Techno-economic assessment of cooperation of hybrid renewable energy sources with hydrogen storage

Techniczno-ekonomiczna ocena współpracy hybrydowych odnawialnych źródeł energii z układem magazynowania wodoru

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The paper presents a technical and economic analysis of the power supply for a model industrial facility with the use of the most promising renewable energy sources (RES), supported by a hydrogen energy storage. This scenario was compared with the variants of supplying the facility directly from the grid and from RES without energy storage. A strategy was proposed for powering the plant aimed at maximising self-consumption of self-generated electricity. In this paper the importance of hybrid renewable energy systems (HRES) with hydrogen energy storage in the Polish Power System is pointed out. For the analysed industrial object, the modelling and optimisation of the systems were performed in the HOMER software, in terms of the lowest net present cost. Attention was also paid to the need to compress hydrogen and the associated electricity consumption.
Keywords: hybrid renewable energy sources (HRES), hydrogen energy storage, green hydrogen, electrolyser, fuel cell, energy analysis

W artykule przedstawiono analizę techniczno-ekonomiczną zasilania modelowego obiektu przemysłowego z wykorzystaniem najbardziej perspektywicznych odnawialnych źródeł energii (OZE), wspomaganych magazynem wodoru. Scenariusz ten porównano z wariantami zasilania obiektu bezpośrednio z sieci oraz z OZE bez układu magazynowania energii. Zaproponowano strategię zasilania obiektu mającą na celu maksymalizację zużycia energii elektrycznej wytworzonej przez OZE na potrzeby własne. W artykule podkreślono znaczenie hybrydowych systemów OZE z wodorowym magazynem energii w Krajowym Systemie Elektroenergetycznym. Dla analizowanego obiektu przemysłowego, z wykorzystaniem oprogramowania HOMER przeprowadzono modelowanie i optymalizację systemów pod kątem najniższego kosztu bieżącego netto. Zwrócono uwagę na konieczność sprężania wodoru i związane z tym zużycie energii elektrycznej.
Słowa kluczowe: hybrydowe instalacje odnawialnych źródeł energii, magazynowanie wodoru, zielony wodór, elektrolizer, ogniwo paliwowe, analiza energetyczna

Nomenclature

c_{avg} – average purchase price of electricity in 2022 [€/MWh]
c_{off_peak} – electricity price in the off-peak period [€/MWh]
c_{peak} – electricity price in peak period [€/MWh]
E_{ann_def} – annual energy deficit [kWh]
E_{ann_ex} – annual surplus energy from RES [kWh]
$E_{ann\_HG\_input}$ – volume of energy directed to hydrogen generators during the year [kWh]
E_{ann_sold} – volume of energy sold to the grid during the year [kWh]
f_{PV} – PV power loss factor [-]
$G_T(t)$ – solar irradiance at time t [W/m^2]
$G_{T,NOCT}$ – solar irradiance under NOCT conditions [W/m^2]
$G_{T,STC}$ – solar irradiance under STC conditions [W/m^2]
k – heat capacity ratio [-]
$L_{res,AC}$ – operating reserve [kW]
M_{H_2} – H_2 molar mass [kg/mol]
$\dot{m}_{FC\_nom}$ – nominal H_2 consumption by fuel cell [kg/kWh]
$\dot{m}_{FC}(t)$ – H_2 mass flow rate consumed by fuel cells at time t [kg/h]
$\dot{m}_{H_2\_comp}(t)$ – compressed hydrogen mass flow rate at time t [kg/s]
$\dot{m}_{H_2\_prod}(t)$ – produced H_2 mass flow rate at time t [kg/h]
$m_{stor}(t)$ – mass of hydrogen in tanks at time t [kg]
$m_{stor}(t-1)$ – mass of hydrogen in tanks at time t-1 [kg]
N_s – number of compressor stages [-]
n_{peak} – number of peak hours [-]
P_{avg_load} – average power demand of the industrial plant during the year [kW]
$P_{HG\_input}(t)$ – power delivered to hydrogen generator at time t [kW]
P_{HG_nom} – hydrogen generator nominal power [kW]
$P_L(t)$ – demand for the power at time t [kW]
$P_m(t)$ – power generated by wind turbine at time t [kW]

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$P_{PV}(t)$ – real PV module power at time t [W/module]
$P_{PV,STC}$ – unit power of a PV installation under STC conditions [W/module]
$P_{total}(t)$ – total power generated by RES at time t [kW]
$P_{WT}(t)$ – wind turbine output power at time t [kW]
$p_{avg}(t)$ – average computational compression pressure at time t [MPa]
$p_{comp}(t)$ – power required to compress hydrogen at time t [kW]
$p_{disc}(t)$ – discharge H_2 pressure at time t [MPa]
p_{suc} – suction H_2 pressure [MPa]
R – universal gas constant [J/(mol·K)]
$RL(t)$ – residual load at time t [kW]
r_{load} – operating reserve as a percentage of load at time t [%]
r_{peak_load} – operating reserve as a percentage of the annual peak load [%]
r_{PV} – operating reserve as a percentage of PV installation power at time t [%]
r_{WT} – operating reserve as a percentage of wind turbine power at time t [%]
$T_a(t)$ – ambient temperature at time t [°C]
$T_{a,NOCT}$ – ambient temperature under NOCT conditions [°C]
$T_{avg}(t)$ – average computational compression temperature at time t [K]
$T_c(t)$ – cell operating temperature at time t [°C]
$T_{c,NOCT}$ – PV module temperature under NOCT conditions [°C]
$T_{c,STC}$ – PV module temperature under STC conditions [°C]
$T_{disc}(t)$ – discharge hydrogen temperature at time t [K]
T_{suc} – suction hydrogen temperature [K]
$U_{data}(t)$ – wind speed at a given altitude above ground level at time t [m/s]
$U_{hub}(t)$ – wind speed at the height of the rotor hub at time t [m/s]
$\dot{V}_{HG\_nom}$ – H_2 nominal production [Nm^3/h]
$Z(t)$ – hydrogen compressibility coefficient at time t [-]
z_{data} – altitude above ground level for which the wind speed is known [m]
z_{hub} – height of rotor hub above ground level [m]
z_0 – terrain roughness coefficient [m]

Greek symbols:

α_P – temperature coefficient of the PV module [%/°C]
ζ_{AC_cab} – AC wiring losses [-]
ζ_{aux} – auxiliary power consumption efficiency [-]
$\zeta_{c\_v\_miss}$ – current-voltage mismatch losses [-]
ζ_{dac} – PV losses on diodes and connectors [-]
ζ_{DC_cab} – DC wiring losses [-]
ζ_{deg} – initial light-induced PV degradation [-]
ζ_{inv} – inverter losses [-]
ζ_{shad} – shading losses [-]
ζ_{soil} – soiling losses [-]
η_c – transformer efficiency [-]
η_{cab} – wiring efficiency [-]
η_{comp_en} – compressor motor efficiency [-]
η_{isen} – compressor isentropic efficiency [-]
$h_{PV,STC}$ – efficiency of the PV module under STC conditions [W]
$\rho_{H2_{p=1\,bar,\ t=25^\circ C}}$ – hydrogen density under normal conditions [kg/Nm^3]
$\tau\alpha$ – solar transmittance-absorption coefficient [-]

Abbreviations:

AC – Alternating Current
AE – Alkaline Electrolyser
BoL – Bill of Lading
CCGT – Combined Cycle Gas Turbine
CSO – Central Statistical Office
DC – Direct Current
DSO – Distribution System Operator
EC – European Commission
EGD – European Green Deal
EPP2040 – Energy Policy of Poland until 2040
EPS – Electric Power System
EU – European Union
FC – Fuel Cell
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
GT – Gas Turbine
IEC – International Electrotechnical Commission
IRES – Intermittent Renewable Energy Sources
ISO – International Organization for Standardization;
LCOS – Levelised Cost of Storage
NASA – National Aeronautics and Space Administration
NBP – National Bank of Poland
NOCT – Normal Operating Cell Temperature
NPC – Net Present Cost
OCGT – Open Cycle Gas Turbine
O&M – Operating and Maintenance
PEME – Proton Exchange Membrane Electrolyser
PEMFC – Proton Exchange Membrane Fuel Cell
PPS – Polish Power System
PV – Photovoltaic
PVGIS – Photovoltaic Geographical Information System
P2H2P – Power to Hydrogen to Power
RES – Renewable Energy Sources
SOEC – Solid Oxide Electrolyser Cell
STC – Standard Test Conditions
WT – Wind Turbine

Introduction

In recent years, the use of renewable energy sources (RES) has become more and more common. The stimulus for the development of RES is the willingness of many world economies to become independent from fossil fuels, and thus to create self-sufficient, low-emission electric power systems (EPS). In the community of countries belonging to the European Union (EU), the document that sets the direction for the development of the energy sector is the European Green Deal (EGD) [1]. In 2020, the European Commission (EC) also released a document entitled 'A Hydrogen Strategy for a Climate Neutral Europe' [2], which aims to indicate the path leading to the development of hydrogen energy in Europe.

The enormous potential of hydrogen is noticed in energy storage issues. Hydrogen can be produced in electrolytic generators, which play the role of systems absorbing excess power, both in separate off-grid systems powered by RES and in systems cooperating with the power grid. Hydrogen produced using RES, called green hydrogen, can be used in many sectors of the economy. Thanks to the use of fuel cells (FC), gas turbines (GT), or hydrogen internal combustion engines (HICE), it can be a secondary source of energy for the power system. This allows increasing the share of electricity from RES in the total energy mix, thus reducing the emission of CO_2 and other pollutants into the atmosphere. Reintroduction of energy stored in hydrogen into the grid can reduce the number of flexible generation sources powered by hydrocarbon fuels, such as open cycle gas turbines (OCGT) or combined cycle gas turbines (CCGT) systems, which are used to maintain the required quality parameters of electricity.

Due to the increasing penetration of intermittent renewable energy sources (IRES) in the generation structure of the Polish Power System (PPS), energy storage systems are adesirable investment. Furthermore, in the 'Energy Policy of Poland until 2040' (EPP2040), a further rapid increase in installed capacity in wind turbines (WT) and photovoltaics (PV) is forecast (from 7.1 GW in 2021 to 17.7 GW in 2040 and from 7.7 GW in 2021 to 16.1 GW in 2040, respectively). In this case, in many regions of Poland, parts of the grid may be saturated with unstable generation sources [3]. The instantaneous power supply may exceed demand. This means problems with the balance of active and reactive power flows, which may result in the rejection of applications for connection to the grid of other unstable RES sources. In the future, the possible scenario may be the obligatory pairing of RES installations with energy storage systems. This will allow for balancing the supply and demand curve, as well as maintaining the required quality parameters of electricity, thanks to the possibility of volume modulation and time translocation of energy consumed and delivered to the grid, depending on the current demand and generation.

Funding for energy storage and hydrogen technologies is already foreseen in many EU countriesand is expected to expand significantly in the near future. In Poland, in the RES micro-installation support programme for prosumers, in 2022 for the first time, it was possible to obtain funding for electricity and heat storage [4]. This is in line with the assumptions of EPP2040 and indicates the desire to increase the self-consumption of locally produced energy. This will allow operators to reduce the costs incurred for the expansion and modernisation of the transmission and distribution grid. Financial support can also be obtained through programmes dedicated to investments with higher capacities. Storage of the electricity produced by RES, depending on the adopted supply strategy, may also allow partial or complete independence from electricity prices. As it was not be possible to connect IRES to the grid without an energy storage, investment in such systems may bring measurable economic benefits.

In recent years, many publications have been published on the production and use of green hydrogen. Several works focus on presenting the potential of green hydrogen in the issue of electricity storage and describing technical aspects of the components of power-to-hydrogen-to-power (P2H2P) systems. Oliveira et al. [5] explain the concept of green hydrogen and focus on presenting the essence of hydrogen energy in the process of decarbonising the economy. Smolinka et al. [6] review the type of electrolyser, includingan alkaline electrolyser (AE), a proton exchange membrane electrolyser (PEME), and a high temperature solid oxide electrolyser cell (SOEC). Khan et al. [7] present the technical and economic aspects of hydrogen compression. Elberry et al. [8] discuss methods of compressed hydrogen storage. Stellen and Jörissen [9] illustrate the problem of converting hydrogen into electricity in fuel cells. Newborough and Cooley [10] discuss the issue of water consumption in the electrolysis process. The water consumption for typical PEME electrolysers connected to the water supply network is reported to be 0.51 t/MWh (17 kg/kgH_2).

Eriksson and Gray [11] review ways to integrate HRES systems based on hydrogen fuel cells. They emphasise the role of energy storage in modern energy systems, as well as the methods of integrating fuel cell systems with the power grid. Ammari et al. [12] provide an in-depth review of the current literature on hybrid energy systems. The study focusses on discussing the existing systems and methods of their modelling, control, and management. It also describes the available software supporting the modelling of hybrid systems, the applied optimisation methods and the main technical and economic strategies of system management. Kalinci et al. [13] present a technical and economic analysis of a dedicated off-grid hybrid system, consisting of a WTs, PVs, hydrogen generator, and FC, which is considered for supplying Bozcaada Island in Turkey. The system was optimised using the HOMER (Hybrid Optimization Model for Multiple Energy Resources) software for the lowest net present cost (NPC). The results obtained indicate that in the analysed region, the addition of an optimally dimensioned PV power plant to wind turbines will reduce the value of NPC and reduce the required volume of the hydrogen tank (HT).

The literature most often considers the independent operation ofan RES system with energy storage in an off-grid structure in areas where the transmission and distribution grid is poorly developed or not at all. The concept most frequently presented is the connection of IRES to energy storage in the form of batteries, P2H2P technology, or a combination of both of these systems [13,14–17]. However, it should be clearly emphasised that applications of systems with energy storage also have a chance of rapid development as installations cooperating with the power grid. There is a gap in this area and insufficient coverage of the cases of linking RES with grid-connected P2H2P systems that can ensure the self-sufficiency of the entity concerned in terms of electricity supply.

This paper is a first part of a technical and economic analysis of power supply for a model industrial facility located in Poland, which was performed by the authors. The target system consists of IRES cooperating with hydrogen energy storage based on electrolysers and fuel cells, integrated with the power grid, in Polish conditions. A multicriteria comparison of the selected variants with the energy storage was performed in relation to systems powered by IRES without storage systems and in relation to the direct supply of the plant from the power grid. In the face of the forecasts for the development of PPS and related challenges, an original approach to energy management was proposed for the variants with energy storage, based on the maximisation of self-consumption of self-produced electricity.

In each variant analysed, the size of devices included in the power supply system was optimised in terms of minimising the net present cost. Modelling and optimisation of the systems was performed in the HOMER programme dedicated to hybrid RES systems [18]. Complementary calculations related to the hydrogen compression problem were performed according to the authors' own algorithms, using the CoolProp thermodynamic factors library [19]. A new aspect of the analysis is also to take into account the financial expenditure on the purchase of a hydrogen compressor (HC), as well as energy expenditure and operating costs, which is skipped in the literature, e.g. [17, 20–23]. Cash flows take into account the revenue generated from the sale of temporary surplus electricity to the grid, in accordance with the adopted power supply strategy and the legal and economic conditions of the domestic energy market. The possibility of maximising revenues by selling energy at fixed prices (resulting from national RES auctions) was considered. Additional benefits of qualifying installations for HRES were taken into account. Moreover, the idea of using HRES in industry is considered in only a few publications [12, 24]. In addition to the technical aspects, detailed economic analysis with results and conclusions as well as environmental benefits of using a zero-emission energy storage system will be presented in the second part of the presented analysis.

Reference facility and selected variants of its power supply

The reference facility is an industrial plant connected to the power grid located near Gdansk (54.319N and 18.542E). The coastal areas are distinguished by one of the best wind conditions in Poland and at the same time they are characterised by high values of the average annual solar irradiance. The vicinity of the Tri-City agglomeration is well-urbanised, with a large number of medium-sized industrial plants. There is also a refinery of an oil company actively working to implement green hydrogen production technology in Poland. The authors believe that by selecting such a location, this analysis and the results obtained will be able to provide real value for potential investments planned in the region, which justifies the need to consider the topic presented in the paper. The proposed methodology may be helpful in choosing the optimal configuration and allows for scaling the installation power.

The maximum electrical load of the analysed industrial plant during the year is 2 MW.

Using data from the literature [25, 26], a normalised load diagram for industrial customers was adopted. It was created based on the analysis of electricity loads occurring in the power grids supplying industrial customers, so in general, it may be treated as a representative diagram. The diagram was scaled so that the maximum load during the year was 2 MW. It was assumed that on each working day of a given month the load curve looks the same, and on weekends the load consists of 80% of the working day load at any time. In addition, variability in load over the year was assumed, resulting from factors such as the need to use heating in winter or cooling and air conditioning in summer [26]. The annual variability of the model facility load is presented in Fig. 1.

In all variants analysed, the reference facility will be connected to the power grid. The reference variant in this study is the purchase from the distribution system operator (DSO) all the energy necessary for the plant to operate (variant 1). Variants 2 and 3 power the plant by WTs and a PVs, respectively. Variant 4 is a hybrid system consisting of WTs and a PVs. Variants 5 and 6 assume the autonomy of the power supply to the facility owing to the use of P2H2P systems. They include electrolytic HGs, high-pressure HTs, a multistage hydrogen compressor and FCs assemblies. Fig. 2 presents model diagrams of the considered configurations.

Due to the self-sufficient architecture of the microgrid connected to the power grid, the temporary surplus energy after filling the tanks with hydrogen can be sold to the grid, thus increasing the economic competitiveness of installations with hydrogen energy storage.

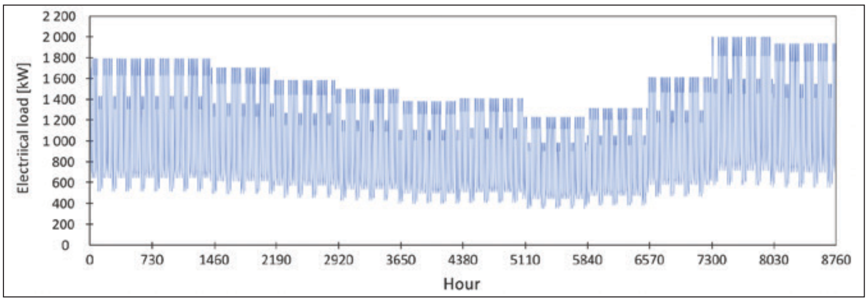

Fig. 1.
Annual variability of the load of the model facility
Rys. 1. Roczna zmienność obciążenia obiektu modelowego

The average annual power demand (P_{avg_load}) is 1.03 MW and the minimum demand is 356.8 kW. The energy consumed in each hour was determined as the product of instantaneous power and time, with steps of 1 hour. The total energy consumed by the plant during the year is 8,987 MWh. It was assumed that the plant in each year of the considered period will have the same load profile and will be characterised by the same energy consumption.

Six variants of the power supply to the reference facility, differing in the configuration of the generating sources, were selected for the research. In systems powered by RES, the basic energy sources are the fastest developingin Poland wind farms and photovoltaic power plants (the increase in installed capacity in 2021 compared to 2020 is 12.1% and 93.7%, respectively). Due to their complementary nature, they have been identified as the most promising technologies for enterprises who want to meet their own electricity needs [26]. An additional stimulus for the development of wind energy in Poland is the recent amendment to the RES act, which liberalises the legal and environmental conditions for connecting new onshore wind farms. Thus, the availability of land for the construction of wind turbines on land will increase significantly, which will positively affect to the attractiveness and profitability of this type of investment.

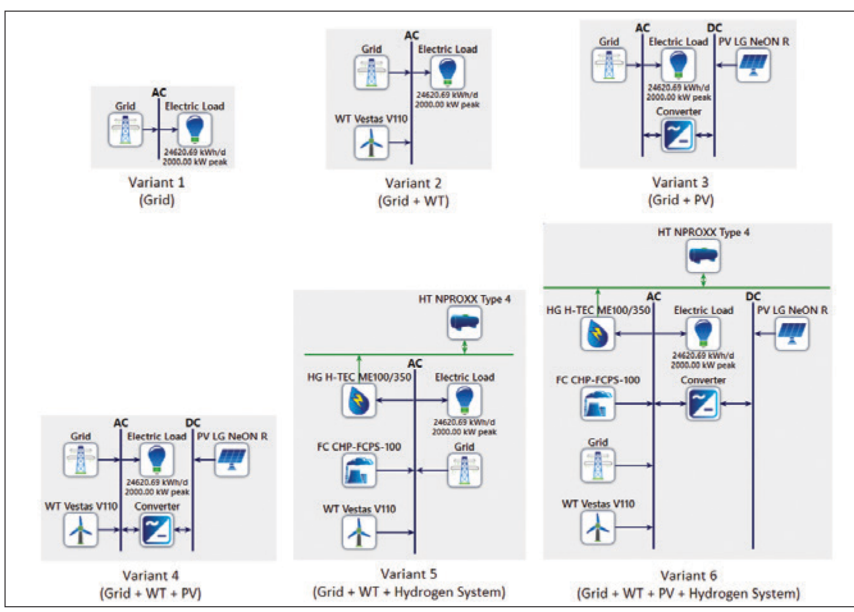

Fig. 2.
Model diagrams of the considered systems
Rys. 2. Schematy modelowe analizowanych układów

System modelling and optimisation

The modelling and optimisation of the system was carried out with the use of the HOMER software. It simulates different configurations of the system based on the calculation of the energy balance at each time step. The demand for power at any moment in time is compared with the current capabilities of the system, and the power can be delivered at the corresponding moment of time, taking into account the given constraints. The energy flows between the various elements of the system are calculated. Optimisation is carried out by simulating all possible configurations consisting of various elements of different sizes, rejecting unworkable systems, and prioritising the remaining configurations for the lowest net present cost for the duration of the project [18]. Weather conditions data for the selected location come from the NASA (National Aeronautics and Space Administration) database implemented in the HOMER programme. The values of selected parameters obtained from the database are presented with time steps every 1 hour. All key devices included in the modelled systems are real devices,and their technical data were obtained from manufacturers' catalogue cards. As in many publications [13, 14, 20, 27], it was assumed that the profitability of the investment will be considered in the perspective of 25 years, which results from the expected service life of the devices selected for analysis.

The modelling assumes that the facility will be connected to the medium-voltage grid. According to the local DSO guidelines, a two-zone tariff for industrial customers will be considered [28]. In Q1 and Q4, according to information provided by the local DSO, there are 7 peak hours, and in Q2 and Q3 there are 4 peak hours. To simplify the calculations, it has been assumed that an average of 5.5 peak hours per year occurs. The average energy price during the year

(c_{avg}), based on the DSO price list for 2022, was estimated using the formula:

$$c_{avg} = c_{peak} \cdot \frac{n_{peak}}{24} + c_{off\_peak} \cdot \frac{(24 - n_{peak})}{24} \quad (1)$$

where:

c_{peak} – electricity price in peak period [€/MWh],

c_{off_peak} – electricity price in the off-peak period [€/MWh],

n_{peak} – number of peak hours [-].

It was assumed that the inflation rate year on year will be constant and equal to the average rate for the years 2012-2021 reported by the Central Statistical Office (CSO) [29]. The value of the nominal interest rate was also assumed to be equal to the weighted average interest rates for the years 2012-2021, announced by the National Bank of Poland (NBP) [30]. All amounts in the paper are presented in euro currency, according to the average exchange rates for 2021 provided by the National Bank of Poland. The value of indicators and electricity prices for the base year are summarized in Table 1.

Table 1. Electricity prices in the base year and basic economic indicators
Tabela 1. *Ceny energii elektrycznej w roku bazowym i podstawowe wskaźniki ekonomiczne*

Parameter	Value
Average inflation rate	1.75% [29]
Average nominal interest rate	1.74% [30]
Average EUR/PLN exchange rate in 2021	4.5670 €/PLN [31]
Average EUR/USD exchange rate in 2021	3.8647 €/$ [31]
Project time	25 years
Peak energy price in the base year	350.12 €/MWh
Off-peak energy price in the base year	224.83 €/MWh
Average number of peak hours per year	5.5
Average price of energy	253.58 €/MWh

Wind turbine

The first considered method of supplying an industrial plant with RES is a wind turbine. The Vestas V110-2.0 MW turbine, installed on a 110 m high tower, was selected as a representative model. This system is dedicated to work in wind conditions specified in the IEC (International Electrotechnical Commission) IIIB class, which occur in the selected location (average annual wind speed at the hub height in the range from 6.0 to 7.5 m/s). The technical parameters of the turbine selected for consideration and the assumed efficiencies of the devices included in the power evacuation system are presented in Table 2. The efficiencies were assumed to be constant and do not depend on the value of generated power and weather conditions. The power characteristic as a function of wind speed obtained from the TheWindPower database [32] is presented in Fig. 3.

Table 2. Technical parameters of the Vestas V110-2.0 MW turbine and the assumed efficiencies [33, 34]
Tabela 2. *Parametry techniczne turbiny Vestas V110-2.0 MW i założone sprawności*

Parameter	Value
Rated power	2,000 kW
Cut-in wind speed	3 m/s
Cut-out wind speed	21 m/s
Re cut-in wind speed	18 m/s
Wind class	IEC IIIA / IEC IIIB
Standard operating temperature range	from -20 to 45°C
Rotor diameter	110 m
Generator type	4-pole (50Hz)
Tower height (for IEC IIIB)	**110 m** / 120 m / 125 m
Wiring efficiency	0.99
Transformer efficiency	0.99
Auxiliary power consumption efficiency	0.98

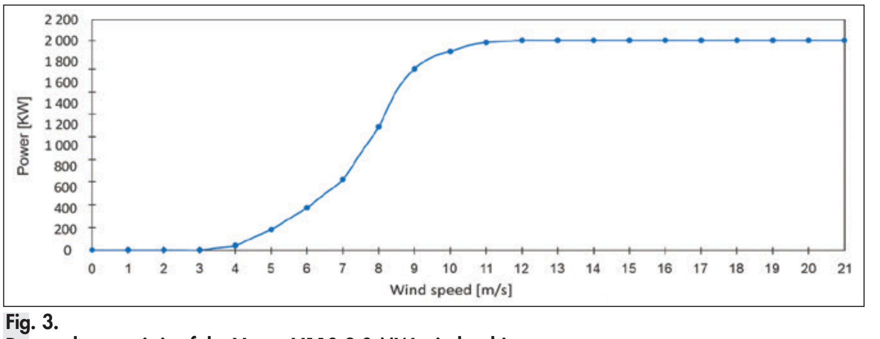

Fig. 3.
Power characteristic of the Vestas V110-2.0 MW wind turbine
Rys. 3. Charakterystyka mocy turbiny wiatrowej Vestas V110-2.0 MW

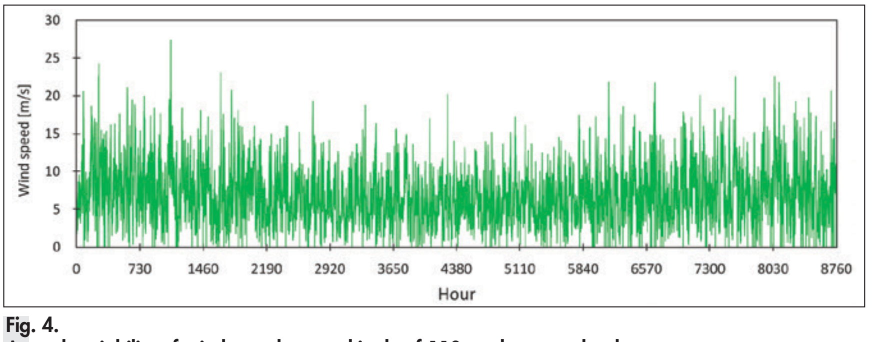

Fig. 4.
Annual variability of wind speed at an altitude of 110 m above sea level
Rys. 4. *Roczna zmienność prędkości wiatru na wysokości 110 m n.p.m.*

Wind speed values taken from the database are presented for a height of 50 m above ground level. Wind speed at the height of the rotor hub ($U_{hub}(t)$) was determined from the formula [18, 35]:

$$U_{hub}(t) = U_{data}(t) \cdot \frac{\ln\left(\frac{z_{hub}}{z_0}\right)}{\ln\left(\frac{z_{data}}{z_0}\right)} \quad (2)$$

where:

$U_{data}(t)$ – wind speed at a given altitude above ground level at time t [m/s],

z_{hub} – height of rotor hub above ground level [m],

z_0 – terrain roughness coefficient [m],

z_{data} – altitude above ground level for which the wind speed is known [m].

The terrain roughness coefficient is selected according to the table included in the literature [35]. The location considered is characterised by a roughness coefficient of 0.25 m. Changes in wind speed during the year at a height of 110 m above sea level are shown in Fig. 4.

The actual electric power supplied by the wind turbine ($P_{WT}(t)$) is reduced in relation to the power read from the characteristics of the turbine by the power losses resulting from the efficiency of the components of the power evacuation system and the auxiliary power consumption. It is described by the formula:

$$P_{WT}(t) = \eta_{cab} \cdot \eta_c \cdot \zeta_{aux} \cdot P_m(t) \quad (3)$$

where:

η_{cab} – wiring efficiency [-],

η_c – transformer efficiency [-],

ζ_{aux} – auxiliary power consumption efficiency [-],

$P_m(t)$ – power generated by wind turbine at time t [kW].

PV power plant

A photovoltaic power plant is the second main source of electricity from the RES group. The calculations of solar energy yield assumed the lack of a system tracking the Sun's

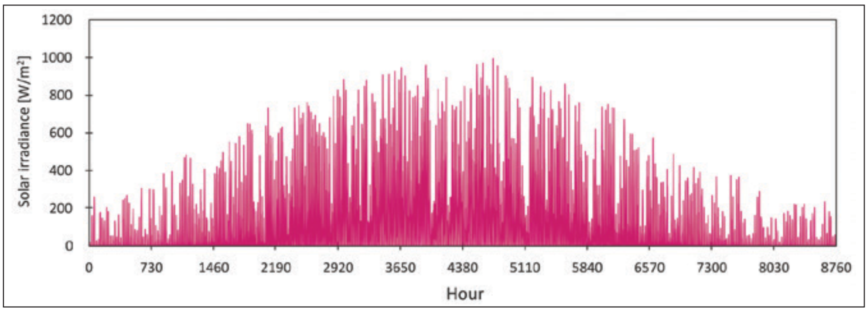

Fig. 5.
Annual variability of solar irradiance in the considered location
Rys. 5. ***Roczna zmienność natężenia promieniowania słonecznego w rozpatrywanej lokalizacji***

movement across the sky. The values proposed by the online tool PVGIS (Photovoltaic Geographical Information System) [36] for the geographical coordinates of the considered location were adopted as the optimal angle of inclination of the PV modules in relation to the horizontal and the most favourable azimuth. The suggested angle of inclination of the modules is 40° and the optimal azimuth is – 3°. The variability of the annual solar irradiance in this location is shown in Fig. 5.

Due to a detailed catalogue card, LG NeON R modules with a rated power of a single module equal to 380 W were used to carry out the calculations. Table 3 summarises the most important parameters of the modules, the adopted value of the transmittance-solar absorption coefficient and the assumed value of the coefficients taking into account power losses in real conditions, related, among others, to shading, soiling of the front surface of panels, and the transformation of direct current (DC) into alternating current (AC).

Table 3. Technical data of LG NeON R PV modules and assumed power loss factors [37–40]
Tabela 3. ***Dane techniczne modułów PV LG NeON R i przyjęte współczynniki strat mocy***

Parameter	Value
Operating temperature range	from -40 to 85°C
Power under STC conditions	380 W
Efficiency under STC conditions	22%
Temperature under NOCT conditions	44°C
Temperature coefficient of maximum power	-0.30%/°C
Solar transmittance-absorption coefficient	0.9
Initial light-induced degradation	0.99
DC wiring losses	0.98
Diodes and connections losses	0.995
Current-voltage mismatch	0.98
Inverter losses	0.96
AC wiring losses	0.95
Shading losses	1
Soiling losses	0.95

The total power loss factor (f_{PV}) is the product of the component factors:

$$f_{PV} = \zeta_{deg} \cdot \zeta_{DC\_cab} \cdot \zeta_{dac} \cdot \zeta_{c\_v\_miss} \cdot \zeta_{inv} \cdot \zeta_{AC\_cab} \cdot \zeta_{shad} \cdot \zeta_{soil} \quad (4)$$

where:
ζ_{deg} – initial light-induced PV degradation [-],
ζ_{DC_cab} – DC wiring losses [-],
ζ_{dac} – PV losses on diodes and connectors [-],
$\zeta_{c\_v\_miss}$ – current-voltage mismatch losses [-],
ζ_{inv} – inverter losses [-],
ζ_{AC_cab} – AC wiring losses [-],
ζ_{shad} – shading losses [-],
ζ_{soil} – soiling losses [-].

The above factor takes into account the inverter losses, so, although it is a separate system in the cost analysis, the inverter will not be modelled separately. Losses on the inverter, to simplify the calculations, were considered independent of the load. The cell operating temperature ($T_c(t)$) is described by the formula [18, 41]:

$$T_c(t) = \frac{T_a(t) + \left(T_{c,NOCT} - T_{a,NOCT}\right) \cdot \left(\frac{G_T(t)}{G_{T,NOCT}}\right) \cdot \left[1 - \frac{\frac{\eta_{PV,STC}}{100} \cdot \left(1 - \frac{\alpha_p}{100} \cdot T_{c,STC}\right)}{\tau\alpha}\right]}{1 + \left(T_{c,NOCT} - T_{a,NOCT}\right) \cdot \left(\frac{G_T(t)}{G_{T,NOCT}}\right) \cdot \left(\frac{\frac{\alpha_p}{100} \cdot \frac{\eta_{PV,STC}}{100}}{\tau\alpha}\right)} \quad (5)$$

where:
$T_a(t)$ – ambient temperature at time t [°C],
$T_{c,NOCT}$ – PV module temperature under NOCT conditions [°C],
$T_{a,NOCT}$ – ambient temperature under NOCT conditions [°C],
$G_T(t)$ – solar irradiance at time t [W/m^2],
$G_{T,NOCT}$ – solar irradiance under NOCT conditions [W/m^2],
$\eta_{PV,STC}$ – efficiency of the PV module under STC conditions [W],
α_P – temperature coefficient of PV module [%/°C],
$T_{c,STC}$ – PV module temperature under STC conditions [°C],
$\tau\alpha$ – solar transmittance-absorption coefficient [-].

The real power of the module ($P_{PV}(t)$) is determined from the formula [18, 41]:

$$P_{PV}(t) = P_{PV,STC} \cdot f_{PV} \cdot \frac{G_T(t)}{G_{T,STC}} \cdot \left[1 + \frac{\alpha_p}{100} \cdot \left(T_c(t) - T_{c,STC}\right)\right] \quad (6)$$

where:
$P_{PV,STC}$ – unit power of a PV installation under STC conditions [W/module],
$G_{T,STC}$ – solar irradiance under STC conditions [W/m^2].

Power surpluses and shortages

The value of temporary power surpluses and shortages is one of the key parameters when selecting the size of the installation. The total power generated by RES in each hour ($P_{total}(t)$) is the sum of the power of the components devices:

$$P_{total}(t) = P_{PV}(t) + P_{WT}(t) \quad (7)$$

In order to express the difference between the total temporary generation from RES and the temporary power demand, the concept of residual load ($RL(t)$), is introduced and defined in this case, to maintain a convenient sign convention, as the difference between total generation and the demand [42].

$$RL(t) = P_{total}(t) - P_L(t) \quad (8)$$

where:
$P_L(t)$ – demand for the power at time t [kW].

The excess capacity of the RES sources in each hour is expressed as a positive residual load. Power shortages occur when the residual load is negative. The energy surplus or shortage in a given hour is characterised by the product of the residual load in each hour and the time step (1 hour). The annual value of the energy surplus from RES (E_{ann_ex}) is described by the formula:

$$E_{ann\_ex} = \sum_{t=1}^{t=8760} RL(t) \cdot 1h, \; if \; RL(t) > 0 \quad (9)$$

The annual energy deficit (E_{ann_def}) is determined by the formula:

$$E_{ann\_def} = \left| \sum_{t=1}^{t=8760} RL(t) \cdot 1h \right|, \; if \; RL(t) < 0 \quad (10)$$

In the case of systems with energy storage, due to the limited range of input power of hydrogen generators, which results from the adopted strategy of powering the facility and the results of optimisation for a given target, part of the surplus energy (E_{ann_sold}) will not be able to be directed to the electrolysis process.

The study assumes that this energy will be sold to the grid. Its value is defined as:

$$E_{ann\_sold} = E_{ann\_ex} - E_{ann\_HG\_input} \quad (11)$$

where:

$E_{ann\_HG\_input}$ – volume of energy directed to hydrogen generators during the year [kWh].

In the case of RES-powered variants without energy storage, all surplus energy will be sold to the grid.

Power supply strategy

There are many power supply strategies that differ according to the objective function. For grid-connected RES systems with energy storage, the literature sometimes uses an approach aimed at minimising the averaged electricity price or the levelised cost of (energy) storage (LCOS). When considering systems in which the sale and purchase price of electricity changes dynamically with a certain time step, the selection of an appropriate strategy and control logic is one of the key optimisation elements [43]. In such systems, the power flow management unit should use the available degrees of freedom, taking into account many input factors, such as available storage capacity, current electricity purchase and sale prices and the dynamics of their changes, or forecasts of power demand [44]. Due to the adopted stability of the sale and purchase prices of electricity during the year, resulting from the RES auction system, the presented paper assumes the operating architecture of the system, in which the energy produced by the RES sources in priority is responsible for covering the current demand of the plant. In line with the idea of maximising self-consumption of self-produced energy, in the variants with the hydrogen system, it was assumed that the excess power was first taken over by the hydrogen generators in order to fill the hydrogen tanks. Electricity is sold to the grid only in periods when there is excess capacity and the hydrogen tanks are full. HOMER adopts a corresponding shipping fuelling strategy, called 'Load Following'. Appropriate constraints have also been set, which it is possible to provide the required operational reserve for an AC load. The operating reserve ($L_{res,AC}$) is the excess working capacity that enables an immediate response to a sudden increase in the load or a decrease in production of energy from RES. It was determined from the formula [18]:

$$L_{res,AC} = r_{load} \cdot P_L(t) + r_{peak\_load} \cdot P_{L\_MAX} + r_{WT} \cdot P_{WT}(t) + \zeta_{inv} \cdot r_{PV} \cdot P_{PV}(t) \quad (12)$$

where:

r_{load} – operating reserve as a percentage of the load at time t [%],

r_{peak_load} – operating reserve as a percentage of the annual peak load [%],

P_{L_MAX} – the highest power demand during the year [kW],

r_{WT} – operating reserve as a percentage of wind turbine power at time t [%],

r_{PV} – operating reserve as a percentage of the PV installation power at time t [%].

Table 4 shows the adopted values of the operating reserve factors, which are the default values proposed by the HOMER programme.

Table 4. Percentage values of the operating reserve factors
Tabela 4. *Procentowe wartości współczynników rezerwy operacyjnej*

Parameter	Value
r_{load}	10%
r_{peak_load}	20%
r_{WT}	25%
r_{PV}	60%

Due to the limitations of the HOMER programme, in order to model the adopted operating structure, the energy sales price was set at 0 €, and the energy sales revenue was calculated according to the authors' own algorithm.

Hydrogen generator

In order to calculate the hydrogen production potential, a system consisting of hydrogen generators based on PEME electrolysers was adopted for analysis. H-TEC PEM Electrolyser ME100/350 generators with a nominal electrical power of 225 kW were selected. Table 5 presents the technical data forsuch a generator.

Table 5. Technical data of the H-TEC PEM ME100/350 Electrolyser [45]
Tabela 5. *Dane techniczne elektrolizera H-TEC PEM ME100/350*

Parameter	Value
H_2 Nominal production	46.3 Nm^3/h
H_2 Minimum production	15 Nm^3/h
Energy consumption nominal (related to Higher Heating Value)	4.9 kWh/Nm^3H_2
Load change time (min. load to max. load)	30 s
H_2 Production modulation range	from 32 to 100%
System efficiency	73%
Electrical power nominal	225 kW
H_2Purity	5.0 (meets ISO 14687:2019)
H_2 Output pressure	from 15 to 30 bar
O_2 Output pressure	unpressurized
H_2O Consumption nominal	60 kg/h (at 10°dH)
Ambient temperature	from-20 to 40°C

For modelling purposes, it was assumed that the generator operates in the power range from 0 to 100%. The HOMER defines the relative value of the minimum load as the minimum load related to the total power of a set of devices. Due to the number of electrolysers capable of independent operation, the adoption of the full range of power modulation has little effect on the results and allows to solve the problem of relating the minimum allowable load to the total power of the system. Moreover, the programme assumes that the mass flow rate of the hydrogen produced depends linearly on the power supplied to the hydrogen generator. The mass flow rate of produced hydrogen ($\dot{m}_{H_2\_prod}(t)$) can be described by the function:

$$\dot{m}_{H2\_prod}(t) = \frac{\dot{V}_{HG\_nom} \cdot \rho_{H2\,{p=1\,bar \atop t=25°C}}}{P_{HG\_nom}} \cdot P_{HG\_input}(t) \quad (13)$$

where:

$\dot{V}_{HG\_nom}$ – H_2 nominal production [Nm^3/h],

$\rho_{H2_{p=1\,bar \atop t=25°C}}$ – hydrogen density under normal conditions [kg/Nm^3],

P_{HG_nom} – hydrogen generator nominal power [kW],

$P_{HG\_input}(t)$ – power delivered to hydrogen generator at time t [kW].

Fuel cells

The study assumes that in the variants with the P2H2P system, power shortages resulting from too low RES temporary generation will be covered with the Nedstack PemGen CHP-FCPS-100 fuel cells with a capacity of 100 kW. The system consists of 12 Nedstack FCS 13-XXL stacks. They are proton exchange membrane fuel cell (PEMFC) type cells with high capacity to work under variable load. The selected parameters of the FCs are presented in Table 6.

Table 6. Technical data of the NedstackPemGen CHP-FCPS-100 FC [46]
Tabela 6. *Dane techniczne zestawu ogniw paliwowych Nedstack PemGen CHP-FCPS-100 FC*

Parameter	Value
Nominal power of single unit	100 kW
Peak power (BoL)	125 kW
Number of stacks	12
Nominal H_2 consumption (BoL)	0.059 kg/kWh
Electrical efficiency	43%
Supply pressure	from 0.3 to 4 bar
Ambient temperature	from -5 to 40 °C
Lifetime	from 24,000 to 30,000 h
Required hydrogen quality	≥ 2.5 (CO < 0.2 ppm)

It was assumed that due to the modular structure of the FC assemblies, they are able to operate in the full range of output power (from 0 to 100 kW), with the possibility of short-term overload up to 125 kW. As the manufacturer does not provide the characteristics of hydrogen consumption in relation to the power unit for selected operating points, it was assumed that it is constant and equal to the nominal consumption. The mass flow rate of hydrogen consumed ($\dot{m}_{FC}(t)$) is calculated as:

$$\dot{m}_{FC}(t) = \dot{m}_{FC\_nom} \cdot |RL(t)|, \ if \ RL(t) < 0 \quad (14)$$

It should also be noted that the increased operating temperature of PEMFC fuel cells (50-80°C) allows considering the possibility of effective use of low-temperature waste heat, which can be used, for example, in technological processes or for heating purposes, thus increasing the overall efficiency of the installation.

Hydrogen tanks

The produced hydrogen was assumed to be stored in thick-walled pressure tanks. For the calculations, NPROXX tanks were selected, which can store 1,000 kg of hydrogen at a pressure of 50 MPa [47]. The mass of hydrogen in the tanks ($m_{stor}(t)$) will be the result of the balance of hydrogen supplied by the generators and the hydrogen used by the fuel cells:

$$m_{stor}(t) = m_{stor}(t-1) + [\dot{m}_{H_2\_prod}(t) - \dot{m}_{FC}(t)] \cdot 1h \quad (15)$$

where:

$m_{stor}(t-1)$ – mass of hydrogen in tanks at time t-1 [kg].

The HOMER does not assume hydrogen losses during the storage period. For the purposes of the calculations, it was assumed that at the time of commissioning the installation, the tanks were filled with hydrogen 10% of their total gravimetric capacity. Such an assumption allows to reduce the need to oversize some elements of the system in order to create a buffer of stored energy, before the first period of unloading the tanks.

Hydrogen compressor

By compressing the hydrogen to high pressures, it is possible to reduce the number of tanks required to store the hydrogen, thus saving space and reducing the investment costs associated with purchasing the tanks. According to the ranges of typical compression ratio values given in the literature [7], for the purposes of the analysis, it was assumed that the hydrogen would be compressed in a 3-stage reciprocating compressor in front of which there is a heat exchanger. It was assumed that it allowed the hydrogen to cool leaving the generator to a temperature of 25°C. The hydrogen output pressure from the generator was assumed to be equal to the maximum pressure that could be obtained in the generator as a result of electrochemical compression. The tanks up to a pressure of 3 MPa will therefore be filled without the need for mechanical compression. Storing hydrogen in them under higher pressure will require compressor operation. The tanks were assumed to be connected in parallel. The total capacity of the tank system is the result of the individual optimisation of each variant in the HOMER. The characteristics of the variability of hydrogen density as a function of pressure available in the literature at an assumed temperature of 25°C allow one to determine the pressure in the tank system (identical to the compressor discharge pressure), depending on the mass of the accumulated hydrogen. This enables the determination of the hydrogen compressibility coefficient (Z) for the thermal conditions at time t. For this purpose, the CoolProp tool was used, which includes a library of hydrogen properties. The hydrogen compressibility coefficient is related to the mean suction and discharge pressures and temperatures. The average values of temperature ($T_{avg}(t)$) and pressure ($p_{avg}(t)$) were calculated from the formulas [7]:

$$T_{avg}(t) = \frac{T_{suc} + T_{disc}(t)}{2} \quad (16)$$

$$p_{avg}(t) = \frac{2}{3} \cdot \left(\frac{p^3_{disc}(t) - p^3_{suc}}{p^2_{disc}(t) - p^2_{suc}} \right) \quad (17)$$

where:

$T_{disc}(t)$ – discharge hydrogen temperature at time t [K].

The power required to compress hydrogen ($p_{comp}(t)$) for the adopted assumptions was calculated as [7]:

$$P_{COMP}(t) = \frac{N_s \cdot \left(\frac{k}{k-1}\right) \cdot \left(\frac{Z(t)}{\eta_{isen}}\right) \cdot T_{suc} \cdot \frac{\dot{m}_{H_2\_comp}(t)}{M_{H_2}} \cdot}{\eta_{comp\_en}} \frac{\cdot R \cdot \left[\left(\frac{p_{disc}(t)}{p_{suc}} \right)^{\left(\frac{k-1}{N_s \cdot k}\right)} - 1 \right]}{} \quad (18)$$

where:

- N_s – number of compressor stages [-],
- k – heat capacity ratio [-],
- $Z(t)$ – hydrogen compressibility coefficient at time t [-],
- η_{isen} – compressor isentropic efficiency [-],
- T_{suc} – suction hydrogen temperature [K],
- $\dot{m}_{H_2\_comp}(t)$ – compressed hydrogen mass flow rate at time t [kg/s],
- M_{H_2} – H_2 molar mass [kg/mol],
- R – universal gas constant [J/(mol·K)],
- $p_{disc}(t)$ – discharge H_2 pressure at time t [MPa],
- p_{suc} – suction H_2 pressure [MPa],
- η_{comp_en} – compressor motor efficiency [-].

Table 7 summarises the values of the parameters adopted for calculating the power consumed by the compressor. It was assumed that the compressor would be powered from the power grid and its annual energy consumption would be included in the costs of operation and maintenance (O&M).

Table 7. Parameter values adopted for calculating the power consumed by the compressor [7, 48]
Tabela 7. Wartości parametrów przyjęte do obliczenia mocy pobieranej przez sprężarkę

Parameter	Value
Number of compressor stages	3
Compression ratio for single stage	2.554
Suction pressure	3 MPa
Isentropic efficiency	65%
Heat capacity ratio	1.4
Suction temperature	298.15 K
H_2 Molar mass	0.002 kg/mol
Universal gas constant	8.314 J/(mol·kg)
Compressor motor efficiency	95%

Summary

In the near future, a significant change in the generation structure in the national power system is expected. European Union regulations created against the background of the idea of sustainable development lead to an increase in the share of unstable renewable energy sources in the total installed capacity. Energy storage systems in the form of hydrogen, working with RES as part of hybrid systems connected to the grid, can effectively support the balancing of the power system, while increasing the level of self-consumption of self-produced electricity. A very important element in the case of hybrid systems is the appropriate selection of devices to maximise energy, economic and environmental benefits. In this publication, which constitutes the first part of the analysis, attention was focused on the technical aspects of modelling a grid-connected hybrid renewable energy system with hydrogen energy storage, intended for cooperation with an industrial facility with an average annual power demand of 1,030 kW. The adopted criterion for optimising the system was to maximise the self-consumption of electricity. Two variants equipped with an installation for the conversion of electricity into hydrogen, a hydrogen storage tank, and a reconversion system based on PEMFC fuel cells were compared with variants based on RES without an energy storage system, and also with a reference variant in which all energy is purchased from the local DSO. Mathematical models of installation elements and the method of determining temporary power surpluses and shortages were presented. The second part of the work will present in detail the results of the economic analysis in relation to Polish conditions. The results obtained on the basis of optimisation will be presented along with a discussion of the results and an analysis of the sensitivity of the systems to changes in selected input values. The environmental benefits that can be achieved by using each system will also be presented.

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