Research of the efficiency of combining nuclear power plants with a multifunctional autonomous hydrogen energy complex

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Abstract. Combining of the nuclear power plant power unit with an autonomous hydrogen complex including a low-power steam-turbine is proposed. This autonomous hydrogen complex makes it possible to increase the power and manoeuvring capabilities of the nuclear power unit, and in case of complete power blackout, provide power supply for own needs for more than 72 hours (IAEA requirement) due the energy of the residual heat release of the reactor. Hydrogen and oxygen can be generated by electrolysis of water at the expense of cheap off-peak energy of nuclear power units at night, after that it is effectively used in the daytime to generate steam, which is sent to a low-power steam turbine. The article evaluates the economic efficiency of the proposed system under conditions of uneven electric load schedule. It is shown that the proposed variant of combining nuclear power units with an autonomous hydrogen complex, including a low-power steam-turbine plant, makes it possible to improve the reliability of power supply for NPP's own needs in emergency situations with blackout. This will, together with the additional benefit from the sale of peak electricity, significantly increase the competitiveness of nuclear power plants.

1. Introduction
At present, the Russian United Energy System (ECO) has a tendency to increase the deficit of peak and semi-peak capacity at power stations, which can economically and reliably work in the off-peak hours of electricity loads and provide the electricity in the peak hours of electricity loads. The majority of thermal power stations using organic fuels have been switched to semi-peak mode, which negatively affects their economy and reliability. At the same time, there is an active growth in the number of nuclear power plants in the ECO, that is exacerbates the problems associated with the unevenness of the schedule of electrical loads, because the maximum of capacity utilization factor is achieved at the NPP, which is operating in the base part of the schedule of electrical loads. One of the ways out can be the combination of nuclear power units with an autonomous hydrogen complex (AHC). AHC will allow to accumulate energy during the off-peak hours of loads in the power system due to the electrolysis of water and producing hydrogen and oxygen. Accumulated energy can be used to generate additional electricity during peak hours of the loads in the power system. The urgency of the development of hydrogen energy based on off-peak production of hydrogen and oxygen at nuclear power plants, followed by their combustion in a hydrogen-oxygen steam generator, has been confirmed by long-term studies both in Russia and abroad [1-4].

Traditional emergency cooling systems of nuclear power plant reactors include independent safety channels with diesel generators (DG) [5]. The new NPPs provide for increased security, by increasing the number of safety channels. Diesel generators are in standby mode, the rapidity of their start-up...
negatively affects of own reliability, due to the occurrence of significant temperature and mechanical stresses in the elements of the diesel engine in the initial period of start-up [6]. At the same time, passive heat removal systems (SPOT) for the emergency events with blackout are developing actively [7-10]. However, SPOT has a number of shortcomings, such as a significant increase in capital costs, which leads to a decrease in the competitiveness of nuclear power plants; additional costs for maintaining the systems in standby mode; dependence of system performance on climatic conditions.

The authors of the article earlier for the first time investigated the possibility of cooling the nuclear power unit using the energy of residual heat release of reactor to generate electricity in an additional low-power steam-turbine unit (STU) [11, 12]. According to the proposed method in an emergency situation with complete blackout in the first circuit natural circulation is maintained, the part of the steam which generated by the residual heat release of the reactor is fed to an additional low-power STU, which generates the power to the station's own needs. The other part of the steam through the pressure relief device (BRU-K) is directed into the condenser.

Work with the AHC is one of the effective ways for using an additional low-power STU in the regular mode. Hydrogen and oxygen, produced on the basis of unclaimed electricity during the night off-peak hours of electric loads, can be accumulated and used during the peak hours for generation of steam for fed to a low-power STU. According to the scheme considered in the work, in the off-peak hours of loads, in addition to hydrogen and oxygen, hot water is accumulated, which during peak hours is used as feedwater in the AHC (Figure 1 [13]). Proceeding from the requirements for safety, it is necessary to duplicate the additional STU - while one STU will be repaired, the other STU will provide a reserve for the station's own needs.

![Figure 1](image-url)

**Figure 1.** Scheme of increasing manoeuvrability and safety of nuclear power plants based on thermal and chemical accumulation: 1 - steam distribution device; 2 - hydrogen-oxygen steam generator; 3 - low-power STU; 4 - electric generator; 5 - the condenser; 6 - condensate pump; 7 - cold water tank (CWT); 8 - cold water pump; 9 - surface heat exchanger; 10 - drain pump; 11 - hot water tank (HWT); 12 - feeding pump; I - steam from the main steam generator (SG); II - to the feed water circuit.

During the off-peak hours of electric loads, hydrogen and oxygen are produced in the electrolysis unit, which are accumulated in the storage tanks through the booster compressor units [14]. At the same time, part of the steam from the main steam generator is sent to the steam-water surface heat exchanger 9, where it transfers heat to cold water, which is pumped from the CWT 7 to the HWT 11. The drainage of the steam is supplied to the feed water circuit of the main STU after the high-pressure heaters before the SG.
During the peak hours of the electrical loads, hydrogen and oxygen are taken from the storage tanks, compressed to the needed pressure and fed to the hydrogen-oxygen steam generator 2. From the HWT 11, hot water is supplied to the hydrogen-oxygen steam generator 2 through the supply line of feed water with integrated injectors [15]. By means of feed water, the temperature and steam flow rate at the outlet of the steam generator 2 are regulated. In addition, the steam generator is cooled by this water during the combustion of hydrogen. The resulting steam is sent to low-power STU 3 for generating electricity. Condensate of working steam after condensers 5 is sent to CWT 7.

In idle hours of the AHC, one of the low-power STU 3 operates in the idle mode (hot standby) due to an insignificant steam flow taken after the steam distribution device 1. During the hours of operation of the AHC, the steam line connecting the low-power STU and the main steam generator of the NPP, is maintained in a hot state due to a small flow of steam that is mixed at the inlet of low-power STUs with steam from the hydrogen steam generator 2. During the emergency cooling-down of reactor in the first hours after blackout, an excess amount of residual heat energy is generated, which can be accumulated in the form of hydrogen or hot water and used in subsequent hours for compensation of shortage of energy. According to the conditions of explosion and fire safety AHC can be placed outside the nuclear power plant site.

2. Thermodynamic analysis

To estimate the economic efficiency of the proposed system, the following initial data were accepted: in the rated operating mode the capacity of the K-1000-60/1500 turbine unit and its absolute internal gross efficiency are 1000 MW and 36.36%, respectively; the number of working days in a year will be ≈ 292 days; the number of operating cycles of electrolysis plants and all equipment of the AHC corresponds to this value; the off-peak period of the electrical load – 9 hours per day; the number of hours of use of AHC for peak loads – 6 hours per day.

Table 1 shows the operational costs of producing hydrogen at $P_{H_2} = 0.1$ MPa, $V_{H_2} = 500$ m$^3$/h (FV-500M). Power capacity of the electrolysis plant is 3000 kW. Specific investments in the electrolysis plant, taking into account instrumentation and equipment and costs for the construction of the electrolysis building, are taken in the amount of 3500 rub./kW [16].

| Title of operating costs          | Value, thos. rubles/year |
|-----------------------------------|--------------------------|
| Electricity costs                 | 2800                     |
| Costs for preparation of electrolyte | 600                     |
| Cooling water costs               | 120                      |
| Nitrogen costs                    | 800                      |
| Depreciation costs                | 1100                     |
| Repair costs                      | 870                      |
| Salary costs                      | 550                      |
| Social costs                      | 140                      |
| Other costs                       | 75                       |
| Total costs                       | 7055                     |

As a storage system for hydrogen and oxygen cylindrical tanks with spherical bottom of 100, 400, 800 m$^3$ are used (Table 2). The gases in the tanks are under pressure [17]. The reduction of specific capital investments with the increase in the storage tank volume is due to the design features known from the practice of designing high pressure tanks [19].

Table 3 shows the specific capital investments in the compressor units of hydrogen and oxygen, taking into account the investment in instrumentation, automation and construction of the compressor station [16].
Table 2. Technical characteristics of hydrogen and oxygen storage tanks [18].

|                      | 100   | 400   | 800   |
|----------------------|-------|-------|-------|
| Volume of tanks, m³  |       |       |       |
| Inner diameter of the tanks, m | 3.2   | 5.6   | 7     |
| Radius of cylindrical part, m | 1.6   | 2.6   | 3.5   |
| Radius of the spherical part, m | 2     | 3     | 4     |
| Length of cylindrical part, m | 8.3   | 13.5  | 13.8  |
| Specific investment in the tank of this volume (at a pressure of 4.2 MPa), rubles/m³ | 18300 | 16900 | 16700 |

Table 3. The specific capital investments in the compressor units of hydrogen and oxygen (1/4.2 MPa)

|                      |       |       |
|----------------------|-------|-------|
| N, kW                | k, rub./kW |
| H₂                   | 2600  | 2670  |
| O₂                   | 3000  | 2540  |

Hydrogen consumption required to generate the steam that required for the nominal operation of a low-power steam turbine with the use of hydrogen combustion chamber is 0.29 kg/s. Taking the specific power consumption for the production of 1 kg of hydrogen ≈ 39.8 kW⋅h/kg [20], we find the main characteristics of the hydrogen complex (Table 4).

Table 4. Main characteristics of the hydrogen complex work.

|                      |       |       |
|----------------------|-------|-------|
| Off-peak power consumption | 11 MW (1.1%) |
| Consumed off-peak electricity, MW ⋅ h | 273   |
| The hydrogen amount produced during off-peak hours of electrical loads, kg | 6191  |
| Available mass flow rate of hydrogen during peak hours of electrical loads, kg/s | 0.29  |
| Hydrogen volume (storage under pressure 4.2 mW), m³ | 1899  |
| Oxygen volume (storage under pressure 4.2 mW), m³ | 900.1 |

Thus, for the operation of this scheme are necessary: twelve electrolysis plants FV-500M with power of 3000 kW (128.9 million rubles), one H₂ compressor and one O₂ compressor (2.59 million rubles), four storage tanks with volume of 800 m³ (58.4 million rubles). The total capital investment in the hydrogen complex of the proposed capacity will be about 190 million rubles.

Power of one low-power STU, included in the AHC, based on the calculations of the provision of reserve of NPP own needs in case of complete blackout, is chosen equal to 6 MW [12]. Specific capital investments in low-power STU required power on the basis of data from the group TURBOPAR are about 48 thousand rubles/kW. Therein, we took into account costs of the condenser and electric generator of the additional steam turbine. Additionally, it was take into account modernization of the transformer cooling system, installation of a high-voltage transformer, modernization of the cooling system of the conductors, modernization of automated control systems of technological processes, and assemblage of steam turbines [11]. Thus, capital investments in low-
power STUs will amount to about 640 million rubles. The total capital investment in the proposed autonomous hydrogen complex will amount to 830 million rubles.

The consumption of fresh steam of low-power STUs in the hot standby at idle is about 1 kg/s, thus, the annual losses from underproduction on the main turbine will be: 4.3 million rubles. As mentioned above, the feed water is accumulated in the hot water tank during the load failure hours. To operate an autonomous hydrogen complex within 6 hours, it is necessary to store 441 tons of hot water. The cost of tanks is thus about 18.6 million rubles. [21].

Currently, on the many operating and projected nuclear power plants additional mobile diesel-generator stations are installing (MDGS). As it was shown earlier, one additional turbine can provide cooling of two reactors [12]. Thus, when installing a AHC with low-power STUs, additional MDGSs for two power units are not required, since the required IAEA safety level is achieved. The cost of one MDGS, according to the procurement site of the state Corporation “Rosatom” is about 130 million rubles.

Thus, when installing the AHC instead of additional MDGS, we get the following positive effect, RUB.: 

\[
K = K_{AHC} - 2 \cdot K_{MDGS}
\]  

(1)

where \( K_{AHC} \) is the capital investments in autonomous hydrogen complex, RUB.; \( K_{MDGS} \) is the cost of the additional MDGS, RUB.

For calculation purposes, the tariffs for electricity and fuel prices were taken from the forecast relating the long-term socio-economic development of the Russian Federation provided by the Ministry of Economic Development of Russia.

The calculations took into account the probable annual economic effect of reducing the risks of the nuclear reactor core damage (CDA) as a result of accidents, accompanied by a complete NPP de-energization [22, 23]. For the resultant economic effect of improving of the nuclear power plant safety, the average annual reduction of the risk of damage from accidents with the CDA is adopted as

\[
\Delta R_{CDA} = (\lambda_{MDGS}^{\text{syst}} - \lambda_{STU}^{\text{syst}}) \cdot n \cdot Y
\]  

(2)

where \( \lambda_{MDGS}^{\text{syst}} \) is the failure rate of three-channel emergency power system with diesel generators and additional MDGS (according to calculations amounted \( 8.2 \cdot 10^{-6} \text{ l/reactor-year} [23] \)); \( \lambda_{STU}^{\text{syst}} \) is the failure rate of three-channel emergency power system with diesel generators and additional STU (according to calculations amounted \( 7.1 \cdot 10^{-7} \text{ l/reactor-year} [23] \)); \( Y \) is the damage from an accident with CDA, according to the various data estimation is made from 80 to 155 billion dollars/reactor (Report of the Minister for Civil Defense, Emergencies and Elimination of Consequences of Natural Disasters of the Russian Federation S.K. Shoigu on the consequences of the Chernobyl accident). For calculations, it is accepted at the rate of 100 billion dollars; \( n \) is the number of power units provided by the energy units reserves.

Thus, the annual decrease of the damage risks from accidents with the CDA for two power units in the case of combination of NPP with AHC and refusal of additional MDGS amounted to 92 million rubles/year (at the dollar exchange rate at capitalized 60 rubles). This effect was taken into account in the calculation of net discounted income. The economic indicators obtained from the calculations are presented in Table 5. As can be seen from Table 5, the installation of an autonomous hydrogen complex can improve the safety of nuclear power plants and, at the same time, pays off and brings income through regular work on electricity generation. It should be noted that the analysis did not consider the forecasts of cheaper equipment of the hydrogen complex.

3. Conclusion

The combination of a two-block nuclear power plant with an autonomous hydrogen complex, including two low-power steam turbines, in order to improve the efficiency and safety of nuclear power plants was investigated. The main parameters and composition of the hydrogen complex equipment have been substantiated. The technical and economic efficiency of the proposed system of combining nuclear power plants with an autonomous hydrogen complex was estimated. As shown by
the calculations, the system pays for itself in 19 years due to regular power generation and allows, at the same time, to obtain the required IAEA level of safety, with refusal of the additional mobile diesel generator stations. At the same time, taking into account the reduction in the risk of reactor core damage, the payback period will be 11.1 years.

Table 5. Expected technical and economic indicators.

| Name of indicator                          | Unit of measure | Without taking into account the CDA risk reduction | Taking into account CDA risk reduction |
|--------------------------------------------|-----------------|---------------------------------------------------|---------------------------------------|
| Available peak power                       | kW              | 12                                                |                                       |
| Amount of hours of installed electric power use generation | h/year          | 1752                                               |                                       |
| Peak electric power generation             | GW · h          | 20.08                                             |                                       |
| Estimated period                           | years           | 25                                                |                                       |
| Investments in the project                 | million rubles  | 670                                               |                                       |
| taking into account the refusal of MDGSs  |                 |                                                   |                                       |
| Operating costs of production              | million rubles. | 173                                               |                                       |
|                                           | million rubles. |                                                   |                                       |
| Net present value                          | million rubles  | 222                                               | 985                                   |
| Discounted pay-back period                 | years           | 19                                                | 11.1                                  |

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