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A practical approach to optimal strategies of electricity contracting from Hybrid Power Sources

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Abstract. Hybrid Power Sources/Systems (HPS) are generally treated as local prosumer supplies. The paper presents a new approach to the strategy of electricity contracting from HPS, considering hybrid systems as a new type of quasi-centrally dispatched power units operating in Polish market conditions. The possibilities of contracting electricity from HPS, consisting of three electricity generation technologies: biogas plant, wind power plant and solar power plant, are presented. The opportunity to obtain additional income from the electricity trading on the balancing market was used. Proposals for a new mathematical description of HPS topology were also presented, including a feasibility function, which can be used for technical and economic analyses. The obtained results can be used as a direction of development in the field of optimization of hybrid source operation in cooperation with the power grid. Based on the conducted analyses, it can be observed that electricity sales contracts concluded for each hour of the day may bring additional profit for the investor. However, the strong dependence of the proposed strategy on the situation on the balancing market or other local electricity markets similar in their operations should be emphasized.

Key words: hybrid power sources, renewable energy sources, distributed generation, electricity market, contracting electricity.

1. Introduction

1.1. State of the art. Nowadays, the power sector is undergoing changes resulting from the development of distributed generation technology (DG) [1]. In particular, photovoltaic (PV) power plants are becoming increasingly popular. It should be noted, however, that the availability of such plants depends on the solar conditions prevailing in each region. In the case of central Europe, the coefficient of utilization of the capacity installed in PV installations is about 10% [2].

Therefore, work has begun on improving the availability of such plants. Currently, one of the most popular solutions is establishing Hybrid Power Sources/Systems (HPS) [3, 4]. Such units are characterized by a combination of at least two power generation technologies, in which electricity is generated jointly and then transmitted to the power system. This is a key statement allowing us to distinguish a hybrid system/source from a Virtual Power Plant (VPP), which aggregates generation sources dispersed in the distribution network [5–7]. Due to this fact, during the process of designing HPS, firstly it is necessary to examine the possibility of making a technical combination of several electricity generation technologies with each other. In previous research [8, 9] several combinations of generation technologies have been proposed. However, technological progress in the RES area has facilitated the development of new HPS solutions, which have not been exploited so far. In the current literature, many of them concern the feasibility of hybrid hydroelectric and solar power plants [10–14]. The main problems presented in previous studies concern the long-term and short-term interaction of unstable generation sources with each other, with an emphasis on ensuring an optimal level of generation capacity [11, 15, 16]. Extensive research has also been done in hybrid systems consisting of wind and solar power plant [17–21]. Regardless of the applied electricity generation technologies, one of the key aspects of establishing HPS is an attempt to optimize the electricity generation process to maximize its efficiency [22]. HPS solutions can be modified by enriching them with energy storage. The studies conducted so far indicate the possibility of using pumped-storage power plants or Battery Energy Storage Systems (BESS) as one of the elements of the hybrid source/system [1, 23].

Diversification of sources within HPS also has a positive economic aspect [24]. The advantage of having HPS is the possibility to generate additional profit for power suppliers by adjusting the contracting profile of electricity sales to the generation from unstable sources and conditions prevailing on the electricity market. There are many strategies for selling electricity to the grid. It can take place based on a bilateral contract between the producer and the consumer (trading company, final consumer). When concluding such a contract, all electricity can be sold to the grid in accordance with the generation profile. Another way is to sell electricity through a power exchange.

Another strategy relates to the diversification of the income stream from the sale of electricity. For this purpose, the part of the electricity market responsible for balancing consumers and generators – the Balancing Market – can be used. The article refers to the Polish power (electricity) market mechanism. The Polish electricity market consists of three main segments: active power market, technical market, and financial market. The division of roles results from the specification of each of these markets, but they are complementary. On the active power mar-

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ket, active power is traded according to parameters such as volume, price, time, place of supply. Electricity can be contracted via several methods such as bilateral contracts, power exchange and balancing offers. The technical part (balancing market) of the electricity market determines the physical amount of electricity in the power system subject to settlements. Ancillary services and system constraints are also considered to ensure the security of electricity supply.

On the financial market, however, contracts are settled without considering the physical place of electricity supply.

Actions intended to balance electricity in the National Power System are taken by the Transmission System Operator (TSO) – Polskie Sieci Elektroenergetyczne. Therefore, the TSO is responsible for the adjustment of generation in power plants to maintain the balance between demand and generation, as well as for the execution of settlements, which are necessary for the settlement of bilateral and exchange contracts. All these actions are conducted within the balancing market. Therefore, it can be observed that the Polish balancing market is a technical market because the main objective is to balance demand and generation and using it to generate additional revenues is an unnecessary, and even undesirable activity.

The basic rules of participation and execution of the Balancing Market are specified in the Instruction of the Transmission Network Code [25, 26].

1.2. Novelty. The article addresses the issue of contracting electricity by a supplier with HPS. Two different approaches to the contracting of electricity purchase are analyzed. The aim of this article is to present an approach that is designed to improve the economic efficiency of HPS by considering two electricity income streams typical for the countries with active balancing markets. The most important contributions are as follows:

1. Proposing a description of HPS using set theory and defining the HPS feasibility function on a set of generation technologies. The proposed mathematical model can be used in technical-economic analyses and optimization of various topologies of HPS. Most studies [7, 11, 12, 15] omit the verification step concerning the feasibility of combining several power generation technologies into one HPS. In most cases, sources are combined based on the location criteria and therefore technical-economic aspects are not included. In publications [11, 15], the source in HPS is a hydroelectric power plant and a photovoltaic farm, located 50 km away from each other and connected by a 330 kV transmission line. According to the authors, in the case of such HPS solutions one can only refer to a virtual power plant. The principle of HPS should be power generation in installations that operate on a joint busbar and are in close range, like in [21].
2. New approach to the use of HPS as a quasi-centrally dispatched power unit in the day-to-day planning of the power system operation. Generally, according to the Transmission Network Code [26], a centrally dispatched unit is called a generating unit that is connected to the transmission network and has an installed capacity of at least 50 MW. The authors believe that the forthcoming changes in the power sector may cause a fundamental change in the optics of the electricity markets, which is noticeable in the scientific community. For instance, in previous studies [27, 28] hybrid systems were treated as an integral part of the microgrid. Therefore, production was adapted to the local demand for power and energy. The authors suggest that HPS generation should be adjusted to the conditions prevailing on the national electricity market and not to the demand of local consumers. The necessity to decarbonize the energy sector relates to the process of creating commercial power plants based on RES. However, such sources are usually not controllable (weather-dependent), so to achieve the desired availability, they should be combined into HPS solutions using controlled (dispatchable) sources or energy storage [28]. Nevertheless, such a concept of use requires fundamental changes on electricity markets (not only Polish). In this article, the authors have tried to indicate a potential situation on the electricity market, when distributed generation units with less capacity than that currently required for a centrally dispatched unit will take part in the system balancing process. This would mean that the legal acts currently in force would have to be amended and adjusted to the given conditions. The idea of presenting hybrid units as quasi-centrally dispatched power unit is to open a discussion on the future use of such units on electricity markets like the Polish model.
3. Developing a dynamic contract profile for electricity sales on the power exchange and balancing markets for power producers with HPS should be established to generate additional income (second income stream).

The literature about contracting electricity produced in HPS is limited. In particular, the balancing market, which has generally a technical character, is not considered in the strategies for contracting electricity. The authors attempted to use this instrument as an element of a regular power exchange trading system. In other studies, income comes only from Day Ahead Market or Real-Time Market on Power Exchanges [29].

2. Hybrid Power Sources/Systems topologies

The topology of Hybrid Power Sources depends on the technology used in each case and the nature of their operation. One of the possibilities is to cover the power and energy demand of local consumers [30, 31]. In that case, the installed capacity of such a hybrid system should ensure uninterruptible electricity supply, i.e. the installation should be adequately oversized. HPS in this case is connected to the local power grid and its generation capacity is used for the purposes of end users.

A general scheme of the system consisting of three generation technologies together with the power output track is shown in Fig. 1a. Another possibility is to use the hybrid source as an integral part of the DC or AC/DC microgrid [32]. In this case, a 50 Hz (AC) or DC power supply can be used. As a result, a higher ability to control the system operation and optimize the point of operation of unstable sources is gained, both in the DC circuit (through power electronic converters with implemented

MPPT algorithm) and AC (through the input parameters, i.e. active and reactive power) [33]. DC systems are also naturally adapted to work with battery energy storage systems, which allow the accumulation of surplus electricity production and provide stable parameters of DC voltage.

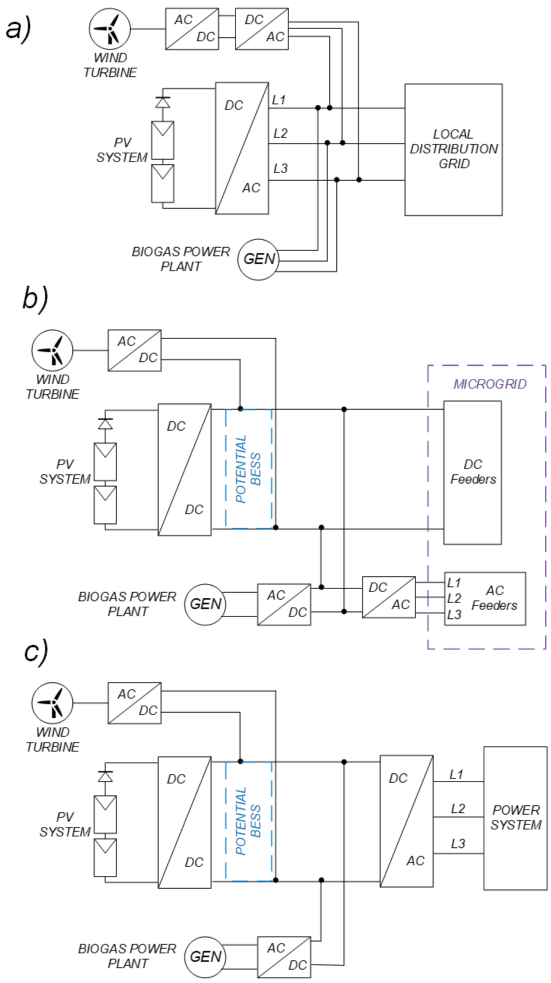

Fig. 1. Topologies of Hybrid Power Sources: a) connected to AC grid for purposes to supply local consumers; b) connected to DC or AC microgrid; c) connected as centrally dispatched generation unit

A general diagram of HPS consisting of three generation technologies is shown in Fig. 1b. It should be highlighted, however, that HPS presented in Fig. 1b can be modified in such a way as to make it a separate generating unit. With the scale effect, it can be concluded that this is an analogous topology to that of centrally dispatched power units consisting of several generators.

Figure 1c shows the modification of the system depicted in Fig. 1b. For further analysis, HPS from Fig. 1c was used.

3. Methodology of research

Let H define the set of technologies of distributed energy sources that can be used in hybrid power systems. Let h determine the i-th of the available technologies while $h_i \in H$. As not all technologies in the H set can be used simultaneously in HPS, the feasibility function of FES_2 $(h_i,\, h_j)$ combining two sources in h_i and h_j technologies, such that $h_i \neq h_j$, in a single generation unit is defined. By a single Generation Unit (GU), the authors refer to a generation unit that has a joint output for all generation technologies and a unified control and monitoring system. The value of the feasibility function depends on the technical capability and economic viability of combining given generation technologies in a single generation source [34]. It is determined based on currently available knowledge in energy sources integration. The FES_2 function is expressed by formula (1):

$$FES_2(h_i, h_j) = \begin{cases} 1, & \text{if } h_i \text{ and } h_j \text{ can create } HPS, \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

HPS consisting of two generation technologies HPS_2 is defined as a set of $\{h_i,\, h_j\}$ technologies such that:

$$HPS_2 = \{h_i,\, h_j\}, \\ \begin{cases} h_i,\, h_j \in H, \\ h_i \neq h_j, \\ FES_2(h_i,\, h_j) = 1, \end{cases} \tag{2}$$

It is therefore possible to define a hybrid power source consisting of n electricity generation technologies HPS_n as the sum of the sets $HPS_{n-1} \cup \{h_m\}$, whereby:

$$HPS_n = HPS_{n-1} \cup \{h_m\}, \\ \begin{cases} n = card\ HPS_n, \\ n > 2, \\ h_i,\, h_j, \ldots,\, h_l,\, h_m \in H, \\ h_i,\, h_j, \ldots,\, h_l \in HPS_{n-1}, \\ h_i \neq h_j \neq \ldots \neq h_l \neq h_m, \\ FES_n(HPS_{n-1},\, h_m) = 1, \end{cases} \tag{3}$$

where: $FES_n(HPS_{n-1},\, h_m)$ means the function of being able to add to a HPS_{n-1}, consisting of $n-1$ generation technologies, an additional generation source made in h_m technology. Therefore, the feasibility function of the hybrid source HPS_n is shown by formula (4):

$$FES_n(HPS_{n-1},\, h_m) = \\ = \begin{cases} 1, & \text{if } HPS_{n-1} \text{ and } h_m \text{ can create } HPS, \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

Examples of feasibility function FES values for selected generation source technologies are listed in Table 1. These values are based on examples from literature and commercial applications [9, 10, 12, 34].

Let T be the period of operation of Hybrid Power Source HPS_n. Let us denote by $P_{h_i,\,t}$ the power generated at time $t \in T$

Table 1
Values of feasibility function for selected generation source technologies

Technology $h_i \backslash h_j$	PV Systems	Wind turbine	Biogas microturbine	Biomass Stirling machine	Natural Gas microturbine	Hydropower plant	MCFC	BESS
PV Systems		1	1	1	1	1	0	1
Wind turbine	1		1	0	1	1	0	1
Biogas microturbine	1	1		0	0	0	1	1
Biomass Stirling machine	1	0	0		1	0	1	0
Natural Gas microturbine	1	1	0	1		0	1	1
Hydropower plant	1	1	0	0	0		0	0
MCFC	0	0	1	1	1	0		1
BESS	1	1	1	0	1	0	1	

in the generation unit, made in h_i technology ($h_i \in HPS_n$). The power generated by HPS_n at t can be determined from the Eq. (5):

$$P_{HPS_n,\,t} = \sum_{i=1}^{n} P_{h_i,\,t}\,. \tag{5}$$

The electricity generated by HPS_n can be determined from the formula (6):

$$E_{HPS_n} = \int_{t=0}^{T} P_{HPS_n,\,t}\,\mathrm{d}t\,. \tag{6}$$

For further analyses, the hourly generated electricity E_τ is used. It is determined for the following hours $\tau \in \overline{1,\,24}$ for one day. The reason for that assumption is the nature of the Polish electricity market, within the balancing segment. The value of hourly generated electricity E_τ is calculated according to formula (7):

$$E_\tau = P_{1\,\mathrm{h},\tau} \cdot 1\,\mathrm{h}, \tag{7}$$

where: $P_{1\,\mathrm{h},\tau}$ is hourly average power generated by HPS_n.

Due to the tight correlation between the amount of electricity generated in HPS_n, consisting of renewable sources, and the time of year and weather, $4 \times d$ days per d for each season were selected for the study.

The main objective of a power supplier is to achieve maximum income from its sale. If it can influence the profile of the contracted electricity, the following objective function can be formulated for the optimization problem:

$$\max\ CI_D(E_{CO,\tau}) = \sum_{\tau=1}^{24} CI_\tau\,, \tag{8}$$

where: $E_{CO,\,\tau}$ – hourly profile of the electricity contract on power-exchange in hour τ; CI_D – daily total income from the sale of electricity on the contract and balancing markets; CI_τ – total income from the sale of electricity on the contract and balancing markets at τ.

Considering the variability of weather conditions and the associated constraints on the availability of renewable sources, it seems appropriate to generate electricity in hybrid plants. The use of different generation technologies and energy storage systems allows us to eliminate the random character of the volume of electricity production in renewable sources and to stabilize the profile of generated power. It should also be mentioned that according to Polish regulations, electricity coming from renewable energy sources is given priority in injecting into the grid. Therefore, no wind and solar control algorithms were applied. In the case of a biogas turbine, two operating modes were assumed – 50% of the rated power from 0.00 to 9.00 and 21.00 to 23.59 and 100% of the rated power from 9.00 to 21.00. Referring to the methods of contracting electricity on the Polish electricity market, an analysis was made of whether the income from the sale of electricity from HPS_n during hourly contracting will be higher than in the case of concluding a base contract for a 24-hour period. For this purpose, a theoretical hourly profile of the contract $E_{CO,\tau}$ was created. This is the electricity contracted for sale by a power generator owning a hybrid plant HPS_n, at $\tau \in \overline{1,\,24}$.

The following assumptions were made when creating the profile $E_{CO,\tau}$:

- The balance ΔE of the electricity generated E_{HPS_n} and contracted E_{CO} at the end of the day must be equal to 0. It is presented in Eq. (9):

$$\begin{cases} \Delta E = 0, \\ \Delta E = E_{HPS_n} - E_{CO} = \sum\limits_{\tau=1}^{24} (E_\tau - E_{CO,\tau})\,. \end{cases} \tag{9}$$

- To ensure that the contract for the sale of electricity is not subjected to operational risk for the power supplier, restrictions were introduced on the contracted electricity $E_{CO,\tau}$

$$a_\mathrm{L} \cdot E_\tau \le E_{CO,\tau} \le a_\mathrm{H} \cdot E_\tau\,, \tag{10}$$

where: a_L – correction factor setting the lower limit of contracted electricity $a_\mathrm{L} < 1$; a_H – correction factor setting the upper limit of contracted electricity $a_\mathrm{H} > 1$.

- The possibility of participation in the balancing market through HPS_n was guaranteed. In accordance with the nature of the Polish electricity market, the purchase price of electricity $p^P_{BM,\tau}$ at τ in the balancing market is equal to the sale price $p^S_{BM,\tau}$ and is equal to the sale and purchase price $p_{BM,\tau}$

$$p^S_{BM,\tau} = p^P_{BM,\tau} = p_{BM,\tau}\,. \tag{11}$$

The average purchase/sale price on the balancing market $\overline{p_{BM}}$ was determined for each day. It was assumed that if in a given hour τ the purchase/sale price on the balancing market $p_{BM,\tau}$ is higher than the average purchase/sale price for a given day $\overline{p_{BM}}$, then the value of electricity contracted in that hour $E_{CO,\tau}$ is lower than the value of electricity generated E_τ by HPS_n. In that case, the excess electricity over the contracted electricity is sold on the balancing market at a preferred price. Otherwise, the value of contracted electricity $E_{CO,\tau}$ will be higher than the value of generated electricity E_τ:

$$\begin{cases} \overline{p_{BM}} = \dfrac{1}{24}\sum_{\tau=1}^{24} p_{BM,\tau}\,, \\ E_{CO,\tau} < E_\tau\,, \qquad \text{if } \; p_{BM,\tau} > \overline{p_{BM}}\,, \\ E_{CO,\tau} > E_\tau\,, \qquad \text{if } \; p_{BM,\tau} \le \overline{p_{BM}}\,. \end{cases} \tag{12}$$

The electricity volumes, which are subject of the financial market, are associated with the contracted electricity profile and the electricity produced by HPS_n, in a considered hour τ:

$$\begin{cases} V^G_{E,\tau} = E_\tau\,, \\ V^{PE}_{E,\tau} = E_{CO,\tau}\,, \\ V^{BM}_{E,\tau} = V^G_{E,\tau} - V^{PE}_{E,\tau}\,, \end{cases} \tag{13}$$

where: $V^G_{E,\tau}$ – electricity production volume from HPS_n, in kWh; $V^{PE}_{E,\tau}$ – electricity sale volume on the power exchange, in kWh; $V^{BM}_{E,\tau}$ – sale and purchase volume of electricity on the balancing market, in kWh (the positive value of the volume means the sale of electricity by the power supplier and the negative value means the purchase of electricity).

The volume of electricity sold on the balancing market at a given hour $V^{BM+}_{E,\tau}$ and the volume of electricity purchased on the balancing market $V^{BM-}_{E,\tau}$ are determined from equations:

$$V^{BM+}_{E,\tau} = \Delta E^+_\tau\,, \quad \text{where}$$
$$\Delta E^+_\tau = \begin{cases} E_\tau - E_{CO,\tau}\,, & \text{if } \; E_\tau > E_{CO,\tau} \\ 0, & \text{otherwise,} \end{cases} \tag{14}$$

$$V^{BM-}_{E,\tau} = \Delta E^-_\tau\,, \quad \text{where}$$
$$\Delta E^-_\tau = \begin{cases} E_{CO,\tau} - E_\tau\,, & \text{if } \; E_\tau < E_{CO,\tau} \\ 0, & \text{otherwise.} \end{cases} \tag{15}$$

The daily volume of electricity sold on the balancing market V^{BM+}_E and the volume of electricity purchased on the balancing market V^{BM-}_E have been determined depending on the relation:

$$V^{BM+}_E = \sum_{\tau=1}^{24} V^{BM+}_{E,\tau}\,, \qquad V^{BM-}_E = \sum_{\tau=1}^{24} V^{BM-}_{E,\tau}\,. \tag{16}$$

Let the electricity sale price on the power exchange at τ hour be denoted by $p^S_{PE,\tau}$. The power supplier obtains the income from two streams: sale of electricity on the power exchange and sale or purchase of electricity on the balancing market. Therefore, the income obtained by the power supplier that owns HPS_n in τ hour is determined by the relation:

$$CI_\tau = CI^{PE} + CI^{BM} = V^{PE}_{E,\tau}\cdot p^S_{PE,\tau} + V'^{BM}_{E,\tau}\cdot p_{BM,\tau} \tag{17}$$

The daily income from the sale of electricity, including hourly changes in the sale volume, was determined by Eq. (18):

$$CI = \sum_{\tau=1}^{24}\left(V^{PE}_{E,\tau}\cdot p^S_{PE,\tau} + V'^{BM}_{E,\tau}\cdot p_{BM,\tau}\right) = \sum_{\tau=1}^{24} CI_\tau\,. \tag{18}$$

To validate the application of the aforementioned methodology for concluding contracts, the second case was also considered. It was assumed that a contract for the sale of electricity would be in baseload, i.e. for a fixed value of the contracted capacity. Therefore, the volume of electricity sales would equal:

$$V'^{PE}_{E,\tau} = const = \overline{V^G_E} = \frac{1}{24}\sum_{\tau=1}^{24} V^G_{E,\tau}\,. \tag{19}$$

The difference between the contracted electricity and the generated electricity is the subject of the trade on the balancing market. Hence, the sale/purchase volume of electricity on the balancing market is determined by the following formula:

$$V'^{BM}_{E,\tau} = V^G_{E,\tau} - V'^{SM}_{E,\tau}\,. \tag{20}$$

Therefore, the daily income from the sale of electricity in the baseload contract is determined by the following formula:

$$CI' = \sum_{\tau=1}^{24}\left(V'^{PE}_{E,\tau}\cdot p^S_{PE,\tau} + V'^{BM}_{E,\tau}\cdot p_{BM,\tau}\right). \tag{21}$$

4. Case study

To validate the research methodology presented in Section 3, the topology of HPS consisting of three power generation technologies: photovoltaic, wind and biogas power plants has been proposed. These are some of the most popular renewable technologies that will ensure uninterrupted electricity supply to the power system. It can be seen that the generation from wind and solar sources is complementary, and the availability of a permanent biogas source allows to maintain the stability of electricity supply. Therefore, the set of available technologies is as follows:

$$H = \{\textit{PV System, wind turbine, biogas microturbine}\}.$$

According to Table 1 (3) and (4), feasibility function equals:

$$\bigwedge_{h_i,h_j\in H,\;\; i\ne j} FES_2(h_i,h_j) = 1,$$

$$\begin{cases} FES_2(\textit{PV System, biogas microturbine}) = 1 \\ FES_2(\textit{PV System, wind turbine}) = 1 \\ FES_2(\textit{wind turbine, biogas microturbine}) = 1 \end{cases}.$$

Therefore, Hybrid Power Source consisting of two generation units can be established:

$$HPS_2 = \begin{cases} \{\textit{PV System, biogas microturbine}\} \\ \{\textit{PV System, wind turbine}\} \\ \{\textit{wind turbine, biogas microturbine}\} \end{cases}.$$

Since it is possible to include the third source into the pair, the *FES* function is set to a value:

$$FES_3(\{PV\ System,\ wind\ turbine\},\ biogas\ microturbine) = 1.$$

Hence, a Hybrid Power Source consisting of three generation units HPS_3 was made:

$$HPS_3 = \{PV\ System,\ wind\ turbine,\ biogas\ microturbine\}.$$

The topology of the developed HPS_3 is presented in Fig. 2. The analysis assumed a Hybrid Power Source with a total capacity of 1600 kW, consisting of renewable generation sources with the following installed capacities:

$$P_{TOT} = \begin{cases} P_{PV} = 300\ \text{kW}, \\ P_{WIND} = 800\ \text{kW}, \\ P_{BIOGAS} = 500\ \text{kW}. \end{cases}$$

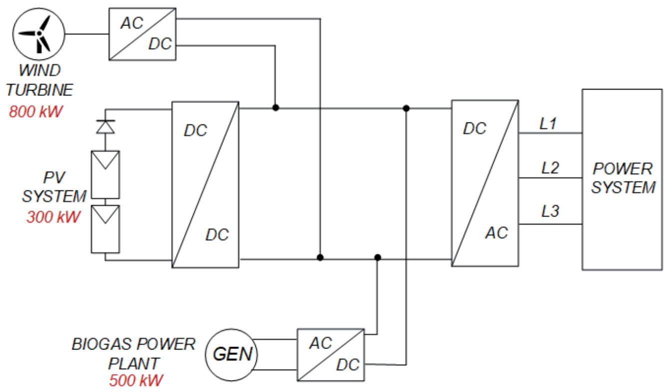

Fig. 2. Chosen topology of Hybrid Power Source used in analysis

Based on weather data obtained from the Homer Pro software [35], the generation profiles were created for individual sources included in HPS_3 hybrid system: $P_{PV,t}$ for photovoltaic power plant, $P_{WIND,t}$ for wind power plant and $P_{BIOGAS,t}$ for biogas power plant. The total power generated by HPS_3 system is determined by the Eq. (22):

$$P_{HPS_3,t} = P_{PV,t} + P_{WIND,t} + P_{BIOGAS,t}\,. \tag{22}$$

The hourly average power $P_{1h,\tau}$ for HPS_3 was calculated according to the assumptions from Section 3. Therefore, the electricity generated during 1-hour E_τ was obtained from relation (7). To determine the hourly profile of contracted electricity $E_{CO,\tau}$, solver tool included in Microsoft Excel 2016 was applied. Nonlinear Generalized Reduced Gradient (GRG) algorithm was used. To reduce the operational risk of the power supplier, the implementation of the algorithm includes defined limits of the $E_{CO,\tau}$ contract size deviation from the hourly generated electricity E_τ, according to (10). The following values of correction coefficients were adopted, determining the lower a_L and upper a_H limits of contracted capacity:

$$a_\text{L} = 0.7; \qquad a_\text{H} = 1.2.$$

Figure 3 shows the generation profiles E_τ and the contracted electricity $E_{CO,\tau}$.

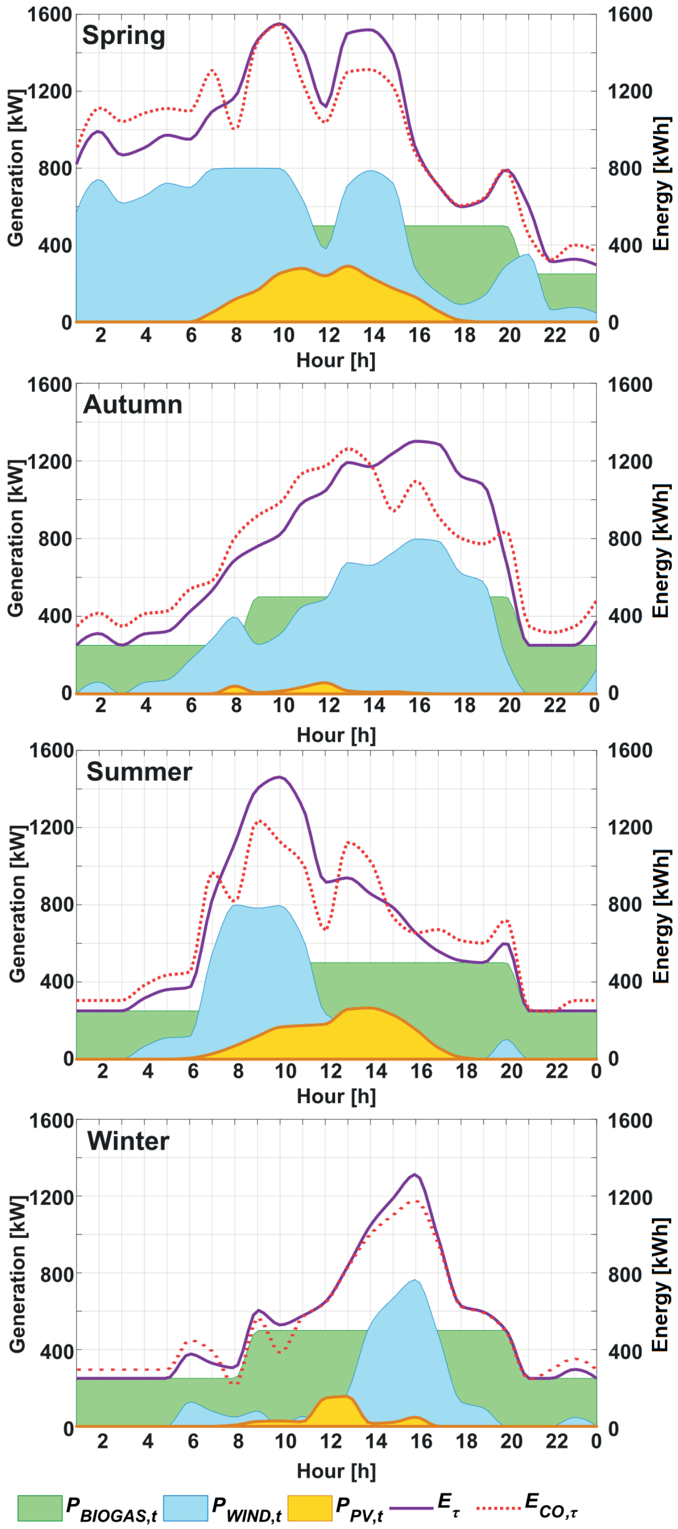

Fig. 3. Generation profiles of RES in analyzed Hybrid Power Source

Archival data concerning the electricity sale price on the Polish Power Exchange in Warsaw [36] and the prices prevailing on the Balancing Market [37] were also obtained. They are presented in Table 2.

Table 2
Prices and generation volumes of electricity on chosen days

Season	Spring			Summer			Autumn			Winter		
Hour τ	$p^S_{PE,\tau}$ [PLN/MWh]	$p_{BM,\tau}$ [PLN/MWh]	$V^G_{E,\tau}$ [MWh]	$p^S_{PE,\tau}$ [PLN/MWh]	$p_{BM,\tau}$ [PLN/MWh]	$V^G_{E,\tau}$ [MWh]	$p^S_{PE,\tau}$ [PLN/MWh]	$p_{BM,\tau}$ [PLN/MWh]	$V^G_{E,\tau}$ [MWh]	$p^S_{PE,\tau}$ [PLN/MWh]	$p_{BM,\tau}$ [PLN/MWh]	$V^G_{E,\tau}$ [MWh]
1	166.82	177.30	0.820	239.81	250.62	0.250	205.57	191.89	0.250	141.90	164.90	0.250
2	161.48	162.40	0.992	226.53	253.70	0.250	203.57	191.89	0.311	137.80	164.40	0.250
3	161.06	154.50	0.868	223.89	253.36	0.250	200.40	191.89	0.250	135.10	154.90	0.250
4	161.72	152.89	0.905	223.15	253.39	0.316	202.04	174.94	0.309	134.30	161.80	0.250
5	160.97	148.28	0.972	227.55	253.70	0.360	204.32	191.89	0.321	138.20	164.90	0.250
6	170.89	150.00	0.949	240.25	260.89	0.372	216.80	210.00	0.422	147.90	168.20	0.377
7	178.21	159.88	1.094	277.44	357.10	0.826	248.67	225.00	0.532	161.10	193.40	0.329
8	213.52	221.16	1.167	299.58	592.40	1.119	298.23	225.00	0.688	186.80	228.90	0.305
9	264.53	252.89	1.465	317.28	626.52	1.401	313.20	230.00	0.759	202.50	233.90	0.605
10	267.27	312.76	1.551	320.19	561.54	1.462	316.58	230.00	0.820	214.40	234.40	0.528
11	245.36	221.16	1.419	315.3	555.42	1.305	329.18	230.00	0.985	208.30	280.00	0.576
12	243.62	252.89	1.118	316.04	425.30	0.917	359.96	269.80	1.045	210.10	300.00	0.648
13	248.39	252.89	1.501	316.52	360.60	0.939	380.52	341.00	1.192	208.00	280.00	0.836
14	247.84	252.86	1.520	312.35	360.60	0.857	367.70	342.00	1.170	209.40	280.00	1.048
15	211.66	221.16	1.398	298.72	380.00	0.786	329.30	376.04	1.239	193.20	241.60	1.188
16	205.87	221.16	0.904	298.40	400.20	0.654	332.45	376.04	1.301	188.60	221.20	1.313
17	202.26	223.14	0.710	301.39	360.60	0.560	409.24	700.00	1.288	186.10	228.00	0.979
18	205.18	217.30	0.599	307.15	360.40	0.510	576.48	1100.00	1.122	194.40	234.40	0.627
19	214.03	222.43	0.633	302.44	350.00	0.500	499.83	840.00	1.077	194.20	234.40	0.596
20	208.60	236.45	0.792	315.72	350.00	0.603	439.03	496.04	0.685	183.30	228.00	0.500
21	197.72	221.16	0.602	315.35	458.37	0.250	330.72	499.00	0.250	176.00	218.20	0.250
22	182.73	215.70	0.312	284.36	400.20	0.250	268.69	316.74	0.250	158.10	185.30	0.250
23	169.63	171.03	0.327	268.13	313.31	0.250	249.75	254.75	0.250	145.50	171.90	0.297
24	160.61	154.10	0.296	248.76	280.89	0.250	223.11	243.67	0.374	137.10	166.30	0.250

Based on the profiles of the contracted capacity during the day, the volume of electricity to be sold on the power exchange and the operation on the balancing market were determined. The results are presented in Table 3.

Table 3
Total volumes of generation and incomes from sales of electricty on chosen days

Season	Total volume of contracted electricity [kWh]	Total volume of electricity placed on balancing market [kWh]	Income from contracting electricity on balancing market [PLN]	Income from contracting electricity on power exchange [PLN]
Spring	22 915.69	2 377.88	91.50	4 771.46
Summer	15 235.82	2 796.59	300.56	4 491.56
Autumn	16 890.34	2 724.32	687.97	**5 739.52**
Winter	12 751.97	1 101.29	35.42	**2 342.74**

Based on Table 3 it can be observed that the highest volume of electricity was contracted on spring day. In terms of electricity volumes placed on the balancing market, the highest value was recorded for a summer day and the lowest for a winter day. The range in volumes is 1695 kWh. However, the highest income from the trading on the balancing market was recorded for an autumn day. After a detailed analysis of the prices on the balancing market on that day, a very large difference between the highest price level and the lowest price level can be observed. From 17.00 to 19.00, prices exceeding PLN 700/MWh were recorded, and for most of the day the price did not exceed PLN 300/kWh.

It should be emphasized that on that day there is a strong correlation between the electricity prices on the commodity power exchange and on the balancing market. As in the case of the balancing market, the prices on the power exchange between 17.00 and 19.00 were the highest, exceeding the level of PLN 400/MWh. Since the day in autumn seems to be the most interesting subject of research, the next step was to estimate the total income from the sale of electricity on the power exchange and on the balancing market in accordance with (16). In Fig. 4

the income is presented together with the relation to the contracted capacity for an exemplary day in autumn.

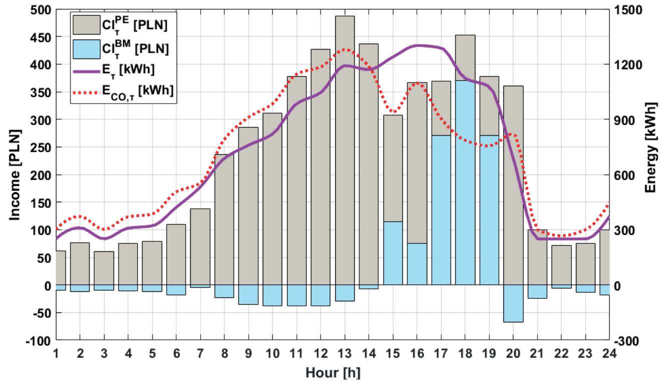

Fig. 4. Total income in relation to generated volume of electricity for an exemplary autumn day

The last part of the analysis was a comparison of income for a fixed contract value (baseload contract), as well as income – if the contract value changes every hour. Results are presented in Fig. 5.

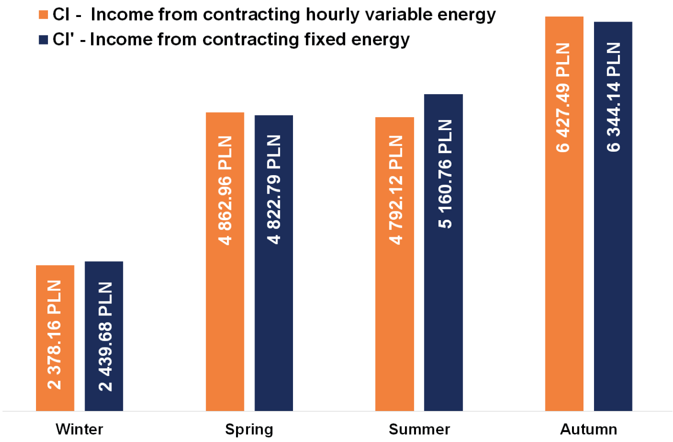

Fig. 5. Comparison between income from baseload contract and hourly changed dynamic contract

5. Conclusions and discussion

The article presents a practical approach to the contracting strategy of electricity from a Hybrid Power Source considering Polish market conditions. The paper presents its operation on the example of HPS consisting of three electricity generation technologies: biogas plant, wind power plant and solar power plant. A mathematical description was made, which allows us to assess the function of technical and economic feasibility of the hybrid source in a remarkably rapid way. Thanks to the algorithm developed, it can be stated that *HPS* is feasible when two generation technologies or their combination create a pair of set elements for which the feasibility function *FES* takes the binary value 1. Table 1 contains exemplary values of feasibility function *FES* of hybrid power generation systems. The values of functions were selected in it based on existing or developed designs of *HPS*. Due to the dynamic development of distributed generation technologies, it has to be assumed that Table 1 should be regularly updated, which means that it is a good material for further research – taking into consideration modern, often unconventional combinations of electricity generation technologies. The research has shown that the system consisting of wind, solar and biogas power plants is feasible. Based on selected technologies, exemplary values of installed capacity were assumed. It should be noted that the hybrid plant in question is not tailored to the specific demand of local electricity consumers. It has been assumed that due to the progressive de-carbonization of the electricity sector, in the future hybrid plants will be treated as existing commercial power plants. In this respect, a methodology has been proposed to calculate the income from the sale of electricity from the two revenue streams. The Solver tool has been used to determine hourly contracted capacity values within a given operational risk range of the generator. The results showed that the contract profile follows the generation profile of the hybrid source but can react accordingly when the price impulse is right. Historical power exchange and balancing market data were used for the purposes of the study. In further research, historical data may be replaced by forecasted values, both in the area of exchange prices or the balancing market, as well as by the use of ultra-short forecasted electricity production from RES. Bearing in mind the aforementioned methodology, it appears to be universal, i.e. it can be used regardless of the installed capacity of the hybrid source. It will be crucial to provide an appropriate set of data (historical or forecast). The results of the simulation show that one of the key factors shaping the value of income on each day is the production of electricity from a wind power plant. On days when it was at a fairly high level (spring, autumn), the income from the contracted electricity, which changes every hour, is higher than from the sale of electricity in the baseload. This contract, to which the values of the variable contract profile were compared, was adopted based on the average capacity generated during the whole day. It can therefore be noted that there is some area in which optimization of incomes from the electricity sold can be achieved. It should be emphasized, however, that the differences between the compared incomes are not large. It is so that the methodology developed considers the Polish model of the balancing market, where, for the time being, the selling price of electricity is equal to the purchase price. Soon, the purchase price and the sale price are to be sold out. Then, it may turn out to be much more profitable to contract electricity with a variable contract value every hour than to conclude long band contracts. Naturally, this is associated with a high investor risk, which should also be considered when developing the electricity contracting strategy. Adequate management of the data concerning the forecast of electricity production in HPS is crucial. We should also not forget about the possibility of using electricity storage facilities (especially Battery Energy Storage Systems - BESS). Thanks to their use, the flexibility of the hybrid source can be significantly improved. However, it complicates the algorithm of determining the contract value. Further research will focus on this topic.

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