

Analysis of cost efficiency of hydrogen production via electrolysis: the Russian case study

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Abstract. The article focused on investigation of cost efficiency of hydrogen production via water electrolysis in Russia up to 2030. Different non-carbon generation technologies were assumed as input sources for electrolysis, namely wind, solar, hydro and nuclear power plants. Analysis is based on levelized cost of hydrogen (LCOH) framework incorporating all cost related to electrolysis (capital cost, operation & maintenance, electricity price, etc.). Additionally, we estimated LCOH sensitivity to some techno-economic parameters – cost of capital, capital expenses and capacity factor of different power supply sources.

1 Introduction

One of the most important issues in the modern energy sector is the necessary to decrease its negative impact on the environment (so called “climate agenda”). The urgency of the problem is widely acknowledged, especially in economically advanced countries. It was resulted in some international agreements to limit the growth of greenhouse gas emissions (e.g., Paris Climate Agreement [1]). Moreover, last year the European Commission had announced the start of so called “Green deal” policy [2] aiming to achieve zero-carbon state of European economy to 2050, with the crossborder carbon tax as a key supporting measure. All those initiatives will significantly influence the Russian Federation as one of the major trade partner of the EU.

Increasing environmental restrictions have already determined the increasing share of ecologically clean (“green”) production sources without using fossil (carbon-containing) fuel. The leading role here is played by wind and solar energy technologies, as well as technologies for using solid biomass and biogas.

But another promising area for non-carbon energy is related with the use of hydrogen technologies. Traditionally, hydrogen had being produced via steam or steam-oxygen reforming of fossil fuel (usually methane, less often coal). However, massive penetration of renewable generation supported by its cost reduction leads to increasing frequency of power oversupply during periods of high solar insolation or strong wind conditions. It causes the potential for massive production of hydrogen by environmentally friendly water electrolysis, previously considered unpromising due to the high cost of electricity consumed.

“Green” hydrogen produced by electrolysis potentially can be used in the electric power industry displacing fossil fuels in order to achieve decarbonization targets. The joint use of hydrogen in a

mixture with natural gas at thermal power plants is considered as the first step to the future transition to power plants that are fully powered by hydrogen. Another area is the use of hydrogen in fuel cells of different unit capacities, primarily for the needs of personal (mobile) and distributed energy.

The mix of renewable and hydrogen energy, in which the later plays a power accumulating function, makes it possible to smooth out the growing system imbalances – daily and seasonal mismatch between demand and supply strengthening by massive utilization of wind and solar power plants. In this case, the excess production of the latters is spent for water electrolysis, while hydrogen produced in this process acts as an energy storage device, competing with electrochemical batteries, pumped storage power plants, and other technologies of power storage.

In this study, we analyzed cost efficiency of water electrolysis under Russian specific conditions. We assessed the economics of electrolysis coupled with different power sources – wind, solar, hydro and nuclear – both today and as of 2030. The research can be useful to estimate the potential of “green” hydrogen production in Russia and specific conditions necessary to make electrolysis economically viable.

2 Methodology

To estimate the economic viability of hydrogen production via electrolysis, we used levelized cost of hydrogen (LCOH) framework incorporating all cost associated with electrolysis production process (electrolyzer capital cost, operation & maintenance of equipment, electricity price, etc.). This concept is similar to the levelized cost of electricity (LCOE) which is widely used in international comparisons of different generation technologies.

Typically, LCOH is calculated by equation (1):

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$$LCOH = (CAPEX \cdot A + OPEX) / CF + ElPr \cdot EfRate \quad (1)$$

where *CAPEX* – capital cost;
A – annuity rate;
OPEX – operation and maintenance cost;
CF – capacity factor of electrolyzer;
ElPr – electricity price;
EfRate – efficiency rate of electrolyzer.

We have created LCOH calculator using MS Excel framework with ability to change the values of all input parameters (*CAPEX*, *OPEX*, capacity factor, efficiency rate, electricity price, cost of capital) and validated it using data from IEA research (i.e., we reproduced LCOH figures with the same input data assumptions and compared with the outcomes provided by IEA). The results show that our calculator successfully reproduced LCOH curves with negligible deviations from IEA figures. It proves its validity for usage in our subsequent research.

In the study, we assumed several power generation sources to supply electrolysis – namely, new wind, solar and nuclear generation units as well as existing hydro and nuclear units. To estimate the price of electricity utilized in electrolysis, we calculated leveled cost of electricity (LCOE) for all of these generation technologies. Its formulae is given in (2).

$$LCOE = (CAPEX \cdot A + OPEX) / CF + FuelPr \cdot EfRate \quad (2)$$

where *FuelPr* – cost of fuel consumed by thermal power plant (for nuclear this parameter is defined as nuclear fuel cost measured in currency per each generated unit of electricity).

Our assumptions necessary for LCOE calculation for each generation source observed are summarized in Table 1.

CAPEX for wind and solar generation were derived from the results of renewable capacity auctions which took part in the Russian power market in 2016-2020. Additionally, we used data provided by major organizations in their studies (IEA [3], IRENA [4], EIA [5], Lazard [6]). Projections of CAPEX until 2030 were made in line with the consensus (mean estimations) of these studies.

For nuclear generation, CAPEX projection was derived from numerous publications of Russian experts from the industry [7]. Their consensus expectation shows the decline in capital cost of nuclear plants in the domestic market up to 2030 thanks to development of new reactor design (“VVER-TOI”). Estimations of nuclear fuel cost of existing and emerging reactor design was also derived from literature publications.

In addition to new generation sources, we also estimated efficiency of electrolysis via electricity from existing non-carbon plants – hydro and nuclear. We supposed their CAPEX equal to zero (assuming fully depreciated power plants). Operational & maintenance costs (*OPEX*) were defined as weighted average regulated capacity prices for these power plants approved by federal anti-monopolistic regulatory body.

Capacity factor figures for all observed technologies are derived from numerous estimations presented in the literature. For wind and solar generation we made our

internal study of their actual utilization rate in different regions of Russia. Our results show significantly lesser utilization rates for renewables contrasting to the figures published by international organization for Europe and North America.

Table 1. Technical and economic performance data of generation technologies

	CAPEX, usd/kW (rub/kW) ^a	OPEX, % of CAPEX	Capacity factor, %	Nuclear fuel cost, rub/MWh
Wind 2020	1100 (80000)	2	25	
Wind 2030	750 (70000)	1,5	35	
Solar 2020	900 (65000)	2	15	
Solar 2030	535 (50000)	1,5	20	
Hydro (existing)	-	1000 rub/kW·year	80	
Nuclear (existing)	-	3000 rub/kW·year	90	300
Nuclear (new) 2020	1750 (125000)	2,5	90	300
Nuclear (new) 2030	1150 (110000)	2,5	90	260

Beyond electricity price (LCOE), we should also evaluate CAPEX, lifetime cycle and efficiency of electrolyzers. To do that, we aggregated estimates from different sources including IEA [8], IRENA [9], NREL [10] and numerous consulting studies. Some of them seem to be too optimistic in regard to CAPEX learning curve as well as projections of electrolyzer stack lifetime. Given that the main parts of electrolyzer are catalysts produced with noble metals (platinum and iridium-based alloys) and titanium-based bipolar plates, we assumed relatively moderate rate of cost reduction and defined CAPEX closer to the upper limit of aggregated array of projections. All CAPEX figures were translated from USD/EUR to RUB using the average currency exchange rate in corresponding years.

We also assume only slight increase of electrolyzer stack lifetime given that this equipment must work in difficult, unstable circumstances (intermittent load, especially working in couple with renewable generation).

Capacity factor of electrolyzer corresponds with capacity factor of generation source connected (in this study, we assume that electrolyzer is supplied by dedicated power plant, not by grid power).

All the assumptions we made about technical and economic performance of electrolyzers are summarized in Table 2. Two types of electrolyzers are analyzed: alkaline (ALK) and proton-exchange membrane (PEM) of which the first type requires stable power source (base-load generation) while the second one allows utilization of intermittent generation (like renewables).

^a assuming currency rate 73 rub/usd in 2020 and 93 rub/usd in 2030 (projected annual inflation 1,5% for dollar and 4% for ruble)

Table 2. Assumptions on technical and economic parameters of electrolyzers

	Alkaline (ALK)		Proton exchange membrane (PEM)	
	2020	2030	2020	2030
Type of generation source connected	stable supply (nuclear, hydro)		intermittent supply (wind, solar)	
CAPEX, usd/kW (rub/kW) ^b	1000 (73000)	550 (51000)	1800 (130000)	700 (65000)
OPEX, % of CAPEX	1,5	1,5	2	1,5
Minimum load, %	30%	30%	10%	10%
Efficiency rate, %	65%	70%	65%	70%
Cells lifetime, hours	10000	12000	5000	8000
System lifetime, years	20	20	20	20

3 Results and discussion

In the study, we investigated economic efficiency of electrolysis under different scenarios. The basic scenario is based on projections provided in Tables 1 and 2. Our estimations show that as of 2020 none of the non-carbon generation technologies is able to produce hydrogen at affordable price (see Fig. 1). Especially high is cost of hydrogen produced with renewable electricity – around 14 USD/kg H₂ for solar and 9,5 USD/kg H₂ – for wind generation. It is caused by relatively low capacity factor of this plants (nowadays most of wind farms in Russia has utilization rate about 25% which is significantly lower than best cases in Europe; for solar this figure is even lesser – typically 15-17% due to moderate insolation of majority of Russian national territory).

Up to 2030, our estimations show significant reduction in cost of hydrogen produced with renewable electricity. In basic scenario we assume further capital cost reduction for both wind and solar generation (mostly due to higher localization level of such equipment production) as well as further increase of their capacity factors. But all in all, by 2030 we forecast that hydrogen will cost around 3 USD/kg H₂ being produced by wind generation and almost 4,5 USD/kg H₂ if it will be produced by solar power. These figures are 2 and 3 times higher than LCOH for traditional steam methane reforming (SMR) with carbon capture and storage, which is assessed by IEA as 1,6 USD/kg H₂ (figure for Russia).

^b assuming currency rate 73 rub/usd in 2020 and 93 rub/usd in 2030 (projected annual inflation 1,5% for dollar and 4% for ruble)

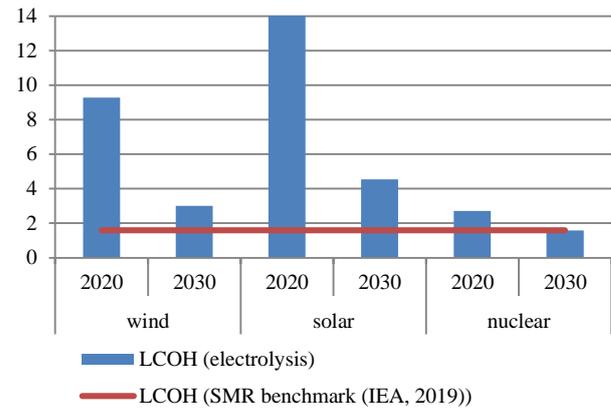


Fig. 1. LCOH for electrolysis with different power sources compared to steam methane reforming (SMR) with carbon capture and storage, USD/kg H₂ (conditions of Russia)

Surprisingly, nuclear power seems to be the best non-carbon option to produce “green” hydrogen in Russian national-specific case. This is due to relatively small capital cost of nuclear plants – almost all necessary equipment and raw materials for such plants is made domestically and the industry benefits greatly from weak national currency (it reduces the equipment and construction cost in USD/EUR). By our estimations, LCOH produced with nuclear power is 2,7 USD/kg H₂ in 2020 and will decrease to 1,6 USD/kg H₂ to 2030 (which is equal to the price of hydrogen production from natural gas in the Russian circumstances).

Because LCOH produced from power generation paid by its “fair” LCOE is too high to be economically feasible until at least 2030, we also evaluated the situation when hydrogen production is fed by existing (fully depreciated) power plant. In this case, LCOE contains only operation cost without investment return cost and therefore is considerably lesser than “full” LCOE. Because of relatively small life time of renewables, in this case we assessed only nuclear and hydro generation which have life time cycle about 2-2,5 times higher their typical depreciation period.

As presented in Fig. 2, existing fully depreciated hydro and nuclear generation in Russia is able to produce hydrogen at equal price with steam methane reforming (1,5 – 1,8 USD/kg). But further reduction of electrolyzer equipment cost can assure much lower cost of “green” hydrogen (around 0,8 USD/kg for both hydro and nuclear electricity with electrolyzer cost at 500 USD/kWe).

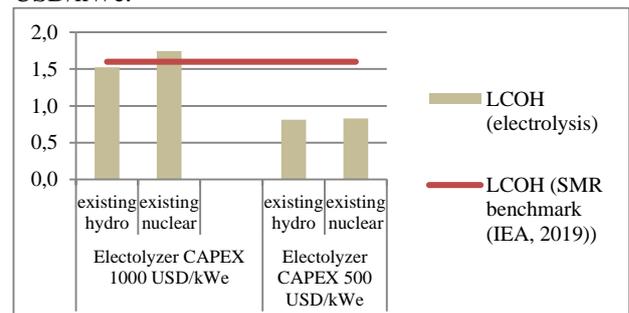


Fig. 2. LCOH for electrolysis with existing fully depreciated non-carbon generation, USD/kg H₂ (conditions of Russia)

We also fulfilled an analysis of LCOH sensitivity to deviations in most important input parameters. Our goal is to find conditions under which renewable-derived hydrogen will be competitive with methane-derived. We estimated the impact of:

- 1) CAPEX of generation sources which feed electrolyzer with electricity
- 2) capacity factor of these generation sources (which predefines capacity factor for electrolyzer connected)
- 3) CAPEX of electrolyzer itself
- 4) cost of capital (assuming equal cost of money for both hydrogen production and power generation)

To evaluate LCOH sensitivity to CAPEX of supplying power generation, we assume more rapid reduction of such cost for renewables. In part of wind generation we assessed its CAPEX lesser by step 150 USD/kW and for solar generation – by step 100-135 USD/Kw (Fig. 3). We also estimated LCOH produced by nuclear generation with more large capital cost (assuming its increase in line with ruble inflation, without technological progress in the nuclear machinery and construction industry).

Our estimations show that CAPEX reduction can lead to 8-15% decrease in LCOH made by both type of renewable sources. However, even such extremely deep (if not said unrealistic) reduction of capital cost cannot help to reach cost-parity between electrolytic and natural gas-based hydrogen.

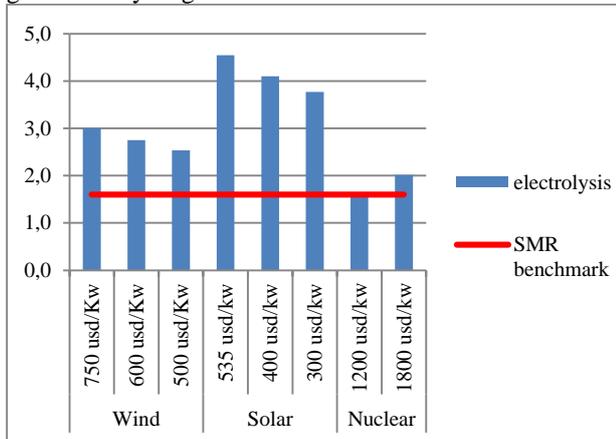


Fig. 3. LCOH for electrolysis at different CAPEX of supplying generation sources, USD/kg H₂ (conditions of Russia)

The second investigated parameter is capacity factor of supplying generation, which directly influence utilization rate of connected electrolyzer and, therefore, the price of hydrogen produced. We estimated only renewable generation in this topic, assuming the step of 5% above the basic scenario figures (Fig. 4).

Even if capacity factor of wind generation increase to 45%, it can only reduce the hydrogen cost to 2,2 USD/kg which is still bigger than cost of natural gas-based hydrogen. For solar generation, 35% utilization rate can lower cost of hydrogen only to 2,7 USD/kg.

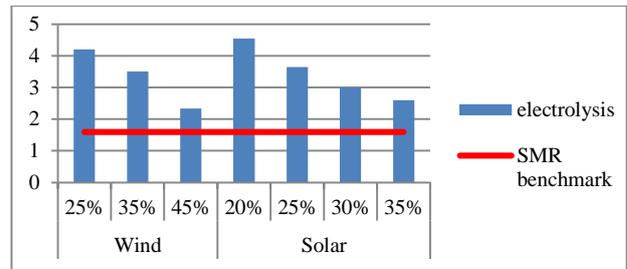


Fig. 4. LCOH for electrolysis at different capacity factors of supplying generation sources, USD/kg H₂ (conditions of Russia)

Decrease in CAPEX of electrolyzer from 700 USD/kW (in our basic scenario) to 400 USD/kW (bottom limit of all observed expert estimations on the horizon till 2030) can reduce LCOH from 3 to 2,2 USD/kg H₂ using wind generation and from 4,5 to 3,2 USD/kg H₂ using solar power (Fig. 5). For nuclear usage, reduction in LCOH is only marginal because of 90% utilization rate of electrolyzer coupled with nuclear plant overweight even relatively big capital cost of equipment replacing it on significantly larger amount of hydrogen output.

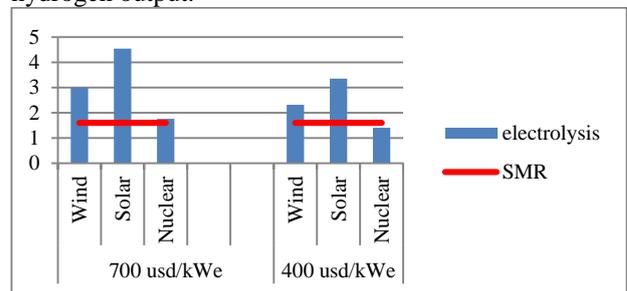


Fig. 5. LCOH at different CAPEX of electrolyzer (700 and 400 USD/kWe), USD/kg H₂ (conditions of Russia)

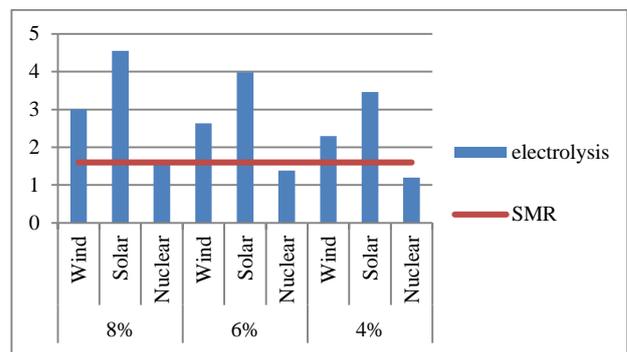


Fig. 6. LCOH at different cost of capital (assuming equal cost of money for both hydrogen production and power generation), USD/kg H₂ (conditions of Russia)

In case of reduction in cost of money (Fig 6), LCOH will demonstrate dynamics similar to the case with CAPEX reduction. LCOH produced with dedicated wind farm will decrease from 3 USD/kg to 2,7 USD/kg (6% discount rate) and to 2,2 USD/kg (4% discount rate). For solar generation usage, LCOH will drop to 4 USD/kg and 3,4 USD/kg, respectively.

Our estimations show that even powerful changes in any individual factor impacting cost of “green” hydrogen is not sufficient to provide its market competitiveness with traditional natural gas-based hydrogen. Exception is

electrolysis with power from nuclear generation – in this case the cost parity with “traditional” hydrogen production is visible to 2030 under some reasonable assumptions.

So that, we have also investigated the potential of LCOH reduction with simultaneous changes in several (and even all) of the above-discussed factors. The results are presented in Table 3. We can see that even under best forecasted conditions (the last string in Table 3) renewable generation cannot outperform nuclear power in LCOH output value.

Table 3. LCOH at simultaneous changes of several effecting factors, USD/kg H₂ (conditions of Russia)

	Wind	Solar	Nuclear
Electrolyzer CAPEX 700 USD/kW Wind and solar CAPEX as in basic scenario Wind capacity factor 45% (solar - 35%) Cost of capital 4%	1,78	1,98	1,33
Electrolyzer CAPEX 700 USD/kW Wind CAPEX 500 USD/kW, solar CAPEX 300 USD/kW Wind and solar capacity factor as in basic scenario Cost of capital 4%	1,93	2,87	1,33
Electrolyzer CAPEX 400 USD/kW Wind and solar CAPEX as in basic scenario Wind and solar capacity factor as in basic scenario Cost of capital 4%	1,78	2,56	1,07
Electrolyzer CAPEX 400 USD/kW Wind CAPEX 500 USD/kW (solar - 300 USD/kW) Wind and solar capacity factor as in basic scenario Cost of capital 4%	1,41	1,96	1,07
Electrolyzer CAPEX 400 USD/kW Wind and solar CAPEX as in basic scenario Wind capacity factor 45% (solar - 35%) Cost of capital 4%	1,38	1,46	1,07
Electrolyzer CAPEX 400 USD/kW Wind CAPEX 500 USD/kW, (solar - 300 USD/kW) Wind capacity factor 45% (solar - 35%) Cost of capital 4%	1,10	1,12	1,07
<i>SMR benchmark for Russia (IEA, 2019)</i>	<i>1,60</i>		

4 Conclusions

Non-carbon methods of hydrogen production attract the growing attention in the world, and this process directly influences Russian energy sector. We estimated price competitiveness of hydrogen production in the interim Russian market using electricity from different non-carbon sources – wind, solar and nuclear – on the horizon up to 2030. Our results show that popular renewable sources such as wind and solar are not able to produce hydrogen at affordable price. As of 2020, LCOH produced from electricity of such sources is 6-10 times higher than LCOH produced by steam methane reforming. Further technological progress in economic

characteristics of both renewable generation and electrolyzers themselves will sharply reduce cost difference between two methods of hydrogen generation, but it will be still visible (2 times higher for wind, and 3 times higher for solar in our basic scenario).

Even more significant improvements in performance characteristics of renewables (their CAPEX and capacity factor) failed to help them to become an affordable power source to feed electrolyzers. Our calculations show that only extremely favorable coincidence of effecting factor (including low interest rate – no more than 4%) can lead to cost parity of “green” hydrogen fed by renewable electricity with SMR-based hydrogen (estimated as 1,6 USD/ kg H₂).

In contrast, nuclear power in the Russian economic and climate circumstances can provide electrolyzers with electricity at economically rational price. Our estimations show that nuclear-based “electrolytic” hydrogen can reach cost parity with SMR-based hydrogen until 2030. Moreover, all technical and economic features of nuclear plant are quite stable, thus cost efficiency of “green” hydrogen in this case will be dependent mostly on electrolyzer manufacturing progress itself than on corresponding progress in nuclear industry. Even at negative dynamics of nuclear CAPEX cost of hydrogen produced will be no more than 2-2,2 USD/kg, which is well below than in most of considered cases for renewable generation technological advance.

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