Energy cost analysis by hybrid power generation system

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Abstract. The article presents an analysis of unit cost of electricity generation in hybrid power generation system (HPGS). The analyzed hybrid system consists of wind power, photovoltaic panels and energy storage electrolyzer – fuel cell. There have been shown the balance sheet equations describing the power flow in the analyzed hybrid system. The analysis was carried out for the six variants. Variant I – the source of electricity in the hybrid system is wind, variants II, III, IV, V – electricity is generated by wind turbines and solar panels, variant VI – the source of electricity in the hybrid system is only photovoltaic installation. The unit cost of electricity generation has been designated for: adopted customer profile, the values of intensity of solar radiation and wind speed for the above mentioned variants.

1. Introduction

A number of scientific publications of recent years concerns the technical-economic analysis of hybrid power generation systems using advanced mathematical methods. The term "hybrid power generation system" means the combination of different technologies in electricity generation, for example, renewable sources together with non-renewable sources (small gas turbines, engine powered generators, fuel cells, etc.) and/or energy storage. These systems are usually built in such a way that they can simultaneously take advantage of individual sources and reduce their defects. This fact makes the hybrid systems very expensive due to the necessity of oversizing the values of installed power [1].

Hybrid systems, which are the subject of the largest number of scientific publications, combine the photovoltaic sources and wind turbines with an electrochemical energy storage (battery, electrolyzer-fuel cell) [2-4]. These systems are often developed by attaching a non-renewable energy sources, for example, micro-gas turbines [5,6] or Diesel generators [7-9]. There are other proposed solutions without electrochemical storage. For example, the author of the publication [10] describes the hybrid power generation system where the electrochemical storage has been replaced by pumped storage power plant power plant.

The total costs of electricity generation depend on the power generation technologies in power system [11]. Among the many proposals of hybrid solutions of hybrid power generation systems commonly used will only be technologies with the least cost of electricity generation. The unit cost of electricity generation depends on the type of devices that make up the hybrid system and the size of the capacity installed in these devices.

The paper presents the results of the analysis of the impact of the value of the installed capacity of wind power and photovoltaic panels in a hybrid power generation system on the unit cost of electric energy.
2. Hybrid power generation system technical and economic analysis

The excess energy produced from renewable sources is used for electrolysis process (decomposition of water into hydrogen and oxygen). Hydrogen is compressed and stored, and then used in a fuel cell to produce electricity, at a time when it is needed. Scheme of the analyzed receiver supply system is shown in Figure 1.

![Figure 1. Flowchart of hybrid power generation system: FC – fuel cell, PV – photovoltaic cell, EW – wind turbine, El – electrolyzer, H2 – hydrogen tank.](image)

The balance of power in the system, depends on the ratio of power generated by RES sources to the demand of the recipient. In the case where the demand is less than the power generated (cell) balance sheet equation takes the form:

\[
P_{\text{load}} = P_{\text{PV}} + P_{\text{WT}} - P_{\text{EL}} - P_{\text{comp}}
\]

where: \( P_{\text{load}} \) [kW] – power consumed by the recipient, \( P_{\text{PV}} \) [kW] – power generated by photovoltaic installation, \( P_{\text{WT}} \) [kW] – power generated by wind power plants, \( P_{\text{EL}} \) [kW] – power consumed by the electrolyzer, \( P_{\text{comp}} \) – power used for compression of hydrogen.

If the demand exceeds the power produced by sources (fuel cells), the receiver power describes the formula:

\[
P_{\text{load}} = P_{\text{PV}} + P_{\text{WT}} + P_{\text{FC}}
\]

where: \( P_{\text{FC}} \) [kW] – power generated by the fuel cell.

Temporary power shortages associated with stochastic nature of energy generation by renewable sources compensates the fuel cell work. Such mode of operation is allowed by operating features of fuel cells which perfectly suit to work with variable loads and present high performance in a wide range of power [12]. A very valuable feature of fuel cells is their high efficiency at low load. Hydrogen is supplied to the fuel cell in the first place from the electrolyzer. In case of hydrogen exhaustion in the tank, the fuel cell can be supplied with hydrogen from the backup.

2.1. Selection of the composition of generating units

The analysis assumes the annual distribution profiles of wind and sunlight [13] and municipal customer profile with a maximum power consumption of 80 kW and an annual electricity demand in the amount of 440 MWh. A daily chart of customer load is shown in the chart (Figure 2).
With a view to the selection of the composition of the generating units to meet the needs of the customer, we used the following equations [14]:

\[ \Delta P = P_{av\_gen} - P_{av\_load} \rightarrow \min \]  

(3)

\[ P_{av\_gen} = n_{cf\_PV} \cdot P_{PV} + n_{cf\_WT} \cdot P_{WT} \]  

(4)

\[ n_{cf\_PV} = \frac{P_{av\_PV}}{P_{PV}} \]  

(5)

\[ n_{cf\_WT} = \frac{P_{av\_WT}}{P_{WT}} \]  

(6)

where: \( P_{av\_gen} \) – mean value of power generated by renewable sources, \( P_{av\_load} \) – average input power by the recipient, \( n_{cf} \) – capacity factor of each renewable energy sources, \( P_{PV} \) – nominal power of photovoltaic installation, \( P_{WT} \) – rated power of wind turbine.

The value under the average for the period T is designated with the dependencies:

\[ P_{av\_PV} = \frac{A_{PV}}{T} \]  

(7)

\[ A_{PV} = W_k \cdot W_w \cdot \int_0^T P_{av\_PV} \, dt \]  

(8)

where: \( A_{PV} \) – electricity produced by photovoltaic system at time T, \( W_k \) – a correction factor that takes into account the angle of installation referral to the South and the angle of deviation of the modules from the level, \( W_w \) - the coefficient of performance.

For the determination of the amount of electricity produced by photovoltaic modules uses the characteristics of the \( P_{PV}=f(E) \) developed on the basis of external characteristics family \( U=f(I) \) (Figure 3). Photovoltaic modules system is equipped with an MPPT maximum power point tracking (\( P_{PV} = P_{MMPT} \)).
In order to determine the average power produced by wind turbines was operational characteristics \( P = f(v) \) and the distribution of wind speeds (Figure 4) presented in the form of a continuous function \( f(v) \) using the Weibull distribution:

\[
f(v) = \frac{k}{\lambda} \left(\frac{v}{\lambda}\right)^{k-1} e^{-\left(\frac{v}{\lambda}\right)^k}
\]  

(9)

where: \( v \) - wind speed [m/s], \( k \) - shape parameter \((k > 0)\), \( \lambda \) - the scale parameter \((\lambda > 1)\)

\[
P_{\text{av,WT}} = \int_0^\infty P(v) f(v) dv
\]

(10)

A graphical interpretation of the determination of the average power is shown in Figure 4.

2.2. Selection of energy storage

Energy storage has been selected based on the following assumptions:

- fuel cell is able to meet the instantaneous maximum demand:

\[
P_{\text{FC}} = P_{\text{max,load}}
\]

(11)
electrolyzer is able to accept temporary power generated by photovoltaic system and wind sources:

\[ P_{EL} = k \cdot (P_{max\_WT} + P_{max\_PV}) - P_{min\_load} \]  

(12)

where: \( P_{EL} \) – power rating of electrolyzer, \( P_{max\_WT} \) – maximum instantaneous power of wind turbines, \( P_{max\_PV} \) – maximum instantaneous power of photovoltaic installation, \( P_{min\_load} \) – the minimum instantaneous demand of a customer, \( k \) – simultaneity factor determining maximum power generation by photovoltaic system and wind sources.

To determine the amount of the hydrogen produced by the electrolyzer and the quantities consumed by the hydrogen fuel cell used, characteristics \( P=f(V_{H2}) \) (Figure 5) developed on the basis of external characteristics of the fuel cell and electrolyzer \( U=f(I) \) was used.

\[ \text{Figure 5. Daily load chart of a municipal recipient.} \]

2.3. The cost of generating electricity in a hybrid power system

The unit cost of electricity generation by hybrid power generation system has been defined as:

\[ k_{HSW} = \frac{K_e}{E_{HSW}} \frac{[\text{PLN}]}{[\text{kWh}]} \]  

(13)

where: \( K_e \) – hybrid circuit operating costs, \( E_{HSW} \) – the amount of energy generated by the hybrid system.

\( K_e \) operating costs are the sum of operating costs and the management of devices that make up the hybrid system (O&M), the costs of purchase and transport of hydrogen and the depreciation costs.

\[ K_e = K_{O&M} + K_{fuel} + K_d \]  

(14)

Depreciation expenses have been adopted at the level of 10% of the investment effort incurred for installation. In the presented case, with today's prices of fuel cell, the investment effort for the analyzed hybrid system is about PLN 5 million. High value of investment effort makes the construction of a hybrid system unprofitable. Therefore, the analysis of profitability of the investment, using the discount methods to determine the other indicators of the economic group, for example, NPV (Net Present Value), IRR (Internal Rate of Return), DPP – (Discounted Payback Period), gives a very adverse result without sufficiently strong support schemes for renewable energy sources [15].

3. The analysis results

Based on the equations 1-12 and the authorial code written in MATLAB it has been chosen for customer a set of devices of a hybrid system (Table 1) and the annual demand for additional hydrogen has been specified in order to ensure uninterrupted power supply (Table 2).
Simulations were performed for six variants of the production of energy in a hybrid power system. In variant I the source of electrical energy in a hybrid power generation system is a wind turbine at the installed power of 335 kW. In subsequent variants, a wind turbine at lower value of installed power has been selected in a relation to variant I and photovoltaic installation of a size which allows you to cover the needs of a recipient. In variant VI the source of electrical power is only photovoltaic installation.

Table 1. Generating units composition of a hybrid power generation system.

| Variant | Wind turbine [kW] | \( n_{c WT} \) [%] | Number of PV Panels 250 Wp | Electrolyzer [kW] | Fuel cell [kW] |
|---------|-------------------|--------------------|-----------------------------|-------------------|----------------|
| I       | 335               | 15.64              | -                           | 325               | 80             |
| II      | 260               | 11.19              | 684                         | 250               | 80             |
| III     | 225               | 12.14              | 741                         | 240               | 80             |
| IV      | 100               | 15.11              | 1.131                       | 220               | 80             |
| V       | 80                | 12.67              | 1.277                       | 230               | 80             |
| VI      | -                 | -                  | 1.616                       | 404               | 80             |

Table 2. The results of energy analysis.

| Variant | Hydrogen production [Nm³/year] | Hydrogen consumption [Nm³/year] | Hydrogen backup [Nm³/year] |
|---------|--------------------------------|---------------------------------|---------------------------|
| I       | 77.560                         | 193.930                         | 116.370                   |
| II      | 70.625                         | 177.290                         | 106.665                   |
| III     | 72.213                         | 181.930                         | 109.717                   |
| IV      | 77.063                         | 205.450                         | 128.387                   |
| V       | 80.340                         | 217.430                         | 137.090                   |
| VI      | 94.408                         | 270.660                         | 176.252                   |

For the obtained values of the installed power of HPGS units and the demand for hydrogen, based on equations 13-14, the unit cost of generating electricity has been determined. The comparison of unit costs for the considered variants is shown in the graph (Figure 6).

Figure 6. The unit cost of electricity generation for individual variants.
4. Conclusions

The conducted analyzes allow to formulate the following conclusions:

- Variant I – the energy generated by a 325 kW wind turbine is characterized by the level of operating costs similar to those where the energy production was distributed between wind turbines and photovoltaic panels,

- Analyzing the results in Table 2, it can be seen that the attachment of a photovoltaic system reduces the operating time of the electrolyzer and the fuel cell. This dependency is fulfilled for the cases where the power installed in a wind turbine is greater than the power installed in a photovoltaic installation (variants II and III),

- Variant VI – energy is produced only by a photovoltaic installation – it is characterized by the highest cost of generating electricity. Resignation from wind turbines must be compensated by more frequent work of the fuel cell and much larger hydrogen consumption with back-up. This is related to the fact that the photovoltaic installation works only during daylight and it power strongly depends on the solar power radiation. During the cloudy days or at night, the recipient will always be powered by fuel cells,

- The variant with the lowest cost of generating electricity at the level of 1.39 PLN/kWh is variant IV – a wind turbine with installed capacity of 100 kW and the average power consumption rate of 15.11% and photovoltaic installation 283 kW. The relatively high power utilization rate of the average wind farm determines the lower power installed in photovoltaics. This affects the incurred HPGS investment expenditure and in consequence operating costs,

- The lowest production and consumption of hydrogen by the energy storage is variant II – a 260 kW wind turbine and a 171 kW photovoltaic system,

- When depending the choice of an optimal structure of generating units of a hybrid power system on total operating costs, variant IV should be selected. On the other hand, if you want the investor to have the lowest possible operating time of the energy storage cell – the fuel cell, variant II should be chosen, where the wind turbine is more expensive, however, the demand for hydrogen is lower,

- For all the cases, the price of one kilowatt-hour in a hybrid system is almost two and a half times higher than the average energy price currently borne by municipal recipients at about 0.56 PLN/kWh. The currently analyzed hybrid system can be used in situations where costs do not play a role, i.e., military applications or pilot installations for research purposes.

In conclusion, the development of hybrid generation systems based on renewable, stochastic sources of electricity should consider the possibility of using both, wind energy and photovoltaic power generation.

The appropriate selection of the HPGS units for the wind and sunshine conditions makes it possible to use primary energy more effectively without significant increase in operating costs. In addition, when selecting a wind turbine with a relatively high value of an average power recovery rate, you can minimize total operating costs.

The cost of use tool proposed by the authors can be used to design hybrid power generation systems intended to power consumers where they do not have an opportunity to be connected to the power grid.

References

[1] Paska J, Biczel P, Klos M, 2009, Renewable Energy, 34, 2414-2421,
[2] Nelson D B, Nehrir M H and Wang C, 2005 IEEE Power Engineering Society General Meeting, 3, 2116 – 2122,
[3] Wang L and Singh C, 2009 IEEE TRANSACTIONS ON ENERGY CONVERSION, 24, 163-172,
[4] Rosli M A, Yahaya N Z, Baharudin Z, 2014, IEEE Innovative Smart Grid Technologies – Asia,
[5] Algabalawy M A, Abdelaziz A Y, Mekhamer S F and Badr M A L, 2016 Eighteenth International Middle East Power Systems Conference (MEPCON), 138 – 146.
[6] Comodi G, Renzi M, Cioccolanti L, Caresana F and Pelagalli L, 2015, Energy, 89, 226-235.
[7] Chen J, Che Yo and Zhao L, 2011 4th International Conference on Power Electronics Systems and Applications, 1 – 5.
[8] Usman M, et all., 2017, J. Electr. Syst. Inform. Technol, https://doi.org/10.1016/j.jesit.2017.06.002
[9] Rahman M M A, Al-Awami A T, Rahim A H M A, 2014, International Conference on Electrical Engineering and Information & Communication Technology (ICEEICT),
[10] Jurasz J, 2017 Energy Conversion and Management, 136, 382-394,
[11] Gawlik L, Szurlej A, Wyrwa A, 2015, Energy, 92, 172-178,
[12] Ceran B and Bernstein P A, 2014, Electrical Review, 10, 102-105,
[13] Ceran B, Hassan Q, Jaszczyzur M and Sroka K, 2017, E3S Web Conf. 14, 01020,
[14] Wang C, Nehrir M H, 2008, IEEE Transactions on Energy Conversion, 3, 957-967,
[15] Szczerbowski R and Ceran B, 2016, E3S Web Conf. 10, 00090,