INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 42 (2017) 21617–21625

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Performance evaluation of hydrogen production based on off-peak electric energy of the nuclear power plant☆

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ARTICLE INFO

Article history:
Received 24 June 2017
Accepted 4 July 2017
Available online 4 August 2017

Keywords:
Nuclear power plant
Excess energy
Hydrogen
Water electrolysis
Membrane unit
Hydrogen market

ABSTRACT

The article investigates the efficiency of commercial hydrogen production by water electrolysis on the base of NPP excess energy with its additional purification higher than 99.9999%, considering its transport. The competitive high purity hydrogen release price has been determined as compared to the market price. Besides, the use of high duty electrolysis plants has been suggested. Moreover, the advantages of water electrolysis cyclic operation while consuming electric energy from NPP as compared to the continuous mode have been presented in the paper.

Introduction

Russian Federal Program of Nuclear Industry Development provides for significant increase of nuclear power plants (NPP) share in energy systems of the European part of the country. So, according to the Energy Strategy of Russia for the Period up to 2035 [1], the development of nuclear power and nuclear fuel cycle is considered to be a strategic target. Today, NPP with fast reactor and proper recycling fuel cycle plants are constructed along with ongoing construction of NPP with traditional thermal reactor. For example, the construction of 9 new power generating units at existing and new NPP sites (1 power generating unit at Beloyarsk NPP; 2 power generating units at Rostov NPP, 2 power generating units at Novovoronezh NPP II and 4 power generating units at Leningrad NPP II), as well as the modification of existing power generating units under life extension program are in progress [1].

NPPs are used traditionally in base load curve, driven by the following two matters [2,3]:

1 High rate of capital investments and lower generating cost, as compared to other thermal power stations, due to low fuel factor rate. Today, nuclear-to-organic fuel cost ratio is

☆ This paper is the English version of the paper reviewed and published in Russian in International Scientific Journal for Alternative Energy and Ecology "ISJAEE" issue number 05–06 (193–194), date31.03.2016 P59-70.

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http://dx.doi.org/10.1016/j.ijhydene.2017.07.132
0360-3199/

Nomenclature

F	Fisher criterion
n	Impeller rotation frequency
r_0	Impeller radius
W	Fluid heating rate

Greek Letters

σ_F	Free surface area
σ_W	Variance
τ	Temperature
ω	Angular velocity

Acronyms

CHPP	Combined heat and power plants
NPP	Nuclear Power Plant
PSHPS	Pumped-storage hydroelectric power station
RUB	Russian rouble
C_{NPP}	Total annual operating costs for the nuclear power plant, rubles/year
C_{H2}	Total annual operating costs for obtaining hydrogen by electrolysis of water, taking into account additional purification in a membrane unit, rubles/year
C_{compr}	Expenses for compression of purified hydrogen, rubles/year
C_{tr}	Transportation costs, rubles/year
R_{H2}	Revenues from sales of hydrogen as marketable products, rubles/year
E_1	Annual electricity supply from NPP tires, kW • h/year
E_2	Annual shortage of electricity from buses of nuclear power plants due to the production of hydrogen (and oxygen) by electrolysis of water, kW • h/year

evaluated as 1:6 approximately. This ratio could be evaluated as 1:10 in some prospect.

2 Technical challenges of power derating and further power ascension, which could occur at some moments of the fuel cycle at NPP, and which are caused by xenon effect at the reactor core. Besides, operation in base mode regulates NPP reliability indexes at sufficiently high level and allows supporting life extension for expensive equipment. In this regard, problems of the improvement of their safety and overall performance under the terms to supply electrical baseload, as well as problems of efficient accumulation storage of night off-peak energy become especially critical today.

However, the increase of NPP share in energy systems could result in necessity for their deloading that motivates the search for essential customers.

Pumped-storage hydroelectric power stations (PSHPS) are intended to be used traditionally to supply electrical baseload for NPP.

It should be noted that the construction of PSHPSs is conjugated with serious technical, economical, energetical and ecological problems, as well as with geological, seismic and hydrological hazards and damages. Thus, their construction requires special natural environment, and it is impossible near NPP as a rule, so they should be loaded from energy systems according to tariff, which is much higher than nuclear generating cost. This could affect PSHPSs generated peak energy cost and their competitiveness significantly, so it is necessary to develop electric energy storage competitive alternative technologies. Hydrogen (as well as oxygen) production at the expense of night excess energy by establishing hydrogen energy system, which has an advantage to be arranged near NPP and to be loaded at nuclear generating cost, could be one of these technologies [4–14].

Produced hydrogen and oxygen could be used for power generation in peaking operation [4–14], or they could be sold as commodities.

Performance evaluation of hydrogen production through water electrolysis on the base of NPP excess energy

The performance of atomic hydrogen energy systems would be determined primarily by water electrolysis system. Today, Russian as well as foreign existing electrolysis plants have low unit output. It would be inefficient to use them in hydrogen and oxygen large scale production. Therefore, it is necessary to develop efficient electrolysis plants with increased unit output.

The efficiency of existing electrolysis plants ranges within the limits of 60–73% [15], while the power consumption is 5–4.1 kWh/Nm^3H_2 ($\approx$55.5–45.5 $kWh/kg\ H_2$). On increasing water electrolysis efficiency up to 80% in prospect, the power consumption would be 3.75 kWh/Nm^3H_2 ($\approx$41.66 $kWh/kg\ H_2$).

The fitted equation for estimation of capital investments in electrolysis plants depending on their capacity has been obtained on the base of data from Table 1, by which predictive capital investments at the increase of their capacity from 3 up to 50 MW has been calculated. Thus, capital investments has amounted to about 14,000–3000 RUB/kW respectively [5].

Electrolysis hydrogen and oxygen could be produced during continuous electrolysis process (stationary during the day), as well as with interruption.

Table 1 – Capital investments in electrolysis plants, made in Russia and USA.

#	Type of electrolysis plant (Producer)	Electrolysis plant capacity, kW	Capital investments, thousand RUB/kW ($ thousand/kW[a])
1	HOGEN (USA)	2–3	1422 (23.7)
2	HOGEN (USA)	10–15	709.8 (11.83)
3	SEU-10 (Russia)	50–60	133.9
4	SEU-20 (Russia)	100	85
5	SEU-40 (Russia)	200–250	55.9
6	TeledyneHM-200 (USA)	50–60	163.2 (2.72)
7	HGM-2000 (USA)	300	73.8 (1.23)
8	BEU-125 (Russia)	625	31.8
9	BEU-250 (Russia)	1250	21.92
10	FV-500M (Russia)	3000	13.7

[a] $1 = 60 roubles (as of March 2015).

Special feature of water electrolysis stationary mode is the fact that on switching the electrolyzer on, cell voltage starts increasing at 4–5% during several days. This phenomenon is related to electrode surface condition changes in time, and to changes of process overvoltage value as a result [16].

Hydrogen and oxygen production through water electrolysis at the expense of NPP night off-peak energy suggests alternant stop-go action. Special feature of intermittent duty for electrolysis is running the process at reduced cell voltage as compared to nominal voltage in a stationary mode, due to depolarization of electrolyzer cells [16].

Electrolysis intermittent duty runs at lowest voltage, as compared to a stationary mode. So, while interrupting the process of water electrolysis in about 6–7 h, which conforms to its period of operation at off-peak nighttime, cell voltage could increase at ~0.03 W from nominal value. Thus, unlike the stationary mode in which cell voltage is about 2.05 W (5 kWh/Nm^{3}H$_2$, ≈55.55 kWh/kg H$_2$), the cyclic operation allows performing water electrolysis at lower cell voltage of about 1.98 W (4.83 kWh/Nm^{3}H$_2$, 53.66 kWh/kgH$_2$).

Fig. 1 shows assessed value of hydrogen production cost with purity of 99.9–99.7% at pressure of 3 MPa, $t = 27°C$ in stationary mode (continuous lines) and in the cyclic operation (dashed lines) of electrolyzers for modifications, when hydrogen energy system is a part of NPP with power consumption at its cost, as well as for separate energotechnological workstation with power consumption from the energy system (tariffs in terms of service areas of Central and Northwest regions of Russia) under conditions of round-the-clock production.

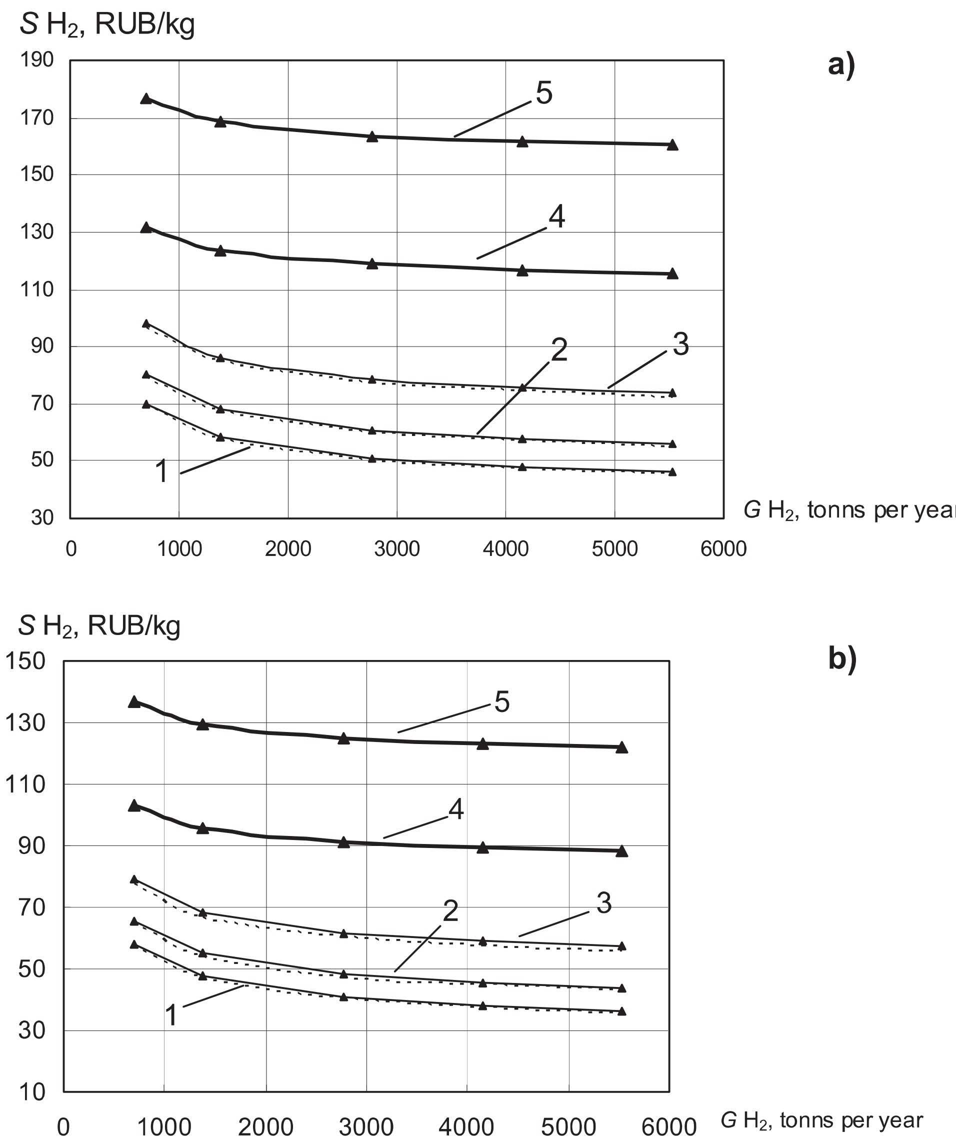

Fig. 1 – Net cost of hydrogen production through water electrolysis using electric energy at cost from NPP in cyclic operation and according to tariff from energy system in a stationary mode: a) at electrolysis efficiency of 60%; b) at electrolysis efficiency of 80%; 1–3 at electric energy price of NPP in the cyclic operation of 0.3, 0.48, 0.8 RUB/kWh respectively; 4, 5 – at electric energy price of energy system in stationary mode of 1.83 and 2.64 RUB/kWh respectively (weighted average tariff including VAT, 2014).

Besides, operating costs are shared proportionally to mass unit of the produced hydrogen. The number of operating hours of electrolysis plants with power consumption from NPP is 2345 h/year, and it is 8040 h/year in case of round-the-clock electrolysis. Electrolysis plant capacity is in the range of 16–130 MW for off-peak electrolysis and it's in the range of 4–37 MW for round-the-clock electrolysis. The modifications are reduced to equalized annual quantity of the produced hydrogen.

Fig. 1 shows that net cost of hydrogen production with power consumption at nuclear generating cost is much lower than its values with power consumption from the energy system.

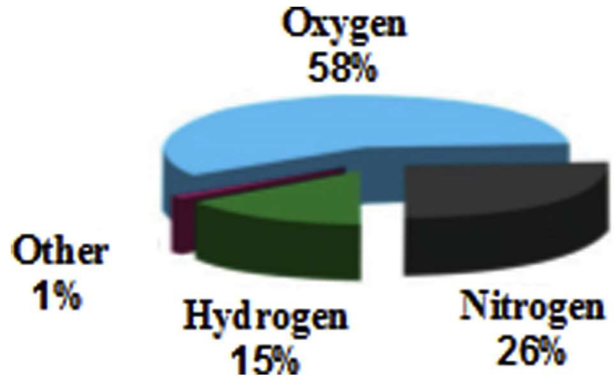

Fig. 2 – Industrial gases production in Russia.

Competitive performance evaluation of electrolysis hydrogen production for commercial use

Global consumption of hydrogen amounted to about 100 million of tons in 2010 [17]. The produced hydrogen purity is of paramount importance here. Electrolysis hydrogen purity ranges within the limits of 99.9–99.7%, while oxygen purity is 99.8–99.0% [16]. For reference, this value amounts to about 97% during methane steam conversion [18].

Of the main consumers of hydrogen, such industries as ferrous and nonferrous metallurgy, coal conversion and shale reprocessing, secondary chemical and petrochemical industries, oil refining, base chemistry and fertilizer manufacturing have maximum demand [19]. Hydrogen is also widely used in glass industry, metal working and machine industry. Hydrogen is produced for these industries mainly by steam conversion of conventional gas, as well as by partial oxidation of hydrocarbon material with purity up to 97%.

Thus, hydrogen facilities are arranged either in the place of its consumption or near proper oil refineries, petrochemical plants and metallurgical works, and the produced hydrogen is delivered through a specific pipeline. The amount of consumed hydrogen could be up to 20 t/day.

Hydrogen of higher purity (more than 99.9%) is required for such industries as electronic engineering, semiconductor manufacturing, pharmaceutics, small energy, transport and food-manufacturing industry, and it is produced mainly through water electrolysis [19]. The demand for pure hydrogen is supplied mainly at the expense of delivery [20], while the amount of consumed hydrogen could be up to 1 t/day.

Today, hydrogen has become one of three most demanded by the industry gases, following oxygen and nitrogen only (Figs. 2 and 3) [21].

The main sphere of consumption of hydrogen in Russia is chemical manufacturing – hydrogen nitride and methanol, first of all. Hydrogen nitride producers are considered to be the leader in consumption of hydrogen. Today, 2.46 million t/year of hydrogen is used at 28 Russian plants. The consumption of hydrogen during methanol synthesis amounted to 0.6 million t/year in 2013 [21].

The consumption of hydrogen in other segments of chemical industry is less than 90 thousand tons, i.e. 3% of the volume of consumption.

The demand of oil refineries for hydrogen, required to produce high-sulfur fuel, also increases. Huge amount of hydrogen is required by facilities for hydrodesulfurization, distillates hydrogen cracking, hydrofining, isomerization and lubricant production. Besides, hydrogen is used at oil refineries to activate reforming catalysts and to regenerate isomerization catalysts [21].

The main use of hydrogen in metallurgy is the production of metals by direct iron reduction. About 320 thousand tonnes of hydrogen is used during this process nowadays [21].

The considerable amount of hydrogen – about 15 thousand t/year – is consumed in rolling processing (during thermal treatment of cold-rolled mill products) [21].

Hydrogen could be also used at iron and steel enterprises to produce protecting nitrogen-hydrogen atmosphere during thermal treatment of pipes.

Hydrogen is used in glass industry to produce flat glass, as well as silica glass, which is fabricated by melting of pure rock crystal, quartz or synthetic silicon oxide in oxyhydrogen flame [21].

Hydrogen is used in power engineering for cooling high capacity electric generators, due to its high thermal conduction and diffusion coefficient, as well as nontoxicity. It has been estimated [21] that about 4–5 thousand tons/year of hydrogen is consumed at combined heat and power plants (CHPP) and NPPs.

And hydrogen is used in food-manufacturing industry during oil and fat hydrogenation in hard fats (margarine) production. The amount of consumed hydrogen is measured at the level of 1.5 thousand t/year [21].

Thus, there are a number of companies in Russia which sell gaseous hydrogen compressed in conventional 40l-pressure tanks at pressure of 14.7 MPa with purity more than 99.9% (Table 2).

Price difference could be explained by the effect of the level of energy tariffs in regions and the price of technological consumables.

Hydrogen production through water electrolysis under pressure on the base of night off-peak NPP electric energy with supplemental hydrogen purification at palladium membranes and with consumer delivery of compressed hydrogen gas could be rather competitive in this connection.

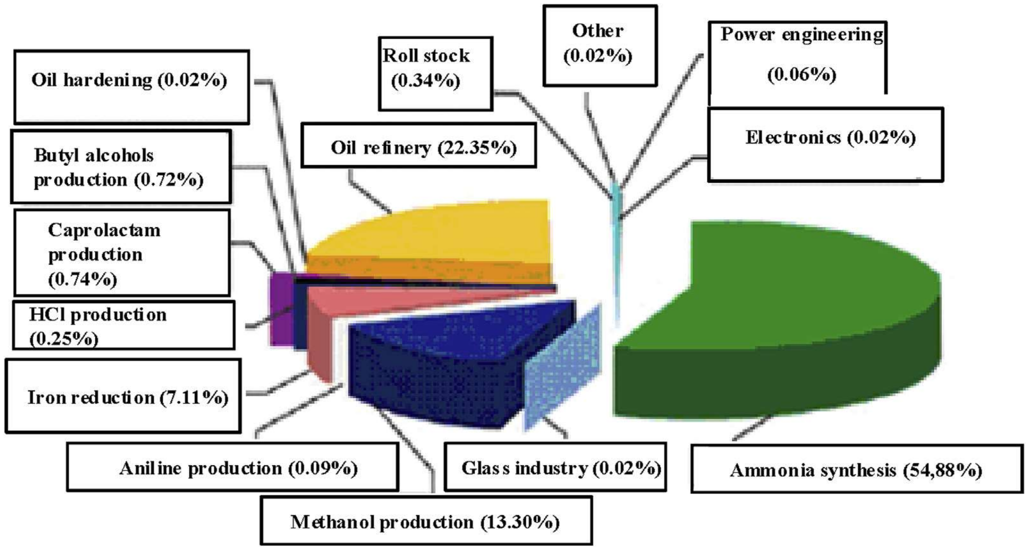

Fig. 3 – Hydrogen consumption in Russia in 2013.

Table 2 – Prices of various Russian companies for compressed hydrogen gas (2015–2016, without VAT).

Hydrogen purity, %	PGS Servis, Moscow	PTK Kriogen, Aramil City, (Sverdlovsk Region)	OksiGasServis LLC Nizhny Novgorod	Uralkriogas, Ekaterinburg
High purity hydrogen, Grade A (99,99,999)	1974 RUB/Nm3 21, 933 RUB/kg	–	–	2121 RUB/Nm3 23,567 RUB/kg
High purity hydrogen, Grade B (99,9999)	1733 RUB/Nm3 19,256 RUB/kg	1697 RUB/Nm3 18,856 RUB/kg	–	1750 RUB/Nm3 19,444 RUB/kg
High purity hydrogen, Grade C (99,999)	–	1262 RUB/Nm3 14,022 RUB/kg	–	1273 RUB/Nm3 14,144 RUB/kg
Hydrogen for industrial use, Grade A (99,99)	275 RUB/Nm3 3056 RUB/kg	385 RUB/Nm3 4278 RUB/kg	315 RUB/Nm3 3500 RUB/kg	284 RUB/Nm3 3156 RUB/kg

Table 3 – A selection of generalized technical characteristics of membrane units.

Item	Value
Acceptable membrane pressure differential, MPa	1–10
Operational temperature, °C	300–600
Maximum dimension, m	$D = 0.3$; $L = 0.5$
Filter assembly weight, kg	5–12
Top performance, m^3/h	480–450
Palladium unit cost, g/(Nm^3H_2/h)	1.6–0.9

The most efficient means of extracting pure hydrogen from industrial gas mixtures is membrane method, especially with palladium sponge membranes which support hydrogen production with desired purity > 99.9999% in one stage without pre-treatment. The required capital investments in is estimated at $20-80/Nm^3 depending on its options [22]. A selection of generalized technical characteristics of membrane units are listed in Table 3.

The flow diagram of high purity hydrogen production is shown in Figure 4.

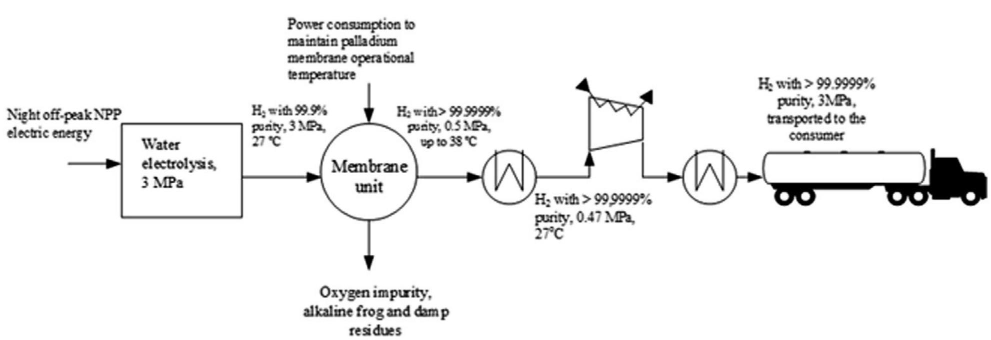

Fig. 4 – Flow diagram of high purity hydrogen production.

As is known, membrane units could vary in a form of membrane element; so there are flat, tubular, spiral and fibrous membrane elements. Thus, the membrane unit with nonorganic membrane in the form of tubular members (Fig. 5) could be the most appropriate for these conditions.

Thus, the produced hydrogen with oxygen impurity, as well as with alkaline frog and damp residues, enter tube side of the membrane element made of palladium (80%) – silver (20%) alloy. The most complete hydrogen decontamination could be obtained as a result of monoatomic hydrogen diffusion processes through membrane under pressure, because nothing but hydrogen could diffuse through palladium membrane. In this case high purity hydrogen is expelled from the tube space, while residues are expelled from the tube side.

Palladium membrane operational temperature could be up to 300–600°C, which results in purified hydrogen heating. On the basis of heat balance, if input hydrogen temperature after electrolysis is 27°C, then purified hydrogen temperature will be 31.7°C at membrane operational temperature of 300°C and 37.6°C at 600°C. It should be noted, that this value of hydrogen heating temperature could be explained by considerably high heating capacity of about 14 kJ/kg°C. Thus, power consumption to maintain operational temperature of 300°C would be 0.1–0.24 kWh at filter assembly weight of 5–12 kg relatively (Table 3), and it would be 0.22–0.52 relatively to maintain operational temperature of 600°C. This low power consumption is determined by palladium alloy low heat capacity of 0.248 kJ/kg°C at 300°C and 0.268 kJ/kg°C at 600°C.

On the base of data on the use of hydrogen membrane extraction from waste gases mixtures of cracking processes, the pressure of extracted hydrogen would be 0.3–0.7 MPa [23,24] at mixture pressure of up to 3 MPa, i.e. membrane pressure differential would be about 2.7–2.3 MPa. Thus, membrane operating pressure differential at a level of 2.5 MPa, as well as purified hydrogen compressing cost to original level by the example of 3 MPa have been considered in order to transport compressed hydrogen further in the gaseous state. As membrane element's life span is about 5 years [25], the membrane unit cost has been considered by adding depreciation allocations to total expenditures of electrolysis plant at depreciation factor of 0.2 in calculations and it has been amounted to 2.46–19.67 million RUB/year for off-peak electrolysis and 0.72–5.73 million RUB/year for round-the-clock electrolysis at the given electrolysis plants capacity.

It is estimated, that hydrogen production cost with additional purification under accepted conditions increases by 3.5 RUB/kg for off-peak electrolysis and by 1.2 RUB/kg for round-the-clock electrolysis, at capital investments in the membrane unit of about $50/Nm^3/h$ and accepted purified hydrogen compressing cost. The difference is mainly occurred due to substantially lower (~3.5 times) depreciation allocations of the membrane unit with round-the-clock electrolysis, as the output per time unit is lower here.

The final hydrogen cost for consumer would be effected by the transport costs. Thus, the transport costs based on various load distances at cargo weight from 2 up to 5 and more tons, which match the amount of produced hydrogen in the range of 2–16.5 tons, while transporting gaseous hydrogen by rail [26,27] using rail tank car, are listed in Table 4.

It might be assumed on the base of the tabulated data that final hydrogen cost could increase by 6–16.5 RUB/kg depending on the load distance and cargo weight.

Fig. 6 shows transport costs while transporting gaseous hydrogen by road [26] exemplified by unit costs of 35 RUB/km at load-carrying capacity up to 20 tons [28] in relation to the

Table 4 – Rail transport costs.

Load distance, km	Transport costs (cargo weight 1.5–3t), RUB/kg	Transport costs (cargo weight more than 5t), RUB/kg
2000	6.8	6.2
3500	10.15	9.88
5000	16.54	15.76

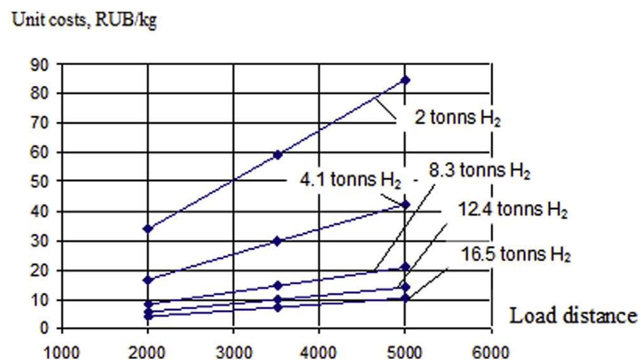

Fig. 6 – Truck haulage transport costs.

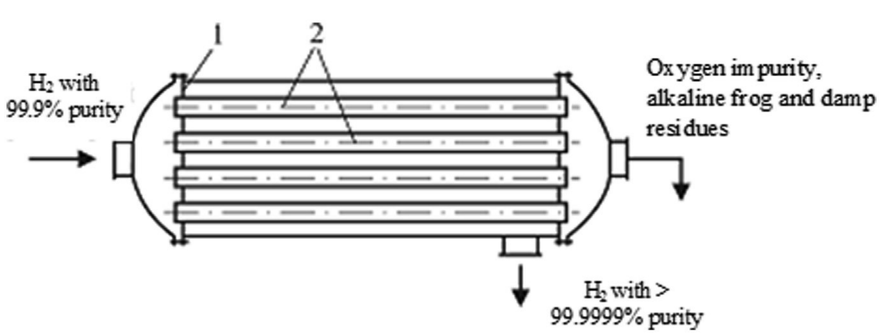

Fig. 5 – The membrane unit on the base of tubular membrane element: 1 – tube sheet; 2 - tubular members made of palladium-silver alloy.

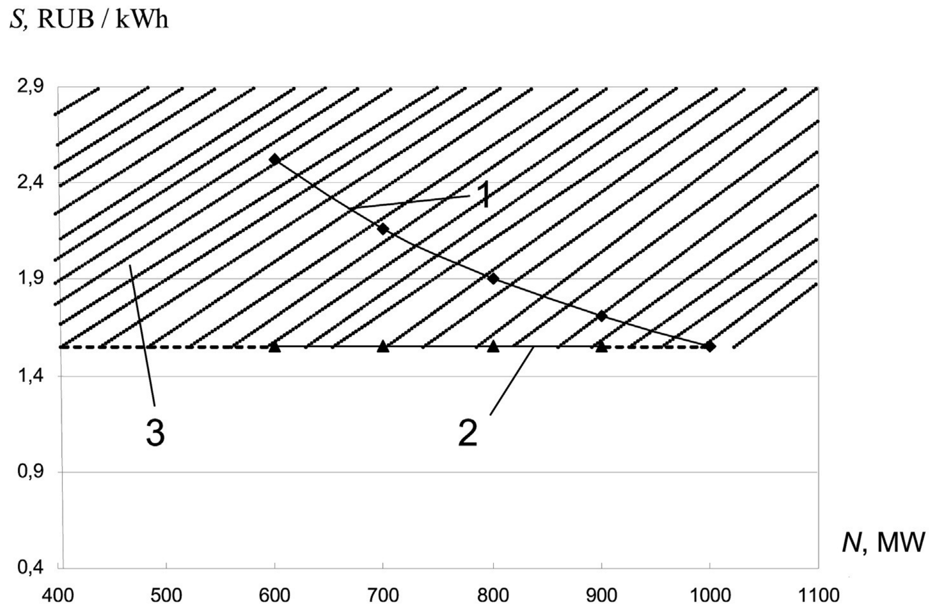

Fig. 7 — Nuclear generating cost of 1000 MW power generating unit in relation to the output power level: 1 — nuclear generating cost in unloading mode; 2 — nuclear generating cost in the mode of electrolysis hydrogen output for commercial use; 3 — ineffectiveness range.

load distance and the quantity of the transported hydrogen from output of 2–16.5 tons requirement.

As shown in Fig. 6, truck haulage costs are mainly higher than rail transport costs. Transportation at 16.5 tons is an exception within the considered range of the distance.

Fig. 7 shows the variances in nuclear generating cost exemplified by 1000 MW power generating unit at capital investments in NPP of about $2400/kW in relation to the night energy sold to the consumers with allowance for an additional economic benefit, obtained from producing hydrogen for commercial use on the stipulation that nuclear generating cost would be at the level which conforms to the nominal load of 1000 MW.

As illustrated in Fig. 7, NPP unloading is mated with increase in the produced electric energy apart from the pointed out above, moving thus to ineffectiveness range. However, due to the fact that discarding the load in favor of hydrogen (and oxygen) production through water electrolysis is economically effective as it could be sold as marketable products, which would serve to eliminate inefficient NPP unloading mode.

Nuclear generating cost has been calculated as following:

$$S^{NPP+H2} = \frac{(C_{NPP} + C_{H2} + C_{compr} + C_{tr}) - R_{H2}}{E_1 - E_2}$$

Table 5 — Release price of compressed hydrogen gas including rail transport costs.

Load distance, km	Release price of compressed hydrogen gas, RUB/kg	
	Cargo weight 1,5–5t, including more than 5t	Cargo weight 1,5–5t, including more than 5t
	Electrolysis efficiency of 60%	Electrolysis efficiency of 80%
2000	348	265
3500	351	268
5000	357	274

Table 6 — Release price of compressed hydrogen gas including truck haulage costs.

Load distance, km	Release price of compressed hydrogen gas, RUB/kg			
	Cargo weight 2t		Cargo weight 16.5t	
	Electrolysis efficiency of 60%	Electrolysis efficiency of 80%	Electrolysis efficiency of 60%	Electrolysis efficiency of 80%
2000	375	292	345	262
3500	400	317	348	265
5000	425	342	351	268

Release prices, including rail transport and truck haulage costs respectively for the considered cargo weight range and load distance presented in Table 4 and Fig. 6 on condition that nuclear generating cost would be maintained at the level which conforms to nominal load of 1000 MW according to Fig. 7, have been listed in Tables 5 and 6 on the basis that the average hydrogen production cost is 58.7 RUB/kg at electrolysis efficiency of 60% and 46.8 RUB/kg at electrolysis efficiency of 80%, taking into account its additional purification in the membrane unit, compressing cost and transport costs.

At the same time, the development of water-cooled and water-moderated reactor (VVER-TOI project) has resulted in significant increase of capital investments in NPP (about $4000/kW and more). Under these circumstances, NPP unloading would result in even higher increase of the cost of electric energy and could justify the development of hydrogen technologies.

Thus, hydrogen production through water electrolysis on the base of NPP night off-peak energy, taking into account its additional purification and transport costs may be rather competitive on hydrogen market.

Conclusion

The development of effective atomic hydrogen energy system on the base of electrolysis techniques of hydrogen (and oxygen) production for commercial use at the expense of NPP excess energy is an important problem as its solution allows producing hydrogen along with supporting NPP with base load in terms of increasing NPP share in energy systems.

The essential singularity of electrolysis hydrogen is its purity of 99.9–99.7%. Moreover, an additional purification at the expense of palladium membranes allows increasing hydrogen purity up to 99.9999%.

The additional economic benefit due to commercial hydrogen production allows eliminating inefficient NPP unloading mode, which could maintain nuclear generating cost at the level which conforms to nominal load.

Besides, stop-go action alternation allows conducting water electrolysis at reduced voltage at electrolytic cells as compared to the stationary mode, which results in less specific power consumption.

Acknowledgements

The study has been supported by the Russian Science Foundation, Grant №15-19-10027.

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