Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Comparative Efficiency Evaluation of Hydrogen Energy Complexes Based on Reversible Fuel Cells and Hydrogen-Thermal Storage When Combined with Nuclear Power Plants

To cite this article: A N Egorov and A N Bayramov 2021 *J. Phys.: Conf. Ser.* **2096** 012083

Comparative Efficiency Evaluation of Hydrogen Energy Complexes Based on Reversible Fuel Cells and Hydrogen-Thermal Storage When Combined with Nuclear Power Plants

A N Egorov[1], A N Bayramov[1]

[1]Department of Energy Problems, Saratov Scientific Centre of Russian Academy of Sciences, st. Rabochaya 24, Saratov 410028, Russia

E-mail: wwwean@gmail.com

Abstract. This work evaluates the technical and economic efficiency of combining NPPs with a system based on reversible fuel cells (RFC) in comparison with the well-known approach of hydrogen-thermal accumulation (HTA) using an additional low-power steam turbine unit. One of the main advantages of RFC is its ability to alternately operate both in the electrolysis mode in order to accumulate off-peak electricity, and in the fuel cell mode to generate peak electricity without converting hydrogen fuel energy into thermal or mechanical energy. The authors developed a schematic diagram and methodology for assessing efficiency of using RFC at NPPs. The calculations have shown that at the present stage of technology development, the use of RFC is less effective in comparison with the system based on HTA. At the same time, until 2035the advantage of the HTA will grow from 9.68%, excluding the economic effect from preventing unloading of the NPP, up to 25.31% in the current scenario, taking into account the economic effect from preventing unloading of the NPP. The target level of base specific capital investments in the proposed RFC system (units with a unit capacity of 250 kW) has been determined, providing equal technical and economic efficiency in comparison with HTA, which amounted to 1079-1134 $/kW

1. Introduction

In the countries with developed nuclear power industry, there are problems associated with unevenness of the daily load, due to economically justified need to load NPPs with the maximum capacity utilization factor (CUF). This is due to the cheapness of nuclear fuel in comparison with organic and, at the same time, high capital investments in comparison with thermal power plants, as well as the presence of technological limitations for maneuvering characteristics [1-2]. The majority of thermal power plants operating on organic fuel have been switched to half-peak mode, which negatively affects their efficiency and reliability [3]. In accordance with the strategy for the development of NPPs in Russia, their share is expected to increase up to 22% by 2050. The shortage of peak and semi-peak capacities will soon become one of the problems of the Russian Unified Energy System (UES) [4]. In the context of an active increase in the power of NPPs in power systems, this will lead to the challenges associated with the passage of the minimal and maximal daily loads.

One of the ways to solve this problem can be production of hydrogen and oxygen on the basis of off-peak energy from NPPs by electrolysis of water with temporary storage and use to generate peak electricity due to overheating of the working fluid in the steam turbine cycle of the plant [5-8]. As follows from [9-11], in the process of hydrogen superheating of steam, the parameters of the steam in front of the steam turbine unit (STU) increase, resulting in an increase in the power of the NPP power unit. Disadvantage of this approach is emergence of variable temperature regimes of operation of the STU [12-15] when operating in the variable part of the electric load graph, which additionally causes occurrence of alternating mechanical stresses.

To solve the problem of variable operating modes of the main STU, the authors developed a power complex based on hydrogen-thermal accumulation (HTA) with additional low-power STU [16]. This power complex allows, when combined with the NPP, to accumulate unclaimed/cheap energy in the hours of decrease in the load of the power system due to electrolysis of water required to obtain hydrogen and oxygen and in the form of hot water in storage tanks. The proposed schemes are more efficient, though avoiding variable operating modes and the need to operate in a hot standby mode requires additional operating costs. Therefore, in this paper, an alternative and a promising version of the production and "cold" combustion of hydrogen in reversible fuel cells (RFC) is considered to provide the NPP with a base load due to accumulation of off-peak electricity and generation of peak electricity due to hydrogen fuel energy.

2. Schematic diagram of the use of RFC at NPP

As mentioned above, the known approaches to hydrogen-thermal storage and generation of peak electricity at NPPs imply the use of hydrogen fuel energy in the cycle of the main or additional STU [17]. An example of such approach in the form of a structural diagram of such energy complex is shown in figure 1. During the night hours of the electrical load in the electrolysis plant 16, H2 and O2 are generated, which are stored in special storage tanks 15. In this case, part of the steam from the steam generators of the NPP power unit is sent to the system of steam-water surface heat exchangers 9, where it gives off heat to the cold water pumped from cold tank 7 into the hot water tank 11. During the hours of increased electrical load, hydrogen and oxygen from storage tanks 15 and hot water from tank 11 enter the hydrogen-oxygen steam generator 2. The obtained steam is fed to the low-power STU 3 to generate additional electricity. During the idle hours of the storage system, the low-power STU 3 is in the idle mode to ensure constant hot reserves.

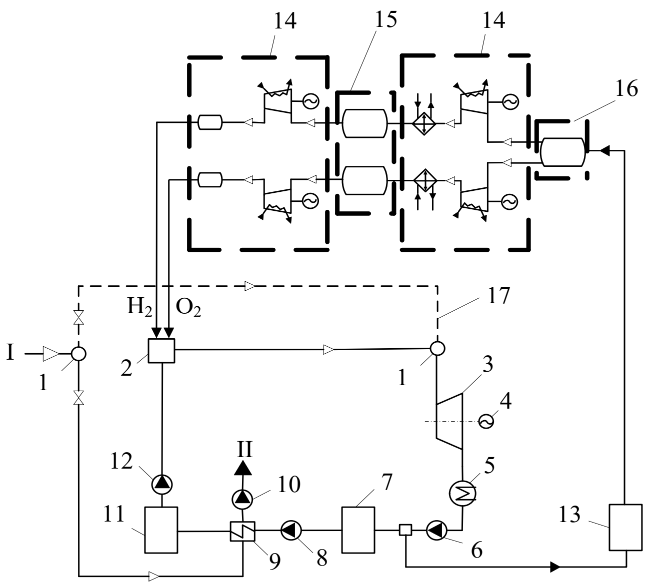

Figure 1. Scheme of combining an NPP with an autonomous HTA system: 1 – steam distribution device; 2 – hydrogen-oxygen steam generator; 3 – low-power multifunctional STU; 4 – electric generator; 5 – condenser; 6 – condensate pump; 7 – cold water tank; 8 – cold water pump; 9 – system of surface heat exchangers; 10 – drainage pump; 11 – hot water tank; 12 – feed pump; 13 – storage tank for the needs of the electrolysis plant; 14 – system for compressing hydrogen and oxygen; 15 – hydrogen and oxygen storage system; 16 – electrolysis plant; 17 – backup steam line; I – steam from the steam generators of the power unit; II – drainage drain into the feed water path.

One of the main advantages of RFC is its ability to alternately operate both in the electrolysis mode to accumulate off-peak electricity, and in the fuel cell mode to generate peak electricity without the need for any other generating equipment. In this case, in the electrolysis mode, during dissociation of water under the electric current, hydrogen and oxygen are formed. And in the fuel cell mode, generation of peak electricity due to direct conversion of the chemical energy of hydrogen fuel. RFCs are fundamentally different from all generators of electricity in the way they convert chemical energy into electrical energy, bypassing the stage of conversion into thermal energy [18-19].

Taking into account peculiarities of RFC operation, figure 2 shows a schematic diagram of combination of the NPP and the electrochemical hydrogen cycle based on RFC. Operation of the NPP in combination with a hydrogen power complex based on the RFC consists of the following stages: at night, due to the use of off-peak electricity, an electrochemical plant with an RFC in the electrolyzer mode produces hydrogen and oxygen, which flows to the storage system, and during the daytime when electrical loads peaks RFC in the fuel cell mode generates electricity due to stored hydrogen and oxygen. The product of reaction in the RFC is water, which is stored in the storage tank to be used in electrolysis. In the power generation mode, the fuel cell also generates additional thermal energy, which can be used to further improve efficiency of the whole plant.

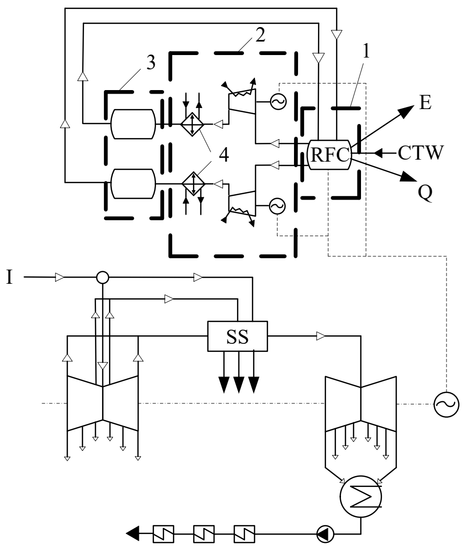

Figure 2. Schematic diagram of combination of the NPP and electrochemical hydrogen cycle with RFC: 1 – reversible fuel cell system; 2 – system for compressing hydrogen and oxygen; 3 – hydrogen and oxygen storage system based on metal tanks; 4 – end cooling heat exchangers; I – steam from the steam generators of the power unit; CTW – chemically treated water; E – electricity generation in the fuel cell mode; Q – heat generation in the fuel cell mode; SS – superheater-separator.

3. Results of comparative assessment of the RFC efficiency at NPPs

For the comparative analysis, calculation of the main technical and economic indicators of the RFC efficiency at NPPs was carried out by comparing the aforementioned HTA system using an additional STU. In this case, the described methodology and methodology for evaluating effectiveness of the existing approaches of HTA were used, which is described in detail in [16, 20-22]. The calculation was made with account for economic effect from preventing unloading of NPPs. The following basic initial data were taken for calculations:

- Duration of off-peak power usage: 9 hours;
- Consumed night off-peak power from the NPP with VVER-1000: 100, 250, 400 and 500 MW;
- Duration of peak electricity supply: 5 hours;
- Relative consumption of electricity for auxiliary needs under compressing hydrogen and oxygen when they are supplied to the storage tank: 0.05;
- Relative electricity consumption for auxiliary needs in the electrolysis mode when generating hydrogen and oxygen: 0.05;
- Efficiency of RFC in the electrolyzer mode: 83% [22];
- RFC efficiency in the fuel cell mode: 60% [22];
- Efficiency of the inverter: 0.98;

- Share of energy for the auxiliary needs in generation of peak electricity: 0.05;
- Number of working days per year: 335 days;
- Calculation period: 25 years.

In addition, the calculations take into account the changes in the cost of nuclear fuel for the current period and for the future until 2035, in accordance with the forecasts of the International Energy Agency (IEA) and the Institute for Energy Research of the Russian Academy of Sciences (ERI RAS) [23], including the price forecast made by the Institute of Economic Forecasting of the Russian Academy of Sciences (EFI RAS). In accordance with the accepted forecast data on the price of nuclear fuel, the price of electricity consumed by the hydrogen complex from the NPP at the cost of the current period is determined at the level of 0.93 rubles/kWh, and 1.11 rubles/kWh within the period up to 2035 at the projected prices of nuclear fuel according to the forecasts of IEA and ERI RAS.

Figure 3 shows the results of the comparative study of the production cost of peak electricity at the NPP power unit with VVER-1000 for two variants combined: with RFC and with the HTA system.

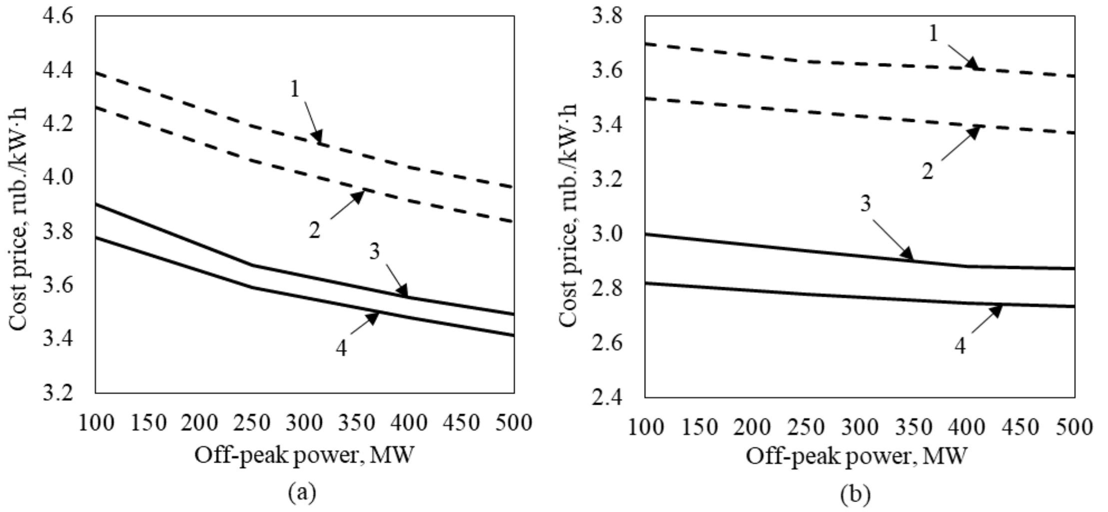

Figure 3. Results of calculating the cost of peak electricity production using a system based on RFC (a) and HTA (b): 1, 2 and 3, 4 – excluding and taking into account economic effect of preventing NPP unloading, respectively; 1, 3 – for the future until 2035 according to the IEA (ERI RAS), respectively; 2, 4 – for the current period.

As can be seen from figure 3, despite the absence of an expensive additional STU and a hydrogen-oxygen steam generator, the combination of an NPP with an RFC is less effective in comparison with the system based on HTA. At the same time, until 2035 advantages of the latter will make from 9.68%, excluding the economic effect from preventing unloading of the NPP, and up to 25.31% in the current scenario with account for the economic effect from preventing unloading of the NPP. This is due to the fact that at the moment RFC-based installations are still at the stage of pre-industrial implementation, which significantly increases their cost. Also, when scaling such systems, at this stage of their development, an insufficient decrease in specific capital investments is achieved to compete with HTA. However, taking into account a great interest in hydrogen energy and in the systems based on RFC in particular, a significant decrease in capital investments in such systems is predicted due to improvement of production technologies and materials. Taking into account reliability and safety of their operation, advantage of the systems based on HTA may not be obvious.

Additionally, the upper limit level of specific capital investments in the RFC system was determined, at which equal technical and economic efficiency is achieved in comparison with HTA (see figure 4). Calculations have shown that at the current overall efficiency of the RFC system, it is necessary to reduce the base specific capital investments (units with the capacity of 250 kW per unit) to 1079-1134 \$/kW.

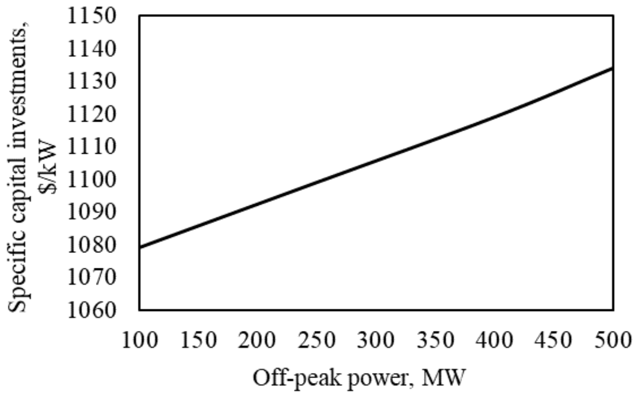

Figure 4. The upper limit level of specific capital investments in the RFC system, ensuring equal efficiency in comparison with the HTA.

4. Conclusion

- The authors proposed and considered an approach to providing NPPs with the base load and increasing their maneuverability based on the use of reversible fuel cell systems. This approach is distinguished by high reliability and safety of hydrogen fuel due to its "cold" combustion without conversion into thermal and mechanical energy.
- A comparative assessment of the system based on reversible fuel cells, and the system based on hydrogen-thermal storage in combination with the NPP was carried out according to the criterion of peak electricity costs. Calculations have shown that at the present stage of technology development, the use of reversible fuel cells is less efficient in comparison with the system based on hydrogen-thermal storage with an additional STU. At the same time, the advantage of the system based on hydrogen-thermal storage will make from 9.68% until 2035, excluding the economic effect from preventing unloading of the NPP, and up to 25.31% in the current scenario, taking into account the economic effect from preventing unloading of the NPP.
- The target level of base specific capital investments (units with a unit capacity of 250 kW) in the proposed system of reversible fuel cells, providing equal technical and economic efficiency in comparison with hydrogen-thermal storage, is determined, which amounts 1079-1134 \$/kW.

5. References

[1] 2012 *Electric Grid Reliability and Interface with Nuclear Power Plants Nuclear Energy Series (Vienna)* vol NG-T-3.8 (Austria: IAEA) p 78
[2] 2018 *Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation IAEA Nuclear Energy Series (Vienna)* vol NP-T-3.23 (Austria: IAEA) p 173
[3] Stoppato A, Mirandola A, Meneghetti G and Casto E Lo 2012 *Energy* **371** 228–36
[4] *Energy strategy of Russia for the period up to 2035: Project* 2014 (Moscow: RF Ministry of Energy) p 93
[5] *Forecast of energy development in the world and in Russia until 2040* 2014 (Moscow: ERI RAS - AC under the Government of the Russian Federation) p 110
[6] Brazhnikov P P Economic Factors Affecting the Market of Nuclear Power Plants 2017 *Trends and Management* **2** 9–25
[7] Aminov R Z, Bayramov A N and Garievskii M V 2020 *Int. J. Hydrogen Energ.* **45(29)** 14614–24
[8] Malyshenko S P Research and development of JIHT RAS in the field of hydrogen energy technologies 2011 *Alternative energy and ecology* **3(95)** 10–34

[9] Aminov R Z and Bairamov A N 2017 *Int. J. Hydrogen Energ.* **42** 21617–25

[10] Ponomarev-Stepnoy N N, Stolyarevsky A Ya and Pakhomov V P 2008 *Atomic-hydrogen energy. Systemic aspects and key problems* (Moscow: Energoatomizdat) p 108

[11] Aminov R Z and Egorov A N 2013 *Therm. Eng+* **60(4)** 255–61

[12] Avrutskiy G D, Krakovskiy D Kh and Nakhimov V I 1982 *Therm. Eng+* **4** 17–20

[13] Bairamov A N 2019 *Int. J. Hydrogen Energ.* **44(12)** 5696–703

[14] Egorov A N 2019 Effect of Thermal Cyclic Loads on the Efficiency of Steam Turbines under Hydrogen Overheating of Steam *Proc. Int. Multi-conf. on Industrial Engineering and Modern Technologies (Vladivostok)* (New York City: IEEE Publishing) 8934379

[15] Egorov A N and Ryzhkov A A 2020 Feasibility Assessment of Hydrogen Superheating of NPP Steam with Load-Following Mode *Proc. Int. Multi-conf. on Industrial Engineering and Modern Technologies (Vladivostok)* (New York City: IEEE Publishing) 9271199

[16] Egorov A N and Yurin V E 2020 A comprehensive method for identifying tariff zones of efficiency of a multifunctional hydrogen-thermal storage system at nuclear power plants *Alternative Energy and Ecology* **25-27(347-349)** 73–83

[17] Jus K A 2016 *Development and research of a bifunctional electrochemical cell with a solid polymer electrolyte: dissertation* (Moscow: MEI) p 168

[18] Grigoriev S A, Porembsky V I and Fateev V N 2009 Development and optimization of a reversible electrochemical system with a solid polymer electrolyte *Proc. of the 3rd Int. Sympos. on Hydrogen Energy* (Moscow: Publishing house MEI) 34–8

[19] Vorontsov V V, Nikitin V A and Fedotov V K 1999 Pat. No. 2173475 RF. Thermoregulation system of a power plant based on a hydrogen-oxygen electrochemical generator operating under gravitational conditions

[20] Aminov R Z and Egorov A N 2020 *Int. J. Energ. Res.* **44(7)** 5609–20

[21] Aminov R Z and Egorov A N 2020 *Int. J. Hydrogen Energ.* **45(32)** 15744–51

[22] Wei M, Levis G and Mayyas A 2020 Reversible Fuel Cell Cost Analysis (Berkeley: Lawrence Berkeley National Laboratory) p 39

[23] Aminov R Z, Bairamov A N and Garievskii M V 2019 *Therm. Eng+* **66(3)** 196–209

Acknowledgments
The research was supported by RSF (project No. 21-79-00174).