Increase of maneuverability of nuclear and geothermal power plants by hydrogen-oxygen complexes

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Abstract. We present results of feasibility analysis of hydrogen-oxygen complexes for base load power plants. To increase flexibility of nuclear and geothermal power plants it is proposed to produce hydrogen and oxygen by excess power and use the gases in hydrogen-oxygen steam generators to produce high temperature steam and provide additional power during power ramps. It is possible to decrease the time of power ramp from 20% to 100% of nominal capacity from 13-15 min to 1.5, while the main steam generator increases capacity with the rate 5-6%/min. Taking into account a rare need in such a big power ramps and low capital intensity of hydrogen-oxygen steam generators, the total increase of capital investments in a nuclear plant should be ca. 1%.

1. Introduction

Nuclear and geothermal power plants offer the highest values of capacity factor (CF), for nuclear power the global average CF has remained ca. 81% over the last 15 years [1], for geothermal power the average CF for the most regions of the world is also higher than 80% [2]. Thus, baseload operation is the preferred mode, which is the simplest, safe and the most efficient use of capital invested in plants.

Nowadays, a grid flexibility becomes necessary and inevitable, with an emphasis on reducing global greenhouse gas emissions and increasing the use of renewable energy and the share of nuclear generation. In general, flexible operation of plants will add incremental capital and O&M costs at the plant level, modifications to existing plants, operational and procedural changes can minimize the impacts of flexible operation [3]. Operating nuclear plants flexibly can help integrate greater shares of variable wind and solar resources, and thus reduce overall power system operating costs and significantly reduce curtailment of renewable energy [4]. One of the instruments for flexible nuclear power are small modular reactors (SMR). The category of SMR includes units with capacity less than 300 MWel and a high degree of factory fabrication, which allows to transport factory-assembled reactor modules or even the whole plant by ship, rail or truck, and with an option to build flexible power plants through a multi-module approach. R&D on SMR are carried out by Russia, Japan, USA, Canada, UK, China, India, etc. [5-9].

Peculiarity of Russian energy sector is that about 2/3 of the Russian territory is not connected to unified electricity grids. Moreover, some 60–70% of Russian territory is affected by permafrost, which complicates large-scale construction and makes it very expensive to develop and maintain reliable transportation routes. These are the large territories in the north and east of the country, which are characterized by sparse population concentrated mostly around mining and raw-material reprocessing enterprises and military bases. The temperatures in winter may be extremely low and production both of electricity and heat is needed for residential demand. Connections to the more populated areas of the country are seasonal (not
available in winter) and unreliable (may be not available in some years due to the damage caused by the permafrost melting). For such harsh environmental conditions, the basic requirements to an energy source are the ability to operate over long periods without the need of fuel delivery and the ability to operate in a co-generation mode, producing heat and electricity. In the Russian Federation the SMRs are built to provide a secure and reliable energy supply to small regional energy systems located in remote and hard to access areas of the country [9]. In isolated systems it is hard to introduce flexibility by system or market measures, thus coproduction of valuable by-product, such as hydrogen, becomes viable. The idea of hydrogen production with the use of the excess energy available during periods of low demand/low electricity price (usually night-time) to produce hydrogen is well known [10, 11].

The same logic is behind coupling geothermal plants with storage technology, it might be uneconomical to ramp or load-follow with a geothermal plant because of higher O&M costs. For example, the Mutnovsky geothermal power plants (Kamchatka, Russia) lose up to 12.3% of the geothermal steam due to dispatching [12]. Storage technology used in conjunction with baseload geothermal would permit conservation of the resource while storing power from geothermal power in off-peak hours and then realizing power during peak demand periods [13]. In addition, a concept of cascade utilization of geothermal power is an effective way to exploit in a sustainable manner the high potential of geothermal resources classified as medium and low enthalpy [14].

Rapid development of water electrolysis technologies with the focus on production hydrogen by renewable power opens the way to increase roundtrip efficiency of the energy storage in hydrogen. Specific costs for proton exchange membrane electrolyzers (PEM) are expected to fall from about 1900 €/kW_d in 2017 to 500 €/kW_d in 2050, and for alkaline electrolysis values are below 500 €/kW_d [15]. Utilization of hydrogen at the MW scale is can be done with the use of hydrogen steam generators (HOSG), as a part of hydrogen-oxygen complexes based on production both of hydrogen and oxygen in off-peak hours, their storage in compressed form and a hydrogen-oxygen steam generator, which provides almost immediate power ramp at demand following the increase of load [16, 17]. The use of such a complex ensures smooth operation of a nuclear power unit, increasing flexibility, service life and safety and decreasing O&M costs. In addition, the high temperature steam form hydrogen combustion permits to reduce moisture content in wet steam turbines of nuclear as well as geothermal power plants, thus increasing the overall efficiency of the plant [18]. Indeed, this technology will increase capital intensity and O&M costs of power plants on 10-15%, thus investigations are needed to find an optimum design and operation modes for the hydrogen-oxygen complex.

The goal of the present paper is to investigate the effect of hydrogen-oxygen complexes on maneuverability of nuclear and geothermal plants.

2. Hydrogen-oxygen complex

The general scheme of the hydrogen-oxygen complex for increase of maneuverability of a power plant is presented in figure 1. The additional steam generation from hydrogen-oxygen steam generators and its supply to ST can help to get rid of the excessive reserve and ensure good dynamics of power control. The use of HOSG can 1.5 times increase the primary reaction of power plant on frequency decrease.

In HOSG hydrogen combustion occurs in an oxygen environment at a stoichiometric ratio of the components, resulting in a high-temperature steam. To control the steam temperature water is used. It also applied to cool the combustion chamber of the HOSG, to achieve thermal efficiency of more than 99%. The first experimental samples of HOSG megawatt-class power created in Germany (Aerospace Center DLR) [19, 20] and Russia (Joint Institute for High Temperatures of Russian Academy of Sciences (JIHT RAS), "Keldysh Research Center") [21, 22]. These organizations also first created and tested kilowatt power class units. Research processes in the HOSG kilowatt class subsequently performed in Japan under the program WE-NET [23]. The JIHT RAS conducts R&D in high-pressure MW-scale HOSG. JIHT RAS research team together with "Khimavtomatika" JSC created a range of HOSG of various capacities 10 and 25 MW for example [22, 24, 25]. The latter is the most advanced device with more than 20 starts of experimental sample without any damage to the structure.

From the point of view of power control the most important HOSG feature is the rapid start with nominal regime achieved less than in 10 seconds (figure 2) [24]. Another substantial advantage is the simple way to
control temperature of generated by the variation of injection of ballasting water. This helps to avoid temperature stresses at steam supply from HOSG to the steam turbine.

![Diagram](image1)

**Figure 1** – Scheme of the hydrogen-oxygen complex: ST – steam turbine, H2O2-SG – hydrogen-oxygen steam generator, El – electrolyzer, G – generator, H2 – hydrogen storage, O2 – oxygen storage

![Graph](image2)

**Figure 2** - The experimental dynamic characteristics of HOSG with thermal capacity up to 25 MW: 1 - thermal capacity; 2 - the steam pressure in the evaporation chamber

The main problem of HOSG integration with the steam turbine is to reach the combustion completeness of H2 in O2 at stoichiometric component ratio. At present JIHT RAS by using new types of mixing elements achieve a completeness of combustion of hydrogen more than 99%, and the total quantity of unreacted gases in the generated steam is not more than 2% (vol.) [24].

HOSG is very compact device with specific volume of the set-up less than 10⁻³ m³/MW. Compactness defines the relatively low capital cost of HOSG. The most expensive part of the complex are water electrolysis and gas storage. Thus, the use of the hydrogen-oxygen complex only for increase of maneuverability of the power plant will substantially reduce capital investments. For example, the typical small-scale nuclear reactor can increase output at the rate 5-7% of nominal capacity per minute [26], thus it would take 12-16 min for a ramp from 20% to 100%, while hydrogen-oxygen complex would need only 1-2 min and is restricted only by stability of the steam turbine. For geothermal power plants the power ramp is greatly depends on the productivity of wells and also is restricted by 4-8% per minute.
We perform cost estimation of a hydrogen-oxygen complex for a $N_{pp} = 150$ MW power plant (nuclear or geothermal) and power ramp from $N_0 = 20\%$ of nominal power $N_{nom}$ to 100\% at $t_{ramp} = 1.5$ min.

During the power ramp steam is supplied by the main steam generator and by the hydrogen-oxygen complex, enthalpy flow at the steam turbine is

$$H_{ST} = H_{main} + H_{SG},\quad (1)$$

Enthalpy flow from the main steam generator $H_{main}$ changes as:

$$H_{main} = (1 - \delta_{ramp})H_{100} + H_{100}v_{main}t; \quad \delta_{ramp} = \frac{N_{nom} - N_0}{N_{nom}},\quad (2)$$

where $v_{main}$ is maneuverability of the main unit.

Assuming, that hydrogen-oxygen complex provides no superheat of steam

$$H_{ST} = h_{ST}(m_{main} + m_{SG}), \quad m_{main}(t) = \dot{m}_{main}^{100}(1 - \delta_{ramp} + v_{main}t)\quad (3)$$

where $\dot{m}_{main}^{100}$ is the nominal steam flow at turbine. Thus, the steam flow from the HOSG is

$$\dot{m}_{SG} = \dot{m}_{main}^{100} (\delta_{ramp} - v_{main}t)\quad (4)$$

and the maximum thermal capacity of the hydrogen-oxygen steam complex is

$$H_{max} = h_{ST} \dot{m}_{SG}^{ramp} = h_{ST} \dot{m}_{main}^{100} (\delta_{ramp} - v_{main}t_{ramp})\quad (5)$$

Consumption of hydrogen can be calculated by condition, that specific enthalpy at HOSG outlet is equal to specific enthalpy of the main steam flow $h_{ST} = h_{SG}$, thus

$$H_{SG} = H_{H2} + H_{H2O}\quad (6)$$

where $H_{H2}$ is enthalpy flow of hydrogen combustion and $H_{H2O}$ is enthalpy flow of ballasting water

$$h_{SG} \dot{m}_{SG} = \eta_{SG} LHV_{H2} \dot{m}_{H2} + h_{H2O} \dot{m}_{H2O}, \quad \dot{m}_{SG} = 9 \dot{m}_{H2} + \dot{m}_{H2O}\quad (7)$$

The maximum flow of hydrogen is

$$\dot{m}_{H2}^{ramp} = \frac{(h_{ST} - h_{H2O})}{(\eta_{SG} LHV_{H2} - 9h_{H2O})} \dot{m}_{main}^{100} (\delta_{ramp} - v_{main}t_{ramp})\quad (8)$$

and total mass of hydrogen during the power ramp is

$$M_{H2} = \frac{1}{2} \frac{(h_{ST} - h_{H2O})}{(\eta_{SG} LHV_{H2} - 9h_{H2O})} \dot{m}_{main}^{100} \left[ \frac{\delta_{ramp}^2}{v_{main}^2} - \frac{v_{main}^2 t_{ramp}^2}{2} \right]\quad (9)$$

Estimation of hydrogen-oxygen complex parameters for three geothermal and nuclear power plants: Mutnovsky GeoPP in Kamchatka, Russia, Bilibino nuclear plant in Chukotka, Russia, project SMR-160, USA are presented in table 1.

Maximum power of the hydrogen-oxygen complex is determined by $H_{max}$. High values of needed additional power are compensated by low cost of hydrogen-oxygen steam generator, which is about 20-30 $/\text{kW}$ [28]. Taking into account that the need in big power ramps is quite seldom (3-5 times a year), regeneration of hydrogen and oxygen storages could take a long time, thus diminishing costs of electrolysers, which are the most cost intensive part of the complex. For example, thermal capacity of the hydrogen-oxygen complex for the SMR-160 unit is around 400 MW with a cost ca. 7.8 million $, resulting in 1.1\% increase of capital investment into the nuclear plant (assuming CAPEX of the nuclear plant ca. 6000 $/\text{kW}$).
Table 1. Parameters of hydrogen-oxygen complexes for several geothermal and nuclear power plants, assuming 20%-100% power ramp at 1.5 min and main unit maneuverability 6%/min

| Power plant       | Power, MW | T, °C | p, MPa | \( \dot{m}_{\text{main}} \), kg/s | Hydrogen-oxygen complex |
|-------------------|------------|-------|--------|----------------------------------|-----------------------|
| Mutnovsky\(^a\)  | 25         | 160   | 0.62   | 42.9                             | \( H_{\text{max}}, \dot{m}_{\text{H}_{2}}, M_{\text{H}_{2}} \), MW, kg/s, kg |
| Bilibino\(^b\)   | 13.2       | 274   | 5.9    | 27.8                             | 84                    |
| SMR-160\(^c\)    | 160        | 295   | 2.3    | 195                              | 416                   |

\(^a\) One geothermal unit with K-25-0.6-Geo turbine (saturated steam)
\(^b\) One nuclear unit with T 12/12-60/2.5 turbine (saturated steam)
\(^c\) developed by Holtec International, USA, (superheated steam)

3. Conclusion
Hydrogen-oxygen complexes could increase flexibility of base load power plants, such as nuclear and geothermal plants, resulting in increase of maneuverability, capacity factor, service life and overall efficiency. It is possible to decrease the time of power ramp from 20% to 100% of nominal capacity from 13-15 min to 1.5, while the main steam generator increases capacity with the rate 5-6%/min. Taking into account a rare need in such a big power ramps and low capital intensity of hydrogen-oxygen steam generators, the total increase of capital investments in a nuclear plant should be ca. 1%.

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5. References
[1] World Nuclear Association 2018 World Nuclear Performance Report (August 2018. Report No. 2018/004)
[2] REN21 2019 Renewables 2019 Global Status Report (Paris: REN21 Secretariat)
[3] International Atomic Energy Agency 2018 Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation (Vienna: IAEA)
[4] Jenkins J D, Zhou Z, Ponciroli R, Vilim R B, Ganda F, de Sisternes F and Botterud A 2018 Applied Energy 222 872-84
[5] Locatelli G, Bingham C and Mancini M 2014 Progress in Nuclear Energy 73 75-85
[6] Cooper M 2014 Energy Research & Social Science 3 161-77
[7] Brunin K, Madzharov D, Delarue E and D’Haeseleer W 2013 Energy Policy 60 251-61
[8] Nian V 2017 Progress in Nuclear Energy 98 131-42
[9] Kuznetsov V 2015 Small modular reactors (SMRs): the case of Russia Handbook of Small Modular Nuclear Reactors ed Carelli M D, Ingersoll D T (Woodhead Publishing) chapter 17 pp. 423-53.
[10] Spilrain E E, Malyshenko S P and Kuleshov G G 1984 Introduction to hydrogen energy (Moscow: Energoatomizdat)
[11] International Atomic Energy Agency 1999 Hydrogen as an energy carrier and its production by nuclear power (Vienna: IAEA)
[12] Dunikov D O 2018 Case Studies in Thermal Engineering 12 736-41
[13] Matek B 2015 The Electricity Journal 28 45-51
[14] Rubio-Mayo C, Ambriz Diaz V M, Pastor Martinez E and Belman-Flores J M 2015 Renewable and Sustainable Energy Reviews 52 689-716
[15] Thema M, Bauer F and Sterner M 2019 Renewable and Sustainable Energy Reviews 112 775-87
[16] Schastlivtsev A I and Borzenko V I Journal of Physics: Conference Series 891 012213
[17] Shapiro V I, Malyshenko S P and Reutov B F 2011 Thermal Engineering 58 741
[18] Malyshenko S P and Schastlivtsev A I 2010 Thermal Engineering 57 931-6
[18] Sternfeld H J and Heinrich P 1989 *International Journal of Hydrogen Energy* 14 703-16
[19] Haidn O J, Fröhike K, Carl J and Weingartner S 1998 *International Journal of Hydrogen Energy* 23 491-7
[20] Bebelin I N, Volkov A G, Gryaznov A N and Malyshenko S P 1997 *Thermal engineering* 44 657-2
[21] Malyshenko S P, Gryaznov A N and Filatov N I 2004 *International Journal of Hydrogen Energy* 29 589-96
[22] Hijikata T 2002 *International Journal of Hydrogen Energy* 27 115-29
[23] Malyshenko S P, Prigozhin V I, Savich A R, Schastlivtsev A I, Il'Ichev V A and Nazarova O V 2012 *High Temperature* 50 765-73
[24] Gryaznov A N, Malyshenko S P, Nazarova O V, Prigozhin V I, Rachuk V S, Savich A R and Schastlivtsev A I 2008 *Hydrogen steam generators for stationary energy applications* (17th World Hydrogen Energy Conference 2008, WHEC 2008 Brisbane).
[25] Locatelli G, Boarin S, Pellegrino F and Ricotti M E 2015 *Energy* 80 41-54