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Economic analysis of an installation producing hydrogen through water electrolysis

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Abstract

This paper presents an economic analysis of an installation that produces hydrogen through water electrolysis. The purpose of the economic analysis performed for the hydrogen generator was to determine the break-even price of hydrogen. In calculations the NPV (Net Present Value) indicator was used. The reference system had installed power of 10 MW and worked 8 hours a day (2920 hours per year) during the valley of demand for electricity. The installation's lifetime was assumed to be 100,000 hours. The efficiency of the hydrogen generator was assumed to be 80% during operation at maximum power.

Keywords: energy storage, hydrogen, hydrogen generator, electrolyzer

1. Introduction

Power-to-Gas (P2G) and Power-to-Gas-to-Power (P2G2P) installations are often considered as candidates for storing energy from wind farms and photovoltaic installations. These systems should be considered for use mainly in countries where renewable energy sources constitute a significant share in the electricity production mix. One way to categorize technological solutions in which hydrogen is used as an energy carrier is by differentiating by origin of electricity used in the energy storage process. They include autonomous systems, powered only by electricity generated from renewable energy sources installations, and systems cooperating in the field of purchase and sale of electricity with the national power system [1].

The P2G concept is to use electricity during times of excess in the power system to supply hydrogen generators tasked with water electrolysis. The main product created in a P2G installation is hydrogen, with oxygen as a potential additional commercial product [2]. Pressure, cryogenic and low-pressure tanks (using metals hydride technology) are the most commonly used tanks for hydrogen storage [3].

P2G2P installations can additionally convert into electrical energy the chemical energy contained in the hydrogen that is generated. For the purpose of electricity generation, in most cases PEM fuel cells are used in P2G2P installations [4]. Compared to other energy storage technologies, such as pumped storage systems or CAES (Compressed Air Energy Storage) power plants, P2G2P installations are characterized by relatively low efficiencies, which usually do not exceed 40% [5–7]. A schematic diagram of a P2G2P installation is shown in Fig. 1.

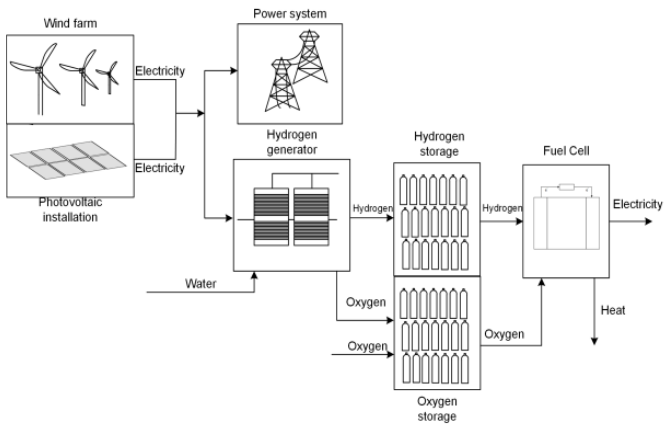

Figure 1: Schematic diagram of a Power to Gas to Power installation

Current power changes in the national power system resulting from the share of renewables in the energy mix (e.g. wind farms or photovoltaic power plants) and from variable activity of electricity consumers through the day are fully compensated by existing system elements, such as pumped storage installations. Further increases in the share of renewables, characterized by variable output due to weather conditions, may trigger a need for new energy storage installations to ensure enhanced network flexibility [8]. Therefore, alongside the dynamic growth in renewables, technologies

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should clearly be developed to store surplus energy. Installations such as P2G and P2G2P may in the future provide an alternative to currently popular energy storage technologies, like pumped storage power plants.

2. Hydrogen production

Hydrogen in large quantities is used in many industries, and in the energy sector as an energy carrier. Hydrogen is obtained mainly in processes using non-renewable fuels, including hard coal, crude oil and natural gas. About 96% of industrial hydrogen is produced in fossil fuel conversion processes, while water electrolysis, which does not require fossil fuels, produces only 4% [9]. The most commonly used technology for obtaining hydrogen is steam methane reforming (SMR), which produces about 50% of current hydrogen demand. The efficiency of hydrogen production in SMR is 74-85% [10]. Water electrolysis is a fundamental solution when using energy from renewables for hydrogen production. This solution does not require fossil fuels, but electrical energy necessary for the electrolysis process may come from energy surpluses elsewhere or directly from renewable energy installations [11]. Electrolysis takes place in electrolyzers. An electrolyzer consists of two electrodes: a positive electrode (anode) and a negative electrode (cathode). Oxidation takes place at the anode, while reduction takes place at the cathode. The overall reaction of the water electrolysis process can be written as:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{1}$$

However, the electrolyzer is not a fully autonomous device. To function properly it needs a number of auxiliary devices: a control system, power supply system (AC/DC conversion process), a cooling system and a gas drying installation. These, together with the electrolyzer, create the hydrogen generator.

3. Economic analysis

The calculations presented in this paper show the economic analysis of an installation producing hydrogen through water electrolysis. The purpose of the economic analysis was to determine the break-even price of hydrogen. In the calculations, the NPV (Net Present Value) indicator was used, calculated using the equation [12–15]:

$$NPV = \sum_{t=0}^{t=N} \frac{CF_t}{(1+r)^t} \tag{2}$$

where: CF_t—cash flows, PLN; t—subsequent years of installation working; N—installation lifetime ($t = 15$ years); r—discount rate (6%).

Cash flows CF_t were calculated using the formula:

$$CF_t = -J + S_{H2} - S_{EN} - K_{OP} \tag{3}$$

where: J—installation investment costs, PLN; S_{EN}—electricity purchase cost, PLN; S_{H2} —hydrogen sale revenue, PLN; K_{OP}—installation operating costs (operation, maintenance and repair), PLN.

The investment costs included the purchase cost of a hydrogen generator. This value included the purchase cost of alkaline electrolyzers, supply power system, control system and gas drying installation. The hydrogen generator investment costs J can be calculated as:

$$J = J_G = k_G \cdot P_G \tag{4}$$

where: J_G—hydrogen generator investment cost, PLN; k_G—unit cost of hydrogen generator, PLN/kW; P_G—hydrogen generator power, kW.

4. Calculation algorithm

The $NPV = 0$ condition was used to determine the break-even price of hydrogen produced through water electrolysis. Assuming constant cost and income and assuming that capital expenditures were incurred during year zero (for $t = 0$), the equation, expressing the NPV index can be written as:

$$J = J_G = k_G \cdot P_G \tag{5}$$

Where ρ is defined as the annual rate of investment costs return and expressed as [16]:

$$\rho = \frac{r \cdot (1+r)^N}{(1+r)^N - 1} \tag{6}$$

The annual rate of investment costs return with the assumptions adopted for the need of economy where calculations $r = 0.06$ and $N = 15$ is equal to 0.1030. Revenues generated from the sale of produced hydrogen and the electricity purchase cost needed to supply the hydrogen generator are shown by equations, and, .

$$S_{\mathrm{H2}} = c_{\mathrm{sH2}} \cdot E_{\mathrm{H2}} \tag{7}$$

$$S_{\mathrm{EN}} = c_{\mathrm{kEN}} \cdot E_{\mathrm{G}} \tag{8}$$

where: c_{sH2}—hydrogen sales price, PLN/kWh; c_{kEN}—electricity purchase price, PLN/kWh; E_{H2}—amount of energy contained in produced hydrogen, kWh; E_G—amount of electricity needed to supply the hydrogen generator, kWh.

The E_G and E_{H2} values can be linked by the following relationship:

$$E_{\mathrm{H2}} = \eta_G \cdot E_{\mathrm{G}} \tag{9}$$

where: η_G—hydrogen generator efficiency,

Electricity purchase price of c_{kEN} was calculated on the basis of data from Towarowa Giełda Energii S.A. as the arithmetic average of monthly average electricity purchase prices off-peak for 6 months and it is equal to 0.1333 PLN/kWh.

Using a $NPV = 0$ condition, the following relationships can be written:

Table 1: Parameters of hydrogen generator reference

	Parameter	Value
1.	Rated power	10 MW
2.	Working time	8 hrs / day (2920 hours per year)
3.	Lifetime	100,000 hours
4.	Efficiency	80%
5.	Unit cost of hydrogen generator	2620 PLN/kW, 16]
6.	Cost of demineralized water	180 PLN/m^3
7.	Monthly salary of employees (4 people)	8320 PLN/person
8.	Maintenance and repairs costs	1% of installation investment costs

$$S_{H2} = S_{EN} + J\rho + K_{OP} \tag{10}$$

$$c_{sH2} \cdot E_{H2} = c_{kEN} \cdot E_G + \rho \cdot (k_G \cdot P_G) + K_{OP} \tag{11}$$

Parameters assumed for hydrogen generator reference installation are shown in Table 1.

Economic analyses of the installation producing hydrogen through water electrolysis were made for three different cases:

1. Assuming installation operating costs $K_{OP} = 0$ and free electricity to supply the hydrogen generator installation;
2. Assuming installation operating costs $K_{OP} = 0$ and the purchase electricity cost from the national power system (including negative electricity purchase price values);
3. Taking into account installation operating costs (K_{OP}) which comprised demineralized water purchase cost, staff pay and periodic maintenance and repairs costs and also electricity purchase cost.

5. Calculation results

The first case was an installation producing hydrogen through water electrolysis, in which it was assumed that: system operating costs equal zero ($K_{OP} = 0$) and there is free electricity to supply hydrogen generators ($c_{kEN} = 0$). The break-even price of hydrogen for this case is expressed by the equation:

$$c_{sH2} = \rho \cdot \left(\frac{1}{\eta_G} \cdot \frac{k_G}{\tau_G} \right) \tag{12}$$

Fig. 2 and Fig. 3 show a break-even price of hydrogen as, ???? THIS EXPRESSION REPEATS???] a function of generator efficiency depending on the working time of installation and the unit price of the hydrogen generator for assumptions $K_{OP} = 0$ and $c_{kEN} = 0$, where 1 EUR~4.16 PLN.

The second case was an installation in which its operating costs were not taken into account, while the reference electricity purchase price (c_{kEN}) was assumed (0.1333 PLN/kWh). The presented results also include variants of negative electricity purchase prices. Such cases may

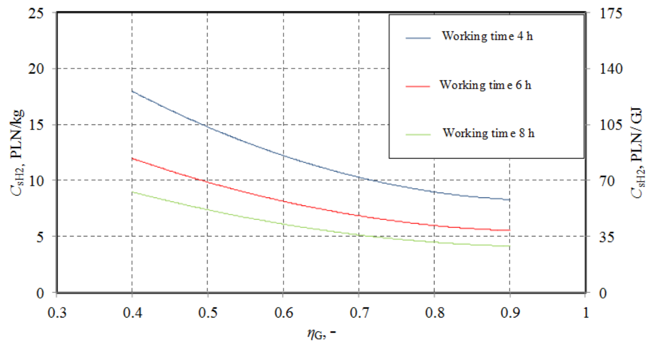

Figure 2: Break-even price of hydrogen as a function of generator efficiency depending on the working time of installation, for the assumptions K_{OP} = 0, c_{kEN} = 0 and for unit price equal 2620 PLN/kW

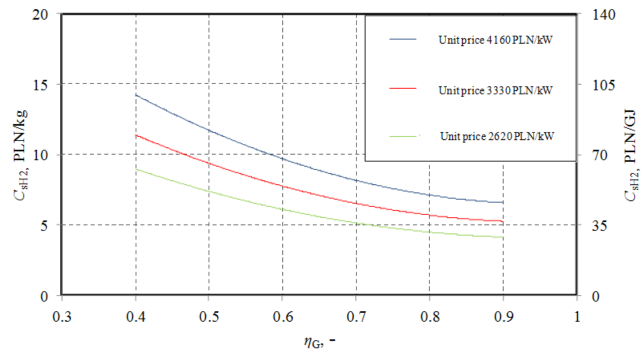

Figure 3: Break-even price of hydrogen as a function of generator efficiency depending on the unit price of the hydrogen generator, for assumptions K_{OP} = 0, c_{kEN} = 0 and for working time 8 hours a day (2920 hours per year)

take place in energy systems that are characterized by a large share of renewables in the energy mix. The break-even price of hydrogen produced through water electrolysis, for the second analyzed case, is given by equation, . Figures 4-6 show the break-even price of hydrogen as a function of generator efficiency depending on the working time, unit price of the hydrogen generator and electricity purchase price.

$$c_{sH2} = c_{kEN} \frac{1}{\eta_G} + \rho \cdot \left(\frac{1}{\eta_G} \cdot \frac{k_G}{\tau_G} \right) \tag{13}$$

In the next calculation variant, the operating costs of the hydrogen generator installation as well as the electricity purchase price were taken into account. The operating costs of the installation were determined from equation, , while the break-even price of hydrogen was calculated by equation, .

$$KOP = SH2O + SES + SR = \frac{\frac{9}{E_{HG}}}{\rho_{H2O}} \cdot \cdot P_G \cdot \tau_G \cdot cH2O + SWP + 0.01 \cdot JG \tag{14}$$

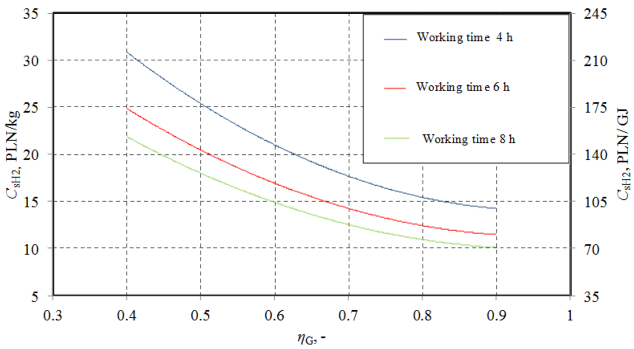

Figure 4: Break-even price of hydrogen as a function of generator efficiency depending on the working time of the installation, for the assumptions K_{OP} = 0, c_{kEN} = 0.1333 PLN/kWh and for a unit price of 2620 PLN/kW)

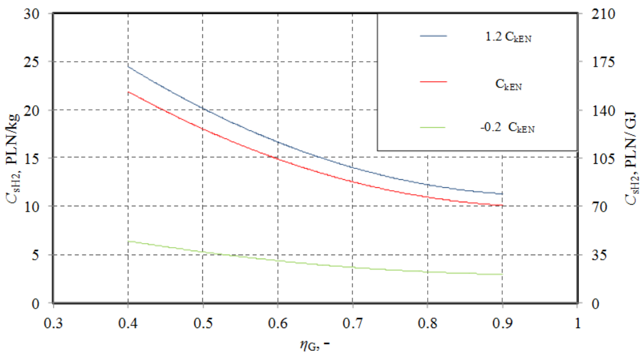

Figure 6: Break-even price of hydrogen as a function of generator efficiency depending on the electricity purchase price, for the assumptions K_{OP} = 0, working time 8 hours a day (2920 hours per year) and for A unit price of 2620 PLN/kW

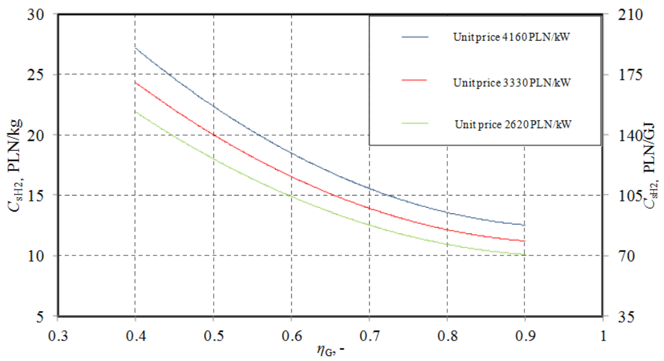

Figure 5: Break-even price of hydrogen as a function of generator efficiency depending on the unit price of a hydrogen generator, for the assumptions K_{OP} = 0, c_{kEN} = 0.1333 PLN/kWh and for working time 8 hours a day (2920 hours per year)

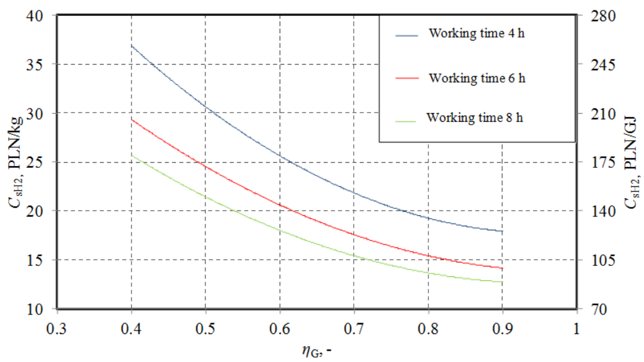

Figure 7: Break-even price of hydrogen as a function of generator efficiency depending on the working time of installation, taking into account installation operating costs K_{OP} and for assumptions: c_{kEN} = 0.1333 PLN/kWh and unit price of 2620 PLN/kW

where: S_{H2O}—cost of demineralized water, PLN; S_{ES}—staff pay, PLN; S_R—cost of repairs, renovations and maintenance (1% of installation investment costs), PLN; ρ_{H2O}—water density, kg/m^3; c_{H2O}—demineralized water purchase price, PLN/dm^3; τ_G—operating time of the hydrogen generator per year, h; E_{HG}—electrical energy consumption of the hydrogen generator, kWh/kg]

$$c_{\mathrm{sH2}} = c_{\mathrm{kEN}} \cdot \frac{1}{\eta_{\mathrm{G}}} + \rho \cdot \frac{1}{\eta_{\mathrm{G}}} \cdot \frac{k_{\mathrm{G}}}{\tau_{\mathrm{G}}} + \frac{KOP}{P_{\mathrm{G}} \cdot \tau_{\mathrm{G}}} \cdot \frac{1}{\eta_{\mathrm{G}}} \qquad (15)$$

Fig. 7–9 shows the break-even price of hydrogen as a function of generator efficiency depending on the working time, unit price of the hydrogen generator and electricity purchase price, taking into account installation operating costs (K_{OP}) which comprise: demineralized water purchase cost, staff pay and periodic maintenance and repairs costs.

6. Summary

There has been a significant increase recently in the popularity of installations producing hydrogen by water electrolysis. Installations like Power-to-Gas or Power-to-Gas-to-Power, which use hydrogen as an energy carrier, may in the future provide an alternative to the current energy storage systems, like pumped storage. This paper presents economic calculations, taking into account three variants of installation producing hydrogen by water electrolysis. The economic analysis determined the break-even price of hydrogen, factoring in NPV.

For the first case in which assumptions were made that the operating costs of the system equal zero ($K_{OP} = 0$) and there is free electricity to supply the hydrogen generator installation ($c_{kEN} = 0$), the break-even price of hydrogen for reference installations was 4.56 PLN/kg. For the second case, in which the operating costs were not taken into account, while the reference electricity purchase price (c_{kEN}) was assumed, the break-even price of hydrogen for the reference installation was 11.10 PLN/kg. In the third case, the operating costs of the hydrogen generator installation and

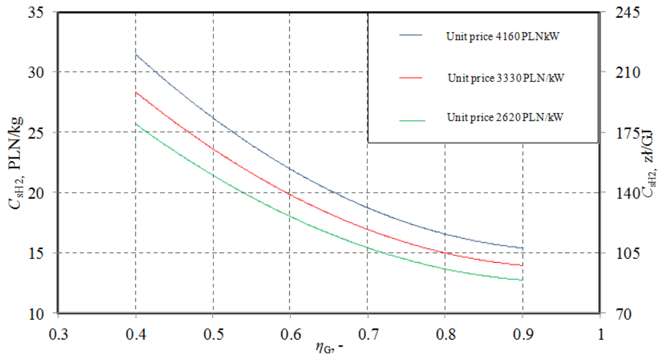

Figure 8: Break-even price of hydrogen as a function of generator efficiency depending on the unit price of the hydrogen generator, taking into account installation operating costs K_{OP} and for assumptions: c_{kEN} = 0.1333 PLN/kWh and working time 8 hours a day (2920 hours per year)

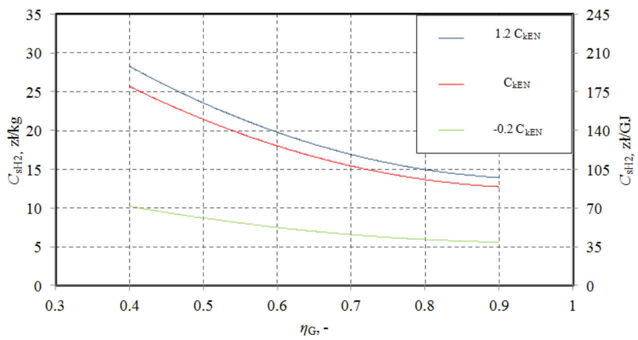

Figure 9: Break-even price of hydrogen as a function of generator efficiency depending on the electricity purchase price, taking into account installation operating costs K_{OP} and for assumptions: working time 8 hours a day (2920 hours per year) and unit price of 2620 PLN/kW

the electricity purchase price were taken into account. This time the break-even price of hydrogen for reference installations was 13.84 PLN/kg.

Fig. 10 shows the share of individual factors included in the economic analysis for the reference hydrogen generator installation.

For the reference system, electricity purchase costs have the largest share (47%) in the hydrogen break-even price. In systems where variable renewables account for a large percentage of the energy mix, it is increasingly the case that electricity prices are negative at times of low demand. Factoring negative prices into the calculation algorithm results in a significant reduction in the break-even price of hydrogen.

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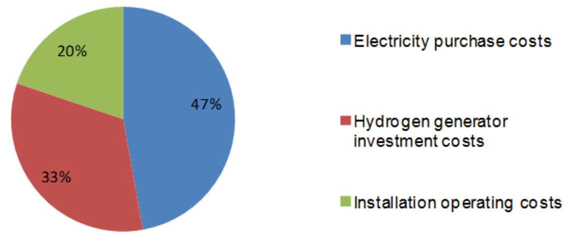

Figure 10: Share of individual factors included in the economic analysis for the reference hydrogen generator installation

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