



Patryk PALEJ¹, Hassan QUSAY², Sławosz KLESZCZ³, Robert HANUS⁴, Marek JASZCZUR⁵

Analysis and optimization of hybrid renewable energy systems

ABSTRACT: Hybrid Renewable Energy Systems connected to the traditional power suppliers are an interesting technological solution in the field of energy engineering and the integration of renewable systems with other energy systems can significantly increase in energy reliability. In this paper, an analysis and optimization of the hybrid energy system, which uses photovoltaic modules and wind turbines components connected to the grid, is presented. The system components are optimized using two objectives criteria: economic and environmental. The optimization has been performed based on the experimental data acquired for the whole year. Results showed the optimal configuration for the hybrid system based on economical objective, that presents the best compromise between the number of components and total efficiency. This achieved the lowest cost of energy but with relatively high CO₂ emissions, while environmental objective results with lower CO₂

✉ Corresponding Author: Marek Jaszczur; e-mail: jaszczur@agh.edu.pl

¹ AGH University of Science and Technology Department of Fundamental Research in Energy Engineering, Krakow, Poland; e-mail: palej@agh.edu.pl; ORCID iD: 0000-0002-5010-7039

² AGH University of Science and Technology Department of Fundamental Research in Energy Engineering, Krakow, Poland; e-mail: qusay@agh.edu.pl; ORCID iD: 0000-0002-2695-5767

³ AGH University of Science and Technology Department of Fundamental Research in Energy Engineering, Krakow, Poland; e-mail: slawosz.kleszcz@frapol.com.pl; ORCIDiD: 0000-0002-8745-0033

⁴ Rzeszów University of Technology, Poland; e-mail: rohan@prz.edu.pl; ORCID iD: 0000-0002-7054-1975

⁵ AGH University of Science and Technology Department of Fundamental Research in Energy Engineering, Krakow, Poland; e-mail: jaszczur@agh.edu.pl; ORCID iD: 0000-0003-3776-7013



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emissions and higher cost of energy and presents the best compromise between the number of components and system net present cost. It has been shown that a hybrid system can be optimized in such a way that CO₂ emission is maximally reduced and – separately – in terms of reducing the cost. However, the study shows that these two criteria cannot be optimized at the same time. Reducing the system cost increase CO₂ emission and enhancing ecological effect makes the system cost larger. However, depends on strategies, a balance between different optimization criteria can be found. Regardless of the strategy used economic criteria – which also indirect takes environmental aspects as a cost of penalties – should be considered as a major criterion of optimization while the other objectives including environmental objectives are less important.

KEYWORDS: hybrid systems, renewable sources of energy, energy safety, optimization

Introduction

Energy is essential to human life regardless of when and where they live especially in the present century where people aim to achieve a better quality of life. Among all types of energy, electrical energy is considered one of the most essential type of energy for human life. Globally due to population growth, the demand for energy is constantly increasing. In recent years, humans have been focusing on the environmental and climatic degradation of the planet, due to the extraction and burning fossil fuel such as global warming, the depletion of the ozone layer and air pollution. For these reasons, quite often, governmental regulations become very rigorous in limiting the harmful gases emissions. In addition to that, the continuous and intensive use of conventional energy sources results in their depletion (EIA 2016). The above generates two significant problems which urge many communities – to find alternative solutions for energy production.

The Earth has enough renewable resources to cope with the growing energy demand for many centuries. However, the energy generated from some of these sources is either intermittent or can't reach the required power quality, due to its indiscriminate nature. Thus, a complete transition from fossil fuel to renewable energy will be a big challenge and require a combination of different energy sources. Alternative sources of energy, such as hydropower, geothermal energy, biomass, wind, solar, hydrogen and nuclear, and fossil fuel need to work together in various combinations and not as a single source or unit to meet the locally required energy demand. Currently, the governments of many countries, especially those that generate high CO₂ emissions, are looking for sustainable development of energy systems. Hybrid renewable energy-based systems today have become very attractive as an energy supply option. These systems are increasingly becoming popular solutions for the electrification of locations with grid connection as well as sites where no grid is available.

Even though renewable energy has a lot of advantages, there are also some drawbacks involved. The real cost of energy can be relatively high, and there is quite often a significant

problem with the stability and reliability of power generation. It is also hard to predict the accurate amount of energy produced in the long term due to the chaotic nature of the atmospheric phenomena which have a key impact on solar and wind energy. One of the options for solving the problem of irregular power generation can be the use of hybrid systems. Such systems are the combination of at least two different sources of energy which produce it in cogeneration.

In the literature, a great deal of research has been devoted to Hybrid Renewable Energy Systems (HRES) in different sites. (Hassan et al. 2016a) developed a model of a hybrid system that consists of both conventional (diesel generator) and renewable energy sources (wind and solar), for electrifying the rural village located in Iraq which were not connected to the grid. The authors performed a technical and economic analysis of the problem, where the diesel generator is the key element of the project as it can allow for meeting the power demand in the periods of low renewable energy production, e.g. during the night when there is no solar radiation. The proposed hybrid energy system was able to electrify the selected area and meet the load demand at the cost of about \$0.321/kWh. (Jaszczur et al. 2019; Hassan et al. 2016b) gave a significant contribution to this topic analyzing several types of systems in the HRES field. Authors in (Jaszczur et al. 2019) studied natural dust deposition on PV panels, and they investigated the temporal distribution of dust deposition density afterwards. They analyzed the daily energy production and calculated the efficiency loss. (Ceran et al. 2017) performed a computer simulation for a large hybrid system that consists of a photovoltaic panel, a wind turbine, an electrolyser and a hydrogen infrastructure to store the excess of energy (proton exchange membrane fuel cells and hydrogen tank). The study has been conducted for the city of Poznan in Poland. The analysis included the annual distribution of solar radiation, wind speed and an energy usage profile. Referring to the researcher's conclusions, such a system can be profitable and the investment cost can be returned. (Jahangiri et al. 2019) conducted a review study on HRES. Authors compared several meteorological stations distributed in Afghanistan and analyzed the available data. The data concerned quantities as wind speed and solar radiation intensity with a clearness index. The authors mapped all the information to the specific place. Another interesting approach related to the wind and solar hybrid system was presented by (Huang et al. 2015). The authors proposed a special multi-turbine system connected with solar panels. The project assumes buildings with a 12 m high tower which would contain eight wind turbines able to cogenerate power with a maximum capacity equal to 60 kW. (Ding et al. 2019) demonstrate a wind-solar power generation system. The authors develop an iterative algorithm that analyses meteorological data in order to propose a thermal storage system based on wind and concentrated solar power – the Thermal Storage Wind-Concentrated Solar power system. (Prashanth et al. 2018) Investigated a hybrid system which uses a charge controller to manage and distribute the generated energy. The proposed hybrid system consists of a solar panel, wind turbine and an additional generator. All these elements worked in cogeneration to produce energy for residential load or exceed energy, which is partially stored in the battery bank. The results show that using the wind turbine and photovoltaic panels, it is possible to obtain high performances, therefore provide the necessary power for the residential load. (Rezzouk and Mellit 2015) performed an optimization and sensitivity analysis of the photovoltaic-diesel-battery hybrid system for rural electrification in Algeria.

The authors carried out the component optimization from an economic perspective. Results showed that the PV unit has a large effect on energy production and helps to reduce diesel consumption and lead to minimizing the overall cost of energy (COE). Using two or more renewable energy sources allows for the effects of energy sources fluctuations to be mitigated and a detailed study on this topic was conducted by (Buonomano et al. 2018). The authors carried out a dynamic simulation of a wind-solar HRES based on economic assessment optimization. The results show that the HRES can be more profitable for users with a stable load demand, while the generated surplus power during summer can balance lower production during winter.

What is also important regarding the economy of hybrid systems is the decreasing price of the photovoltaic panels. Mirowski and Sornek (Mirowski and Sornek 2015) showed that there was a significant increase in PV panels production in most parts of the world between 2008 and 2013, even 600%. This may have been caused by the rapid decrease in prices of the panels in these years, about 57% between 2010–2013. The decreasing prices of the components enhance the economic benefits of the newly installed systems.

In the present research, the hybrid energy system which consists of a photovoltaic panel (PV) and a wind turbine (WT) is analyzed and optimized in order to find the best compromise between the number of components, total efficiency, cost of energy as well as CO₂ emissions. The analyzed system is designed to be used for the residential needs of a single household.

1. Mathematical model

The modelled hybrid energy system consists of a photovoltaic panel, wind turbine, controllers and is connected to the grid. The target is to optimize the system in order to find the best compromise between the number of components, for selected objectives criteria. During the simulation and optimization of the hybrid power system, process and system components are interdependent. That's why the problem becomes more complex due to the uncertainty of renewable supplies and load demand as well as non-linear characteristics of the system components. Furthermore, the system optimization relies on different criteria such as: economic, technical, environmental etc. A typical task for hybrid power systems optimization is to obtain the best configuration for all components (renewable energy components, conventional generators and energy storage unit) based in the specified objective that will encounter the expected demands load with a sufficiently satisfactory level of safety. For optimal hybrid power systems design, in this research, some adopted criteria are based on the reliability and electrical loads targets.

1.1. Total hybrid power generated at any time

The power generated by each component of the hybrid power system is the total power generated by the system. It can be described at any time t as follows:

$$P_{h,t} = P_{WT,t} + P_{PV,t} + P_{Grid,t} \quad (1)$$

where $P_{h,t}$ is the total power of the hybrid system, $P_{WT,t}$ is the power generated by a wind turbine, $P_{PV,t}$ is the power generated by PV modules, $P_{Grid,t}$ is the power exchange with the grid. The electrical load demand equation for the PV , WT components and grid system ensures that the electricity demand is satisfied at any time according to the formula:

$$P_{Load,t} = P_{WT,t} + P_{PV,t} + P_{From\ grid,t} \quad (2)$$

1.2. Cost of energy

The cost of the energy is the average cost in EUR (or any other currency) per kWh. This cost, in hybrid power systems, depends on many factors such as initial capital cost, operation & maintenance costs, depreciation period, energy production, the potential downtrend of the equipment cost with rising volumes etc. (Dawoud et al. 2015; Ma al. 2015). It can be evaluated as follows:

$$COE = \frac{C_{ann,tot}}{E_{prim,AS,DC} + E_{grid,sales}} \quad (3)$$

where $E_{prim,AC,DC}$ is the AC and DC primary load served, $E_{grid,sales}$ is the total grid sales and $C_{ann,tot}$ is the total annualized cost of the system that includes the annualized costs of each system component, with the others, annualized costs.

1.3. Annualized costs of each system component

Annualized costs of each system component include the initial capital of each component over the project lifetime. It can be calculated using the following equation:

$$C_{ann,cop} = C_{cap} \cdot CRF(i, R_{proj}) \quad (4)$$

where: R_{proj} is the project lifetime, C_{cap} is the initial capital cost of the component, $CRF(i, R_{proj})$ is the capital recovery factor calculated as follows:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (5)$$

where N is the number of years and i is the real interest rate (%) calculated as:

$$i = \frac{h - f_e}{1 + f_e} \quad (6)$$

where h is the nominal interest rate and f_e is the annual inflation rate.

1.4. Annualized costs of component replacement

Annualized costs of component replacement can be calculated as follows (Dawoud et al. 2015):

$$C_{a,rep} = C_{rep} \cdot f_{rep} \cdot SFF(i, R_{comp}) - S \cdot SFF(i, R_{proj}) \quad (7)$$

where f_{rep} is a factor arising (component lifetime can be different from the project lifetime) and is given by:

$$f_{rep} = \begin{cases} \frac{CRF(i, R_{proj})}{CRF(i, R_{rep})}, & R_{rep} > 0 \\ 0 & R_{rep} = 0 \end{cases} \quad (8)$$

where R_{proj} is the project lifetime, R_{comp} is the component lifetime, R_{rep} is the replacement cost duration:

$$R_{rep} = R_{comp} \cdot INT\left(\frac{R_{proj}}{R_{comp}}\right) \quad (9)$$

where $INT\left(\frac{R_{proj}}{R_{comp}}\right)$ is the integer function which returns the integer portion of real value, S is the salvage value of the component considered at the end of the project lifetime, and it is proportional to its remaining life. Therefore, the salvage value S is defined as follows:

$$S = C_{rep} \cdot \frac{R_{rem}}{R_{comp}} \quad (10)$$

where R_{rem} , is the remaining life of the component at the end of the project lifetime:

$$R_{rem} = R_{comp} - (R_{proj} - R_{rep}) \quad (11)$$

1.5. Total net present cost

The system total net present cost (NPC) is the value of all the costs that incur over the lifetime, minus the present value of all the revenue that earns over its lifetime. Costs include: capital costs, replacement costs, operation and maintenance costs, fuel costs, emissions penalties and the costs of electrical energy purchase from the grid. Revenues include the salvage value and grid sales revenue; this value can be calculated by using the formula (Dawoud et al. 2018):

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \quad (12)$$

1.6. Operation and maintenance cost

The operation & maintenance (O&M) cost includes system fixed O&M cost, the penalty for the capacity shortage and penalties for emissions of pollutants as follows:

$$C_{om,other} = C_{om,fixed} + C_{cs} + E_{cs} + C_{emissions} \quad (13)$$

where C_{cs} is a capacity shortage penalty that applies to the system for any capacity shortage that occurs during the year and E_{cs} is a total or annual capacity shortage that occurs throughout the year, $C_{om,fixed}$ is the fixed operation and maintenance cost throughout the year, $C_{emissions}$ is a penalty for emissions.

2. Results and discussion

The results presented in this work have been executed based on the experimental measurement (Jaszczur et al. 2018) and load profile provided by Polskie Sieci Elektroenergetyczne (PSE). The weather data (solar radiation, wind speed and ambient temperature) has been acquired from the weather meters (anemometer and thermometer) located at the AGH University of Science and Technology campus, building C3 for the period January 1, 2017–December 31, 2017. The wind turbine unit (Aeolos-H 1KW) was selected based on the measured electrical load and wind speed average. The WT size is 1.0 kW AC, cut-in wind speed 2.0 m/s, cut-out wind speed 25 m/s, lifetime 25 years and the manufacturing process generate CO₂ about 300 kg/kW.

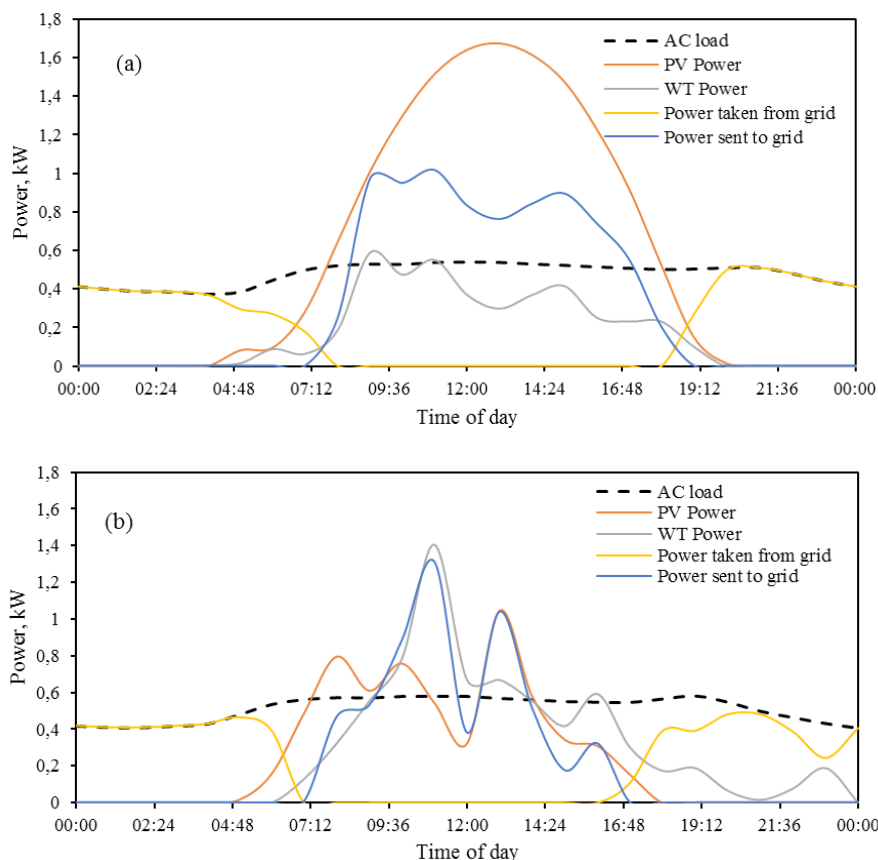


Fig. 1. Power generation from different sources and grid flows for (a) sunny (April 12, 2017) day and (b) cloudy (June 1, 2017) day

Rys. 1. Produkcja energii elektrycznej z różnych źródeł i przepływ energii dla: (a) dnia słonecznego (12.04.2017) oraz (b) dnia pochmurnego (01.06.2017)

The selected photovoltaic modules were Schott ASI200 type photovoltaic modules, with technical specifications at STC: nominal power 200 W_p, solar cells per module 72 (3 × 24), dimensions 1.308 × 1.108 mm weight 20.8 kg, NOCT 49°C, the temperature coefficient of power -0.2%/°C. The manufacturing process generates about 800 kg/kW_p of CO₂ emissions.

Figures 1(a)–(b) show the hourly output power distribution for the hybrid system with the economic target. For the sunny day and partly cloudy day, the energy distribution in those days is shown in Table 1.

It is clear from Figures 1(a)–(b) and Table 1, that the power flow and the energy generated during different periods of sunny and partly cloudy days are different. During a sunny day energy generated from PV component is higher than energy consumption. At the same time, the wind turbine also generates flow energy, and the energy surplus is fed to the grid.

Table 2 shows seven best hybrid system configurations based on the economic target (minimize NPC and COE) which listed the most optimized results of the system's configurations

TABLE 1. The daily energy distribution for two selected days sunny (April 12, 2017) and partly cloudy (June 1, 2017)

TABELA 1. Dzienna produkcja oraz przepływ energii dla dwóch wybranych dni: słonecznego (12.04.2017) i częściowo zachmurzonego (01.06.2017)

Day	Load (kWh)	PV energy (kWh)	WT energy (kWh)	Energy from grid (kWh)	Energy feed to the grid (kWh)
April 12, 2017	11.90	14.18	4.25	5.31	8.00
June 1, 2017	12.81	6.12	7.09	5.84	5.64

TABLE 2. Results for economic optimization of the system – 7 most optimal configurations in terms of NPC

TABELA 2. Wyniki optymalizacji ekonomicznej NPC systemu – 7 optymalnych konfiguracji pod względem kosztów NPC

No.	NPC (EUR)	COE (EUR)	CO ₂ (kg/yr)	PV No.	WT No.	Renewable energy (kWh/yr)	Excess (kWh/yr)
1	27 775.90	0.27	2 515.9	7	1	4 341	2 743
2	28 267.28	0.27	2 477.3	7	1	4 374	2 775
3	28 135.03	0.29	2 452.1	8	1	4 640	3 013
4	28 636.93	0.3	2 434.3	8	1	4 673	3 045
5	28 510.22	0.31	2 423.2	8	1	4 938	3 285
6	29 012.22	0.31	2 491.1	8	1	4 971	3 317
7	28 891.66	0.31	2 470.8	9	2	5 237	3 559

(lowest NPC). The number of PV modules and wind turbines varies depending on the configuration as well as renewable energy produced during the year. Similar results but for environmental optimization are presented in Table 3 where the seven configurations with the lowest NPC based on the environmental target (minimizing CO₂ emissions) are shown.

TABLE 3. Results for ecological optimization of the system – 7 most optimal configurations in terms of CO₂ emission

TABELA 3. Wyniki optymalizacji ekologicznej systemu – 7 optymalnych konfiguracji pod względem emisji CO₂

No.	NPC (EUR)	COE (EUR)	CO ₂ (kg/yr)	PV No.	WT No.	Renewable energy (kWh/yr)	Excess (kWh/yr)
1	47 747.3	0.51	2 327.8	19	9	12 779	10 693
2	46 456.8	0.49	2 328.2	19	8	12 587	10 515
3	45 169.8	0.48	2 329.7	18	7	12 395	10 336
4	43 887.4	0.47	2 332.6	19	6	12 203	10 158
5	42 609.8	0.45	2 337.2	17	5	12 012	9 980
6	41 339.9	0.44	2 344.1	16	4	11 820	9 805
7	40 238.9	0.43	2 329.0	16	4	11 412	9 712

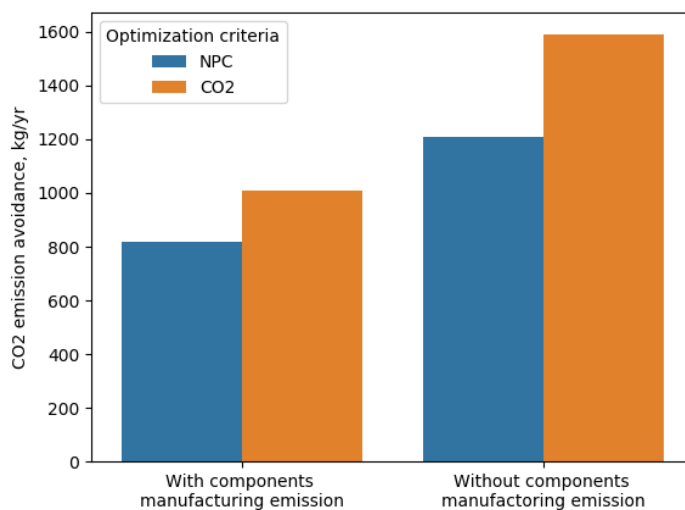


Fig. 2. CO₂ emission for two different criteria of optimization with or not considering components manufacturing emission

Rys. 2. Emisja CO₂ dla dwóch różnych kryteriów optymalizacji z uwzględnieniem oraz bez uwzględnienia emisji pierwotnej wytworzonej podczas produkcji komponentów systemu

Most researchers, during the system analysis in the case of hybrid energy systems, consider renewable energy components such as a WT and PV, which are fully pollution free. However, during the manufacturing process of these components, a large number of harmful gases is generated. In the present analysis, CO₂ emissions have been considered in terms of the amount presented in the system assumption. The CO₂ emission for the two types of optimal configurations are shown in Figure 2. The results are presented without manufacturing emissions and with manufacturing emissions. Taking the emissions due to production into account, CO₂ emission increase is still the lowest for an ecological optimization.

The total energy generated by the system for environmental optimization and economic optimization is presented in Figure 3. It can be noticed that for CO₂ objectives, energy from PV panels is significantly larger, which means that PV power generation enhances the ecological cost of the system.

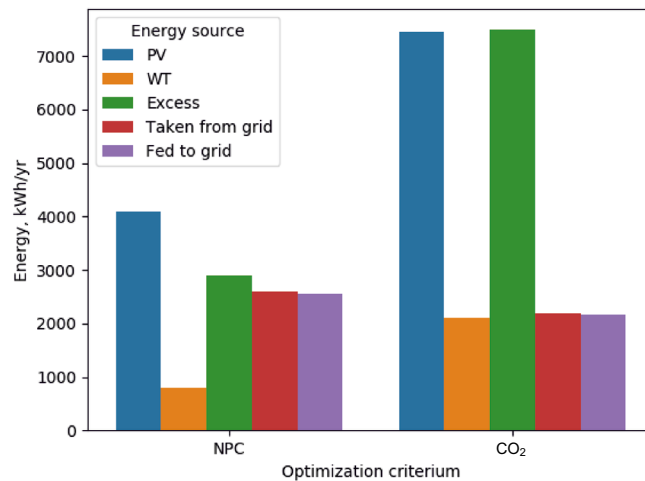


Fig. 3. The energy produced from the subsequent sources/grid for two different criteria of optimization

Rys. 3. Energia wyprodukowana/pobrana z sieci zależnie od kryterium optymalizacji

Conclusions

This work aims to study the economic and environmental feasibility for PV/Wind Grid-on hybrid renewable energy based system destined to electrify a single household. For this aim two objectives of optimization have been studied for systems under different operating conditions.

For the economical objective, the system has been designed and optimized to get a maximum energy output at the lowest cost, while for the environmental goal, the power system has been designed and optimized to get maximum energy output at the lowest CO₂ emission. The results showed that the optimal configuration of HRES on the economic target presents the best compromise between components and total efficiency, which achieved the lowest cost of energy but with higher CO₂ emissions, while the environmental goal offers the best compromise between components and achieves a higher cost of energy than economic objective but with lower CO₂ emissions. The most important optimization parameters are Net Present Cost (NPC) (or Cost of Energy) and CO₂ emissions. However, the study shows that these two main criteria cannot be optimized at the same time. Reducing the system cost causing an increase in CO₂ emissions and enhancing ecological effects makes the system NPC more significant. However, depending on the strategies, a balance between different optimization criteria can be found. Regardless of the strategy used, economic criteria – which also indirectly takes environmental aspects as a cost of penalties – should be considered as a major criterion of optimization while the other objectives including environmental objectives are less important.

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Patryk PALEJ, Hassan QUSAY, Sławosz KLESZCZ, Robert HANUS, Marek JASZCZUR

Analiza i optymalizacja hybrydowego systemu bazującego na odnawialnych źródłach energii

Streszczenie

Energia elektryczna produkowana z dostępnej powszechnie energii odnawialnej ze względu na nieprzewidywalność wytwarzania ma często bardzo niską jakość. Rozwiązaniem tego problem mogą być układy hybrydowe, w których systemy bazujące na energii odnawialnej połączone zostają z tradycyjnymi systemami bazującymi na energii nieodnawialnej. Integracja takich układów może znacząco zwiększyć ich niezawodność energetyczną i poprawić jakość dostaw energii. W niniejszym artykule przedstawiono analizę oraz optymalizację hybrydowego systemu energetycznego wykorzystującego moduły fotowoltaiczne oraz turbiny wiatrowe i podłączonego do sieci elektroenergetycznej. Komponenty systemu podlegają optymalizacji przy wykorzystaniu dwóch kryteriów optymalizacyjnych: ekonomicznego i środowiskowego. Optymalizacja została przeprowadzona w oparciu o wyniki pomiarów eksperymentalnych dla całego roku.

Uzyskane wyniki pozwoliły na określenie optymalnej konfiguracji systemu hybrydowego, który stanowi najlepszy kompromis między liczbą komponentów a całkowitą jego wydajnością. Wykazano, że system hybrydowy można zoptymalizować w taki sposób, aby emisja CO₂ była minimalna lub w taki sposób, aby całkowity koszty systemu NPC był minimalny. Przeprowadzone analizy pokazują jednak, że tych dwóch kryteriów nie można jednocześnie zoptymalizować. Zmniejszenie emisji CO₂, a tym samym zwiększenie efektu ekologicznego sprawia, że system kosztuje znacznie więcej. Niezależnie od zastosowanej strategii kryterium ekonomiczne, które pośrednio uwzględnia aspekty środowiskowe (w postaci kar lub opłat środowiskowych), powinno być traktowane jako główne kryterium optymalizacji, natomiast inne kryteria, w tym środowiskowe, należy traktować jako drugorzędne.

SŁOWA KLUCZOWE: optymalizacja, odnawialne źródła energii, bezpieczeństwo energetyczne, systemy hybrydowe