Optimisation of cooperation of hybrid renewable energy sources with hydrogen energy storage toward the lowest net present cost

Optymalizacja współpracy hybrydowych źródeł energii odnawialnej z wodorowym magazynem energii w kierunku najniższego kosztu bieżącego netto

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The paper presents the results of a technical and economic analysis of the power supply for a model industrial facility based on intermittent renewable energy sources in the form of wind turbines and photovoltaic modules, supplemented with hydrogen energy storage. The adopted power supply strategy assumed the maximisation of self-consumption of self-produced electricity. Six variants were considered, including two with an energy storage system, three using only RES, and a reference variant in which the model facility is powered by the power grid. The modelling and optimisation of the proposed variants was carried out in the HOMER software, in terms of the lowest net present cost. The results obtained indicate that the most advantageous configuration is a grid-connected hybrid renewable energy system consisting of wind turbines and a photovoltaic power plant. A system with hydrogen energy storage is much more profitable than powering the facility from the grid. The profitability of hydrogen energy storage increases even more with the projected increase in electricity prices and the falling prices of hydrogen system components.
Keywords: hybrid renewable energy sources (HRES), economic analysis, environmental analysis, green hydrogen, fuel cell

W artykule przedstawiono wyniki techniczno-ekonomicznej analizy zasilania modelowego obiektu przemysłowego energią elektryczną pochodzącą z niestabilnych źródeł energii odnawialnej. Jako źródła OZE rozpatrzono turbiny wiatrowe i moduły fotowoltaiczne współpracujące z wodorowymi magazynami energii. W przyjętej strategii zasilania założono maksymalizację zużycia na potrzeby własne samodzielnie wyprodukowanej energii elektrycznej. Rozważano sześć wariantów, w tym dwa z systemem magazynowania energii, trzy wykorzystujące wyłącznie OZE oraz wariant referencyjny, w którym modelowy obiekt był zasilany z sieci elektroenergetycznej. Modelowanie i optymalizację zaproponowanych wariantów przeprowadzono w programie HOMER pod kątem najniższego kosztu bieżącego netto. Uzyskane wyniki wskazują, że najkorzystniejszą konfiguracją jest przyłączony do sieci hybrydowy system energii odnawialnej, składający się z turbin wiatrowych i elektrowni fotowoltaicznej. Taki system z układem magazynowania energii za pośrednictwem wodoru jest znacznie bardziej opłacalny niż zasilanie obiektu z sieci. Rentowność magazynowania energii znacząco rośnie wraz z prognozowanym wzrostem cen energii elektrycznej i spadkiem cen elementów instalacji wodorowych.
Słowa kluczowe: hybrydowe instalacje odnawialnych źródeł energii, analiza ekonomiczna, analiza środowiskowa, zielony wodór; ogniwo paliwowe

Nomenclature

- ANC – annualised cost [€]
- CRF – capital recovery factor [-]
- C_{cap} – capital cost [€]
- $C_{O\&M}$ – operating and maintenance cost [€]
- C_{rep} – devices replacement cost [€]
- C_{sal} – salvage value [€]
- C_{sold} – income from energy sales [€]
- $E_{ann_{sold}}$ – volume of energy sold to the grid during the year [kWh]
- $E_{serv_{ACprim}}$ – volume of energy generated to cover the primary AC load during the year [kWh]
- $E_{tot_{serv}}$ – total volume of energy supplied by the system during the year [kWh]
- f – average inflation rate [-]
- $f_{d,N}$ – discount factor in year N [-]
- i – annual real interest rate [-]
- i' – average nominal interest rate [-]
- INT() – function that returns the nearest integer less than or equal to the given value [-]
- $LCOE$ – levelised cost of electricity [€/kWh]
- N – calculation year [-]
- NPC – net present cost [€]
- t_{comp} – lifetime of the device [years]
- t_{proj} – project time [years]
- t_{rem} – the useful life of the equipment that remains after the end of the project [years]
- t_{rep} – time from the beginning of the project to the last device replacement [years]

Abbreviations:

- DGC – Distribution Grid Code
- DSO – Distribution System Operator
- EC – European Commission
- EGD – European Green Deal
- EPS – Electric Power System
- EU – European Union
- FC – Fuel Cell
- GT – Gas Turbine
- HC – Hydrogen Compressor
- HG – Hydrogen Generator
- HICE – Hydrogen Internal Combustion Engine
- HOMER – Hybrid Optimization Model for Multiple Energy Resources
- HRES – Hybrid Renewable Energy Sources
- HT – Hydrogen Tank

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IRES – Intermittent Renewable Energy Sources
LCOE – Levelised Cost of Electricity
NPC – Net Present Cost
O&M – Operating and Maintenance
PPE – Polish Power Exchange
PPS – Polish Power System
PV – Photovoltaic
P2H – Power to Hydrogen
P2H2P – Power to Hydrogen to Power
RES – Renewable Energy Sources
TGC – Transmission Grid Code
WT – Wind Turbine

Introduction

For many years, actions have been taken around the world to shape economies in accordance with the idea of sustainable development. In the European Union (EU), which aspires to be a leader in the pursuit of zero emissions, the document setting the direction for energy development is the European Green Deal (EGD) presented in December 2019 [1]. One of the priorities is a rapid increase in the share of renewable energy sources (RES) in the electricity generation structure, which is to be achieved by systematically connecting a significant number of renewable sources processing primary wind and solar energy. However, these sources are characterised by high instability of energy production, which is strictly dependent on current weather conditions at a given location. The dynamic increase in the share of these sources in the installed capacity, without appropriate remedial actions, leads to difficulties related to effective balancing of the power system. In Poland, due to the priority of introducing power from wind and photovoltaic (PV) sources into the system, imposed by the Act of February 20, 2015 on renewable energy sources [2], the problem becomes ensuring the required active and reactive power flows in local parts of the transmission and distribution grid. Another challenge is to maintain appropriate quality parameters of the electricity supplied to consumers, specified in dedicated standards and regulations, as well as in the Transmission Grid Code (TGC) [3] and the Distribution Grid Code (DGC).

One of the key solutions to counteract these phenomena is the rapid development of energy storage systems and the attempt to increase the self-consumption of electricity generated by independent economic entities as a part of distributed energy [4]. Among the most promising technologies, energy storage in the form of hydrogen stands out. Hydrogen can be produced in the electrolysis process. If the electricity supplied to the electrolysis process comes from RES, it is called green hydrogen. Electrolytic hydrogen generators (HG) can function as systems taking over excess power that occurs in separate RES systems, as well as systems that cooperate with the grid. The most popular method of storing hydrogen is the use of thick-walled pressure tanks in which compressed hydrogen is injected. Then, if the energy demand increases, hydrogen can be reused to produce electricity through the use of fuel cells (FC), gas turbines (GT), or hydrogen internal combustion engines (HICE). Systems that produce hydrogen from electricity and convert it back into electricity are called power-to-hydrogen-to-power (P2H2P) systems.

The high potential of hydrogen in terms of electricity storage, recognised by the EU, was formalised in 2020 by the European Commission (EC) in a document entitled 'Hydrogen Strategy for a Climate Neutral Europe." [5]. The paper outlines the prospects for the development of the hydrogen market in Europe and indicates the directions that should be followed to achieve the goals set in the document. The idea of energy storage and its benefits are even more important in the case of hybrid renewable energy sources (HRES) systems. Hydrogen energy storage may be the answer to the problems of balancing the power supply resulting from the growing penetration of the production structure by intermittent renewable energy sources (IRES). If P2H2P systems are used as autonomous units connected to the grid or separate systems, they can be a way to minimise the impact of electricity prices on the operation and economic situation of the entity or make it completely independent of the energy price. Due to the local saturation of the network with RES, the use of P2H2P systems or other energy storage systems in the near future may also be the only way to obtain permission to connect new RES installations to the grid. In the face of rising electricity prices, such systems will be able to bring tangible economic benefits.

Literature studies on P2H2P systems present various approaches to the implementation of this technology, depending on its application and the adopted power supply strategy. Guandalini et al. [6] consider the potential of power-to-hydrogen (P2H) technology in cooperation with the Italian power system. They conducted a long-term analysis based on the development forecasts of the Italian electric power system (EPS) until 2050. They point to the importance of P2H systems in terms of EPS balancing, the possibility of local saturation with IRES sources, and limitations of power flows resulting from the topology of transmission and distribution grids. Zaik and Werle [7] presented a description of the methodology and preliminary research results of a HRES system with a power of several hundred watts, integrated with a hydrogen generator, under Polish conditions. The aim of the first stage of the research was to determine the influence of the input values on the selected operating characteristics of the electrolyser. The authors also presented the current structure of hydrogen production in the world and the projected share of individual raw materials by 2050. They presented the issue of storing energy in hydrogen in the EU.

Thirunavukkarsu and Sawle [8] conduct a technical and economic analysis of stand-alone and grid-connected hybrid electricity and heat generation systems for an Indian tea plantation. Various combinations and variants of RES supported by a diesel generator and an oil boiler were compared. In each case, the energy is also used to produce hydrogen which is to be used as fuel for a local vehicle refuelling station. The results indicate that systems connected to the grid are more profitable than systems operating off-grid. Li et al. [9] compared the validity of using HRES systems operating on-grid and off-grid. The analysis was carried out in a rural area in western China. In the case of an autonomous system, the most advantageous solution turned out to be a combination of a PV power plant, a wind power plant, a biogas-powered generator, and a battery system. In the on-grid mode, the best result was the system consisting of the same generation sources, but without batteries. In both cases, the value of the levelised electricity cost (LCOE) is lower than the cost of purchasing energy from the grid. Okundamija [10], using HOMER software, optimised the power system size of the computer centre at Ambrose Alli University in Nigeria. The installation consists of PV cells, hydrogen storage, and fuel cells. The analysed system is connected to the power grid, which is characterised by high unreliability of energy supplies. Economic analysis and comparison with the grid-connected variant showed that despite the high investment costs of the energy storage system, the average cost of electricity will decrease by 88%. Additionally, the facility's annual CO_2 emissions will be reduced by 97.33% in relation to the power supply from the grid (from 471 kg to 17,661 kg).

The article presented in this issue is a continuation of the considerations undertaken in the authors' previous publication [11] and concerns the economic analysis of selected methods of supplying a model industrial plant based on IRES. Both publications constitute a coherent whole and contain the results of energy, economic and environmental (3E) analyses prepared for the optimized system. Modelling and optimisation were performed using HOMER software (Hybrid Optimization Model for Multiple Energy Resources) [12], where the objective function was to minimise the net present cost (NPC). Supplementary calculations were performed according to own algorithms, using an Excel spreadsheet and the CoolProp fluid properties library [13]. The adopted energy supply strategy assumed maximisation of self-consumption of self-produced electricity. Similarly to other works [14-17], it was assumed that the profitability of the investment would be considered in the perspective of 25 years, which results from the expected service life of the devices selected for analysis.

The description of the model facility along with the adopted load profile was presented in publication [11]. All considered system variants were discussed there and the characteristics of the elements of individual systems were presented. The basic technical and economic indicators adopted for calculations, as well as the methodology of energy modelling of the system, were also presented. Currently, attention is focused on the presentation of the optimisation algorithm and the methodology of the economic analysis. The results obtained for the base scenario are presented and discussed, as well as the results of the sensitivity analysis of the considered configurations to changes in selected input parameters.

A distinctive feature of the work is the analysis of the use of HRES in the industrial sector. Only a few works refer to this type of applications [18, 19]. Moreover, there is a significant gap in the area of cooperation of this type of systems with hydrogen energy storage, especially in the case of power supply strategies aimed at maximising self-consumption of self-generated electricity. Also new in the paper is the inclusion of energy input and costs incurred for compressing hydrogen. It was decided to extend the analysis to include the need to purchase a compressor and take into account the costs of its operation. Cash flows include the revenue that can be achieved by selling surplus electricity to the grid. In addition to technical and economic aspects, the environmental benefits obtained thanks to installations with the P2H2P system were also presented.

Economic analysis

It was assumed that the criterion determining the profitability hierarchy of the considered system variants will be the total net present cost. It is a method of assessing the economic effectiveness of an investment based on discounting cash flows at an assumed discount factor. The NPC value is a commonly used economic indicator that helps in investment decision-making processes. The total net present cost of a system is the present value of all the costs the system will incur over its life, minus the present value of all revenues received over its life. A negative net present cost value means that the future cash flows from the investment, in today's money, exceed the initial investment outlay. Cash flows include purchasing and selling energy, operating and maintenance (O&M) costs, replacement costs as well as salvage value and in each year were discounted to year zero. The discount factor ($f_{d,N}$) was defined as:

$$f_{d,N} = \frac{1}{(1+i)^N} \tag{1}$$

where:
i – annual real interest rate [-],
N – calculation year [-].

Annual real interest rate (i):

$$i = \frac{i'-f}{1+f} \tag{2}$$

where:
i' – average nominal interest rate [-],
f – average inflation rate [-].

Net present cost (*NPC)*:

$$NPC = C_{cap} + \sum_{N=1}^{N=t} f_{d,N} \cdot (C_{rep} + C_{O\&M} - C_{sal} - C_{sold}) \tag{3}$$

where:
C_{cap} – capital cost [€],
C_{rep} – devices replacement cost [€],
$C_{O\&M}$ – operating and maintenance cost [€],
C_{sal} – salvage value [€],
C_{sold} – income from energy sales [€].

The total net present cost of the examined variant is the sum of the NPCs of all its components. Capital costs, O&M costs, replacement cost, and salvage value were calculated on a unit cost basis, depending on the power and size of the equipment. The costs of replacing individual elements are related to the estimated service life of the devices. Depending on the replacement device, the cost may be different than the capital cost as only part of the device may need to be replaced [12, 15, 20, 21]. It was assumed that the costs of O&M costs will be taken into account for wind turbines (WT), PV, HG, HC, and FC will be taken into account [16]. The O&M costs for the inverter and HT were considered negligible. The salvage value represents the capital remaining after the end of the use of the device. This capital is invested in devices that can be used for further operation. The HOMER assumes a linear variation in the salvage value over the expected lifetime. This relationship is related to the capital cost in the case of devices that have not been replaced and to the replacement cost in the case of devices that have been replaced. The salvage value is calculated as:

$$\begin{cases} C_{sal} = C_{rep} \cdot \dfrac{t_{rem}}{t_{comp}}, \\ \textit{if device was repalced} \\ C_{sal} = C_{cap} \cdot \dfrac{t_{rem}}{t_{comp}}, \\ \textit{if device was not replaced} \end{cases} \tag{4}$$

where:
t_{rem} – the useful life of the equipment remaining after the end of the project [years],
t_{comp} – lifetime of the device [years].

The remaining useful life after the end of the project (t_{rem}) is calculated from the formula:

$$\begin{cases} t_{rem} = t_{comp} - (t_{proj} - t_{rep}), \\ \textit{if device was repalced} \\ t_{rem} = t_{comp} - t_{proj}, \\ \textit{if device was not replaced} \end{cases} \tag{5}$$

where:
t_{proj} – project time [years],
t_{rep} – time from the beginning of the project to the last device replacement [years].

The time that has elapsed from the beginning of the project to the last replacement of the device is defined as:

$$t_{rep} = t_{comp} \cdot \int\left(\frac{t_{proj}}{t_{comp}}\right) \tag{6}$$

where:
$\int()$ – function that returns the closest integer less than or equal to the given value [-].

The annualised cost (ANC) for each variant was determined as:

$$ANC = NPC \cdot CRF \tag{7}$$

where:
CRF – capital recovery factor [-].

The capital recovery factor is calculated from the formula

$$CRF = \frac{i \cdot (1+i)^{t_{proj}}}{(1+i)^{t_{proj}} - 1} \tag{8}$$

The levelised cost of electricity (LCOE) in the analysed case is calculated as [12, 16, 22]:

$$LCOE = \frac{ANC}{E_{tot_{serv}}} = \frac{ANC}{E_{serv_{AC_{prim}}} + E_{ann_{sold}}} \tag{9}$$

where:
$E_{tot_{serv}}$ – total volume of energy supplied by the system during the year [kWh],
$E_{serv_{AC_{prim}}}$ – volume of energy generated to cover the primary AC load during the year [kWh],
$E_{ann_{sold}}$ – volume of energy sold to the grid during the year [kWh].

Table 1 presents the unit costs of the individual components based on literature studies. In the case of technologically mature equipment such as WT, PV and inverter, it was assumed that the replacement cost would account for 80% of the capital cost. In the case of devices that are in the initial market stage, a decline in their prices in the future was assumed [23, 24]. All components of the P2H2P system were considered such devices. It was assumed that after working through the service life, these devices could be replaced at a price that represents 50% of the capital cost.

Table 1. Unit costs of devices included in the analysed systems
Tabela 1. Jednostkowe koszty urządzeń wchodzących w skład analizowanych konfiguracji

Component	Lifetime	Capital cost	Replacement cost	O&M costs
WT	25 years [15]	1,430,116 €/MW [14]	1,144,093 €/MW	44,000 €/MW/year [29]
PV	25 years [15]	703 €/kW [14]	562 €/kW	7.05 €/kW/year [30]
Inverter	15 years [14]	178 €/kW [14]	142 €/kW	0 €/kW/year [14]
HG	15 years [14]	1,269 €/kW [27]	635 €/kW	12.8 €/kW/year [23]
H_2 Compressor	10 years [25]	1,208 €/kW [25]	604 €/kW	(4.23 + c_{avg}) €/MWh [27]
HT	25 years [14]	490 €/kg [28]	245 €/kg	0 €/kg/year [14]
FC	27,000 h [26]	1,117 €/kW [27]	559 €/kW	0.0005 €/kWh [23]

ment of the system is calculated. In the next step, the actual possibility of implementing a given system is determined due to its ability to cover the demand for electricity in specific conditions. Then, the optimisation algorithm, taking into account all component costs, searches for the most advantageous system, in terms of the defined objective function, and presents all configurations that meet the criteria in a hierarchical form [12]. Fig. 1 presents a block diagram of the optimisation algorithm used by the HOMER software [33].

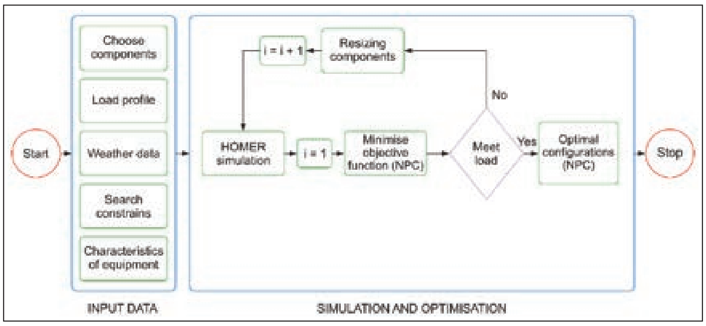


Fig. 1. Flowchart of the optimisation algorithm used in the HOMER software
Rys. 1. Schemat blokowy algorytmu optymalizacyjnego zastosowanego w oprogramowaniu HOMER

Costs associated with purchasing and selling energy

The sale and purchase of electricity from DSO is considered in variants where there will be power surpluses and deficiencies that cannot be compensated for. Due to the higher unit cost of purchasing electricity from the grid in relation to the selling price of energy produced by RES and the adopted strategy of maximising the self-consumption of electricity, energy from RES supplies the plant in priority and only the surplus that cannot be taken over is resold. The surplus energy may be sold at the current price on the Polish Power Exchange (PPE) or at the price resulting from the RES auction. The study assumes that electricity directed to the grid will be sold at the reference price of the RES auction for a given group of sources. This price is indexed annually with the average annual inflation rate. The adoption of such a billing model allows this analysis to be independent of the volatility of instantaneous energy prices on PPE. Due to the auction system, a producer that has obtained this type of financial support can sell energy at a fixed price.

If the system is powered by at least two types of RES installations and is supported by sources using primary energy, then, according to the Polish legislator, it can be considered a hybrid renewable energy source. Hybrid installations can be additionally equipped with energy storage, and the energy returned from the storage is then treated as energy from the RES source. Qualifying a system as HRES requires meeting several criteria, the most important of which are [31]:

- The total degree of utilisation of the installed electrical capacity is greater than 3,504 MWh/MW/year,
- none of the generating devices has an installed capacity greater than 80% of the total installed electrical capacity of this unit.

Recognition of a generating equipment set as an HRES installation allows to reap the benefits provided for this type of installation. Benefits refer to installations that sell energy to the grid. One of them is the possibility of selling electricity to the grid at a higher price than for separate systems. In this study, the electricity sales price was made conditional on meeting the HRES requirements. The calculations showed that only variant 4 meets the above-mentioned criteria. In other variants, the energy directed into the grid, coming from the selected source, is sold at the reference price for that source, according to its share in the total amount of electricity production. Table 2 shows the reference prices for energy sales for 2021.

Table 2. Reference price of energy sales in 2021, for entities participating in RES auctions [32]
Tabela 2. Cena referencyjna sprzedaży energii w 2021 r. dla podmiotów uczestniczących w aukcjach OZE

Type of source	Power range [MW]	Price [€/MWh]
Using only wind energy	≤ 1	70.07
	> 1	54.74
Using only solar energy	≤ 1	74.45
	> 1	70.07
HRES	≤ 1	90.87
	> 1	89.77

Optimisation algorithm

Optimisation of the considered configurations was carried out using HOMER software. Graham's original optimisation algorithm implemented in the HOMER software was used, which searches for the most favorable configurations based on minimisation of the objective function. The objective function in this case is the total net present cost. Four groups of parameters are used as input data, including: the entity's load profile, meteorological conditions in a given location, costs related to the purchase and operation of devices, and external limitations of the search space. The algorithm simulates all possible system configurations, performing energy balance calculations at each time step. Balance calculations come down to comparing the demand for electricity (and heat, if it is taken into account) at each time step with the energy that a given system is able to supply. In this way, the energy flow to and from each element of the system is calculated.

Results and discussion

This section presents the results of the optimisation of individual power supply variants. A multi-criteria comparison of the variants was made, assuming that the investment cost of each of them does not exceed the investment cost of a system with a wind farm and energy storage in the form of hydrogen (the most expensive variant). The size and number of individual elements were selected to obtain the lowest net present cost, provided that the above condition was met. The first part of the chapter will present the results obtained for the variants in the base scenario, referring to the current prices. The second part will present the results of the analysis of the sensitivity of variants to changes in input parameters.

Comparison of power systems for baseline conditions

Table 3 summarises the results of the optimisation carried out in the HOMER for the base input parameters.

The results obtained indicate that the most economically advantageous investment is an HRES system consisting of a WTs and a PVs connected to the grid. Negative values of NPC and LCOE, amounting to – 36.47 mln € and – 0.038 €/kWh, respectively, indicate the possibility of obtaining income in the analysed period. This income results from the relationship between capital and operating costs and the costs of purchasing energy from DSOs to the revenues obtained from the sale of surplus energy. Such a significant difference in the economic indicators in relation to the other variants results from the surplus energy sales price. Because in this configuration, the system

Table 3. Optimisation results for base input parameters
Tabela 3. Wyniki optymalizacji dla bazowych parametrów wejściowych

Variant number	1	2	3	4	5	6
Components	Grid	Grid + WT	Grid + PV	Grid + WT + PV	Grid + WT + P2H2P	Grid + WT + PV + P2H2P
WT power [kW] (No.)	-	8,000 (4)	-	8,000 (4)	4,000 (2)	4,000 (2)
PV power [kW] (No.)	-	-	16,232 (42,716)	2,535 (6,671)	-	308 (811)
FC power [kW] (No.)	-	-	-	-	2,100 (21)	2,200 (22)
HG power [kW] (No.)	-	-	-	-	2,025 (9)	1,575 (7)
HT capacity [kg] (No.)	-	-	-	-	6,000 (6)	6,000 (6)
Inverter power [kW]	-	-	12,187	2,001	-	169
NPC [mln €]	56.85	-7.49	24.36	-36.47	23.81	23.51
LCOE [€/kWh]	0.254	-0.008	0.045	-0.038	0.106	0.105
Annual O&M costs [mln €/year]	2.283	-0.760	0.386	-2.017	0.207	0.204
Capital cost [mln €]	0	11.44	13.58	13.58	13.58	13.36

meets the basic conditions allowing it to be treated as a HRES (installation capacity utilisation rate equal to 3584 MWh/MW/year, share of PV and WT installed capacity in the total installed capacity of the system, 24.06% and 75.94% respectively) the energy selling price was assumed to be equal to the reference price for hybrid systems with a capacity above 1 MW.

The difference in NPC and LCOE indicators between the variant with HRES and the wind turbine only is 28.98 mln € and 0.030 €/kWh respectively, while the difference in NPC and LCOE between the variant with HRES and the PV power plant only is 60.83 mln € and 0.083 €/kWh, respectively. This illustrates the scale of benefits that can be obtained in Poland by qualifying the installation as an HRES system. This type of support for investments in HRES also indicates the importance for the Polish legislator of introducing RES with different availability characteristics into the EPS. The natural limitation of variants 3 and 4 may be environmental conditions. The availability of the space required for the installation of many thousands of PV modules, in some cases, may constitute a fundamental barrier to the application of these variants in the sector under consideration. Results also show that the least profitable option in the perspective of 25 years is to supply the facility by purchasing all electricity from the DSO. This variant reached the highest value of NPC and LCOE, already at the base electricity prices.

In the optimisation performed in the HOMER for variants with energy storage, due to the optimisation objective, the adopted power supply strategy, and the inability to introduce certain limiting conditions, the above results did not take into account the possibility of reselling surplus energy. Part of the energy produced in variants with energy storage that is not taken over by hydrogen generators can be sold to the grid. Revenue from the sale of energy can noticeably increase the attractiveness of systems with energy storage. The HOMER does not take into account the necessity of mechanical hydrogen compression and the energy required for this purpose. Table 4 presents the corrected values of the economic indicators for variants 5 and 6 along with selected energy values. The cost of selling energy, in line with the earlier assumptions, is indexed with the real interest rate. The sale price in the variant with WT and PV, due to the failure to meet the criteria of the HRES installation, is set as the result price, in line with the share of both sources in the total annual electricity production. The costs associated with the purchase and operation of the compressor, as well as the energy needed to drive it, were also taken into account. It was assumed that this energy would be purchased from the grid.

Table 4. Real economic and energy indicators for variants with an hydrogen energy storage system
Tabela 4. Rzeczywiste wskaźniki ekonomiczne i energetyczne dla wariantów z wodorowym magazynem energii

Variant number	5	6
Components	Grid + WT + P2H2P	Grid + WT + PV + P2H2P
NPC [mln €]	20.28	18.79
LCOE [€/kWh]	0.098	0.094
Capital cost [mln €]	13.68	13.43
Annual O&M costs [€]	58,222	8,986
WT electricity production [MWh/year] (share in tot. prod. [%])	17,471.61 (89.22)	17,470.61 (88.13)
PV electricity production [MWh/year] (share in tot. prod. [%])	-	341.84 (1.72)
FC electricity production [MWh/year] (share in tot. prod. [%])	2,110.32	2,010.79 (10.14)
Total electricity demand [MWh/year]	15,917.47	15,563.47
Surplus energy [MWh/year]	3,663.45	4,253.59
H_2 production [kg/year]	128,344	121,804
H_2 consumption [kg/year]	124,509	118,637
The amount of H_2 in the tanks at the end of the year [kg]	4,435	3,767
Energy consumed by the compressor [MWh/year]	223.35	183.16
Required compressor power [kW]	79.2	61.6

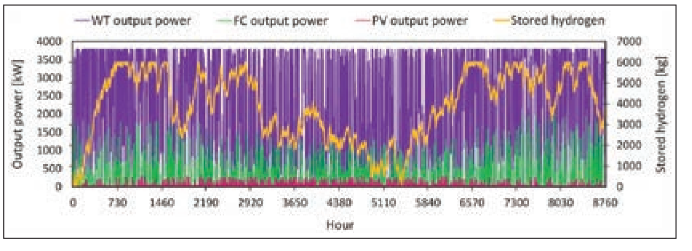


Fig. 2. Instantaneous power generation from different sources in variant 6
Rys. 2. Chwilowe wytwarzanie energii z różnych źródeł w wariancie 6

The results prove that the sale of energy to the grid in both cases allows a noticeable reduction of the NPC. Although taking into account the additional capital and O&M costs related to compression, the value of the NPC decreased by 4–5 mln € compared to the cost originally estimated by HOMER. At the same time, it can be seen that the hydrogen compression system does not significantly increase capital and operating costs. The results indicate that among the considered variants with energy storage, the more advantageous solution is to use a hybrid system combining sources using solar and wind energy. The system extended with PV has lower NPC and LCOE indicators of 1.49 mln € and 0.004 €/kWh, respectively. In optimal configuration, the share of PV in the total power of the installed system is 4.73%, and in the total production 1.72%. Fig. 2 shows the instantaneous power generation curve for generation sources and the level of filling of hydrogen tanks over the year, occurred in variant 6.

Sensitivity analysis

A sensitivity analysis was performed to examine the behaviour of the considered variants in the response to a change in selected input quantities. The analysis focusses on the parameters that are most likely to change over 25 years and that may significantly affect the results obtained. Such parameters were considered to be the real interest rate, the purchase cost of electricity, and the investment cost of selected devices. The real interest rate as a variable parameter was chosen due to its rapid change in recent times and the difficulty in forecasting values in the future. In the baseline scenario, it is 0% (approximately to a hundredth). According to the values observed in Poland in the last 20 years, cases with a negative and positive real interest rate were considered [34, 35].

The willingness to investigate the behaviour of the variants in the event of a change in the cost of electricity purchase is dictated by the increasing prices of electricity in Poland. Based on the electricity price lists for 2018–2022, the average increase in the electricity price in the tariff considered was 21.90% year on year [36]. This increase significantly exceeded the average inflation rate for the last five years, which amounted to 2.88% [34]. The reference price of electricity sales, which was used in the calculations, is indexed by the annual inflation rate. Therefore, further deepening of the disproportion between the purchase price and the selling price of electricity is expected. Scenarios in which the purchase price of electricity will be 100%, 150%, 200% and 250% of the current price have been taken into account.

The last input parameters analysed are the investment costs of the system components. It was assumed that due to the large supply on the market and the maturity of the PV cells and wind turbine technologies, their prices in the future will remain at a similar level. However, a significant decrease in the investment costs of the components of the hydrogen system is expected [23, 24, 37]. Scenarios were considered in which the cost of all devices in the hydrogen system will be, respectively: 100%, 80%, 60% and 40% of the current price. It was assumed that, similarly to the baseline scenario, the replacement cost will account for 50% of the investment costs. Table 5 shows the values of the input parameters considered in the sensitivity analysis.

Table 5. The values of the input parameters considered in the sensitivity analysis
Tabela 5. Wartości parametrów wejściowych uwzględnianych w analizie wrażliwości

Input parameter	Value			
Real interest rate [%]	-2.00	0.00	2.00	4.00
Electricity purchase price [€/kWh]	0.254	0.381	0.508	0.635
HG capital cost [€/kW]	1,269	1,015	761.4	508
HT capital cost [€/kg]	490	392	294	196
Compressor capital cost [€/kW]	1,208	966	725	483
FC capital cost [€/kW]	1,117	893	670	447

In all RES-powered variants, the preferred system structure turned out to be a hybrid system. Figs. 3 and 4 present charts for variants 1 and 4, showing their sensitivity to changes in the real interest rate and the purchase price of electricity. Figures 5-8 show the diagrams for the variant 6, for various configurations of the assumed capital costs. The graphs were made in the MATLAB software [38].

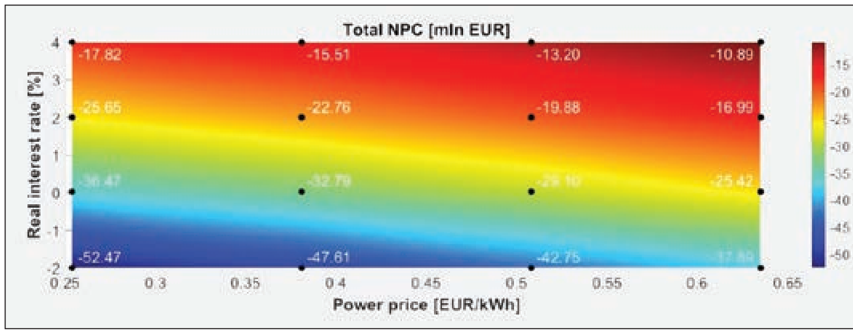


Fig. 4.
Sensitivity analysis of variant 4 to changes in the real interest rate and the purchase price of electricity
Rys. 4. Analiza wrażliwości wariantu 4 na zmiany realnej stopy procentowej i ceny zakupu energii elektrycznej

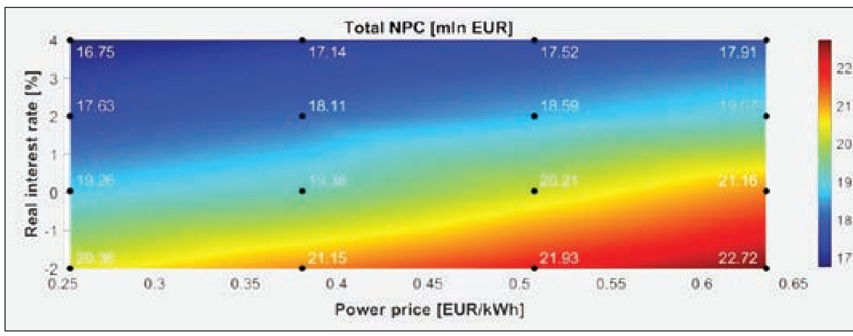


Fig. 5.
Sensitivity analysis of variant 6 to changes in the real interest rate and the electricity purchase price – capital cost of the hydrogen system equal to 100% of the current price
Rys. 5. Analiza wrażliwości wariantu 6 na zmiany realnej stopy procentowej i ceny zakupu energii elektrycznej – koszt inwestycyjny systemu wodorowego równy 100% ceny bieżącej

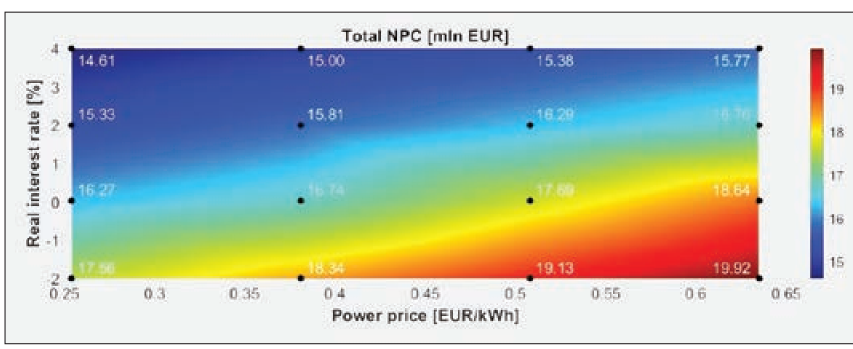


Fig. 6.
Sensitivity analysis of variant 6 to changes in the real interest rate and the electricity purchase price – capital cost of the hydrogen system equal to 80% of the current price
Rys. 6. Analiza wrażliwości wariantu 6 na zmiany realnej stopy procentowej i ceny zakupu energii elektrycznej – koszt inwestycyjny systemu wodorowego równy 80% ceny bieżącej

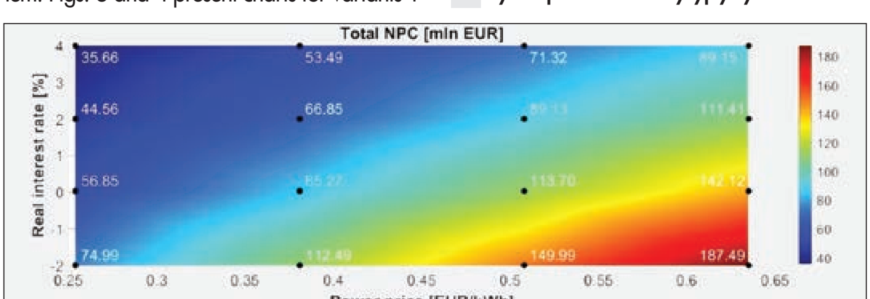


Fig. 3.
Sensitivity analysis of variant 1 to changes in the real interest rate and the purchase price of electricity
Rys. 3. Analiza wrażliwości wariantu 1 na zmiany realnej stopy procentowej i ceny zakupu energii elektrycznej

For electricity prices and real interest rate adopted as input variables, in each configuration, the most advantageous variants turned out to be the ones with WTs and PVs cooperating with the grid. On the other hand, the least profitable is to supply the plant from the power grid only. In the case of the power supply from the grid, the sensitivity analysis shows a large increase in the NPC value with an increase in the electricity price and a significant decrease in the NPC index in response to the growing real interest rate. In variant 4, each configuration of the input parameters allows to reach

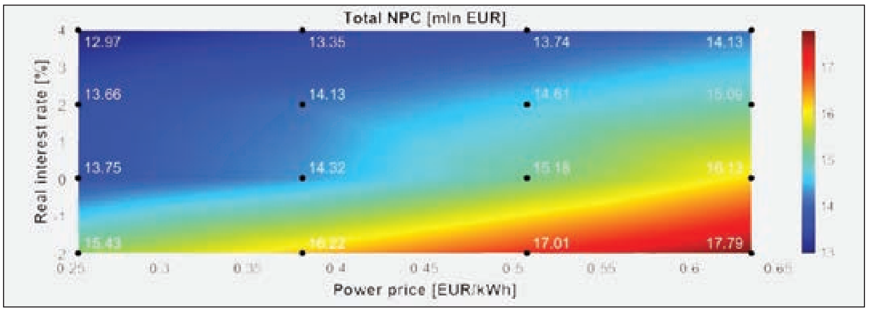


Fig. 7.
Sensitivity analysis of variant 6 to changes in the real interest rate and the electricity purchase price – capital cost of the hydrogen system equal to 60% of the current price
Rys. 7. Analiza wrażliwości wariantu 6 na zmiany realnej stopy procentowej i ceny zakupu energii elektrycznej – koszt inwestycyjny systemu wodorowego równy 60% ceny bieżącej

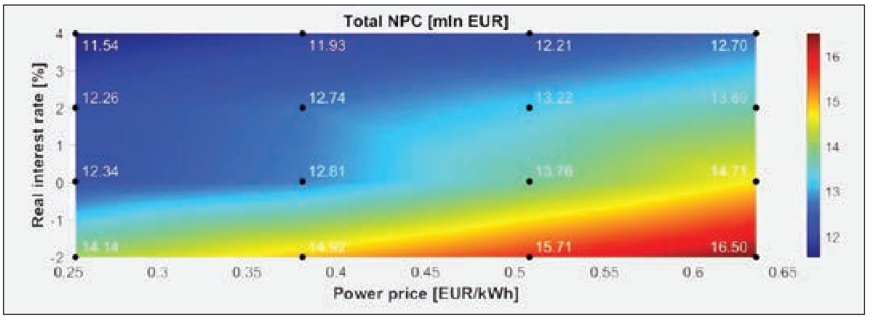


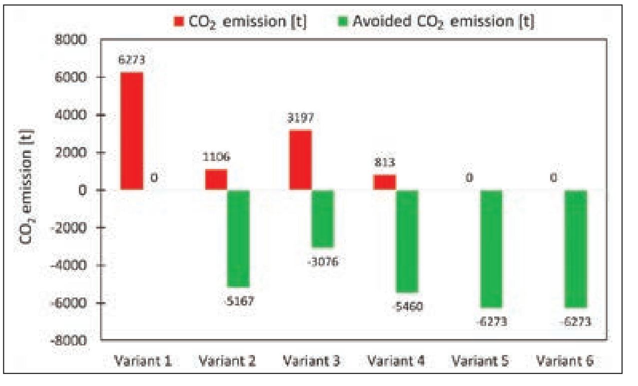
Fig. 8.
Sensitivity analysis of variant 6 to changes in the real interest rate and the electricity purchase price – capital cost of the hydrogen system equal to 40% of the current price
Rys. 8. Analiza wrażliwości wariantu 6 na zmiany realnej stopy procentowej i ceny zakupu energii elektrycznej – koszt inwestycyjny systemu wodorowego równy 40% ceny bieżącej

a negative NPC value. At the same time, a slight sensitivity of the system is observed to changes in the electricity purchase price. This is due to the small volume of electricity required to purchase. In the case of variant 6, with HRES and hydrogen storage, a slight decrease in the NPC is observed, in response to the higher real interest rate. An increase in the real interest rate from – 2% to 4% reduces the value of the NPC in the range from 15.9% to 23.0%, depending on the considered capital costs of the system and the price of electricity. In the case of increasing electricity prices, the increase in NPC results from the growing share of costs incurred to power the compressor. In the scenario with the baseline capital costs, with individual real interest rate (-2%; 0%; 2% and 4%), the NPC growth is, respectively: 2.36 mln € (11.6%); 1.9 mln € (9.9%); 1.44 mln € (8.2%) and 1.16 mln € (6.9%), for 2.5 times higher electricity price. In variant 6, a decrease in NPC is also observed along with decreasing capital costs and equipment replacement costs. For the scenario with the baseline electricity price and current real interest rate, these decreases for capital costs equal to: 80%; 60% and 40% of the baseline costs are respectively: 2.99 mln € (15.5%); 5.51 mln € (28.6%) and 6.92 mln € (35.9%). The percentage of NPC decline with a change in capital costs decreases slightly with higher electricity prices.

Environmental benefits

In countries where the production structure includes sources powered by hydrocarbon fuels, the purchase of energy from the grid is

Fig. 9.
Total annual CO_2 emissions for each of the variants considered and the amount of emissions avoided in relation to power supply from the grid as a result of the use of RES
Rys. 9. Całkowita roczna emisja CO_2 dla każdego z rozpatrywanych wariantów oraz ilość unikniętych emisji w wyniku wykorzystania OZE w odniesieniu do zasilania z sieci



associated with the emission of pollutants. In Poland, the share of hard coal and lignite-fired sources in the total electricity production in 2021 was 79.74% [39]. By separating the selected facility as a detached system and supplying it from the grid or from RES sources without energy storage, it cannot be considered as a zero-emission entity. The purchase of energy from the grid is associated with the emission of significant amounts of pollutants. Therefore, CO_2 emissions occur in variants 2–4, in which it is necessary to supplement electricity shortages by purchasing it from the supplier, and in the reference variant 1, where all electricity consumed comes from the grid. Only RES systems with energy storage can be considered as zero-emission. Assuming the constant CO_2 emission factor for the electricity of the Polish power grid, reported in 2021 by the National Centre for Emissions Management at the level of 698 kg/MWh [40], the amount of carbon dioxide emitted, directly depends on the volume of purchased energy, which is the result parameter determined on the basis of the optimisation performed in relation to the adopted objective function. Fig. 9 shows the total annual CO_2 emissions for all variants analysed in the baseline scenario. The avoided CO_2 emissions are also presented in relation to the variant with the grid power supply.

The autonomous systems with hydrogen storage allows to avoid the annual emission of approx. 6,273 t CO_2 in relation to power supply from the grid and approx. 813 t CO_2 in relation to the variant with a HRES system without energy storage.

Conclusions

The paper compared selected prospective power sources for a model industrial facility located in northern Poland, based on RES and connected to the power grid. The main goal of the work was the technical and economic evaluation of an autonomous power supply system with hydrogen energy storage, using a power strategy aimed at maximising the self-consumption of self-produced energy. The main indicator of the economic evaluation of variants was the net present cost. The analysis was conducted in light of the current and expected local legal regulations related to RES and energy storage.

The results obtained indicate that as long as it is possible to connect RES to the grid without energy storage, the best solution is to use a hybrid system consisting of WTs and a PV power plant. With the assumed limitation in the form of maximum investment costs, the system consisting of 4 WTs with a capacity of 2 MW supported by a PVs with a capacity of 2.54 MW performed best. In the baseline scenario, the NPC was – 36.47 mln € and the LCOE was – 0.038 €/kWh. The sensitivity analysis showed that for all considered configurations of real interest rate and electricity prices, this option provides income over a period of 25 years (negative value of the NPC). The limitation may be the availability of land for the construction of a PV power farm consisting of nearly 7,000 PV modules.

If it is not possible to connect uncontrollable RES without energy storage to the grid, a HRES system with hydrogen energy storage is the most preferred option. In the baseline scenario, it consists of two WTs with a total capacity of 4 MW, a PV farm with a capacity of 0.308 MW, hydrogen generators with a total capacity of 1,575 MW, hydrogen tanks with a capacity of 6,000 kg, and fuel cells with a capacity of 2.2 MW. The calculated NPC value was 18.79 mln € and the LCOE was 0.094 €/kWh. The system is characterised by low sensitivity to changes in the inflation index and electricity prices, and in any case will be more advantageous than the purchase of all electricity from the grid. The profitability of this type of installation will increase even more with the forecast decrease in the prices of hydrogen system devices and the simultaneous increase in the price of electricity. Additional economic benefits can be expected through the implementation of such a solution in sectors that use oxygen in technological processes and through the management of waste heat from the cooling of fuel cells. Investigating such scenarios will help to define the economic aspect of hydrogen energy storage systems in a more comprehensive way and could be an important direction for future research.

LITERATURE:

[1] Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. Available online: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en#documents [accessed on 04 May 2023].

[2] Act of February 20, 2015 on renewable energy sources (in Polish). Journal of Laws (abbreviated Dz. U.), 2015, item 478) https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20150000478/U/D20150478Lj.pdf [accessed on 12 May 2023].

[3] Transmission Grid Code of Polish Transmission System Operator. Available online: https://www.pse.pl/dokumenty [accessed on 19 May 2023].

[4] Bronk L.; Czarnecki B.; Magulski R.: Flexibility of the National Power System. Diagnosis, potential, solutions. (in Polish), 02.2019. Available online: https://forum-energii.eu/pl/analizy/elastycznosckse [accessed on 28 Apr 2023].

[5] Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. A hydrogen strategy for a climate-neutral Europe. Available online: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf [accessed on 04 May 2023].

[6] Guandalini G.; Robinius M.; Grube T.; Campanari S.; Stolten D.: Long-term power-to-gas potential from wind and solar power: A country analysis for Italy. *Int. J. Hydrog. Energy* 2017, 42, 13389-406. DOI:10.1016/j.ijhydene.2017.03.081.

[7] Zaik K.; Werle S.: Solar and wind energy in Poland as power sources for electrolysis process – A review of studies and experimental methodology. *Int. J. Hydrog. Energy* 2022 (In Press). DOI:10.1016/j.ijhydene.2022.02.074.

[8] Thirunavukkarasu M.; Sawle Y.: An examination of the techno-economic viability of hybrid grid-integrated and stand-alone generation systems for an Indian tea plant. *Frontiers in Energy Research* 2022, 10. DOI:10.3389/fenrg.2022.806870.

[9] Li J.; Liu P.; Li Z.: Optimal design of a hybrid renewable energy system with grid connection and comparison of techno-economic performances with an off-grid system: A case study of West China. *Computers and Chemical Engineering* 2022, 159, 107657. DOI:10.1016/j.compchemeng.2022.107657.

[10] Okundamiya M.S.: Size optimization of a hybrid photovoltaic/fuel cell grid connected power system including hydrogen storage. *Int J Hydrog. Energy* 2021, 46, 30539-46. DOI:10.1016/j.ijhydene.2020.11.185.

[11] Łukasik J., Jewartowski M., Wajs J.: Techno-economic assessment of cooperation of hybrid renewable energy sources with hydrogen storage. *Instal* 2023, 11(456), 23-31. DOI: 10.36119/15.2023.11.3.

[12] HOMER software. Available online: https://www.homerenergy.com/ [accessed on 22 Jun. 2023].

[13] CoolProp library. Available online: http://www.coolprop.org/[accessed on 16 Jun. 2023].

[14] Kharel S.; Shabani B.: Hydrogen as a long-term large-scale energy storage solution to support renewables. *Energies* 2018, 11(10), 2825. DOI:10.3390/en11102825.

[15] Kalinci Y.; Hepbasli A.; Dincer I.: Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options. *Int. J. Hydrogen Energy* 2015, 40, 7652-64. DOI:10.1016/j.ijhydene.2014.10.147.

[16] Acakpovi A.; Adjei P.; Nwulu N.; Asabere N.Y.: Optimal hybrid renewable energy system: A comparative study of wind/hydrogen/fuel-cell and wind/battery storage. *Journal of Electrical and Computer Engineering* 2020, 1756503. DOI:10.1155/2020/1756503.

[17] Shabani B.; Andrews J.: Standalone solar-hydrogen systems powering fire contingency networks. *Int. J. Hydrog. Energy* 2015, 40, 5509-17. DOI:10.1016/j.ijhydene.2015.01.183.

[18] Ammari C.; Belatrache D.; Touhami B.; Makhloufi S.: Sizing, optimization, control and energy management of hybrid renewable energy system – A review. *Energy and Built Environment* 2021 (In Press). DOI:10.1016/j.enbenv.2021.04.002.

[19] Nguyen N.T.; Matsuhashi R.; Vo T.T.B.C.: A design on sustainable hybrid energy systems by multi-objective optimization for aquaculture industry. *Renewable Energy* 2021, 163, 1878-94. DOI:10.1016/j.renene.2020.10.024.

[20] Luta D.N.; Raji A.K.: Optimal sizing of hybrid fuel cell-supercapacitor storage system for off--grid renewable applications, *Energy* 2019, 166, 530-40. DOI:10.1016/j.energy.2018.10.070.

[21] Longe O.M.; Rao N.D.; Omowole F.; Oluwalami A.S.; Oni O.T.: A case study on off-grid microgrid for universal electricity access in the Eastern Cape of South Africa. *Int. J. Energy Engineering* 2017, 7(2), 55-63. DOI:10.5923/j.ijee.20170702.03.

[22] Mohamed M.A.; Eltamaly A.M.; Alolah A.: PSO-based smart grid application for sizing and optimization of hybrid renewable energy systems. *PLOS ONE* 2016, 11(8), e0159702. DOI:10.1371/journal.pone.0159702.

[23] Mongird K.; Viswanathan V.; Alam J.; Vartanian C.; Sprenkle V.: *2020 grid energy storage technology cost and performance assessment.* Pacific Northwest National Laboratory Technical Report, DOE/PA-0204, Richland, WA 99354, US, 2020.

[24] Whiston M.M.; Azevedo I.; Lister S.; Whitefoot K.S.; Samaras C.; Whitacre J.F.: Expert assessments of the cost and expected future performance of proton exchange membrane fuel cells for vehicles. *PNAS* 2019, 116(11), 4899-904. DOI:10.1073/pnas.1804221116.

[25] Parks G.; Boyd R.; Cornish J.; Remick R:. Hydrogen station compression, storage, and dispensing technical status and costs. NREL/BK-6A10-58564 Technical Report, NREL: Denver West Parkway Golden, CO, US, 2014.

[26] Nedstack PemGen CHP-FCPS-100 brochure. Available online: https://nedstack.com/en/pemgen-solutions/stationary-fuel-cell-power-systems/pemgen-chp-fcps-100 [accessed on 30 Jun. 2023].

[27] DOE technical targets for hydrogen delivery. Available online: https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-delivery [accessed on 28 Jun. 2023].

[28] Gorre J.; Ruoss F.; Karjunen H.; Schaffert J.; Tynjälä T.: Cost benefits of optimizing hydrogen storage and methanation capacities for Power-to-Gas plants in dynamic operation. *Applied Energy* 2020, 257, 113967. DOI:10.1016/j.apenergy.2019.113967.

[29] Wiser R.; Bolinger M.; Lantz E.J.: Assessing wind power operating costs in the United States: Results from a survey of wind industry experts. *Renewable Energy Focus* 2019, 30, 46-57. DOI:10.1016/j.ref.2019.05.003.

[30] Steffen B.; Beuse M.; Tautorat P.; Schmidt T.S.: Experience curves for operations and maintenance costs of renewable energy technologies. *Joule* 2020, 4, 359-75. DOI:10.1016/j.joule.2019.11.012.

[31] Act of 27 January 2022 amending the act on renewable energy sources and the act amending the act on renewable energy sources and certain other acts (in Polish). Available online:https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20210000610 [accessed on 16 Jun. 2023].

[32] Reference energy prices (in Polish). Available online: https://www.ure.gov.pl/pl/oze/aukcje-oze/ceny-referencyjne/6539,Ceny-referencyjne.html [accessed on 08 Jun. 2023].

[33] Tazay A.: Techno-Economic Feasibility Analysis of a Hybrid Renewable Energy Supply Options for University Buildings in Saudi Arabia. *Open Engineering* 2021, 11, 39-55. DOI: 10.1515/eng-2021-0005.

[34] Annual price indices of consumer goods and services since 1950 published by Central Statistical Office (in Polish). Available online: https://stat.gov.pl/obszary-tematyczne/ceny-handel/wskazniki-cen/wskazniki-cen-towarow-i-uslug-konsumpcyjnych-pot-inflacja-/roczne-wskazniki-cen-towarow-i-uslug-konsumpcyjnych/ [accessed on 18 Apr. 2022].

[35] Basic NBP interest rates in 1998-2022 (in Polish). Available online: https://www.nbp.pl/home.aspx?f=/dzienne/stopy_archiwum.htm [accessed on 26 Jun. 2023].

[36] ENERGA standard price lists for business (in Polish). Available online: https://www.energa.pl/ [accessed on 16 Jun. 2023].

[37] Thomanssen M.: Cost reduction and performance increase of PEM electrolysers, Programme Review Days, Brussels, Belgium, 21-22 Nov. 2016.

[38] MATLAB Software. Available online: https://www.mathworks.com/products/matlab.html [accessed on 04 Jul. 2023].

[39] National Power System Report 2021 (in Polish). Avaliable online: https://www.pse.pl/dane-systemowe/funkcjonowanie-kse/raporty-roczne-z-funkcjonowania-kse-za-rok/raporty-za-rok-2021#r6_1 [accessed on 04 Jul. 2023].

[40] National Centre for Emissions Management. *Emission indices of CO_2, SO_2, NO_x, CO and total dust for electricity based on the information contained in the National Base on emissions of greenhouse gases and other substances for 2020* (in Polish). Available online: https://www.kobize.pl/pl/file/wskazniki-emisyjnosci/id/171/wskazniki-emisyjnosci-dla-energii-elektrycznej-za-rok-2020-opublikowane-w-grudniu-2021-r [accessed on 7 Jul. 2023].

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