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Design Problems of the Hybrid Electric Power Supply System for Energy Balanced Floated House

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1. Introduction

If at least two different useful products can be produced in one process, then this process is called conjugated or combined (Szargut 1983, Szargut 2007). Particularly important associated processes are those in which heating products and electricity are useful products In the case of two products produced simultaneously in the combined process, there is talk about a cogeneration system, with three – trigenerative, and with a larger number of useful products – polygeneration.

Since the accession of Poland to the European Union, new trends in modern energy have been introduced and developed. Large, centralized systems of the combined economy (based mainly on combined heat and power plants) began to be replaced by local systems, so-called distributed generation. Distributed generation is understood to mean systems of small or medium size, including heating heat generation and electricity working in cogeneration (hence distributed cogeneration) (Malko 2004, Paskaa 2007) Classification of distributed generation systems (sometimes also known as a distributed generation – if the production of electricity and heat in cogeneration sources has power from about 1 MW to about a dozen MW) can be made taking into account various criteria. For example, according to the amount of power installed in the source: large distributed generation – 50-150 MW, medium distributed generation – 5-50 MW, small distributed generation – 1 kW-5 MW, distributed micro-generation – 1 W-5 kW; distinguishes due to the amount of power and location range distributed generation: pico generation (up to 2 kW of installed electrical power), microgeneration (up to 5 kW of power) and mini generation (up to 50 kW of power) (Charun 2015, Charun 2016).

Current, developed trends in the development of distributed generation point to the preference for the so-called hybrid manufacturing systems (HSW).

They are a combination of two or more different manufacturing technologies to obtain specific useful products. According to (Paska 2013), the concept of hybrid system was introduced into Polish legislation in the Regulation of the Minister of Economy of 18 October 2012 (Dz.U. 2012, poz. 1229), in the form of a record: a hybrid system is a generating unit producing electricity or electricity and heat, in which in the process in production, energy carriers produced separately in renewable energy sources are used, with the possibility of using auxiliary fuel and in energy sources other than a renewable energy source, working on a common collector and consumed jointly in this generating unit for the production of electricity or heat. In hybrid systems, for example, diesel generators (including diesel engines, small wind farms and solar cell batteries) are used. A typical example is the cooperation of solar panels with a wind energy generator. Other examples of hybrid systems are given in the literature, e.g. (Paska 2013, Paska 2005).

The problems described above fit into the design issues of the hybrid home power supply system (WH). In article (Charun 2020) selected design aspects of the heat extraction system using renewable energy sources (RES) using a compressor heat pump, with a lower heat exchanger placed in the surface water of the lake are given. This article presents hybrid systems, used to generate electricity for an example WH water house.

2. Aims of using hybrid systems in the WH

"House on the water" (WH) is a non-standard solution of a recreational and leisure facility in the form of a residential superstructure built on a float. Such a floating object is usually moored to a small pier or marina at the waterfront of a lake or river. Various global companies and Polish manufacturers WH offer various construction and installation solutions, without presenting detailed solutions. In most cases, the houses are powered by electricity from conventional coastal sources, which is fed in via power cables and used in the WH residential structure for heating, lighting, domestic hot water etc. This means that, in terms of power supply, the WH facility is organically dependent on external connections located on the waterfront.

The purpose of modernization changes introduced to the example of a WH house placed on a float 8 x 3.5 x 1 m (Charun 2020) was to reduce the energy dependence of WH on external power to the necessary minimum (excluding emergency cases). The name WH was obtained as "an energy-balanced floating house". The article (Charun 2020) presents some selected design aspects of heating such a house. Electricity is necessary not only to drive the compressor heat pump proposed in this solution but also for the living needs of residents.

The general assumption regarding the solution to the problem of independence from the external power supply has been turned towards the use of renewable energy sources (RES), especially wind energy and solar radiation.

In this way, the concept of using an electric hybrid system was obtained. The proposed hybrid power supply system includes the following basic components: wind turbines, photovoltaic panels, electricity storage system, control systems, intelligent control and measuring panels. The given set of elements is associated with the heating system using a heat pump cooperating with a renewable energy source (lake surface water).

A mini-scale distributed generation system in cogeneration was proposed as a classic form of the CHP (Combined Heat and Power) system. The hybrid solution uses renewable energy sources, and at the same time allows to achieve an increase in energy efficiency to the solutions used so far with external electricity supply from the waterfront.

3. Design assumptions for the hybrid system

The design assumptions for the hybrid electric power supply used for the WH floating home were:

- electricity demand to operate the receiving part of the installation,
- the scope of coverage of this demand by the generating elements of the system.
  - The hybrid system for the sample house WH was based on two subsystems obtaining energy from two different renewable energy sources, ie solar radiation energy – solar panel system and wind energy – wind turbine system. The interaction of both subsystems should cover the required demand
  - in the daily and annual cycle. To determine the size of actuators of both subsystems and installation instrumentation, balance sheets and analyzes were performed.
  - In the balance sheet of the receiving part of the electrical installation serving the WH residential structure, basic electricity receivers are specified, in particular: electric kitchen hob, household appliances, lighting, control system power supply, heat pump drive motor, etc. Balance, daily electricity demand, taking into account the factors their daily use and simultaneity of work is about 20.6 kWh/day.
  - A standard, a conventional floating house with similar dimensions of a residential superstructure requires a total electricity demand of about 7500 kWh/year. The use of the proposed hybrid power supply system should ensure significant savings in electricity consumption, obtained primarily through the proper selection and cooperation of executive elements of electricity generators, their control and all modernization measures. According

to preliminary simulations, the possibility of a daily reduction of electricity demand by about 85% was determined.

Based on the simulation analyzes, it was determined that obtaining the possibility of increasing the energy efficiency of the object requires the use of the hybrid system components listed in the following calculation conditions:

- wind turbines with a vertical axis of rotation with unit power of 50-150 W; turbine power is generated at an average airspeed of 2-3 m/s; according to the Weitbull Statistical Distribution. These wind speed parameters occur in Northern Poland for approximately 2500 hours/year. Due to the above, the possible power of wind turbines should be in the range of 200-600 W. It follows that in the estimated annual operating time, e.g. 4 wind turbines, energy in the amount of 500-1500 kWh/year can be obtained, i.e. 1.4-4.11 kWh/day;
- The photovoltaic subsystem should contain 4-6 photovoltaic panels with a maximum power of 250 W and real efficiency at an efficiency of approx. 10%. Normative sunshine duration in the conditions of northern Poland of 7.2 hours is assumed. in winter and 15.5 hours – in summer; the average calculated solar radiation energy value of 1065 kWh/m² was adopted, which will allow an annual energy yield of approx. 640 kWh/year, i.e. 1.75 kWh/day;
- in the calculations of cooperation of the hybrid system used to drive the compressor heat pump, it was assumed that the heat pump efficiency factor is COP = 3.5, generating a heating power of about 3.5 kW with an input power of about 1 kW.
- If the above-mentioned assumptions are met, the optimum yield should be: 5.86 [kWh/day] of electricity and 3.5 kWh of thermal energy. Assuming that the heat pump would work for 5 hours/day, almost all electricity can be allocated to the work of the heat pump, which would give 17.5 kWh/day of thermal energy. This results in a reduction of electricity consumption by 85.15% compared to the daily output value of 20.55 kWh. However, in extremely adverse weather conditions this figure can be as low as 15%.

Fulfilment of the above-mentioned design assumptions required a detailed analysis, taking into account statistical data of atmospheric parameters in the field of sunlight and windy conditions. Analyzes were carried out, for example, for the area of northern Poland in the coastal belt. Due to the limited volume of this study, only an outline of the methodology and some design calculations are provided.

3.1. Determination of wind energy resources in the WH foundation area

The basis for the wind installation design calculations was the distribution of average monthly wind speed values for the WH foundation basin. Values of this speed were determined for the windiness of the area located in the coastal belt from Łeba to Kołobrzeg. In the considered case, the results of the authors' research were carried out using the apparatus placed on a measuring mast with a height of 13 m located on the campus of the Koszalin University of Technology. The measurements were carried out over 12 months, with the test results in Table 1 taking into account the fact that in the case of the WH house wind turbines will be located at a height of up to about 3 m above the reference surface. In calculating the wind speed distribution as a function of height, the Sutton formula was used in the form (colective work 2008, Tytko 2016):

$$C_H = C_o \cdot \left(\frac{h}{h_o} \right)^{\alpha} \tag{1}$$

where: C_H – wind speed measured at the height of the [m/s], C_o – the speed at the height of ho (equal to 10 m) of the location of the anemometer, α – power exponent depending on the roughness class of the substrate and the averaging time (averaging values of 10 minutes were adopted, hence α = 0.20.

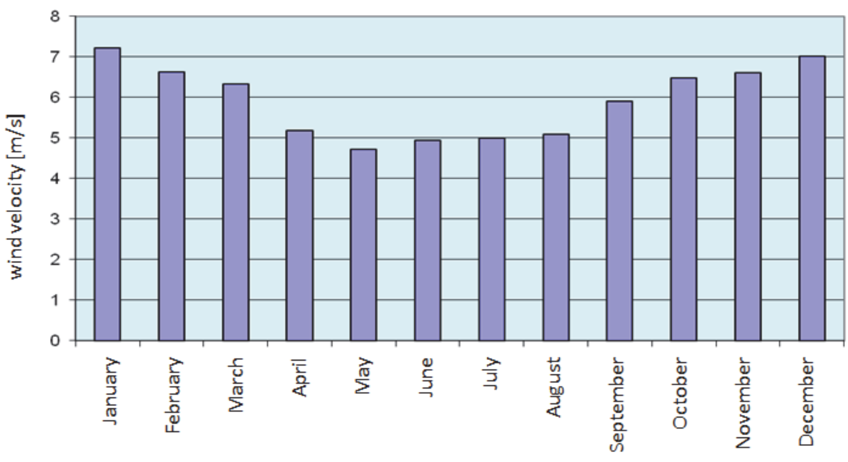

Fig. 1. Distribution of average monthly wind speed during the year at the WH foundation point at a height of 3 m

After the transformation of formula (1), the values of wind speed Co distribution at 3 m height were determined as average values in individual months of the year (Fig. 1). The average annual wind speed Cr was calculated from the formula:

$$C_r = \frac{\sum_{i=1}^{12} C_{o,i}}{12} \tag{2}$$

Using the statistical *Weibull* distribution, the frequency distribution of wind speeds at a given speed over a year was determined, according to the relationship:

$$f(x) = k \cdot C_r^{-k} \cdot x^{k-1} \cdot e^{-\left(\frac{x}{C_r}\right)^k} \tag{3}$$

where: x – wind speed at which the calculations were made [m/s], C_r – average annual wind speed [m/s], k – shape parameter (k = 3 was adopted).
Fig. 2 shows the wind speed distribution, depending on its frequency.

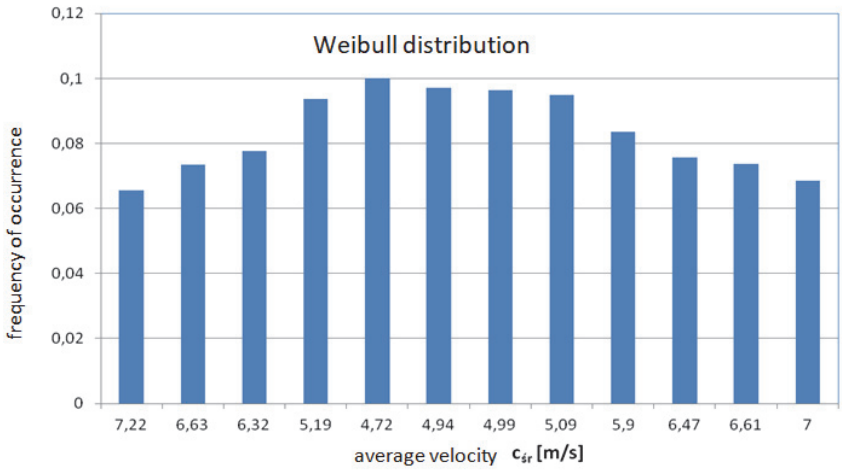

Fig. 2. Weibull distribution of wind speed depending on the frequency of occurrence

To determine the number of hours of the occurrence of individual values of wind speed, the percentage frequency of occurrence of these wind speeds was multiplied by the duration of the measurement (8760 hours/year). The results are presented in Table 1.

Table 1. Hourly amount of wind speed data occurrence

Velosity [m/s]	Frequency [Hz]	Grequency [h]
7.22	0.065646	575.06
6.63	0.073413	643.10
6.32	0.077645	680.17
5.19	0.093544	819.44
4.72	0.100115	877.01
4.94	0.097059	850.24
4.99	0.096359	844.11
5.09	0.094954	831.80
5.9	0.083501	731.47
6.47	0.075586	662.14
6.61	0.073684	645.47

Knowing the average monthly wind speed values and the terrain in the place where the wind turbine was founded, the amount of energy that could be generated by a given turbine was calculated based on the formula:

$$P_t = 0{,}5 \cdot \rho_{pow.} \cdot A \cdot c_p \cdot c_s^3 \tag{4}$$

where:
ρ_{pow} – air density (1.225 kg/m^3 was used for calculations), A – wind stream area [m^2], C – wind speed [m/s], c_p – wind turbine utilization coefficient. Further calculations were made using the methodology related to *Savonius* wind turbines (Jagodziński 1959, Wekesa 2016).

The maximum value of the power factor $c_{p,max}$ of the wind generator, using wind resistance usually does not exceed 0.2, which means that only 20% of wind energy can be used in devices such as the *Savonius turbine*. In practice, this value refers to the aerodynamic power achieved when the turbine is idling with a vertical axis of rotation. Consequently, the useful power achieved will be much lower and it can be assumed that it is close to the level of 50% of aerodynamic power.

Based on the applied calculation methodology, the power distribution possible to be obtained by one *Savonius* turbine in individual months of the year was determined – Table 2.

Table 2. Distribution of power generated by the Savonius turbine in individual months of the year

Month	Monthly average wind speed $C_{śr}$ [m/s] at a height of 3 [m]	The estimated amount of energy generated by 1 turbine [kWh/doba]	The estimated amount of energy generated by 4 turbines [kWh/doba]
January	7.22	2.43	9.70
February	6.63	2.23	8.91
March	6.32	2.12	8.49
April	5.19	1.74	6.98
May	4.72	1.59	6.34
June	4.94	1.66	6.64
July	4.99	1.68	6.71
August	5.09	1.71	6.84
September	5.90	1.98	7.93
October	6.47	2.17	8.70
November	6.61	2.22	8.88
December	7.00	2.35	9.41

a) b)

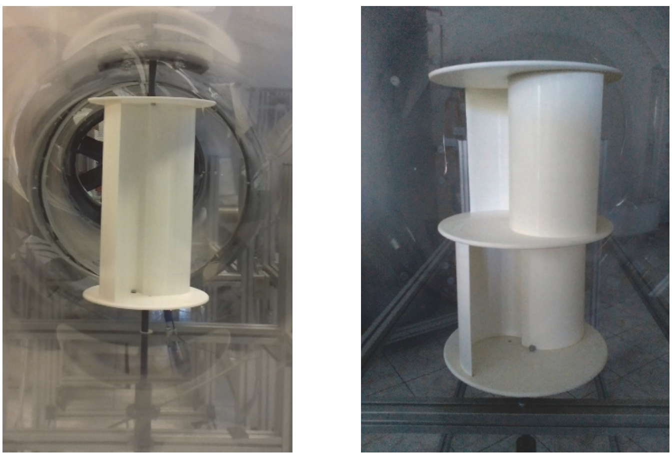

Fig. 3. View of model wind turbine rotors proposed in a hybrid system: a) Savonius, b) double Savonius

Power plant data:
propeller diameter – 50 cm
propeller length – 90 cm
wind-up speed – 1 m/s
working range – 1-20 m/s
weight – 8 kg
generator voltage – 12 or 24 V
PMG generator – weight 2 kg
generator power – 280 W

Fig. 4. View and technical parameters of the Savonius wind turbine – 280 W

Fig. 3 shows a model version of Savonius wind turbines. The project envisages the use of 4 Savonius turbines, the view and characteristics of which are shown in Fig. 4. This allows generating electricity in the amount of 6.3-9.70 kWh/day, with the average annual value of generated energy being. 2665 kWh/year for a set of 4 turbines. Even taking into account the reduction in turbine rotor operating speed, it is possible to obtain practically 3.32-4.85 kWh/day, i.e. 1332 kWh/year. To the planned demand specified at 500-1500 kWh/year, i.e. 1.4-4.11 kWh/day, the calculated amount of generated energy covers the planned demand.

3.2. Determination of solar energy resources in the WH foundation area

To estimate the local amount of solar radiation energy, several years of sun exposure studies are necessary.

The values of insolation were adopted from data obtained from the interactive Photovoltaic Geographical Information System (PVGIS). This system is based on data on the amount of solar radiation and terrain. The obtained values are shown in Fig. 5.

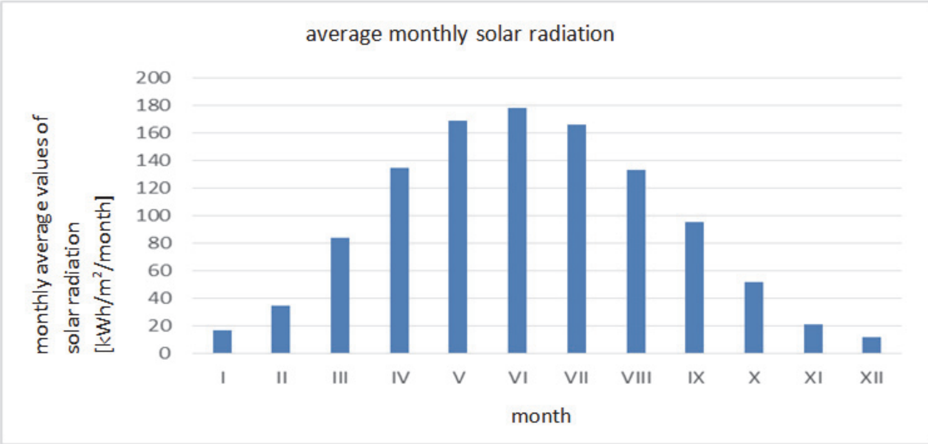

Fig. 5. Graph showing average monthly insolation values for the city of Kołobrzeg, data taken from PVGIS

Based on the above data, the annual value of sunlight for the city of Kołobrzeg was calculated:

$$E_{sr} = \Sigma E_{sm} = 16.8 + 34.8 + 83.7 + 134.7 + 169.2 + 178.2 + 165.9 + 133.2 + 95.7 + 52.2 + 21.1 + 11.9 = 1097.4 \text{ [kWh/m}^2\text{/year]}$$

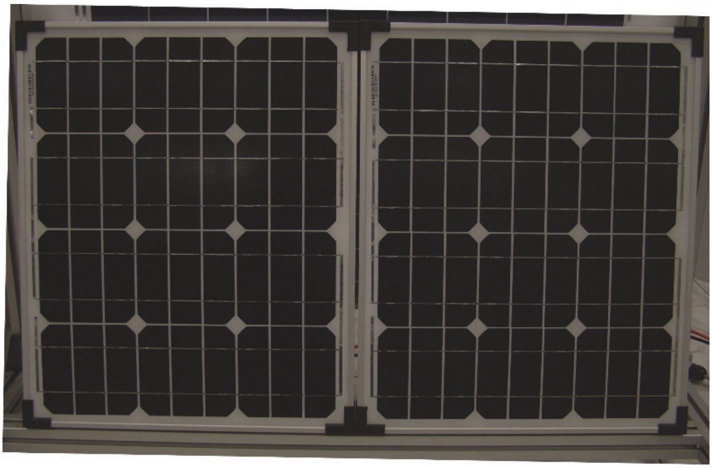

Fig. 6. View of monocrystalline panels in parallel connection

Fig. 6 shows a view of the proposed solar panel for use in a House on the Water. To obtain energy from solar radiation, the use of 6 monocrystalline photovoltaic panels with the following parameters is planned:

- rated power PMPP 290 W,
- rated voltage UMPP: 31.3 V,
- IMPP rated current: 9.25 A,
- open circuit voltage UOC = 39.3 V,
- short circuit current ISC 9.80 A,
- area: 1.47 m^2,
- efficiency η = 17.6%.

Electrical parameters were determined under standard test conditions (STC): 1000 W/m^2; 25°C; AM 1.5.

For real conditions, the efficiency of photovoltaic cells is assumed to be about η = 10% and the potential of useful energy from solar radiation H = 1097400 Wh/m^2 for one year (Kołobrzeg actinometric station). For the above parameters, it is estimated that it is possible to obtain 2.65 kWh electricity during the day. The following algorithm was used for the calculation:

$$H = \frac{1097400\left\|\frac{Wh}{m^2}\right\|}{365[day]} = 3006{,}58\left[\frac{\frac{Wh}{m^2}}{day}\right] = 3{,}01\left[\frac{\frac{kWh}{m^2}}{doy}\right], \tag{5}$$

$$\eta = \frac{P_{el}}{H \cdot A} = P_{el} = \eta \cdot H \cdot A, \tag{6}$$

$$P_{el} = 0{,}1 \cdot 3{,}01\left[\frac{\frac{kWh}{m^2}}{day}\right] \cdot 6 \cdot 1{,}47[m^2] = 2{,}65\left[\frac{kWh}{day}\right],$$

Compared to the planned amount of 1.75 kWh/day and 640 kWh/year over a 12-month scale, the calculated amount of energy that can be obtained from the proposed set of photovoltaic modules and solar radiation determined by PVGIS is much higher. It is on average 2.65 kWh/day and 969 kWh/year.

4. Design concept of hybrid system construction

Due to the uneven distribution of solar radiation in individual months of the year, there is a need to combine them with other electricity generators, e.g. wind turbines. In this case, two basic connection schemes are usually used:

1. photovoltaic generator + battery + inverter – connection by direct current lines,
2. photovoltaic generator and other elements, including receivers – connected to the AC system.

To the hybrid electric power supply system for the floating house WH, the second connection option was used. Fig. 7 shows an electrical diagram of connections of elements of the hybrid power supply system of the house on the WH water.

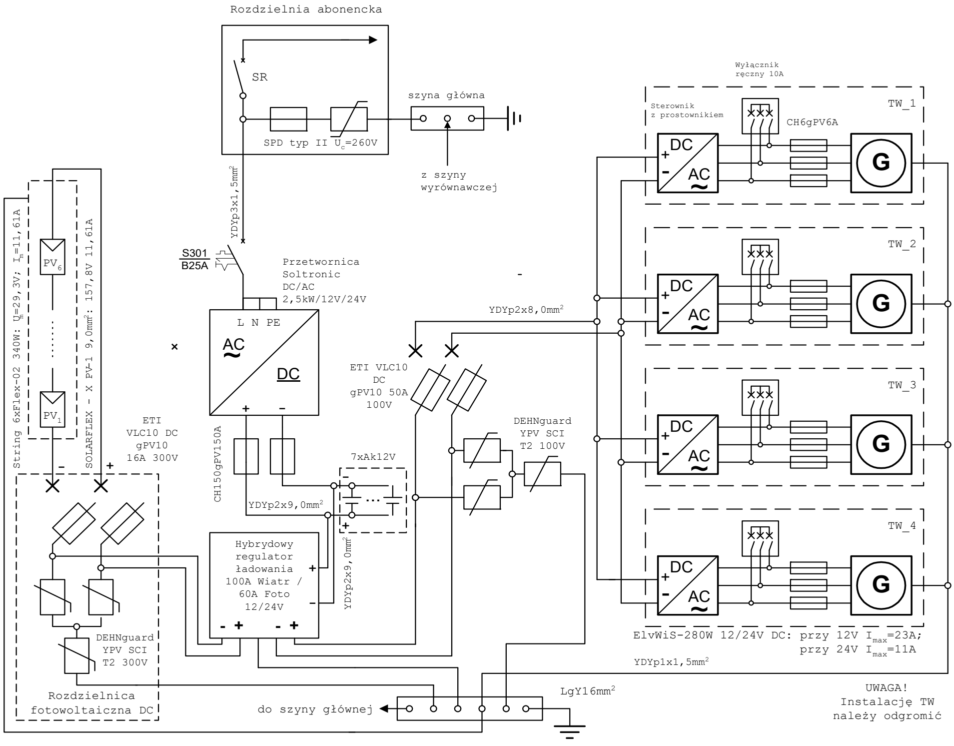

Fig. 7. Diagram of a hybrid electricity supply installation

The hybrid electric power system for WH was designed with the use of photovoltaics – monocrystalline photovoltaic modules type FLEX -02 340 W with a rated power of 340 Wp – 6 pcs. Connected to the system are 4 wind turbines of the Savonius type – ElvWiS III ALUMINUM. The electricity generated in the panels will be diverted via solar cables to the 100A wind 60A hybrid 48A photo 48/24/12V 8KW charging controller, and from it to the energy storage block (batteries with 6 pcs. 12 V). A set of four wind turbines is connected to this voltage regulator. The generated electricity, after converting it to DC 12/24 V through the voltage regulator, will supply the battery block. External devices are used to store electricity generated by a wind generator and photovoltaic panels in a battery. A hybrid controller having PWM wind and solar controller operation parameters will ensure cooperation with: max 5 kW wind generator, max 3 kW electric photovoltaic cells and a set of batteries.

Fig. 8 presents a general view of the WH assembled hybrid power supply system located in a separate WH superstructure room. All elements of the hybrid system were tested on laboratory stands and in operational conditions after the completion of WH assembly works. Research results will be the subject of a separate study.

Fig. 8. General view of the WH hybrid power supply system

5. Summary

The content of the study presents selected design problems of the hybrid electric power supply system for the recreation and leisure floating house WH moored at the lake quay located in the coastal belt in the Central Pomeranian area. The proposed power supply installation combines two independent systems for obtaining energy from renewable sources. The hybrid system is intended to make the floating object independent of the consumption of electricity from external sources located on the waterfront. The basic elements of the hybrid system are a subsystem of photovoltaic panels and a subsystem of wind turbines of the Savonius type with a vertical axis of rotation. The designed system not only performs the function of independence from external sources and the use of renewable energy sources (RES) but also shows significantly greater energy efficiency concerning dimensionally similar WH houses powered by external power cables. The proposed system, controlled by intelligent systems, is also a source of power for the compressor heat pump using the surface water of the lake as the lower heat source.

The present study was performed under in accordance with the application for funding by the National Centre for Research and Development No. POIR.01.01.01-00-0466/17 for the implementation of the project entitled "Construction of energy balanced floating leisure house" with Ekosun Paweł Czupajło company, based in Koszalin at 4 Boh. Warszawy Street, 75-211 Koszalin

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Abstract

Recreational houses (WH) of a recreational nature may constitute an offer for the development of non-standard forms of recreation proposed by the domestic tourist industry. The paper presents some selected design problems of heating an exemplary WH house. For central heating (central heating) and domestic hot water (domestic hot water), it is proposed to use a compressor heat pump. It works with the central heating installation (water underfloor heating) and hot water, and with a lower source in the form of surface water in the lake. The heat exchanger for the brine is immersed in the lake water. The methodology for calculating the dimensions of the lower heat exchanger was presented. It was proposed that it will be made in the form of two coils made of polyethylene pipes and WH float sides placed on both sides. The design solution presented in the paper meets the conditions for qualifying as using renewable energy sources (RES).

It should be noted that covering the demand for electricity for the WH house, including to drive the heat pump motor and for other living purposes in a residential superstructure, is also made using a hybrid system in the form of cooperation between wind turbines and photovoltaic panels. Problems regarding the WH hybrid electricity supply system will be the subject of a separate study.

Keywords:
floating house, renewable energy sources, designing, heat pump