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Domestic hydrogen installation in Poland – technical and economic analysis

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Abstract: The application of renewable energy sources poses the problems connected with output volatility. In order to decrease this effect the energy storage technologies can be applied, particularly fuel cells connected with hydrogen storage. In this paper the application of SOFC system for a household in Poland is proposed. Economic and technical analysis is performed. It was found that the proposed installation is profitable after 25 years of operation when compared with conventional solution – heat pumps and gas-fired boilers.

Key words: hydrogen, fuel cells, energy storage

1. Introduction

The increase in the applications of renewable energy sources (RSE) requires the application of auxiliary systems. Due to the volatility of their output the need for storage and output control appears. Two major RSE are wind turbines and photovoltaic cells (PV). Electric energy produced by them can be stored during the high power output periods and released when the production is low. Hydrogen technologies can be applied for this purpose. Hydrogen can be obtained with water electrolysis. This process can be applied in small scale by carrying out the endothermic reaction (1)[1]:

$$\mathrm{H_2O}_{(aq)} + 237.2\,\frac{\mathrm{kJ_{el}}}{\mathrm{mol}} + 48.6\,\frac{\mathrm{kJ_{th}}}{\mathrm{mol}} \rightarrow H_2 + 0{,}5\,\mathrm{O_2}. \tag{1}$$

Systems using such installations are immune to the power output volatility and, when properly scaled, do not require peak units. Hydrogen can be also used as a fuel for electric cars. The goal of this work is the economic analysis of hydrogen installation and the comparison with the other solutions. Data from Polish energy market will be used.

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2. Methods

2.1. Analysed household

Hydrogen obtained with water electrolysis is the basic primary energy carrying medium in a hydrogen household. Electrolysing unit can be powered with RSE. Expected monthly RSE power outputs have been shown in figure 1. It can be noted that in winter period when the insolation is smaller, the wind power output increases.

A household considered is the building with 20 rooms inhabited by 5 persons with a total area of approximately 200 m^2. Monthly heat and electric energy requirements have been shown in Figure 2. It was assumed that the RSE – hydrogen installation will be capable of fully supplying the household's heat and power needs. Heat needs have been approximated based on [2], electric on [3]. The example of an independent hydrogen installation have been presented in [4].

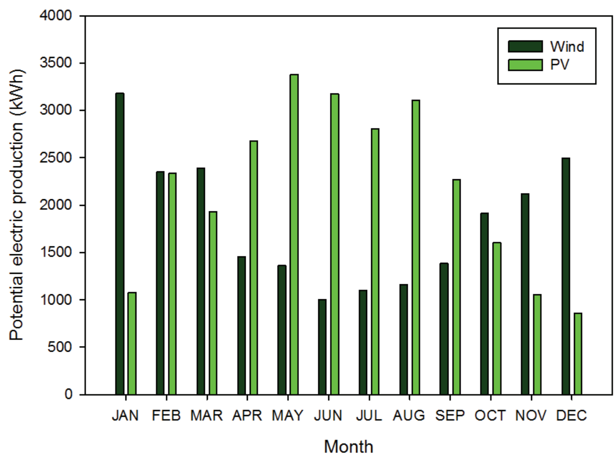

Fig. 1. Potential electric energy production from RSE installations

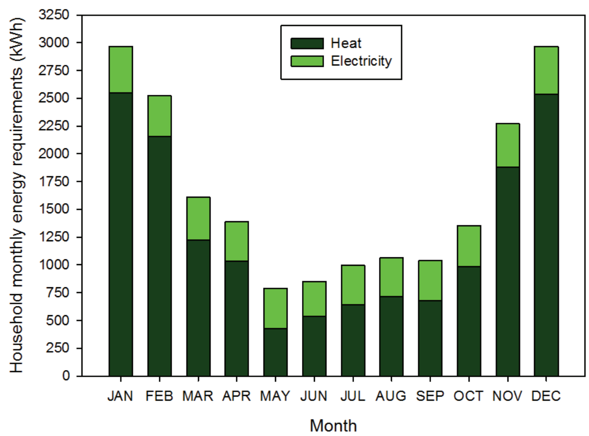

Fig. 2. Heat and electric energy requirements of the analysed household

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To find insolation computer software SOLARSYM ver. 2.2 has been used. The cells azimuth is 180°, slope is 30°, location – the city of Wroclaw. Energy production has been calculated with formula (2):

$$E_s = e_s \cdot A \cdot \eta_{ws}, \tag{2}$$

e_s is there an area insolation in W/m^2, A – PV cells area, η_{ws} – PV electric efficiency.

In order to calculate the wind energy potential, the average monthly wind velocities were based on [5], with an average yearly velocity assumed as 6.2 m/s, measured at the height of 3 m. Terrain roughness coefficient has been assumed as 0.18.

The wind velocities on optimal height of 15 m have been found with the formula (3):

$$v = v_p \left(\frac{h}{h_p} \right)^{\alpha}, \tag{3}$$

v is there the wind velocity at the height h, v_p is the wind velocity at the height h_p, α – terrain roughness coefficient. Wind energy potential e_w was found with formula (4) [3]:

$$e_w = \frac{1}{2} \rho_{air} v^3 t, \tag{4}$$

ρ_{air} is the density of air (assumed as 1.23 kg/m^3); v – wind velocity, t – the period of wind turbine operation. Estimated wind energy production potential was found with formula (5):

$$E_w = e_w \cdot \frac{\pi \cdot d_w^{\,2}}{4} \cdot n \cdot \eta_{ww}, \tag{5}$$

d_w is there the diameter of a turbine's rotor, n – the numer of installed turbines, η_{ww} – the wind turbine efficiency (assumed as 0.2).

2.2. Hydrogen installation

In this paper it is proposed to apply the solid oxide fuel cell (SOFC) technology. Such device can work also as electrolysing units (SOEC). In SOEC mode the device is supplied with power and heat and water is separated into hydrogen and oxygen. The products of this reaction are then stored and utilised in SOFC mode to produce heat and power. SOFCs have high operating temperature (approximately 700°C). Electric efficiency of fuel cell has been assumed as 50%. Additionally 40% of chemical energy supplied can be utilised as heat with the temperature of 190°C [6]. Electrolysis efficiency in a domestic system is approximately 80% [7]. It was assumed that the installation will operate in each of modes for the half of the operating period. Hydrogen tank volume should be sufficient to supply power for 12 hours a day. The amount of hydrogen required have been calculated with formula (6):

$$V = \frac{M_{H2} \cdot E_{D\max} \cdot k}{2 \cdot \eta_{FC} \cdot e_{H2} \cdot \rho_{H2}} \tag{6}$$

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V is there the required volume, M_{H2} is the molecular mass of hydrogen, k – safety coefficient (assumed as 4), E_{Dmax} is the daily energy usage in the month with the highest requirements, η_{FC} – fuel cell efficiency, e_{H2} – electric potential of the single mole of hydrogen (based on the equation (1)), ρ_{H2} – the density of hydrogen. Using the same assumption required RSE nominal power can be found (7):

$$P_{RSE} = \frac{k \cdot E_{D\max}}{\tau \cdot \eta_{EC}}, \tag{7}$$

P_{RSE} is the nominal *RSE* power, τ – expected daily electrolysis period (12 hours), η_{EC} – electrolysis efficiency.

Hydrogen is often stored in a gaseous state in pressure tanks or in a liquid state in cryogenic tanks. Required liquid hydrogen tank volume is approximately 30 dm^3, while storage of gas under the pressure of 30 bar requires 10 m^3. The application of the cryogenic tank requires complex and expensive cryocoolers therefore pressure tank variant will be analysed. Installation scheme has been shown in the Figure 3.

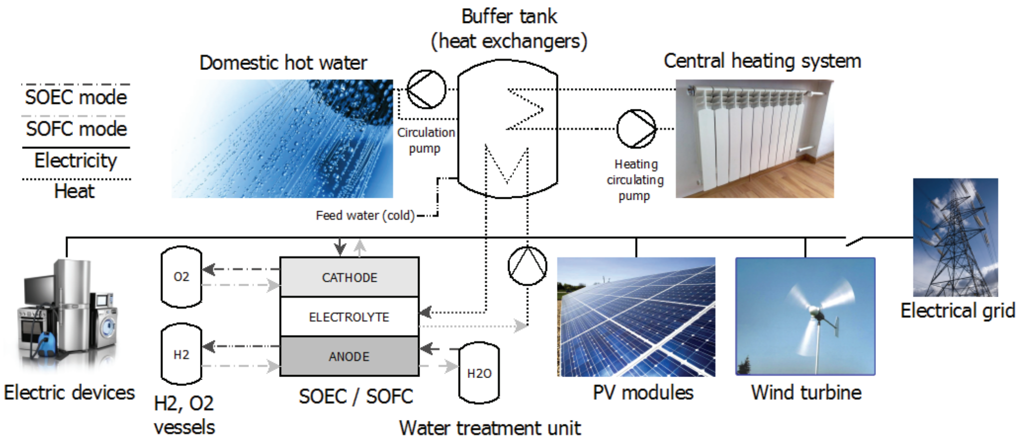

Fig. 3. Hydrogen installation scheme

2.3. Economic analysis

Total capital cost of the hydrogen installation consists of the costs of fuel cell, hydrogen storage and RSE purchase and assembly. Fuel cell stack costs have been approximated based on [8, 9] as 2 500 €/kW. The cost of a single wind turbine with nominal power is 1 900 €, PV installation with the power of 3.5 kW – 6 300 € [10]. Pressure tank cost is approximately 6 300 €. Auxiliary equipment costs approximately 1300 €. Additional 20% of costs have been added as the assembly and legal costs.

Variable costs come from the need to service the installation and supply it with fuel and consumables and the costs of technical supervision. The proposed installation is expected to operate for 20 years without major service [11, 12]. After that the general inspection is required and, in the case of a mechanical damage or the significant decrease of efficiency, the replacement of elements. The cost of such modernization is assumed as 20% of the total capital costs. The yearly cost of technical supervision is approximately 40 €.

The typical alternative for the proposed system is to apply heat pump for the heat production and to supply electric power from the electric grid. The capital costs in this case is the purchase of heat pump and assembly. The estimated cost of 8 kW heat pump installation in a 200 m^2 house is between 11 000 € and 20 000 € [13-15]. Yearly operation cost of heat pump in a 200 m^2 house is estimated as 650 € [14, 16].

Another possible solution is to apply only a boiler. The price of an automated boiler and auxiliary devices is estimated as at least 3 800 € [17-19]. In the case of lacking gas connection the tank should be bought costing approximately 2 500 € [18, 20]. Variable costs consist of technical supervision (40 € yearly) and the price of fuel (1000 € yearly). Every ten years major inspection and modernization should take place, costing approximately 25% of the initial capital cost. In case of the hydrogen installation electric energy surplus can be sold back to the electric grid. The price of electric energy has been assumed as 0.13 €/kWh. It was assumed that in the analysed building no technical possibility of installing heat or gas installation exists. To compare investment profitability the annual costs method is applied [8, 21, 22]. In order to apply this method capital recovery factor r is calculated according to the formula (8):

$$r = \frac{p \cdot (1+p)^N}{(1+p)^N - 1}, \tag{8}$$

p is there a bank rate, assumed as 2% and N is the annuities number. Annual cost is found with the Equation (9):

$$K_t = K_y + K_c \cdot r - R \tag{9}$$

K_t are there the total annual costs, K_c – capital costs, K_v – yearly variable costs, R – revenues from the installation.

3. Results

3.1. Size of production and storage system

Nominal power of RSE calculated with the formula (7) is 6.1 kW_{el}. Considering the data from Figure 1. it was decided to apply 5 wind turbines with the rotor diameter of 2.5 m situated at the height of 15 m, PV panels taking the area of 100 m^2 and fuell cell stacks with the nominal power of 3 kW_{el} i 2.4 kW_{th}. Based on formula (6) the pressure tank with the volume of 10 m^3 and pressure of 30 bar was chosen.

3.2. Economic analysis

According to the taken assumptions the total cost of hydrogen installation is 51 000 €. The application of such installation brings the yearly profit of 950 €. The investment cost of the heat pump installation is 13 000 €, the yearly cost is 1 200 €. In the case of the boiler installa-

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tion investment cost is 6600 €, the yearly cost is 1600 €. The comparison of annual costs of each installation is shown in the Figure 4.

4. Discussion

With the given assumptions the proposed installation appears to be economically justified. In larger time perspective the high investment costs (almost 3 times higher than the heat pump installation) are reduced with revenues from selling the surplus of electric energy. In the considered period the economics of conventional solutions is similar, while hydrogen installation becomes cheaper after approximately 25 years.

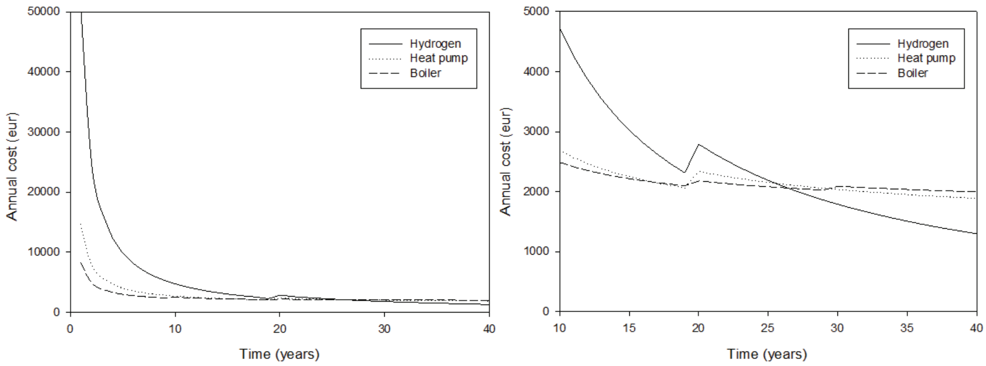

Fig. 4. Annual cost of the different solutions. Graph in the left contains the data excluding the first 10 years for greater clarity

Further technical development of fuel cells will lead to the decrease of prices and the increase of operation time. In turn the profitability and popularity will increase. Spread of hydrogen installations will help to intensify the progress of prosumer society and smart grid networks by the increase of the distributed generation potential. By the decentralization of power production capacity the energy safety will improve. Wide introduction of a hydrogen economy will allow for the significant reduction of the harmful substances emission. Mass usage of energy storage will lead to flatter demand curve and thus better operating conditions for the network power stations. Produced hydrogen can be also used to power cars using fuel cells or hydrogen combustion engines. Obtained oxygen has multiple applications as well – it is commonly used in metallurgy and chemistry. Since fuel cells can use air oxygen, pure oxygen from electrolysis can be sold separately.

The major danger in utilising hydrogen is its flammability. Installation safety can be ensured with pressure regulation, safety valves, proper ventilation and detection systems. Additionally, in order to inert the operating environment system can be equipped with argon or nitrogen tanks. Operation safety is also affected by the application of non-flammable construction materials and proper training. Proposed system causes some exploitation and introduction problems. It is complex, therefore its operation requires the possession of some knowledge

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and technical qualifications. Hydrogen is commonly perceived as a dangerous fuel. Therefore the proper education is required.

5. Conclusions

The installation described in this paper is economically profitable after 25 years when compared to conventional solutions. However, it requires the significant investments. In the time scale of 40 years currently used solutions are more expensive due to high fuel costs. By combining hydrogen unit with RSE almost complete energy autonomy can be achieved. The usage of two production systems ensures continuous supply and large control possibilities.

It is expected that the hydrogen application in households will be gaining popularity. The increase of legal limitations for conventional generation connected with environmental policy can cause SOFC to popularise and become the important element of the future energy system. In this paper it was shown that the assumption of hydrogen economy are correct and may be profitable.

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