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Storage system for electricity obtained from wind power plants using underground hydrogen reservoir

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Abstract

Wind power is characterized by high variability and unpredictability. Due to limited opportunities for electricity storage and the power grid's limited carrying capacity, an increase in the use of renewable sources may bring about unfavorable technical and economic consequences. Energy storage systems may mitigate the negative effects of electricity generation in wind power plants. Energy storage systems can also aid the cause of clean coal technologies, by increasing working time and efficiency and reducing CO2 emissions in coal power plants. This paper presents a simplified model of a system of energy storage in the form of hydrogen. Hydrogen is produced through electrolysis and is stored in underground storage sites. A hydrogen-fired gas turbine is used in the process of chemical energy-to-electricity conversion. Calculations are performed to determine hydrogen mass and volume flow needed for storage to make up for the insufficient amounts of electricity produced over time. A preliminary economic analysis for various power storage systems is also presented.

Keywords: Hydrogen, energy storage, economic analysis

1. Introduction

Energy a basic human need. It is used in different forms such as mechanical or thermal energy or the energy of electromagnetic waves. One of its most useful forms is electrical energy. As electricity cannot be stored easily, a large part of it is generated in amounts purposed to satisfy current demand. Electrical energy storage could be an effective way to lower manufacturing costs, as well as to reduce the size, number and mass of the devices generating electricity. The need to produce more electricity during periods of peak demand or during a limited energy production from renewable energy sources can result, in the case of gas systems, in a decrease in their average performance and economic efficiency [10]. Energy storage can contribute to better use, increase efficiency and reduce emissions of pollutants and CO2 in coal power plants.

Energy storage systems should first and foremost be characterized by economic efficiency, which is usually the effect of high storage efficiency and low investment and operating costs. To date, large-scale energy storage has been delivered by pumped hydroelectric storage power stations. Other options, such as underground compressed air energy storage (CAES), are much less common [10, 3]. In this range of technologies, systems in which heat is collected from the compression process [3] are also being developed. Compared to other technologies, underground storage of gas is relatively expensive, so systems of this type are uncommon [11, 9].

Taking account of the complexities of the power grid and the limited possibilities of storing energy, continuous change in the power output of at least some of the generating facilities becomes a necessity [9]. This need for flexibility of electrical energy generation is further aggravated by the unpredictability of the amount of electricity supplied to the system by wind and solar energy plants. Increasing the share of renewable energy sources in electricity generation in the coming years must involve the use of additional sources that will be able to respond promptly to changes in load. This role may be played by energy storage systems, which will additionally improve the efficiency of other energy sources.

Underground storage of hydrogen has been given little attention to date beyond installations built to serve the needs of oil refineries. These issues are now attracting interest, also due in part to the development of fuel cells [12, 13] and the growing use of hydrogen in transport [3, 11, 9, 2].

Special attention is drawn herein to the possibility of storing electricity from wind power plants in the form of compressed hydrogen, produced in electrolysis, stored in underground storage sites and used in gas turbines to generate

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Email address: `sebastian.lepszy@polsl.pl` (Sebastian Lepszy) electricity. Research on this particular problem was driven by a desire to develop the technical and economic characteristics of a generation and storage system that makes it possible to compensate for electricity generation from renewable sources.

2. Energy storage

It may be stated that energy contained in any of its forms is in fact stored in them. One basic factor that differentiates these forms from each other is the time scale. In electrical capacitors energy is stored for a period measured in seconds; in chemical storage cells—in hours or days. For biomass it may be years, whereas in the case of solar energy or fossil fuels—millions of years.

Energy storage technologies may be categorized based on the use of the stored energy and the associated main characteristic parameters. You can then distinguish: mobile technologies - the main parameter is the size of devices and stationary technologies - and the main parameter: the price of energy storage.

A list of parameters for selected storage technologies is shown in Table 1 [15, 4].

The energy storage technologies that may prove useful in an electrical power system using renewable energy sources are those that can store energy for about a year.

This may be of special importance for solar power engineering, less so for wind power generation.

Examples of technologies capable of storing large amounts of energy for a long time that offer the possibility of converting it efficiently to electricity are: pumped-storage power plants, underground compressed air energy storage systems and the still little-known hydrogen storage systems.

Though the general principle of the systems mentioned above is similar, they may be used in a different way. Due to their capacity, they differ in terms of the storage time, too. Owing to the short start-up time of pumped-storage power plants, they often operate in 24-hour cycles meeting the peak demand for energy. Owing to the involvement of gas turbines and high-temperature processes, compressed air energy storage systems are characterized by a longer storage time, which for hydrogen storage systems may reach a year due to their capacity to store large amounts of energy, .

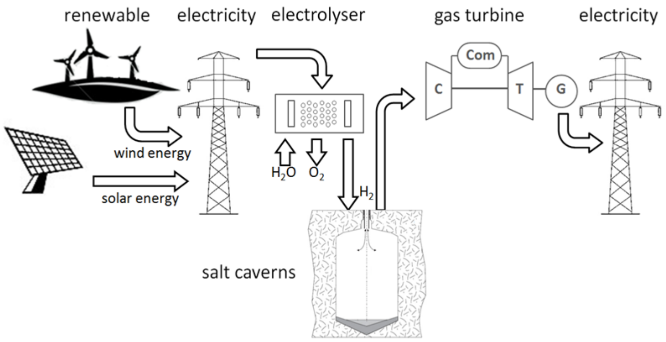

Figure 1: Proposed Method Flowchart

The concept of an underground hydrogen storage system operation is presented in Fig. 1. It consists of producing hydrogen from electricity generated from renewable energy sources in the process of electrolysis. Appropriately compressed hydrogen is injected into an underground storage cavern. In periods of high demand for energy, hydrogen is fed to a gas turbine generating electricity.

The analyzed storage technologies are also characterized by other features, such as their environmental impact at ground level. Pumped hydroelectric storage systems have a dramatic effect on ther surroundings, the landscape and the water environment in particular, because with two water reservoirs built at different altitudes, the lower one often involves major changes in river flow. CAES systems do not interfere dramatically with the environment or the landscape that much, but their operation requires the use of fossil fuels. Because a combustion process occurs in the system, this storage method leads to the gradual depletion of fossil fuels. The typical fuel here is natural gas, which is characterized by low emissions of pollutants. Considering the above, storing energy in the form of compressed hydrogen in underground storage caverns seems an interesting alternative. Due to the high calorific value of hydrogen, the technology can be used to store large amounts of energy. And because electrolysis can be controlled easily, the capacity for changing loads in the energy storage process is great. The time needed to start production from stored hydrogen may be broadly comparable to CAES systems, because the energy conversion technology is based on the same principle. However, it should be remembered that the rate of change in the operating system load may be high.

Compressed air and hydrogen storage systems pollute the air with nitrogen oxides, which is not the case in pumped-storage power plants. Moreover, in the hydrogen storage system there is no need to use additional amounts of conventional fuels (so it is not a case of replacing one baseload power plant with another). These technologies require specific conditions in their locations, such as special topographical features for pumped-storage power plants or an appropriate geological structure in the case of underground storage of gases.

3. Wind energy production

Units generating electricity from renewable energy sources are characterized by little or no emissions of pollutants into the atmosphere on the one hand, and—due to no costs related to fuel—by low variable costs of electricity generation on the other. The downside of renewable energy sources is the low efficiency of utilization of the electricity they generate. This is due to unforeseeable change in the amount of power generated imposed on the time-varying grid power demand.

Wind and solar power pose the greatest problems in terms of forecasting power generated from renewable sources. The main difficulty is the forecasting of weather conditions (which

Table 1: Parameters of energy storage systems

Technology	Power, MW	Discharging time, h	Lifetime, years	Inv. costs, $/kW
CAES	15–400	2–24	35	600–750
Pumped hydro	250–1,000	12	30	2700–3300
High Power Flywheel	0.7–1.6	0.0042–0.25	20	3695–4313
Ultra capacitor	10	<0.008	500 k cycles	1500–2500
Superconducting magnetic energy storage	1–3	0.0003–0.0008	30 k cycles	380–490
Superconducting magnetic energy storage	100–200	0.03 (1 MWh) 0.5–1 (100 MWh) 5–10 (GWh)	30 k cycles	700–2000
Lead acid (cells)	3–20	0.003–4	4–8	1740–2580
Lithium ino (cells)	5	0.25–4	15	4000–5000
Sodium sulphur (cells)	35	8	15	1850–2150

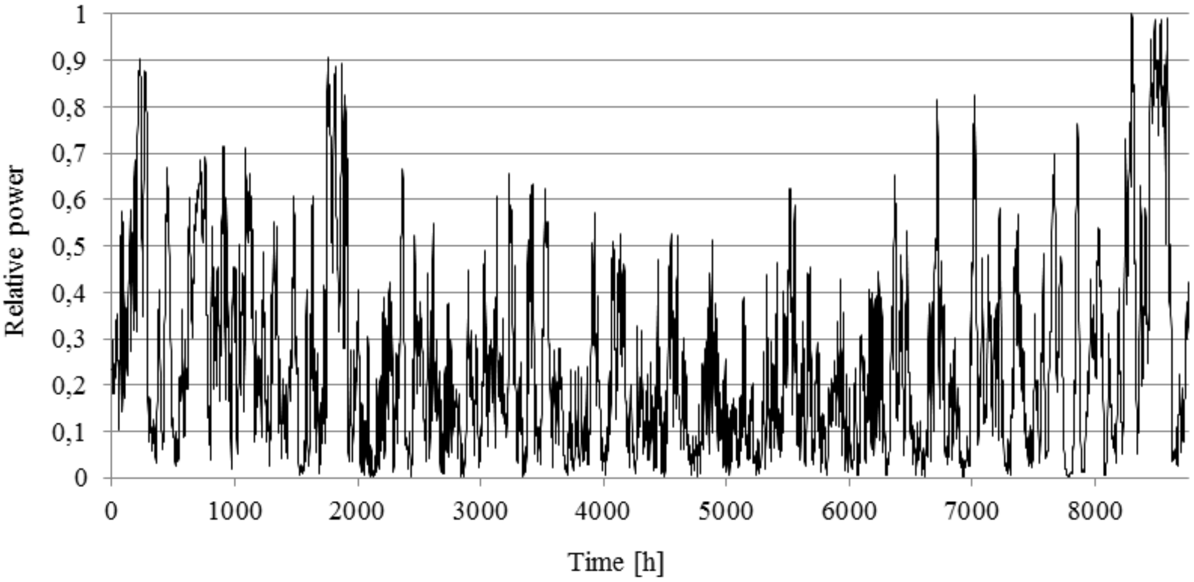

Figure 2: The dependence of the relative power of wind power as a function of hours a year (own study based on data from the Energy Regulatory Office)

have a direct impact on generation). The variability of meteorological parameters results in variable electricity production over time. An example of the dependence of the relative power of wind power in the Polish power system is shown in Fig. 2 [1]. It is difficult to find reliable trends in the charts concerning wind energy that would allow for production planning in short periods of time. It is also characteristic that the power generated by wind farms may vary by 80-90% within a period of several hours.

Considering the installed power of these sources in Poland at the level of 3.83 GW, this may jeopardize electricity transmission system stability.

The amount of electricity produced by wind turbines or solar strictly depends on the meteorological conditions at that location. For the calculation of electricity produced from wind power, statistical data from meteorological stations can be used. Using the mean values of wind speed and the coefficients of the probability distribution, the annual amount of energy produced and operating times with specific power can be determined [9]. For the purpose of storage systems, such analysis may be insufficient due to a lack of information on the variability of the wind speed over time, which affects the variability of the production of hydrogen.

More useful data could come in the shape of information from existing wind farms in the area. This data may take the form of a set of values of wind speed, temperature, and power of the wind turbine, for each hour of the year. Using this type of data bears the risk that the selected values are not representative in relation to the average values obtained from a number of years. In the case of data covering many years, the problem may be the substantial expansion of calculation time.

Another possibility is to use data for a typical meteorological year. The data are obtained by a combination of meteorological parameters obtained in a selected measurement station for the twelve months of the year. Among the data sets covering hourly average parameters for each month selected are those months whose average performance is close to the average values from many years. Due to the relatively large proportion of the weight of average wind speed (25%), data of this type appear to be reasonable for use in estimating the variability of the wind speed data in particular locations for a particular month. Due to the impact of air density power generated in wind turbines, information on air temperature can also be used, but due to the linear relationship of turbine power the density of air may be sufficient only for the use of an average value for the whole year.

Fig. 3 shows the relationship between wind speed and Gdansk time, based on the typical meteorological year data.

To calculate the quantity of produced electricity, a model based on the characteristics of the wind turbines can be used. A wind turbine or a group of them working in an area generates electricity depending on the wind speed. In the speed range from 0 to the minimum speed vmin the wind turbine does not generate electricity. In the range from minimum speed to the nominal speed vnom (ie., at which the turbine reaches rated power) the turbine is characterized by constant efficiency defined by the formula:

$$\eta_w = \frac{N_{el\_w}}{N_w} \tag{1}$$

where: N_w—power of wind stream, N_{el_w}—electric power of the wind turbine.

Power of the gas steam can be determined from the relationship:

$$N_w = \frac{1}{2} \cdot A \cdot v^3 \rho \tag{2}$$

where: A—perpendicular cross-sectional area through which flows a stream, v—velocity stream, ρ—density of gas.

For large wind turbine power plants the efficiency is now is in the range of 35% - 45%, which represents between 60% and 80% compared to the theoretical maximum realizable efficiency of 59.3% [9].

In terms of nominal speed vn to maximum speed it is assumed that the wind turbine operates at constant power (maximum). The characteristics of a wind turbine are illustrated in Fig. 4.

Taking into account wind speeds from a meteorological station, in the calculations the significant impact of wind turbine height should be considered [9]. Meteorological stations often measure wind speed at a height of 10 m, whereas the height of the nacelle of a wind turbine can reach 150 m. In the literature there are correlations to determine the wind speed at a given height. The simplest formulas require knowledge of only height measurements, more complex formulas take into account the type of terrain in the form of 'roughness'. One of the simplest formulas describing the change in the value of wind speed with height is as follows:

$$\frac{v(z)}{v(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha} \tag{3}$$

where: $v(z)$—average speed at the height z, $v(z_r)$—average speed at a reference height, z—height, z_r—height of the reference, α—exponent.

Corrected values can now form the basis for calculating the amount of energy produced and its variation over time.

4. Hydrogen production

The cheapest and the most common method of hydrogen production used at present is steam reforming of light hydrocarbons or methane. Other methods include for example partial oxidation of hydrocarbons and coal or biomass gasification. There are also thermochemical processes (using zinc oxide) or photothermochemical processes (used to a very limited extent). If electricity is used to produce hydrogen, the most effective and technologically mature method is electrolysis [4]. In the process, electrodes are separated from each other by electrolyte, and hydrogen and oxygen are formed on the cathode and anode, respectively. The general equation for the reaction on the cathode is as follows:

$$2H^+ + 2e^- \rightarrow H_2 \tag{4}$$

And for the reaction on the anode:

$$H_2O \rightarrow 0.5O_2 + 2H^+ + 2e^- \tag{5}$$

According to Faraday's law, the consumption of energy needed to produce hydrogen in the electrolysis process is proportional to the charge flowing through the electrolyte and to the difference in the electrode potentials. The theoretical electrochemical potential of water decomposition is 1.480 V but due to irreversibility and resistance in the devices it is in reality 1.75-2.05 V, which justifies the statement that the efficiency of electrolyzers is included in the range of 75-85%. Generally, three electrolyte types are used in electrolyzers: bases, solid polymer membranes and solid oxides. Electrolytes using bases are currently the most popular type. Due to high conductivity and because stainless steel is used for the electrodes, the electrolyte is a 30% solution of caustic potash. The electrolyzers operate in a temperature and pressure range of 70-100℃ and 0.1-3 MPa, respectively [8].

5. Underground gas storage caverns

The idea of storing gases in underground caverns originated from the need to supply natural gas consumers in periods of higher demand. Unlike above-ground storage tanks, underground caverns can store greater amounts of gas and at higher pressure. Other advantages include their small demand for land and the minimal impact of external factors on storage. Underground gas storage sites may be depleted oil or gas fields, deep aquiferous layers, salt caverns, occasionally—unmined coalbeds, or rock caverns. All of these sites have their own physical and economic characteristics. The key factors are: storage site capacity, the capacity of the gas blanket, the gas injection and extraction output and the cyclic operation parameters. The characteristic feature of depleted oil and gas fields is their high capacity. They are used in yearly cycles and contain a large amount of the medium in the gas blanket. Salt caverns are characterized by smaller capacities, large outputs involved in gas injection and extraction, as well as small demands related to the gas amount in the blanket. The effect of such features is that salt caverns are taken into consideration if energy is stored in the form of compressed air or hydrogen. Table 2 presents the parameters of two example hydrogen storage installations in salt caverns [15].

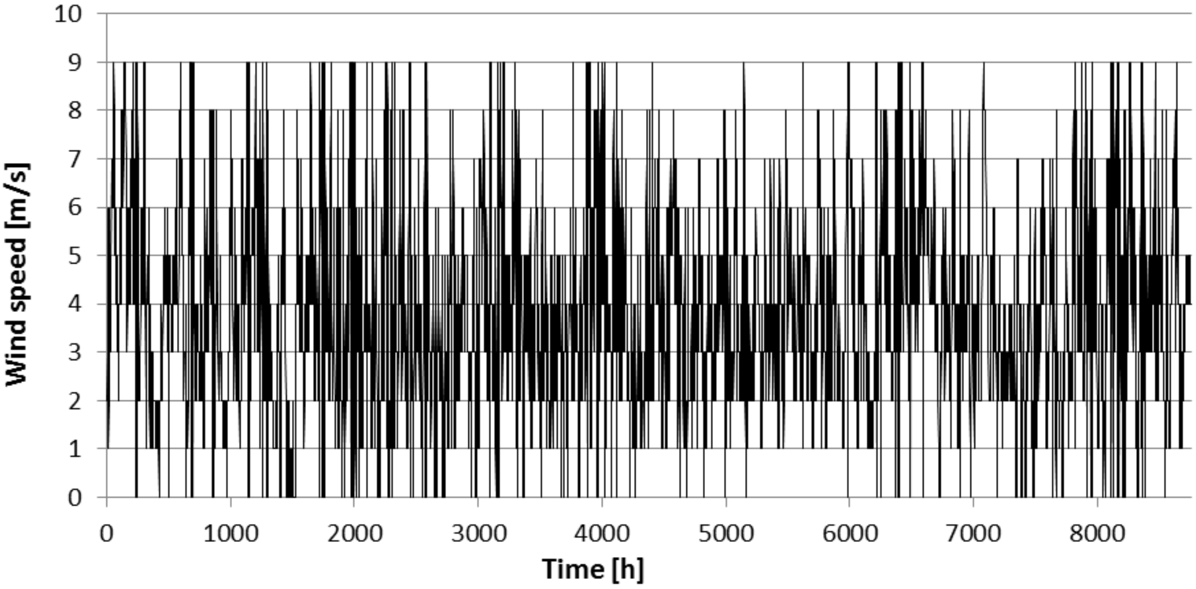

Figure 3: Wind speed as a function of time for a typical meteorological year in Gdansk

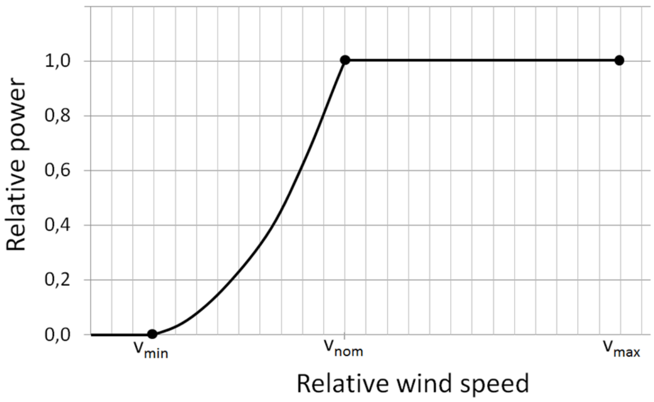

Figure 4: Characteristics of a wind power plant

Table 2: Example parameters of hydrogen storage in salt caverns

Location	Teeside—Great Britain	Cevron Texas—USA
Total capacity, m^3	3×150,000	580,000
Site depth, m	370	850–1150
Gas pressure, bar	45	70–135
Stored energy, GWh	24.4	83.3

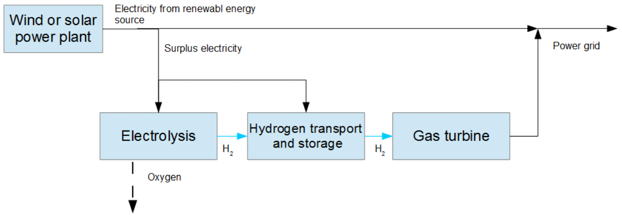

Figure 5: Schematic operation of the energy storage system

6. Electricity production from hydrogen

Systems with hydrogen storage devices that produce electricity from hydrogen should be characterized by high efficiency and a high degree of flexibility to ensure that variable electricity demand can be met. In this respect, interesting solutions can be integrated with gas turbines or fuel cells. One of the significant advantages of gas turbines in relation to the fuel cells is the relatively low investment required.

When planning the use of a gas turbine to generate electricity from hydrogen, among other things economies of scale should be considered. Smaller gas turbines are relatively expensive and have lower efficiency of electricity generation.

Working at partial load, which may take place in power storage systems, influences energy efficiency. That relation can be described by the equation:

$$\eta_{el\_cor} = \eta_{nom} \cdot \lambda_2 \tag{6}$$

where: λ_2—correction factor.

7. Energy analysis system

The main objective of the analysis was to determine the values of parameters for economic analysis. The most important ones are: the nominal power of wind turbine and gas turbine units, the amount of hydrogen and electricity produced, the quantity of stored hydrogen. A block diagram depicting these considerations is presented in Fig. 5.

The basic assumption of the energy calculation was the planned load profile of the system during the year. During periods of time when the power of the wind turbine exceeded the planned system power, the gas turbine was not

Table 3: Values representative of the nominal efficiency of gas turbines

Nominal power, MW	5	15	45	135
Nominal efficiency of electricity production, %	32	35	37	38.5

working, and the surplus was directed to the production of hydrogen; when the power of renewable sources was lower than planned power, the gas turbine worked (the power of the system was the sum of the power of the wind turbine and a gas turbine). A summary of assumptions and other system parameters are shown in the list below:

- Meteorological parameters: Location: Gdańsk; height of wind speed measurements 10 m; average wind speed: 3.8 m/s; average temperature: 8.7℃
- Wind power plant: nominal power is a function of storage system power; wind turbines axis height: 150 m, the minimum wind speed: 4 m/s; nominal wind speed 11 m/s; maximum wind speed 25 m/s; the efficiency of the wind turbine: 47.2% in the range from the minimum speed to the nominal speed
- Production of hydrogen: the electrolyzers efficiency: 62.5% (based on LHV); pressure of hydrogen: 3 MPa
- Compression and storage of hydrogen: consumption of electricity for hydrogen compression: 4 MJ/kg$_{H_2}$, average pressure in the cavern: 15 MPa; loss of hydrogen: 0%
- Production of electricity: Electric energy produced in the simple gas turbine, four levels of nominal power: 5, 15, 45, 135 MW, additional production of electricity using hydrogen expansion: 1 MJ / kg$_{H_2}$

The expansion of hydrogen upstream of the turbine increases the amount of recovered energy. A summary of the nominal value of the electricity generation efficiency of the gas turbine used for calculation is shown in Table 3.

Using the above assumptions, it was possible to determine the quantity of stored hydrogen. Examples of hourly values stored and hydrogen extracted in a system with a 5 MW gas turbine are shown in Fig. 6. The gas maximum mass flow determines the electrolyzer size. The gas minimum mass flow determines the size of the gas turbine. Fig. 7 presents the amount of stored hydrogen over time. The useful capacity of the hydrogen storage cavern must therefore be adequate for the difference between the hydrogen maximum and minimum amount. The figure shows a lack of seasonality and the high use of the working capacity of electricity from wind.

Detailed characteristics of the energy storage system are shown in Table 4. Based on the results, the proportion between the values of nominal power of renewable power plants and the nominal gas turbines power can be calculated. For the considered systems, this ratio ranged from approx. 6.6 to 7.4. An important parameter of analysis was the value of the hydrogen storage working capacity. It was determined that every megawatt of rated power of wind power corresponds with approx. 2.9 tons of hydrogen storage capacity. A significant increase in the value of storage efficiency can be observed with the increase in system power, mainly due to the increase in gas turbine efficiency.

Table 4: List of parameters of energy storage systems

Nominal electricity power gas turbine, MW	5	15	45	135
Electricity power wind power plant, MW	74.2	209	602	1756
Operating gas storage capacity, Mg	203	561	1598	4623
Maximum flux of hydrogen injected, kg/h	1270	3560	10230	29744
Maximum flux of hydrogen extracted, kg/h	590	1590	4464	12788
Storage efficiency, %	15.57	17.34	18.51	19.39
Operating time of the gas turbine, h	4260	4260	4260	4260
Operating time the wind power plant, h	6198	6198	6198	6198
Average power of the gas turbine during operation, MW	3.47	10.7	32.6	98.7
Average power of wind turbines in operation, MW	20.0	56.2	162.1	473.0
Average power of the gas turbine in the year, MW	1.68	5.19	15.84	48.01
Average power of a wind turbine in the year, MW	14.1	39.8	114.7	334.6

8. Economic analysis of energy storage system

As in many other fields, the development of energy production using renewable energy sources and of energy storage systems are determined by economic effectiveness. Although power systems using renewable energy sources are usually less cost-effective than systems that use fossil fuels, many countries, including European Union member states, support their development.

Generally accepted methods for evaluation of economic efficiency are used to calculate the profitability of power system investments, one of the most popular being the net present value (NPV) method.

Net present value is expressed in monetary profit that reaches the investor by investing in equity or originating a loan. The NPV quantity is defined as a sum of cash flows discounted separately for each year realized in the entire period covered by the account, with a known rate of discount:

$$NPV = \sum_{t=0}^{N} \frac{CF_t}{(1+r)^t} \tag{7}$$

where: CF—cash flows, r—discount rate, N—last year under consideration
Cash flow can be calculated as follows:

$$CF_t = -I_0 + S_t - [K - (A + F) + P_d + K_{obr}]_t + L_t \tag{8}$$

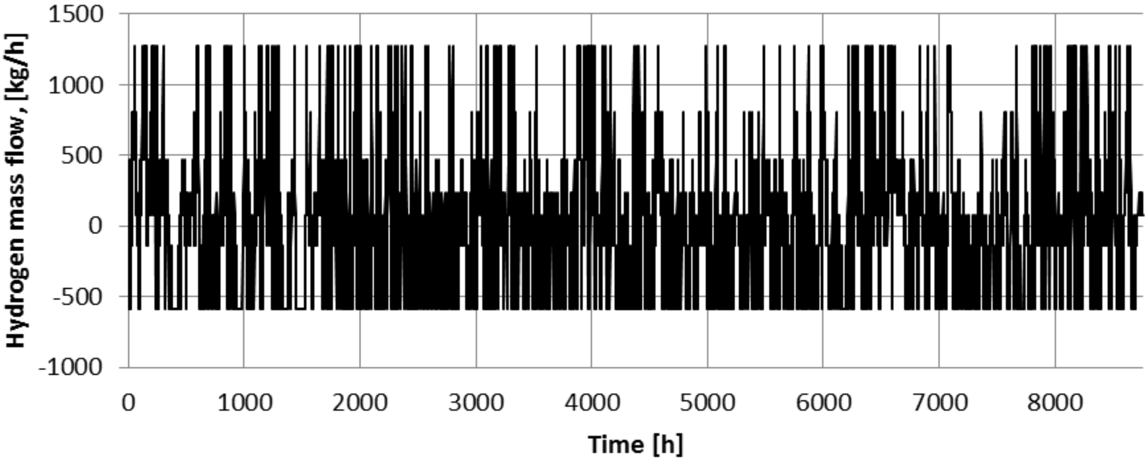

Figure 6: The stream of hydrogen injected into and extracted from storage

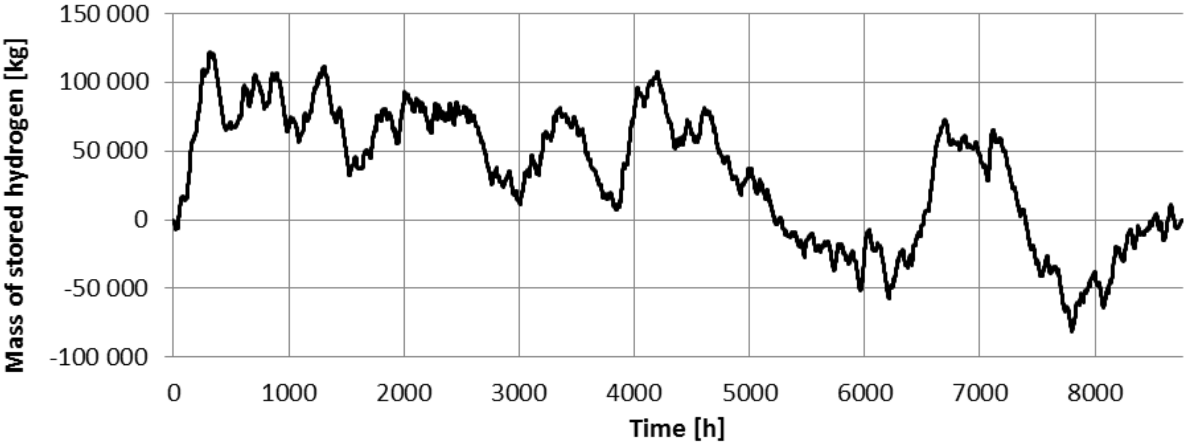

Figure 7: The mass of stored hydrogen for an energy storage system of nominal power 5 MW

where: I_0—total investment, S_t—revenues from sales of electricity and other products, K—total annual production costs, A—depreciation, F—financial costs, P_d—income tax, K_{obr}—change in working capital, L_t—liquidation calue ($L_t = 0\, for\, 0 \leq t \leq N - 1$)

Analyses were based on the value of the minimum selling price of electricity for which the net present value NPV is zero:

$$NPV = \left(\boldsymbol{c}_{el}^{gr}\right) = 0 \tag{9}$$

The investment costs I significantly affect the results. In the simplified calculation for electricity generation systems it can be determined from the following relationship:

$$I = i_x \cdot N_{el} \tag{10}$$

where: i_x—unit investment cost dependent on the applied technical solution of, eg. USD/kW, N_{el}—electric power of unit

Investments in power systems are characterized by the fact that most often during the construction period they produce no income, so the value of the loan should be increased by the interest paid during construction.

Unit investment costs related to construction of the gas turbine in the analysis were determined from the relationship:

$$I_{TG} = 5006 \cdot N_{el\_TG}^{-0.223} \tag{11}$$

where: I_{TG}—gas turbine investment costs, USD/kWe, N_{el_TG}—rated power of the gas turbine, kW.

Investment costs of wind power were calculated using the value of the unit investment at the level of 1400 USD/kWe, similarly for photovoltaic power plants the value of 3500 USD/MWh was assumed. The value of investment for electrolyzers was determined by the formula:

$$I_{ele} = 224490 \cdot m_{H_2}^{0.6156} \tag{12}$$

where: I_{ele}—electrolyzers investment costs, USD, m_{H_2}—hydrogen mass flow, kg/h.

The calculations assume that the discount rate is 0.06, time of economic analysis 23 years, construction time 3 years and 80% of total investment cost is met by commercial loans.

Table 5: Electricity prices as a function of the cost of hydrogen storage and the size of the gas turbine

Parameters	Case I		Case II		Case III		Case IV	
Power of gas turbine	5 MW		15 MW		45 MW		135 MW	
Cost of hydrogen storage, USD/kg	1.6	0.8	1.6	0.8	1.6	0.8	1.6	0.8
Breakeven price of electricity, USD/MWh	418.6	385.9	376.4	346.3	347.1	318.6	329.3	301.5

The calculations take into account the additional annual costs that reflect the costs of hydrogen storage.

It was assumed that one kilogram of hydrogen storage costs 1.6 USD. In this case, data from the literature [11] were used and the indicated value was calculated taking into account: cavern working capacity—1912 Mg, working pressure 138 bar, hole depth 1158 m, the amount of gas in the gas cushion 30% of total capacity, maximum compression station capacity 2960 kg/h, transport system performance 4.78 Mg/h, 16 km length of transport pipeline, 30 years of installation durability. Based on these assumptions, results were calculated including the limit sales price of electricity for systems with a different power gas turbine (Table 5). The results include the results for the reduced cost of hydrogen storage to determine the effect of the value on the final result. The results obtained indicate that the limit price of electricity for the system under consideration is higher than the current market price of electricity. The change in storage costs has only a relatively limited effect on the value of the limit sales price. An essential element impinging on the obtained values are large capital expenditures related to the construction of wind power plants.

9. Summary

Based on the analysis it was possible to determine the main parameters of the energy storage system and produce a preliminary economic evaluation.

The results indicate that due to the low capacity utilization factor of the wind turbine, the ratio of electric power from wind power to the power of the storage system is very large. Due to the low efficiency of the storage process the development of each element of the system needs to be revisited. However, the greatest potential area for progress is in the technology of generating electricity from hydrogen through the use of fuel cells (also in combination with systems for gas turbines). Increased storage efficiency can also be achieved through the use of efficient and flexible mobility systems with gas and steam or gas-air systems.

The main factor contributing to the low efficiency of the economic system was the investment required with wind power.

The economic efficiency of energy storage can probably be increased inter alia by increasing the efficiency of storage, reducing the cost of power generation for the storage process, and using additional products from the process (heat from the generation system, oxygen from the electrolysis process).

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