. Priority hydrogen technologies in the Russian Federation.

includes *10 technologies:* catalytic and plasma pyrolysis of methane; SOE; technologies for LH_2 producing; containers for transportation and storage of LH_2; metal hydride storage of H_2; technologies for hydrogen storage in LOHC (hydrogenation/dehydrogenation processes); PEMFC; SOFC; methanol technologies (CO_2-based syntheses) (see Fig. 1).

At the same time, it is important to note that the potential for the development of the hydrogen economy in the Russian Federation is associated with the presence of competitive advantages. In particular, advanced technological solutions in the field of hydrogen energy are being developed in the Russian Federation:

- There is a unique experience (Kurchatov Institute) in the field of plasma chemical decomposition of hydrogen sulfide, TRL more than 6 [59]. Today, work is underway in the field of plasma pyrolysis of methane [60], pyrolysis in molten metals, e.g., in iron (high temperature) according to the scheme of oxidation-reduction of iron at temperatures of 1200 °C [61,62].
- With regard to nuclear reactors in the hydrogen industry, technologies have been developed by the State Atomic Energy Corporation ROSATOM – Rosatom State Corporation for the use of HTGR [63], and molten salt reactors capable of generating heat with a temperature of 950–1000 °C°, for the production of hydrogen by SMR, pyrolysis or thermolysis of water with simultaneous provision of expanded production of nuclear fuel [36,64,65]. Russia's first nuclear power plant for hydrogen production is planned to be launched by 2033 and put into commercial operation by 2036. It is planned that the HTGR-based systems for hydrogen production by the SMR method will consist of four reactor modules with a total thermal capacity of 2400 (4x600) MW. Annual hydrogen production will be 0.84 million tons, methane consumption – 2700 million Nm^3 [65].
- The State Atomic Energy Corporation ROSATOM develops technological bases for the creation of gas diffusion layers and bipolar plates. Bipolar plates with a high graphite content are distinguished by exceptional electrical conductivity, corrosion resistance, mechanical strength and flexibility. Developments are being conducted at the Niigrafit [66], TRINITI JSC.
- Technological cooperation between IGIC RAS [67–72], TRINITI JSC, JINR and Rosatom State Corporation, on the creation of a nanostructured membrane with high proton conductivity for low-temperature fuel cells. The work is planned to be completed by 2024.
- Rusnano JSC, together with InEnergy Group, has developed a pre-production sample of a 45 kW electrochemical generator [73] based on a stack under an Axane license for use in hydrogen buses and other vehicles.
- Rusnano JSC together with Sintez OKA Group are engaged in the development of solutions and the supply of reagents for the release of CO_2 in the production of low-carbon hydrogen by steam reforming of methane. Special absorbers based on MDEA have been developed to purify hydrogen and remove CO_2 from gas streams [74]. Construction of a plant for the production of MDEA with a capacity of 15 000 tons (MONAMIN LLC, Dzerzhinsk) has begun. Commissioning is planned in 2023.
- Rosatom State Corporation (together with IPCP RAS, JIHT RAS, JSC SDEBE, Niigrafit, Mashtest Company), is developing a metal hydride hydrogen storage system [75,76].
- JSC Plastik has the production capacity to create gas polymer composite cylinders of 4 types [77]. The time frame for mass production of hydrogen cylinders is ~1.5 years in case of sufficient investments.
- JSC "Cryogenmash" has a great background in the field of designing and creation of the installation for LH_2 production. The organization is competent in the field of design of liquefaction plants with a capacity from 180 to 700 kg/h of liquid hydrogen (4.3 – 16.8 t LH_2/day) [58]. Today, the production capacity of tanks for LH_2 (4 million tons) is 5 pcs/year. According to the manufacturer, in 3 years it is possible to introduce a plant with a capacity of 500 to 1000 tanks.
- Rusnano JSC, together with InEnergy Group, has developed a complete set of arrangements for a hydrogen filling station [78] with hydrogen delivery for certification in the Russian Federation. Productivity – from 90 kg H_2/day, the source of hydrogen is cylinders.

The technologies of electrolyzers and fuel cells have the greatest potential for cost reduction (more than 40 % by 2050), primarily due to the economies of scale associated with a decrease in unit costs with an increase in the unit installed capacity of the system and an increase in efficiency associated with the optimization of the technological line [79].

At the same time, the current backlog of the Russian Federation in all technological areas is 1–7 years. The vast majority of technologies are at the readiness level TRL 3–6: the concept has been confirmed, laboratory tests have been carried out, in some cases experimental prototypes have been created. Another reason for the insufficiently high level of technological readiness of hydrogen technologies is the peculiarity of the scientific and technological landscape of the Russian Federation in the field of hydrogen technologies, characterized by fragmentation and lack of coordination in the research and development agenda. So, there is a groundwork in the field of hydrogen production, but there are no comprehensive solutions in the following areas:

- Steam reforming of hydrocarbons: developments exist in the IC SB RAS, Krylov State Research Center (TRL 5–7), TIPS RAS (membrane converters, TRL 3–5 [80–82]).
- Autothermal reforming: in IC SB RAS, TRL 5 has been established [83–87].
- Decomposition (pyrolysis) of hydrocarbons: IC SB RAS (nanotubes as a target product, TRL 7–8 [88–90]), TIPS RAS (pyrolysis on nickel catalysts, TRL 3–4) [91], JIHT RAS (pyrolysis of biomass, TRL 2) [92–94], Samara Polytech (pyrolysis in molten metals, TRL 5) [61].
- Plasma pyrolysis: the groundwork exists in TIPS RAS (TRL 4) [95–98], TPU (TRL 4) [60,99,100], Kurchatov Institute (TRL 3–4).
- In the field of adsorption release of hydrogen, low-tonnage solutions are provided by JSC Grasys (pressure swing adsorption) [101], however, the production of adsorbents for the technology (a critical component) is practically absent in the Russian Federation. Sorbent developments are carried out in IC SB RAS [102,103], ZIOC RAS and MSU [104], TIPS RAS [105,106], and TSTU (TRL 2–3) [107,108].
- The groundwork in the field of hydrogen storage technologies in metal hydrides exists in MSU [109,110], IPCP RAS [111,112], JIHT RAS [113–115], Krylov State Research Center; SDEBE have been [116] brought to TRL 5.
- Experience in the development of technologies for storing hydrogen in liquid organic carriers is available at ZIOC RAS [117,118], TIPS RAS, Samara Polytech [119], the level of development of these technologies corresponds to TRL 3–4.
- Critical technologies in the field of fuel cells are sufficiently advanced in the NTI Competence Center for the novel and mobile energy sources technologies at IPCP RAS [120–123], Krylov State Research Center [124,125], and InEnergy Group [73,126], Kurchatov Institute (catalysts and electrodes for PEM electrolyzers and PEMFC [127,128], TRL 4–5). The TRL of the end product technologies can be estimated at 5–7 for various applications of these products.
- In the field of SOFC, there are a number of organizations with a set of competencies in this field (ISSP RAS and MIPT [129–132], IHTE UB RAS [133–135], ISSC UB RAS [136], ISSCM SB RAS [137–140]). Products with an power output of 1–2 kW have been created and tested.

Components and parts of hydrogen technologies in some cases have no groundwork in the territory of the Russian Federation. For example, for the method of SMR, groundwork for most components and parts is absent or at low TRL. The key reason for the low level of development of groundwork is the lack of required materials on the territory of the Russian Federation (for example, zeolites, silica gels, Al_2O_3 for the production of pressure swing adsorption adsorbents, membranes for hydrogen purification and production plants, etc.). For autothermal methane reforming, catalytic and plasma-chemical decomposition of methane, technological barriers are the lack/absence of high-temperature hydrogen-resistant structural materials, domestic efficient and cheap catalysts, as well as schematic solutions in the field of reactor design, mixing devices, hydrogen burners, plasma generators, etc. In terms of hydrogen production by PEM electrolysis, the main barrier is the lack of mass production of a polymer electrolytic membrane and gas diffusion layers for electrolyzers in the Russian Federation. In terms of the storage and transportation of hydrogen in the LOHC, the main barrier is the lack/absence of mass production of effective catalysts for hydrogenation/dehydrogenation of organic liquids. In the field of ammonia technologies, the main barrier is the lack of new effective catalysts for the synthesis/dissociation of ammonia, schematic solutions for generators of hydrogen from ammonia, materials for separation and purification units of hydrogen from ammonia (adsorption, membrane separation). In the field of decarbonization of hydrogen-containing gases by absorption by alkanolamines, the main technological barriers are the lack of production of domestic additives to significantly improve the operational properties of absorption liquids: activators (for example, piperazine), corrosion inhibitors, defoamers; a significant difference between the absorption and desorption temperatures. Regarding the use of hydrogen for power generation in solid oxide fuel cells, the main technological barriers are the lack/absence of materials (iron-chromium steels, spinels based on Cu-Mn-Co-Ni-Fe complex oxide phases) for the production of bipolar plates and end plates with protective coatings.

Overcoming technological limitations requires financing for research, development and infrastructure – more than 20 billion rubles, for pilot installations – more than 100 billion rubles. The format of financing of the priority technologies development should provide for the unification of the efforts of scientific and industrial organizations and the creation of public-private partnerships within the framework of unified thematic programs.

Based on the experience of foreign colleagues (by analogy with the plans of the US Department of Energy), it seems appropriate to consider the possibility of creating national laboratories that interact with industrial leaders to develop technologies and bring them to TRL 4, as well as the creation of engineering centers for the development of pilot plants to work with high-readiness technologies and their introduction into mass production. The presence of a qualified state customer working with a bundle of applied and fundamental science becomes critical.

Standardization in the field of hydrogen technologies

In addition to the development of the technologies themselves, the development, updating and harmonization of standards are also necessary for their introduction into mass production To date, there are 138 international ISO and IEC standards in the field of hydrogen technologies in the world. In the Russian Federation, 39 existing hydrogen standards are available. For the development of hydrogen technologies in the Russian Federation, it is advisable to develop more than 100 national standardization documents. The Profile TC 29 needs to ensure interaction with related standardization committees; it is also necessary to establish coordination with committees in the field of metallurgy, chemical industry and mechanical engineering. It is important to note that Rosstandart, with the assistance of the Ministry of Energy of the Russian Federation, has created a new technical committee for standardization TC 239 "Carbon Dioxide capture, transportation and storage" [141]. Today, the development of the main part of the standards is assigned to TC 29 "Hydrogen Technologies"; 78 standardization documents should be developed by specialized transport standardization committees, where the use of hydrogen as fuel is a priority. In turn, TC 29 will act as a related technical committee. In 2022, TC 29 "Hydrogen Technologies" will develop 35 national standards. TC 56 "Road Transport" included the development of 9 original (having no international analogues) standards in terms of fuel cell vehicles in the National Standardization Program for 2022. In total, 135 standards in the field of hydrogen technologies need to be developed by 2024: TC 29 "Hydrogen technologies" – 57 pcs, TC 56 "Road transport" – 30 pcs, TC 45 "Railway transport" – 27 pcs, TC 05 "Shipbuilding" – 12 pcs, TC 323 "Aviation equipment" – 6 pcs, TC 403 "Ex-equipment" – 3 pcs; the total cost of work on the development of national standardization documents will be ~142 million rubles.

Educational issues for the hydrogen industry

The development of technology also requires a significant increase in educational area. At the moment, training of specialists in programs in the field of hydrogen energy technologies within separate courses or in courses of alternative and/or electrochemical energy is conducted in such leading universities as MSU, National Research University "Moscow Power Engineering Institute", Saint Petersburg Mining University, MIPT and others. To increase human resources, it is necessary to introduce new educational programs of higher and secondary vocational education in the field of hydrogen technologies at 19 Russian universities, including universities: Mendeleev University of Chemical Technology of Russia, National Research Nuclear University MEPhI "Moscow Engineering Physics Institute", Sakhalin State University, etc. It is planned to increase the number of specialists in the field of hydrogen economy from 200 to 5400 per year by 2030. This requires the development and updating of more than 100 professional standards for 41 professions of workers and 23 positions of employees in the field of hydrogen technologies by 2026; the development of new profiles and modernization of about 80 educational programs in 26 specialties of higher professional education by 2026, including specialties: power engineering and electrical engineering, electric transport (unconventional and renewable energy sources), chemistry and chemical technologies, composite materials technologies, nanotechnologies and nanomaterials, aviation and rocket and space technology, standardization and metrology, etc. In addition, it is planned to create corporate educational programs in the field of hydrogen energy by 2024. Costs are estimated at 15.4 billion rubles. The implementation of the human resources development program should be carried out at the expense of state resources, as well as universities in cooperation with their industrial partners (targeted training at the expense of employers).

Hydrogen industry relevance toward sustainable development goals

The SDGs show the major challenges that mankind face with [142]. Since the introduction of SDGs in 2015 by the UN, many countries worldwide and their institutions have been engaged in drawing policies that concern environmental, social, and human development [143,144]. There are 17 SDGs, each covering a critical field of sustainable development defined by many societal, economic, or ecological metrics. Russian Federation established a set of strategic documents (Energy Strategy of the Russian Federation for the period up to 2035 [34], the Hydrogen Energy Development Concept [45], the Roadmap "Development of Hydrogen Energy in the Russian Federation until 2024″ [46]) with different targets for H_2 industry development. A lot of them are also directly intended to achieve a number of SDGs. Table 3 presents the specific targets set in Russian Federation related to development low-carbon hydrogen fuel industry, clean technologies, and proposed actions. The data presented provide clear correlation between Russia's future energy strategy and its contribution to the global green energy and climate impact issues.

Table 3
Summary of related SDGs and targets/proposed actions set by Russian Federation.

SDG	Global Target within SDG	Global Indicator within SDG	Targets set by Russia [45,46]
4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	4.4 By 2030, substantially increase the number of youth and adults who have relevant skills, including technical and vocational skills, for employment, decent jobs and entrepreneurship	4.4.1 Proportion of youth and adults with information and communications technology (ICT) skills, by type of skill	1. The number of hydrogen industry specialists is increased to 5400/year by 2030. 2. Development/updating of >100 professional standards for 41 professions of workers and 23 positions of employees in the hydrogen industry by 2026. 3. Development of new profiles of 80 educational programs in 26 specialties of higher education by 2026.
7. Ensure access to affordable, reliable, sustainable, and modern energy for all	7.1 By 2030, ensure universal access to affordable, reliable, and modern energy services 7.2 By 2030, increase substantially the share of renewable energy in the global energy mix	7.1.2 Proportion of population with primary reliance on clean fuels and technology 7.2.1 Renewable energy share in the total final energy consumption	- Development, manufacture and testing of gas turbines on Hythane fuel by 2024–2025; - Approbation of the use of H_2 and Hythane fuels (with different H_2 content in the mixture) in gas power plants (gas turbine engines, gas boilers, etc.) and as a motor fuel in various transport types; - Target and actions within SDG 9.
9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities	9.4.1 CO_2 emission per unit of value added	- Creation, upscaling, and use of pilot H_2 production plants without CO_2 emissions by 2024; - Creation of pilot polygons for low-carbon H_2 production at hydrocarbon processing or natural gas production facilities by 2023–2024; - Pilot project for the H_2 production using the capacities of nuclear power plants by 2023–2024; - Providing R&Ds on technologies and greenhouse gas emissions in the production chain for various schemes for the production, transportation, and use of H_2 by 2024–2025; - Development of a concept for ensuring safety in the production, storage and transportation of H_2 at nuclear power plants by 2023–2024;
11. Make cities and human settlements inclusive, safe, resilient and sustainable	11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	11.6.2 Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)	- Ensuring the creation of a prototype railway transport on hydrogen fuel by 2024–2025; - Development of H_2-based cars and H_2 fuel stations.
12. Ensure sustainable consumption and production patterns	12.2 By 2030, achieve the sustainable management and efficient use of natural resources 12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse	12.2.2. Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP 12.5.1 National recycling rate, tons of material recycled	- Provision of research on the use of carbon released during thermal and plasma-chemical processes (low-carbon H_2 production with pyrolysis) by 2024–2025.
13. Take urgent action to combat climate change and its impacts	13.2 Integrate climate change measures into national policies, strategies and planning	13.2.1 Number of countries with nationally determined contributions, long-term strategies, national adaptation plans and adaptation communications, as reported to the secretariat of the United Nations Framework Convention on Climate Change 13.2.2 Total greenhouse gas emissions per year	- Targets and actions within SDG 9; - Development of proposals for the creation of a certification system for low-carbon H_2 by the end of 2022; - Development of a methodology for assessing the life cycle of various methods of H_2 production by the end of 2022; - Development and approval of a methodology for life cycle assessment and classification of H_2 in terms of greenhouse gas emissions by 2023–2024;

Conclusion

Transition to decarbonization and the need to reduce the carbon intensity of the national economy open up additional opportunities for the Russian Federation associated with the development of a new high-tech hydrogen industry and related areas. At the same time, significant experience has been accumulated in the Russian Federation in the field of creating and implementing technologies for industrial production of hydrogen. The current technology readiness level of hydrogen energy makes it possible to ensure a return on investment in the long term, which determines the need to concentrate efforts on overcoming fundamental technological barriers with the creation of a complex of domestic technologies that ensure the production, storage, transportation and use of hydrogen. In the field of hydrogen production in the near future (until 2030), in order to create such a complex in the Russian Federation, it is important to improve traditional methods of hydrogen production (steam and autothermal reforming) in combination with hydrogen purification and the release/disposal of CO_2. It is necessary to bring processes using methane as a raw material to a high TRL with the production of hydrogen and commercial products (pyrolysis of methane with the production of carbon in commercial form). It is important to develop technologies and materials for pressure swing adsorption and membrane technologies for the production and purification of hydrogen, improving the domestic technology of alkanolamine CO_2 capture. The development of chemical-technological complexes using the heat of high-temperature nuclear reactors, which can significantly reduce the price of hydrogen, is extremely relevant. It is important to develop the production of electrolytic hydrogen; it requires technical solutions and modern materials for electrolyzers of various types with a significant reduction in the costs of their production and operation. It is essential to solve these problems in order to create solid oxide electrolyzers that can use the heat of industrial plants and nuclear reactors of a new type, etc. In the field of transportation and storage of H_2, it is necessary to develop or localize technologies for the production of materials for pipelines, technologies for underground hydrogen storage, pressure vessels for H_2 storage and equipment for compression, liquefaction and transportation. After 2030, the introduction of technologies of hydrogen storage in organic (LOHC) and inorganic compounds is fundamentally important.

In the medium and long term (2030–2050), it is fundamentally important to switch to distributed systems for generating thermal and electrical energy based on technologies of electrochemical transformation of hydrogen energy in generators with fuel cells with high efficiency. To do this, it is necessary to reduce the cost of production of fuel cells and their components (catalysts, ion-conducting membranes (polymer and ceramic), materials for bipolar plates, corrosion-resistant alloys) by localizing production and developing own technologies. The implementation of these technological solutions will provide power supply to remote facilities and isolated territories, including territories with difficult climatic conditions even in the short term. The formation of platform solutions based on these technologies will make it possible to transfer public urban and intercity transport, municipal equipment to electric traction using hydrogen before 2030. In the long term (until 2050), it is necessary to implement appropriate technical solutions for large-capacity trucks, construction equipment, water and rail transport.

The period of transition to appropriate technologies will be determined by a set of factors: the speed of finding fundamental and technological solutions, the level of necessary investment costs, cross-border regulation by exporting countries; the level of readiness of related industries for the implementation of technologies, availability of qualified personnel, etc. In general, the development of the hydrogen industry within the framework of the Technological Strategy will contain more than 10 industrial hydrogen technologies (bringing technologies to TRL 8) by 2035; the creation of several (8) engineering centers, testing grounds for technologies and equipment by 2030, the development of about 30 new standards by 2024, as well as about 100 registered results of intellectual activity by 2035.

CRediT authorship contribution statement

S. Bazhenov: Data curation, Methodology, Investigation, Writing – original draft. **Yu. Dobrovolsky:** Investigation, Validation, Conceptualization. **A. Maximov:** Funding acquisition, Conceptualization, Writing – review & editing. **O.V. Zhdaneev:** Investigation, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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