Hydrogen energy and large scale hydrogen production with nuclear power plants based on high-temperature reactors

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Abstract. At the present moment resource and ecological issues and challenges related to energy supply have become more acute. Key contradiction lies between constantly growing energy consumption and need for CO2 emission reduction. In the search of the solution hydrogen plays significant role as multi-purpose energy source and accumulator for transport, electric power, industry, distributed generation and public utility. It is expected that hydrogen energy development will benefit for the world’s energy system, environment and economy. Hydrogen may be used as pure fuel for transport and independent energy sources based on fuel elements. Global demand for hydrogen is expected to increase due to the growth of its consumption as a chemical agent in oil processing, petrochemical, chemical, metallurgical and other industries. In developed countries more than 80 % of hydrogen is derived from natural gas and petrochemicals. Large-scale hydrogen production is mainly accomplished by steam methane reforming. For natural gas saving and combustion products emission elimination steam methane reforming technology with heating from high-temperature gas cooled reactors (HTGR) is suggested. In 2018 hydrogen energy was declared as high priority area for scientific and technology development of Rosatom State Corporation. This area is integrated to the Comprehensive program project “Technology and scientific research development in nuclear energy of Russian Federation” and aims at design and demonstration of key technological solutions for nuclear hydrogen energy for large scale ecologic hydrogen production with heating from HTGR, hydrogen consumption infrastructure and integration of hydrogen energy into the economy. “Hydrogen energy” program implementation will diversify nuclear power non-electric applications.

Hydrogen energy is a branch of energy based on large-scale hydrogen production for energy generation and accumulation, its transportation and utilization in industry as chemical agent and fuel for transport.

There has been continuous population growth in the world in compliance with increasing demand for goods and services that results in respective growth of energy demand.

At the present moment more than 80% primary energy (electricity, industrial and utility heat) is generated with fossil fuels.

Global energy demand growth is the reason for increasing emission of “greenhouse gases”, which are one of the key negative factors impacting the climate and population life conditions. CO2 global emission in 2019 was approximately 33 Gt, that is 1.6 times more than in 1990 r. [1]. Emissions are thought to be the reason for global climate change with negative consequences for environment and population. This became inducement for the countries to assume Global Climate
Obligations. In this connection hydrogen as green energy source may become the way to zero-carbon energy.

From the point of view of de-carbonization renewables (wind, solar energy) as well as nuclear energy today are used for electricity production only.

Besides electricity fossil fuels are utilized in industry, transport, utilities sector, which totally consume about 65% resources.

Intensive research on usage of nuclear power for hydrogen production started in 1960-s in Soviet Union Academy of Sciences.

Institute of Atomic Energy n.a. I.V. Kurchatov (NRC “Kurchatov Institute”) was in charge of scientific and technical policy concerning this research and finally it was proposed to utilize high temperature gas cooled reactor technology (HTGR) for large-scale hydrogen production. The project manager academician A.P. Alexandrov wrote in 1978: «Large-scale nuclear energy development (for electricity and heat production for industry and municipal heating, heat and electricity supply of metal and its reducers production, heat and electricity supply of numerous types of chemical production...) will help to replace coal which is more expensive and economize oil and gas. Perhaps considerable percentage of autonomous vehicles will consume centrally derived hydrogen as a fuel safe for the environment. Cheap hydrogen production is one of the major prospects of nuclear energy». [2] This task remains relevant today as well.

Therefore mission of HTGR consists in the following:

- Broadening of nuclear energy application for non-electric use;
- Large-scale production of hydrogen as energy source for transport, autonomous and portable power sources and chemical agent for industry;
- Saving of fossil fuels for manufacturing of high added value products with the use of hydrogen;
- Implementation of highly effective power generation thermodynamic cycles with the use of high temperature heating.

Nuclear energy utilization for hydrogen production with HTGR was named «Nuclear-hydrogen energy».

Key problem of hydrogen energy transition is ecological large-scale hydrogen production with low production costs.

Today 75 million tons of hydrogen is produced, 95% of this is produced by steam methane and coal reforming. Hydrogen production pattern demonstrates continuous growth. (Fig.1)

![Hydrogen consumption pattern](image)

**Fig. 1.** Hydrogen consumption pattern [3]

As International Council on Hydrogen Technology estimates by 2050 hydrogen energy will satisfy 18% of global energy demands. This will help reduce CO2 emissions by 20%.
Russia has been continuously turning to high-temperature helium-cooled reactor projects, which aim at high-temperature heating use for technological processes in industry and hydrogen production.

In 1970-1980-s in course of state-run program «Hydrogen energy» basic designs and technologies of Nuclear power engineering plants with high-temperature reactors were developed. В

The technical features of such reactors are given in Table 1.

The function of program coordinator was performed by Commission for Hydrogen Energy of USSR Academy of Sciences.

Table 1. Reactor main features

| Features                     | VGR-50 VNIIAM | VG-400 OKBM | VGM OKBM |
|------------------------------|---------------|-------------|----------|
| Thermal power, MV            | 136           | 1060        | 200      |
| Purpose                      | Electricity generation and radiational material modification | Electricity and heat generation for industry | Electricity and heat generation for industry |
| Helium outlet temperature, °C | 810           | 950         | 950      |
| Fuel/ enrichment, %          | UO₂ / 21      | UO₂ / 6.5   | UO₂ / 8 |
| coolant                      | Helium        | Helium      | Helium   |
| Status                       | Basic design, 1978 | Basic design, 1987 | Basic design, 1992 |

In support of basic designs key RD were carried out as well as high-temperature ceramic fuel was made. As a result of this work in 1987 USSR Council of Ministers made the decision to build Nuclear power engineering plant with HTGR for four industrial plants and one demonstration facility. The projects were not carried out due to reformation period called “Perestroika”.

In 1990-s и 2000-s the works were resumed in course of industry-based programme. Starting from 2018 Rosatom State Corporation forms the attitude to hydrogen energy as technological development priority. [4].

Preconditions for this were well-established competences and technological groundwork in nuclear hydrogen energy, fuel elements, electrolyser and other components:
- increasing demand for hydrogen in advanced economies of the world;
- resources for hydrogen production at adequate price available in Russia.

In this connection Rosatom State Corporation launched comprehensive program “Development of technology and scientific research in nuclear energy utilization in Russian Federation for the period from 2020 to 2024”.[5]

According to the presidential decree No. 270 of April, 16, 2020 this program is expected to accelerate technology and scientific research development, energy safety within nuclear energy utilization.

The program includes the following tasks up to 2024:

- Nuclear hydrogen energy technology development for large-scale hydrogen free from CO2 emissions and based on HTGR.
- Basic infrastructure elements development (storage, transportation, local electrolytical production, fuel elements, hydrogen production, distribution and consumption safety).
- Hydrogen energy integration into the Russian economy and hydrogen export. This task comprises works on pilot projects in transport and local grid infrastructure at the regional level.

In 2018-2019 study was conducted on different variants of clean hydrogen production including:
- electrolysis with the use of electricity provided by Russian nuclear power plants during load reduction period.
- steam methane reforming without CO₂ emissions using HTGR heating;
- high temperature steam electrolysis with ceramic fuel elements is considered as long-term perspective.

After 2024 construction of nuclear hydrogen plant with HTGR is planned with progressive building up of new reactor units. The first unit is expected by 2030. Before this time it is planned to
establish electrolytic hydrogen production based on operating NPPs. Besides experience in storage transportation and utilization of hydrogen will be gained and studied from the point of view of safety. Roadmap on nuclear hydrogen energy technology implementation is designed for short-, mid-, and long-term perspective. (Fig.2).

![Fig.2. Roadmap on nuclear hydrogen energy technology implementation](image)

At the first stage, in order to gain experience in the safe handling of hydrogen while utilizing it, construction of a pilot electrolysis production using reserve power at operating Russian nuclear power plants is planned. Steam methane reforming (SMR) without carbon dioxide emission has been selected a basic process for large-scale hydrogen production.

This technology is based on proven processes, catalysts and equipment. The raw materials for hydrogen production are natural gas and water, sufficiently available in Russia. Safe integration of nuclear and chemical-engineering systems into a single complex – nuclear power engineering plant (NPEP) – becomes a new element of this technology. As shown in Fig. 3, the application of a HTGR unit with a thermal capacity of 200 MW saves about 135 million nm³/year of natural gas.
Fig. 3. Flowchart of Nuclear Power Engineering Plant with HTGR

Carbon dioxide is separated in the production process using established technologies and is accumulated compressed.

One of the objectives of the Comprehensive Program regarding nuclear-hydrogen energy is the CO₂ management.

Two options for the further usage of CO₂ (Fig. 4) are proposed:
- by-products production;
- underground storage and deep-in-the-sea storage.

Fig. 4. Variants of recovery and utilization of CO₂ [6], [7], [8]

Table 2 shows the expert technical and economic characteristics of pure hydrogen for a four-unit NPEP with HTGRs with thermal power of 4x600 MW and 4x200 MW.
Table 2. The results of expert technical and economic assessment of NPEP with HTGRs.

| Parameter                                         | Type          | 4x600 MW | 4x200 MW |
|---------------------------------------------------|---------------|----------|----------|
| Thermal power, MW                                 |               | 2400     | 800      |
| H₂ production capacity (ICUF=0.9), mln. kg/y      |               | 836      | 278.8    |
| Total cost (R&D + project work + fuel facility + construction), mln. $ |               | 4227     | 2334     |
| Overall operating costs, mln. $                   |               | 975      | 418      |
| H₂ production cost, $/kg                          |               | 1.4      | 1.8      |

The implementation of hydrogen energy in Russia has its own specifics as the country possesses vast reserves of primary energy resources (oil, gas, coal). The main hydrogen consumers today are oil refineries, chemical industries and petrochemicals which are forced to build and operate hydrogen production facilities to produce output of higher quality, and therefore the expansion of hydrogen consumption by these industries is an irreversible process. However, hydrogen production is not core for these industries and remains a necessary measure, because there is no large-scale hydrogen production in Russia. In a number of countries, industries producing hydrogen for their own needs intend to purchase commercial hydrogen. Therefore, there is an opportunity to establish the Russian hydrogen market in the future.

Air pollution in some cities is another aspect of this problem. The Russian National project “Ecology” approved December 24, 2018, requires a radical reduction in the level of air pollution in large industrial centers, including a reduction of no less than 20% of the total volume of pollutant emissions. The use of hydrogen, for example in transport, can help to improve the environmental situation.

Hydrogen atomic energy is a high-tech science-based industry impossible to be created within the minimum period of time, so you need to be prepared for the main importers of fossil fuels reduce their consumption, replacing them by environmentally friendly hydrogen.

Rosatom State Corporation Comprehensive Program, including hydrogen energy development, is a timely response to the transformation of power industry.

Nuclear power engineering systems with HTGR are capable of providing large-scale production of environmentally friendly hydrogen. At the first stage hydrogen should be produced from water and natural gas and in the future – from water solely based on the development of high-temperature fuel cells.

The implementation of Hydrogen Energy expands the scope of nuclear power application for the production of energy resources for distributed power generation, industry and transport.

References
[1] https://www.iaea.org/articles/global-co2-emission-in-2019
[2] A.P. Aleksandrov. Perspektivy razvitiya atomnoy energetiki. V sbornike “Atomno-vodorodnaya energetika i tekhnologiya”, 1978
[3] https://investvitrina.ru/articles/makroekonomicheski-obzor-vodorodnaya-ekonomika-perspektivy-perehoda-k-alternativnym-energonositelyam-i-vozmozhnosti-eksporta-dlya-rossii/
[4] https://topwar.ru/152773-vodorod-toplivo-buduschego.html
[5] https://plus.rbc.ru/issue/5dfc76c97a8aa9f9563bd9fed
[6] News.rambler.ru, Oil and gas fields development, November 10, 2017
[7] Sovremennye problemy nauki i obrazovaniya, №5, 2013, http://www.science-education.ru/
[8] https://vseonauke.com/264166560222153076/biotoplivo-iz-vodorosley/