BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 68, No. 4, 2020
DOI: 10.24425/bpasts.2020.133125

SPECIAL SECTION

Sizing of prosumer hybrid renewable energy systems in Poland

M. BARTECKA*, P. TERLIKOWSKI, M. KŁOS, and Ł. MICHALSKI

Warsaw University of Technology, Electrical Power Engineering Institute, ul. Koszykowa 75, 00-662 Warsaw, Poland

Abstract. Nowadays the demand for renewable energy sources is constantly growing. There are several reasons of such state, including requirements for energy-efficient new buildings and reduction of greenhouse gas emissions. An exemplary solution that may help to reduce "traditional" primary energy consumption is local energy source utilization. The article presents a simplified feasibility study of hybrid energy system under Polish law and economic conditions for a self-government unit, that is legally obliged to apply means of energy efficiency improvement. The aim of this paper is to provide a simple algorithm to find optimal hybrid PV and wind power source sizing for a prosumer. Resource data used in analyses are imported from Photovoltaic Geographical Information System and cover a period of one year. The paper includes two different methodologies applied to solve the problem of optimal hybrid energy system sizing. The first approach is heuristic and based on monthly energy balancing while the second is iterative and takes into account hourly energy balance. The results from both methods are compared and verified by HomerPro software, that shows significant differences between two algorithms. At the end economic assessment based on Net Present Value method is performed.

Key words: hybrid renewable energy systems, prosumer, energy efficiency, techno-economic analysis, optimal power source sizing.

1. Introduction

A hybrid energy system (HES) comprises of different energy sources. It may contain photovoltaic, wind, biogas or small scale fossil fuel turbines, fuel cell, diesel generator etc. Its main objective is to assure higher reliability of power supply in comparison with the system based on one type of energy source, better energy efficiency and overall integration of distributed energy sources [1, 2]. Especially, in the field of renewable energy, PV and wind turbine hybrid energy systems (PV-WT HES) are gaining in popularity [3, 4]. Many studies have been taken out to analyse the operation of HES and to optimize a designing process, as a relevant power source sizing and energy management strategy determine the system performance and cost [5]. However, to find the best fitted power capacity and control strategy, first questions should concern constraints and requirements for a planned HES. One of the fundamental aspects is the type of HES cooperation with an electrical grid. In off-grid installations both energy sources and storages should be optimized to assure reliable power supply [6]. On the other hand, grid-connected hybrid energy systems are a good alternative to reduce energy cost. Nevertheless they constitute only 20% of renewable HES and are not widely investigated in the literature [7]. Moreover, in case of grid-connected systems, legal conditions very often encourage or discourage potential investors. Objective functions may concern the minimization or maximization of various indicators, such as reliability factors, battery state of charge, economic indicators, e.g. net present cost, levelised cost of energy etc. [6, 8, 9], environmental impact [10].

Regardless of objective function, hybrid energy systems based on renewable energy sources (RES) may have significant contribution in reduction of greenhouse gas (GHG) emission. In Poland, GHG emission decreased strongly by 37% in the period 1990–2002, but after 2002 emissions grew by 3% until 2015 [11]. Poland has a growth target of 14% for the 2005–2020 period under the Effort Sharing Decision (ESD), and it is on track to reach this target. However, comparative indicators such as emission intensity indicate that Poland performs worse than most Eastern European countries and average EU-28 Member States in terms of emission reductions and decarbonisation in the energy sector which is due to its strong reliance on coal. Some legislation in the energy sector might lead to an increased role of coal in energy supply compared to past plans and a much slower expansion of renewable energy than in recent years, in particular for wind power. At the same time, European Directives: first 2009/28/EC with aims to year 2020 [12], and its substitute 2018/2001/EC with aims for years 2021–2030 [13] oblige member countries to diminish the emission of harmful gases of carbon and nitro to the atmosphere and to enhance the share of renewable energy. Another Directive 2018/2002/EC [14] deals with energy efficiency and the 32.5% decrease of primary energy consumption is the goal to achieve by 2030. In order to fulfil the aforementioned aims, Polish regulations have been changed. The Act on Renewable Energy Sources [15] introduces the definition of prosumer in order to enhance the number of small renewable energy systems. "Prosumer" is defined as a person/subject who produces energy for mostly non-commercial purposes such as own con-

*e-mail: magdalena.bledzinska@ee.pw.edu.pl

Manuscript submitted 2019-11-29, revised 2020-01-27, initially accepted for publication 2020-02-13, published in August 2020

sumption from micro-installation. A micro-installation is a renewable energy source of power less or equal 50 kW. For such units so called "rebate" scheme is the form of financial support. This mechanism is cashless transactions between customer and distribution system operator (DSO). The inter-connected grid plays a role of storage for a renewable non-commercial installation. The prosumer may enter energy to the grid in any time and retake it in the period of one-year in the amount of 80% for systems less or equal 10 kW and in the amount of 70% for bigger micro-installation. This rebate is DSO operational cost. To the aforementioned levels, the consumer does not pay any charge to DSO, but in the same time if the energy is not retaken within the set period from the time of its introducing to grid it is "lost". Current assessment of the development of prosumer energy sector in Poland has been elaborated in [16]. Moreover, with reference to the Act on Energy Efficiency [17] as well as the Act on Electromobility [18], self-government units shall be the protagonists in development of environmentally-friendly solutions. Concept and assumptions for building of the municipal energy centers using distributed energy sources were described in [19].

Once the constraints, requirements and cost function for HES are defined, another issue is the technique to solve the optimization problem and find a feasible solution. The basic division is based on three groups: classical (iterative, analytical, probabilistic, graphical construction) [20], artificial or hybrid methods (neural networks, particle swarm optimization, genetic algorithm) [20–22] or software tools (Homer, iHOGA, RET Screen, Hybrid2) [8, 9, 23]. The optimization of Hybrid RES System, based on the experimental data acquired for the whole year, using economic and environmental criterion, has been performed in [24].

In [8], the authors adduce two methods, available in the literature, for finding HES size. First one is based on average monthly method, the second on the worst months. The worst months concern the lowest possible energy production due to insufficient resources separately for PV and wind turbines. According to these methods PV size is fitted to the month with the lowest unit solar radiation and a number of wind turbine is fitted to the month with the lowest wind speed. However, in moderate climate (as in Poland) these kind of methodologies in our opinion are not adequate. The differences between energy unit production in summer and winter are so high that averaging these values may cause that the system will not match the load in any month. This is particularly important while Polish legislation and "rebate ratio" are taken into account. On the other hand, applying the worst month methodology may lead to overestimation of energy sources, higher costs and possibility of energy loss in terms of Polish law. Hence, the survey shows that many studies are conducted to find optimal sizing, however, any of them is not suitable under Polish legislation and climate conditions. Moreover, there is no data about an error that may be caused while too long balancing period is applied.

Considering the above, the objective of this work is twofold. First aim is to check the feasibility of prosumer installation for a public self-government institution under Polish law conditions. Two algorithms are developed to determine power of HES comprising of wind turbines and photovoltaics. The objective function is to maximize net present value and in the meantime minimize lost energy, that is not retaken from the grid. The constraints are related to persmissible power level and rebate ratio. The first algorithm is more heuristic and analytical, it is similar to the average month methods while the second is iterative and it is based on hourly average values. The second aim is to compare the results and divergences between these two approaches. To this purpose spreadsheet, Matlab and HomerPro software are used. Similar approach, but for Serbia, has been described in [25]. Small, grid-connected hybrid system, consisting of solar photovoltaic panels and small wind turbine for power supply was analised as a case study. In that case, authors conducted their system analysis using RETscreen software. Furthermore, in [26] authors examined the techno-economic feasibility of four hybrid power generation systems applied to cover the demand of a typical off-grid residence for a 20 year period in Greece. Each one of these hybrid power solutions should involve at least one renewable energy source technology and be able to cover all load needs. They were looking for an optimal solution based on a minimal total cost criterion. Regarding Polish conditions, e.g. [16] and [10] analysed the issue of development of prosumer energy sector especially using hybrid power systems and their sizing. Interesting research has been done in [27], presenting a review of the topologies of hybrid RES installations, possible to be used as alternative energy sources in microgrids and energy clusters in Poland. Authors discussed the methods of configuration of hybrid sources, possibilities of creating combinations of given technologies and their feasibility. The production profile of such an installation, for different seasons of the year, was also estimated. On the basis of the data received, a strategy of contracting electricity was designed, which maximizes the use of energy sources included in the hybrid RES installation.

The paper is structured as follows: section 2 includes methodology of simulations, load profile and renewable energy source description, optimization function and algorithms. Section 3 shows the results of simulation while section 4 conclusions.

2. Methodology

The main objective of this work is to find optimal sizing of HES for specified load under certain constraints. Hence, in this paragraph the development of load profile and renewable energy sources is discussed. Next, the optimization task is defined and two algorithms to solve it are presented.

2.1. Product parameters. Final results of applied algorithms are obtained on the basis of market products. A mono-crystalline PV module is selected. Its parameters are summarize in Table 1 [28]. An inverter price is estimated at 250 €/kW. A wind turbine with vertical axis (VAWT) is selected, due to low start wind-speed, smaller area of blades and possibility of installing it on rooftops. Some features are summarized in Table 1. The characteristic $P(v_{wind})$ is illustrated in Fig. 1 [29].

Table 1
PV and wind turbine parameters

PV				
Power P [W]	PV eff. η_{PV} [%]	Surface S [m^2]	System eff. η_{system} [%]	Price C_{PV} [€]
300	18	1.6	88	180

Wind turbine				
Power P [W]	Start speed v_{start} [m/s]	Rated speed v_n [m/s]	Max. speed $v_{\max}$ [m/s]	Price $C_{WT,single}$ [€]
2800	1.25	12	25	3 000

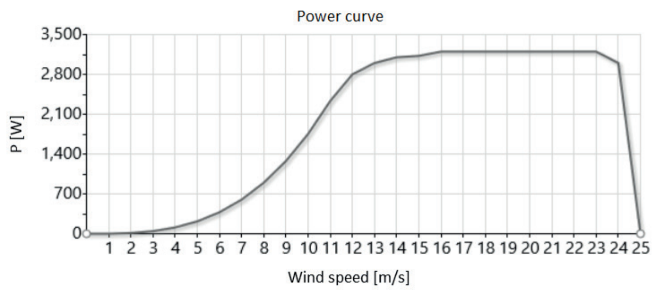

Fig. 1. Power-wind speed curve of selected wind turbine

2.2. Load profiles. Several assumptions are done to determine required power of RES. Firstly, a load profile of consumers is defined. In our work, these consumers are public institutions, which working time is mostly fixed from Monday to Friday. The buildings are located in a middle-size city of 50 thousand inhabitants in Masovian Voivodeship, Poland. In the paper [30], the authors gather results from 80 institutions and analyse them using statistics in order to develop generic load profiles. These results are used to create the normalized load profile for consumers with one hour time step – $F_{norm,t}$, where $F_{norm,t} \in \langle 0,1 \rangle$. Moreover, usually during weekends offices do not work, thus demand is at the same level as during night period of workdays, what is treated as a baseline. There is a possibility in the model to distinguish load profile for seasons, however, for this specific work it is not applied. Based on the observations and some experimental results, it has been noticed that for this group of consumers the load is slightly lower for summer and the differences may be neglected. The observations are also reflected in standard load schedules for low-voltage single-zone consumers prepared by DSO every year. Once normalized loadshape are obtained, consumed power is calculated. On the basis of data gathered and developed by Central Statistical Office in Poland [31], information about consumed energy by public institution buildings in Masovian Voivodeship are extracted. Then, average demand for single object – P_b is estimated. A load curve with power ratings is defined by:

$$P_{load_b,t} = F_{norm,t} * P_b \,. \tag{1}$$

In the further step an electrical vehicle demand is added to the profile – P_{EV} as a way to fulfil the requirements of Act on Electromobility. It is assumed that during a day a car will be used by officers to work. Hence, a vehicle is charged during nights for 10 hours with power equal to 10% of nominal capacity from Monday to Friday. During weekends an office does not work so a car is not discharged. The constant charging strategy has been chosen to avoid high load peaks and partially smooth the demand. The nominal battery capacities for cars produced in 2017 are assessed based on the data provided by manufacturers [32, 33] and equals to 20 kWh. The final loading states as (2) while consumed energy over a year as (3):

$$P_{load,t} = P_{load_b,t} + P_{EV,t} \,, \tag{2}$$

$$A_{load} = \int_{t=0}^{T=8760} P_{load,t} \,. \tag{3}$$

Fig. 2 illustrates this overall daily profile for a workday and a weekend. The total annual load of the building is about 40 MWh.

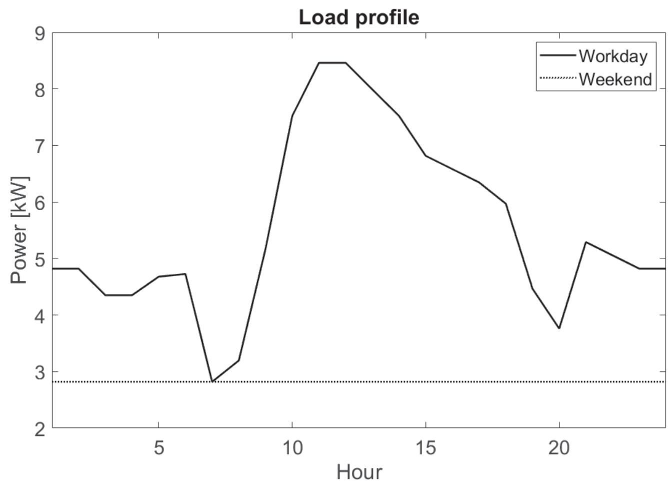

Fig. 2. Daily load profile of consumers

2.3. Renewable energy sources. Next step is the estimation of power source capacity which covers the yearly demand. As the building is located in urban area, only small wind turbines and photovoltaic panels, which can be placed on the rooftops, are taken into account.

Resource data for solar radiation A_{irr} [kWh/m^2/h], temperature [°C] and wind speed v_0 [m/s] available in the Photovoltaic Geographical Information System (PVGIS) [34], supported by European Commission, are used to estimate potential energy produced by power sources. Data from 10-year period 2007–2016 are averaged. The resolution of the measurements is 1 hour and it is assumed that during this time step a value is constant.

Since PV performance is strongly dependent on the cell temperature and module age, additional correction factors are applied to provide accurate data. Based on the critical review presented in [35], an actual cell temperature dependent on wind and ambient temperature is calculated from the formula [36]:

$$T_c = \frac{U_{PV}(v_w)T_a + I\left[\tau\alpha - \eta_{STC}\left(1-\beta_{STC}T_{STC}\right)\right]}{U_{PV}(v) + \beta_{STC}\eta_{STC}I}, \tag{4}$$

where: T_c – cell/module temperature, $U_{PV}(v_w) = 26.6 + 2.3v_w$ – heat exchange coefficient for the total surface of the module, v_w – wind speed close to the module, T_a – ambient temperature, I – in-plane irradiance, STC – Standard Test Conditions ($T_c = 25°$C, $AM = 1.5$, $I = 1000$ W/m^2), β_{STC} – temperature coefficient in STC, η_{STC} – efficiency in STC, T_{STC} – ambient temperature in STC, τ – transmittance of the cover system, α – absorption coefficient of the solar cells, $\tau\alpha = 0.81$.

Further, the cell temperature is used to estimate exact PV electrical efficiency [37]:

$$\eta_c = \eta_{ref}\left[1 - \beta_{ref}\left(T_c - T_{ref}\right)\right], \tag{5}$$

where: reference values – *ref* are given by the producers, usually defined in STC.

Another parameter that influences PV yield is the degradation of a module over time. Based on the research [38], the degradation rate $r_{PV_{degrad}}$ is estimated at 0.7% per year.

Taking all the correction factors into account, the approximate PV output energy from 1 m^2 is calculated using (6) [kWh/m^2]. The raw data are already defined for south direction and 35° module inclination in [34] in i-th year:

$$A_{PV,m^2,i,t} = A_{irr,t}\,\eta_c\,\eta_{system}\left(1 - r_{PV_{degrad}}\right)^i, \tag{6}$$

where: $A_{irr,t}$ – global horizontal radiation scaled to a slope [kWh/m^2/t], η_c, η_{system} – PV module and system efficiency respectively.

For further calculation an additional parameter is introduced based on market data. It tells about real power for square meter: $P_{PV,single,m^2} = P_{PV_{single}}/S_{PV_{single}}$, where $P_{PV_{single}}$ is the rated power of a module [kW] and $S_{PV_{single}}$ is its surface [m^2]. It allows to calculate output energy from 1 kW photovoltaic at a time [kWh/kW] in i-th year:

$$A_{PV,1kW,i,t} = \frac{A_{PV,m^2,i,t}}{P_{PV,single,m^2}}. \tag{7}$$

A power-wind speed characteristic – $P(v_h)$ based on the manufacturer data is used to estimate output power of a single wind turbine ($P_{WT,single,t}$). For a time step, a wind speed value is matched with the corresponding power on the curve $P(v_h)$. In the following year, in order to accurate assess the wind turbine yield, the electrical efficiency is decreased by a degradation rate equal to 1.6% per year [39]. Moreover, formula (8) is used to obtain wind speed on the required building height – 20 meters, while the input comes from 10-meters height anemometer.

$$v_{h,t} = v_{0,t}\left(\frac{h}{h_0}\right)^{\alpha}, \tag{8}$$

where: $v_{h,t}$ – wind speed at the turbine height h in time t, $v_{0,t}$ – wind speed at anemometer height h_0 in time t, $\alpha = 0.22$ – roughness factor.

2.4. Excess and shortage energy. Once the load and power source unit energy are given, few more variables required to find optimal system size are defined.

Produced power (9) and energy (10) at a time step are calculated as follows:

$$P_{prod.,t} = P_{PV,t} + n_{WT}\cdot P_{WT,single,t}, \tag{9}$$

$$\begin{aligned} A_{PV} &= \int_{t=1}^{T} P_{PV,t}\,\mathrm{d}t, \\ A_{WT} &= \int_{t=1}^{T} n_{WT}\cdot P_{WT,single,t}\,\mathrm{d}t, \\ A_{prod.} &= A_{PV} + A_{WT}, \end{aligned} \tag{10}$$

where: $P_{PV,t}$, $n_{WT}\cdot P_{WT,single,t}$, A_{PV}, A_{WT} are the values of power at a time step and energy for the period T respectively for sought PV sizing (P_{PV}) and number (n_{WT}) of single wind turbines of power $P_{WT,single}$.

Further excess power (11) and energy (12) are defined:

$$P_{exc,t} = \begin{cases} 0 & \text{if } P_{prod.,t} - P_{load,t} \le 0, \\ P_{prod.,t} - P_{load,t} & \text{if } P_{prod.,t} - P_{load,t} > 0, \end{cases} \tag{11}$$

$$A_{exc} = \int_{t=1}^{T} P_{exc,t}\,\mathrm{d}t \tag{12}$$

and shortage power (13) end energy (14):

$$P_{sh,t} = \begin{cases} 0 & \text{if } P_{prod.,t} - P_{load,t} \ge 0, \\ P_{prod.,t} - P_{load,t} & \text{if } P_{prod.,t} - P_{load,t} < 0, \end{cases} \tag{13}$$

$$A_{sh} = \int_{t=1}^{T} P_{sh,t}\,\mathrm{d}t. \tag{14}$$

Then for selected period energy balance (15) is calculated:

$$\Delta A = A_{prod.} - A_{load}. \tag{15}$$

2.5. Optimization task. Since the aim of this work is to provide a method that will be useful for wide range of consumers, simplified algorithms are used. The optimization task of this work is to find optimal size of a HES comprising wind turbines and photovoltaics that will cover yearly demand under specific legal conditions. The cost function of this problem is the maximum economic efficiency of the project.

Various methods of determining the economic efficiency of investment projects [40,41] may be applied. One of them is the net present value method. NPV is calculated as the sum of the discounted differences between cash inflow and cash outflow, realized throughout the lifetime of the project, separately for each year. The value of this sum expresses benefit, which development of the project can bring to the investor. Discounting can be carried out for any time, but usually chooses the moment in which it is planned to start construction of the facility. The discount rate should be defined in accordance with certain rules. It can be interpreted as the rate of profit, below which it does not pay to invest (i.e. the minimum rate of efficiency). Net present value is calculated using the following formula:

$$NPV = \sum_{t=0}^{n} (CI_t - CO_t) \cdot (1+r)^{-t} = \sum_{t=0}^{n} \frac{NCF_t}{(1+r)^t}, \tag{16}$$

where: NPV – net present value, NCF_t – net cash flow in year t, n – period of discounting (facility life length), CI_t – cash inflows in year t, CO_t – cash outflows in year t, r – discount rate.

Positive NPV value is the condition of the profitability of the project. The boundary of profitability is $NPV = 0$. Project which gives the highest net present value should be selected. Net Present Value method is applied as a cost function of the optimization task (17):

$$f(P_{PV}, n_{WT}) = NPV \to \max, \tag{17}$$

where: P_{PV}, n_{WT} are the sought variables – PV size and wind turbine number.

To solve the problem the following assumptions are made:

- Energy consumption is assumed to be constant over the whole life cycle. This is due to European Directive on energy efficiency [14] that imposes for public institutions decrease in final energy consumption.
- The cash outflow in "zero" year are the capital expenditures (CAPEX), $CO_0 = C_{system}$ [€], calculated as a sum of PV and wind turbine costs: $CO_0 = C_{PV,1kW} \cdot P_{PV} + C_{WT,single} n_{WT}$, where: $C_{PV,1kW}, C_{WT,single} \in \mathbb{R}^+$, are the costs referred to 1 kW PV [€/kW] and a single wind turbine [€] respectively.
  The capital expenditures C_{system} are as in Tables 2, 3 and are estimated based on the market prices including converter costs as well.
- The power units efficiencies are assumed to decrease by a constant degradation rate over the entire life cycle.
- The energy price equals to $C_A = 0.14$ €/kWh in the first year. In the next 5 years, it grows by 3.7% per year, in next 10 years, by 0.3%. Then it is constant [42].
- Every year, the operation and maintenance costs $C_{o\&m}$ (OPEX) for PV system are equal to 20 €/kW/year and for wind turbines 30 €/kW/year [43].
- The cash outflow beyond the "zero" year are OPEX costs and if happens – the energy purchased from the grid over rebate rate, $C_{out,i} = C_{o\&m} + A_{purchased,i} C_A$.
- The cash inflows are the savings of energy cost that has not been purchased from the grid $C_{in,i} = A_{saved} \cdot C_A$ [€].
- Lifetime of PV modules and wind turbine is $n = 20$ years.
- There are two discount rates r equal to 3% and 7% [44], constant over a whole period.

The set of feasible solutions is subject to the following constraints, defined by the Polish law:

- total power of installation can not exceed 50 kW
  $P_{total} = P_{PV} + P_{WT} \leq 50$ kW,
  $P_{WT} = n_{WT} \cdot P_{WT,single}$,
- overproduced energy entered to grid (A_{exc}) could be retaken in the time of energy shortage (A_{sh}) in the rebate ratio r_{reb} 1:0.7 in annual net metering
  $r_{reb} = \frac{A_{sh}}{A_{exc}} \leq 0.7.$

2.6. Algorithm 1 – monthly balance. The first method of solving the optimization problem is based on the monthly energy values from unit power sources. The algorithm is presented in Fig. 3(a). Having the hourly output power from every source, monthly energy of 1 kW of photovoltaic, single wind turbine and load respectively (18) are calculated. Due to variable weather conditions these values differ in every month.

$$\begin{aligned} A_{PV,1kW,m} &= \sum_{h=0}^{H} A_{PV,1kW,h}, \\ A_{WT,single,m} &= \int_{h=0}^{H} P_{WT,single,h}\, \mathrm{d}h, \\ A_{load,m} &= \int_{h=0}^{H} P_{load,h}\, \mathrm{d}h, \end{aligned} \tag{18}$$

where H corresponds to number of hours in a month m.

The next step is to determine required power source capacity to cover the demand. In Polish climate, weather conditions are changeable over a year. Solar radiation is very slight during autumn/winter period and quite high in summer season. As for wind turbine production, it is in opposite. During autumn/winter it generates almost twice more energy than during summer. Taking it into account it is concluded that these two sources may work complementary and form a HES that could be more reliable and independent.

Further, the priority in power capacity selection is given to PV. This is dictated by the lower CAPEX of PV/kW, higher production per kW, less social resistance associated with the installation of PV compared to WT and easier way of finding an installation place. Hence, to find an optimal capacity of PV system, it is assumed that it should cover most of the demand during summer months. Therefore, required PV power for July (19) is calculated, as it is one of the most sunny months. The value is obtained including previously calculated corrected efficiency, which takes into account actual climate conditions deviation from STC.

$$P_{PV,July} = P_{PV} = \frac{A_{load,July}}{A_{PV,1kW,July}}. \tag{19}$$

Further monthly energy served by selected power of photovoltaic – $P_{PV,July}$ (20) and unserved energy (21) are calculated:

$$A_{PV,m} = A_{PV,1kW,m} \cdot P_{PV}, \tag{20}$$

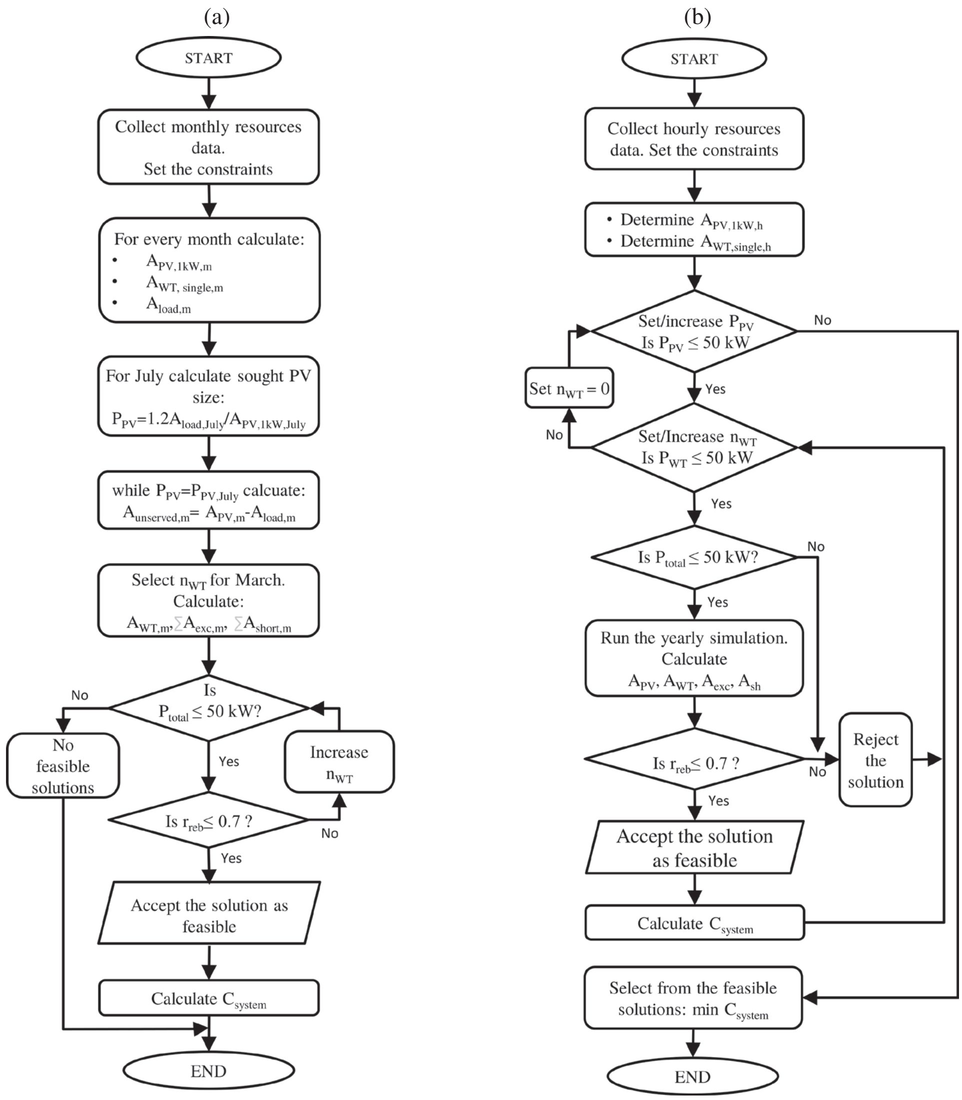

Fig. 3. The algorithm to select power of renewable sources: a) on the basis of monthly balance, b) on the basis of hourly balance

$$A_{unser.,m} = A_{PV,m} - A_{load,m}\,. \tag{21}$$

Once unserved energy in every month is given, it is noticed that the smallest value from autumn-winter period appears in March. Since the indirect aim of the design process is to minimize CAPEX and not oversize the installation, selected initially the number of wind turbines is sufficient to cover unserved energy in March. The item number is obtained by dividing unserved energy by production of a single turbine:

$$n_{WT,March} = \frac{A_{unser.,March}}{A_{WT,single,March}}\,. \tag{22}$$

If for initial number of WT the constraint of ratio r_{reb} is not met, the number is increased by one untill it reaches this condition. At each iteration, the constraint of maximal total power P_{total} is verified to assure feasibility of a solution. At the end, NPV is calculated. Proposed approach for solving the problem resembles a greedy algorithm. The local optimum at a time is sought under certain constraints. However, looking for local optimum does not always lead to global optimum.

2.7. Algorithm 2 – hourly balance. The second method for solving optimization problem is based on hourly energy balance calculation over a year. A simple iterative algorithm is developed and presented in Fig. 3(b). Every possible combination of sought variables under set constraints is checked using to this purpose iterations. To solve the problem Matlab software is used but every script language may be used to this purpose as well.

In the first step, on the basis of 1-hour resolution input resource data, output energy for unit 1 kW PV – $P_{PV,1kW,t}$ and a single wind turbine – $P_{WT,single,t}$ for every hour over a year are calculated. Next by iteration within the allowable range ($P_{total} \le 50$ kW) the number of wind turbines $n_{WT} \in \left\langle 0, \left\lfloor \frac{P_{total}}{P_{WT,single}} \right\rfloor \right\rangle$ and PV power $P_{PV} \in \langle 0, 50 \rangle$ are set or increase resulting in $n_{WT} \cdot P_{PV}$ number of combinations. For i-th iteration corresponding hourly energy production during a year: $A_{PV,i}$, $A_{WT,i}$, $A_{exc,i}$, $A_{sh,i}$ are calculated. In this case, the total excess energy (A_{exc}) and shortage energy (A_{sh}) are the sum of hourly values. This approach corresponds more to real net metering process.

From all the solutions, these which do not fulfil criterion of rebate ratio r_{reb} and maximum total power P_{total} are rejected. The pool of feasible solutions is narrowed by lower limit of $r_{reb_{\min}} = 0.69$. This margin is set to avoid significant energy loss, which after specific time could not be retaken and simply is lost. At the end, the solutions are sorted in descending order of NPV and the most profitable one is selected.

2.8. HomerPro. HomerPro is the software for optimizing microgrid design. It supports off-grid and on-grid systems and helps to find optimal solution with regard to size, technology, number of renewable energy sources and cost. By default, it uses the NASA Surface meteorology and Solar Energy database to import resource data. Input solar data are global horizontal radiation (GHI) monthly averaged values from 22 year period – 1983–2005. They are the base to create hourly data with use of build-in algorithm with statistical parameters. According to manufacturer, the accuracy of artificial data is over 95%. Wind speed data are monthly averaged values from an anemometer of 50 m height placed on the terrain of roughness factor 0.01, what corresponds to flat or undulating terrain with open, large spaces.

The software includes two optimization algorithms. The first provides information about all feasible solutions under specified by user conditions and power source combinations. The second looks for system with minimal cost independent of power sources defined by user. After calculations, detailed data about operation of every component in a system as well as its cost are available. The aspect which is particularly of our interest is the methodology of calculating output power of PV and wind turbine. From user manual [45], the equation to calculate PV output power (23) is extracted. To calculate output power of wind turbine, the software uses the same equations as we to estimate wind speed at certain height (8) and next compares this value with wind-power curve. The software provides its own algorithm to generate artificial time-series wind speed data from monthly averaged values, which with high probability corresponds to real measurements. This algorithm is based on Weibull distribution.

$$P_{PV_{Homer}} = Y_{PV} f_{PV} \frac{G_T}{G_{T,STC}}, \tag{23}$$

where: Y_{PV} – rated capacity of the PV array under Standard Test Conditions (STC) [kW], f_{PV} – PV derating factor (80%), which corresponds to reduced output power comparing to rated power under STC, G_T – the solar radiation incident on the PV array in the current time step calculated for specific PV azimuth, slope and Sun position, $G_{T,STC}$ – the solar radiation incident on the PV array under STC.

Except from the aforementioned data, the software allows a user to import own files with time-series data. This option is used at the end of the study to investigate the impact of resource data on final scores. The solar and wind data from PVGIS database are imported and compared.

3. Results

3.1. Comparison of methods. Since different methods are used to solve the optimization problem, another objective of this work is to establish the divergence between them. In this section, the results obtained with use of two approaches are compared and further, the results are benchmarked with the output of HomerPro software to validate the overall correctness.

Following the methodology predicated only on monthly energy balance, the sought variables are as follows: PV power – $P_{PV} = 27$ kW and number of wind turbines $n_{WT} = 7$, each of 2.8 kW. That leads to total power of $P_{total} = 46.6$ kW.

The analysis based on hourly data yields to different results: PV power – $P_{PV} = 46.8$ kW and $n_{WT} = 0$ wind turbines. It leads to the total power of $P_{total} = 46.8$ kW.

At this point, it is noticeable that two proposed in this paper algorithms lead to almost the same system size, although the choice of particular source capacities is completely different. Then, the next step is to validate which of the algorithm is more accurate. To this purpose HomerPro software is used and obtained results are compared. Table 2 summarizes the yearly outcomes for solution based on Method 1 – monthly balancing. The reference values (on the basis of which the source power capacities have been obtained) are placed in the column *Spr-sh* while three next columns present results obtained with use of other software. Table 3 summarizes the yearly outcomes for solution based on hourly balancing respectively. The reference values are placed in the column *Matlab*. Comparing our calculations to HomerPro calculations few interesting issues are noticed.

Table 2
Comparison of results – Method 1

	Method 1 – monthly data $P_{PV} = 27$ kW $P_{WT} = 7 * 2.8$ kW			
	Spr-sh (PVGIS)	Matlab (PVGIS)	Homer (PVGIS)	Homer (NASA)
A_{PV} [MWh/year]	27.91	28.43	24.93	21.57
A_{wind} [MWh/year]	15.53	14.04	13.76	11.96
A_{load} [MWh/year]	40.17	39.82	40.94	40.94
A_{exc} [MWh/year]	7.82	17.19	12.77	9.18
A_{sh} [MWh/year]	4.55	14.84	16.76	18.56
Max. allowed energy purchase for $r_{reb} \leq 0.7$ [MWh/year]	5.47	12.03	8.94	6.43
if $r_{reb} \leq 0.7$?	Yes	No	No	No
C_{system} [€]	43 275			

Table 3
Comparison of results – Method 2

	Method 2 – hourly data $P_{PV} = 46.8$ kW $P_{WT} = 0$ kW			
	Spr-sh (PVGIS)	Matlab (PVGIS)	Homer (PVGIS)	Homer (NASA)
A_{PV} [MWh/year]	45.58	49.28	44.14	37.4
A_{wind} [MWh/year]	0	0	0	0
A_{load} [MWh/year]	40.17	39.82	40.94	40.94
A_{exc} [MWh/year]	14.66	30.84	24.88	19.01
A_{sh} [MWh/year]	7.12	21.39	23.89	24.51
Max. allowed energy purchase for $r_{reb} \leq 0.7$ [MWh/year]	10.26	21.59	17.40	13.31
if $r_{reb} \leq 0.7$?	Yes	Yes	No	No
C_{system} [€]	38 610			

First, according to Table 2, solar energy values for the same input database (PVGIS) for spreadsheet and Homer calculations differ about 9%. While the selected PV power, found with method 1, is an input to hourly Matlab calculations the divergence between spreadsheet and Matlab outcomes is very slight – about 2%. Concerning wind energy values, the deviations between HomerPro and spreadsheet is higher – about 11%. However, in terms of HomerPro only, the change of input database causes difference by ca. 14% for solar and ca. 13% for wind energy. Thus, it is concluded that the deviations of total yearly produced energy are not so significant and are within yearly weather variations. Moreover, HomerPro processes solar irradiance and wind speed data in more sophisticated way adding additional correction and deterioration factors that result in lower energy generation from both power sources. According to Table 3 the discrepancies between the results from the different software are similar to percentage level as in Table 2.

Apart from the above, the most significant differences are observed for excess (A_{exc}) and shortage energy (A_{sh}) values in proposed algorithm 1 (monthly analysis) comparing to HomerPro – about 72% and 264% respectively. It results from the calculation method that in the case of method 1 is simply the difference between produced energy during a month and load. HomerPro as well as proposed method 2 contain input data with 1-hour time step which is more accurate and leads to similar results. The deviation in this case is 12–19% for PVGIS database. However, this difference between results lead to not complying with the constraint of rebate ratio $r_{reb} \leq 0.7$ for HomerPro solution as shown in the Table 3.

For further result analysis, detailed monthly data over a year are presented. Fig. 4 presents the comparison of method 1 and 2. Obviously, distinct power selection problem solutions yield to the totally different outputs. Although, at first sight, the bar charts give an impression of higher energy imbalance in the case of hourly analysis, a deeper look revises this impression.

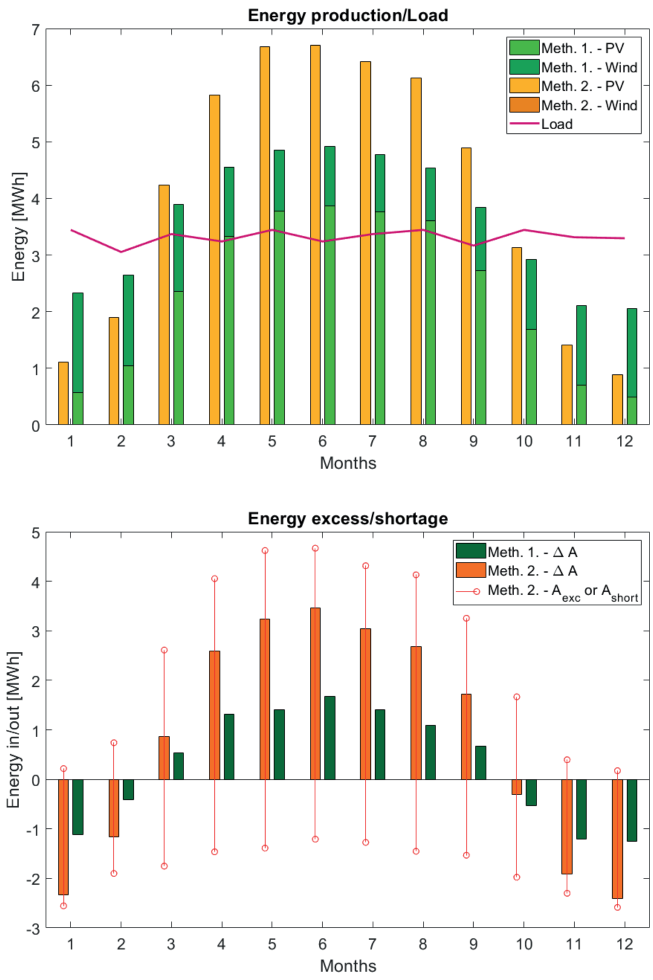

Fig. 4. Energy production and load and excess and shortage energy over a year solved with use of method 1 – monthly data, and method 2 – hourly data

The values of shortage and excess energy are worth highlighting. Monthly method provides only cumulative results and energy balance is based on difference between production and load in a month (ΔA). There is no information about temporary lack or overproduction of energy. Hourly method provides more detailed results, energy shortage or excess is calculated at every hour and at the end of the month the values are summed up. Energy balance is, as in previous case, calculated as the difference between total generation and load. Thus, the figure shows that the yearly ratio of shortage energy (A_{sh}) to excess energy (A_{exc}) in the case of monthly analysis, understood as the energy balance with appropriate sign, may lead to incorrect interpretation and wrong decisions. Fig. 5 illustrates comparison of method 1 (monthly balancing) results with HomerPro output for PVGIS database. Again, it is shown how misleading the interpretation of shortage and excess energy is, understood as the energy balance in a given month. Fig. 6 shows the results for method 2 (hourly balancing). The most interesting are the values of energy balance and excess and shortage energy. In this case, results from both HomerPro and Matlab are more convergent. The differences come from calculation methodology and resource data processing.

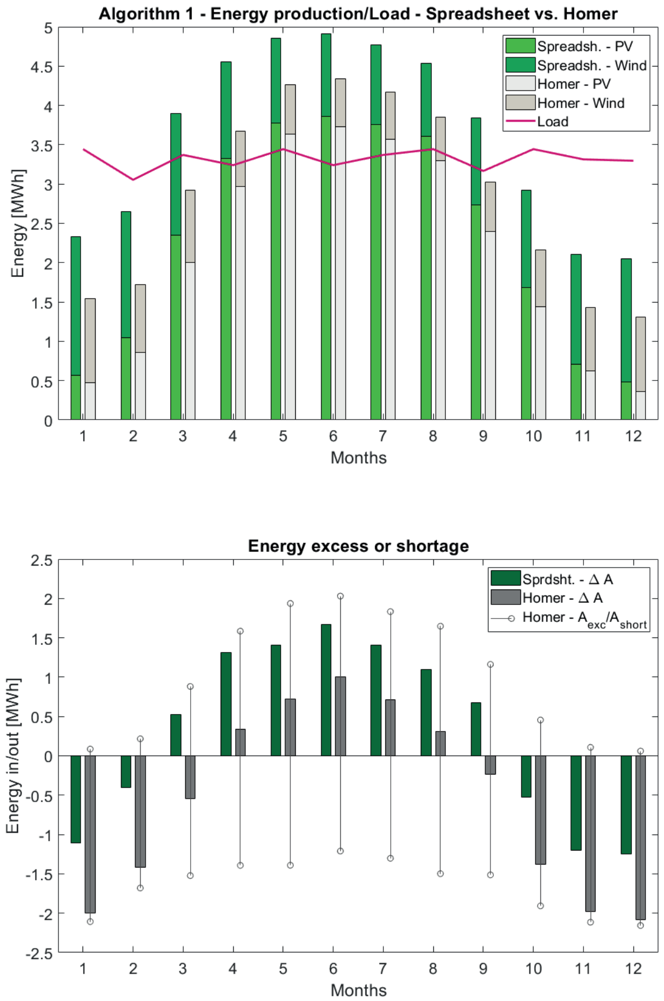

Fig. 5. Results over a year obtained from Spreadsheet and HomerPro on the basis of monthly analysis solution

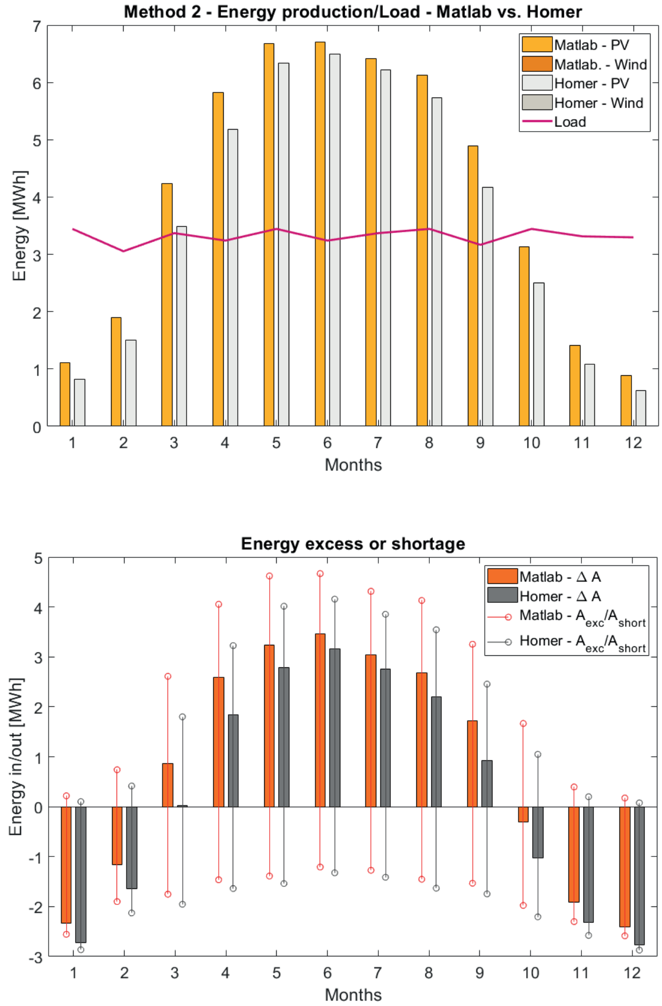

Fig. 6. Results over a year obtained from Matlab and HomerPro on the basis of hourly analysis solution

3.2. Economic analysis. In the Fig. 7, net present values over 20-year installation lifetime are illustrated. The results show that for 3% discount rate NPV value starts to be positive in 9-th year for hourly balancing method and in 12-th year for monthly balancing method. For 7% discount rate the period of return is 13 and 19 years respectively. It is worth highlighting that over the years, the NPV curves for both methods become more divergent. It is caused by decreased energy production due to including power source degradation factors. For monthly method, the amount of energy that has to be purchased from the grid grows in the following years more than for houlry method, resulting in higher yearly costs.

Although, at the beginning hybrid energy system has been assumed, the method 2 shows that taking into account the constraints more efficient will be system based only on PV. This comes from two reasons: first is the price of wind turbine that in comparison with 1 kW PV is still higher. If the cost of a wind turbine fell by 30%, the solutions would change. The number of wind turbines would increase and the capacity of PV would decrease. However, such a scenario is rather improbable in the near future. The second reason are the climate conditions. Even

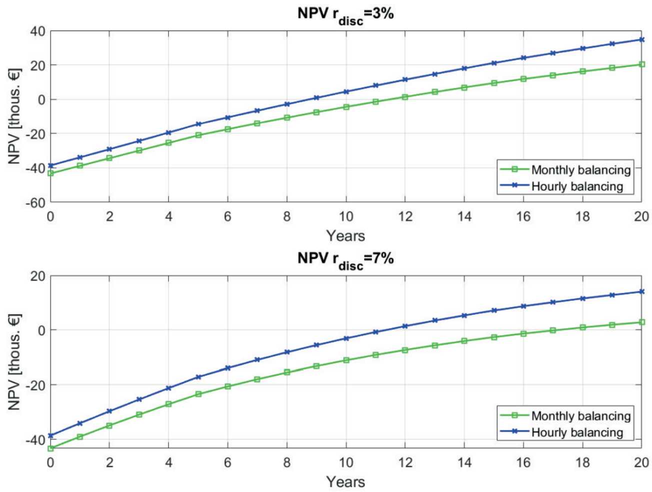

Fig. 7. NPV for different methods and two discount rates

though a VAWT seems to be more appropriate for low wind speed, its performance is still not sufficient to cover the demand in an efficient way.

4. Conclusions

The results confirmed the well-known statement that input data have the strongest impact on obtained output. Thus, for HES design the most crucial is climate condition analysis. Regardless of the calculation method, the resource data may lead to totally different solutions. Many databases may be found online and every year their number available for public is growing. Many countries also have national meteorological institutes that collect detailed, local measurements. In Poland, such a unit is the Institute of Meteorology and Water Management. However, data available to public on the server does not contain solar radiation or wind speed. The resolution of measurements is also limited to a day. Therefore, when designing renewable energy systems it is recommended to gather detailed measurements on site.

HomerPro software assures high accuracy of results and provides sophisticated algorithms to create synthetic hourly data from monthly averaged values for both wind and solar. Its calculations also include correction factors for rated power defined by a user, which corresponds to real conditions. However, as it has been shown, its output quite strongly depends on the used resource database. In comparison with two methods proposed in this paper, it is observed slight divergence between total yearly values of solar and wind energy. However, more detailed study of monthly values give quite high discrepancies.

As long as analysis based only on monthly total energy values is concerned, it seems that the results are not sufficient to consider them meaningful. Especially when an owner is subject to net metering process and Polish law regulations of rebate ratio. Thus, the consideration of too long time period (such as a month) to energy balance calculation will lead to improper sizing of hybrid energy system and in the end will affect the capital expenditures and incomes.

On the other hand, although some correction factors have been neglected by us in hourly analysis, the results obtained on the basis of PVGIS data seem to be highly accurate. These results coming from hourly analysis are surely more reliable and comprises data similar to the one received by net metering. The algorithm proposed in this paper may be easily applied to any script language. The results of this work are in our opinion particularly helpful and meaningful for prosumers in preliminary design process in Poland. Thanks to them, self-government units (or individual low voltage end-users) may apply the developed approach to check the future incomes and to find optimal power source sizes. It seems to be extremely important when the requirements imposed by the standard of energy efficiency are taken into account. However, research shows that renewable generation may not be treated as stable and predictable. Potential owners should be aware of possible deviations from the assumed goals.

References

[1] J. Paska, *Distributed energy sources*, Publishing House of Warsaw University of Technology, Warsaw, 2017 [in Polish].

[2] J. Paska, M. Kłos, and P. Biczel, "Hybrid power systems – an effective way of utilising primary energy sources", *Renewable Energy* 34, 2414–2421 (2009).

[3] Y. Sawle, S. Gupta, and A.K. Bohre, "Review of hybrid renewable energy systems with comparative analysis of off-grid hybrid system", *Renewable and Sustainable Energy Reviews* 81, 2217–2235 (2018).

[4] V. Khare, S. Nema, and P. Baredar, "Solar–wind hybrid renewable energy system: A review", *Renewable and Sustainable Energy Reviews* 58, 23–33 (2016).

[5] L. Bartolucci, S. Cordiner, V. Mulone, V. Rocco, and J.L. Rossi, "Hybrid renewable energy systems for renewable integration in microgrids: Influence of sizing on performance", *Energy* 152, 744–758 (2018).

[6] M.D. Al-Falahi, S. Jayasinghe, and H. Enshaei, "A review on recent size optimization methodologies for standalone solar and wind hybrid renewable energy system", *Energy Conversion and Management* 143, 252–274 (2017).

[7] J. Lian, Y. Zhang, C. Ma, Y. Yang, and E. Chaima, "A review on recent sizing methodologies of hybrid renewable energy systems", *Energy Conversion and Management* 199, 112027 (2019).

[8] K. Anoune, M. Bouya, A. Astito, and A.B. Abdellah, "Sizing methods and optimization techniques for PV-wind based hybrid renewable energy system: A review", *Renewable and Sustainable Energy Reviews* 93, 652–673 (2018).

[9] J. Kartite and M. Cherkaoui, "Study of the different structures of hybrid systems in renewable energies: A review", *Energy Procedia* 157, 323–330 (2019).

[10] J. Jurasz and J. Mikulik, "Economic and environmental analysis of a hybrid solar, wind and pumped storage hydroelectric energy source: a Polish perspective", *Bull. Pol. Ac.: Tech.* 65 (6), 859–869 (2017).

[11] European Parliament Think Tank, "Climate and energy policies in Poland", http://www.europarl.europa.eu/thinktank/en/document.html?reference=IPOL_BRI(2017)607335, 2017.

[12] Directive (EU) 2009/28 of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources, EUR-Lex Portal, https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32009L0028.

[13] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, EUR-Lex Portal, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32018L2001

[14] Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency, EUR-Lex Portal, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32018L2002.

[15] Act on renewable energy sources, L.J. of 2015, item 478, http://prawo.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20150000478 [in Polish].

[16] J. Kuchmacz and L. Mika, "Description of development of prosumer energy sector in Poland", *Polityka Energetyczna – Energy Policy Journal* 21 (4), 5–20 (2018).

[17] Act on energy efficiency, L.J. of 2016, item 831, http://prawo.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20160000831 [in Polish].

[18] Act on electromobility and alternative fuels, L.J. of 2018, item 317, http://prawo. sejm. gov. pl/ isap.nsf/ DocDetails.xsp?id= WDU20180000317 [in Polish].

[19] J. Kiciński, "Do we have a chance for small-scale energy generation? The examples of technologies and devices for distributed energy systems in micro & small scale in Poland", *Bull. Pol. Ac.: Tech.* 61 (4), 749–756 (2013).

[20] A.S.A. Busaidi, H.A. Kazem, A.H. Al-Badi, and M.F. Khan, "A review of optimum sizing of hybrid PV–Wind renewable energy systems in Oman", *Renewable and Sustainable Energy Reviews* 53, 185–193 (2016).

[21] A. Maleki, and F. Pourfayaz, "Optimal sizing of autonomous hybrid photovoltaic/wind/battery power system with LPSP technology by using evolutionary algorithms", *Solar Energy* 115, 471–483 (2015).

[22] S. Zahraee, M.K. Assadi, and R. Saidur, "Application of artificial intelligence methods for hybrid energy system optimization", *Renewable and Sustainable Energy Reviews* 66, 617–630 (2016).

[23] A.P. Kumar, "Analysis of hybrid systems: Software tools", *2016 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB)*, 327–330 (2016).

[24] P. Palej, H. Qusay, S. Kleszcz, R. Hanus, and M. Jaszczur, "Analysis and optimization of hybrid renewable energy systems", *Polityka Energetyczna – Energy Policy Journal* 22 (2), 107–120 (2019).

[25] N. Dragutinovic and B. Smaragdakis, "Hybrid renewable energy system application for electricity and heat supply of a residential building", *Thermal Science* 20 (2), 695–706 (2016).

[26] I. Panapakidis, D. Sarafianos, and M. Alexiadis, "Comparative analysis of different grid-independent hybrid power generation systems for a residential load", *Renewable and Sustainable Energy Reviews* 16 (1), 551–563 (2012).

[27] J. Paska, M. Kłos, K. Pawlak, K. Zagrajek, P. Marchel, M. Błędzińska, Ł. Michalski, and P. Terlikowski, "Topologies of hybrid RES installations with the strategy of contracting energy", *Przegląd Elektrotechniczny* 10/2019, 94–97, [in Polish].

[28] Monocrystalline PV module specification, https://www.sharp.pl/cps/rde/xchg/pl/hs.xsl/-/html/product-details-solar-modules.htm?product=NUAK300.

[29] Power-wind speed characteristic, Hipar turbine 2.8 kW, http://hipar.pl/turbiny-wiatrowe/kalkulator-oplacalnosci-turbinecorote/kalkulator/ (Accessed: 18.04.2019) [in Polish].

[30] P. Banasiak, A. Gorczyca-Goraj, and M. Przygrodzki, "Analysis of load schedules of a selected segment of low-voltage customers", *Energetyka* 01/2017, 23–27 (2017), [in Polish].

[31] Central Statistical Office in Poland, Report: Study of the energy efficiency of public administration buildings (government and self-government) in the years 2007–2013 (Accessed: 18.04.2019), https://stat.gov.pl/statystyki-eksperymentalne/srodowisko-efektywnosc-energetyczna/badanie-efektywnosci-energetycznej-budynkow-administracji-publicznej-rzadowej-i-samorzadowej-za-lata-2007-2013-popt-2007-2013,4,1.html [in Polish].

[32] Nissan website, electric car parameters, https://www.nissan-global.com/EN/index.html

[33] BMW website, electric car parameters, https://www.bmw.com/en/index.html.

[34] PVGIS portal, http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html.

[35] C. Schwingshackl, M. Petitta, J.E. Wagner, G. Belluardo, D. Moser, M. Castelli, M. Zebisch, A. Tetzlaff, "Wind Effect on PV Module Temperature: Analysis of Different Techniques for an Accurate Estimation", *Energy Procedia* 40, 77–86 (2013).

[36] M. Mattei, G. Notton, G. Cristofari, M. Muselli, and P. Poggi, "Calculation of the polycrystalline PV module temperature using a simple method of energy balance", *Renewable Energy* 31, 553–567 (2006).

[37] E. Skoplaki and J.A. Palyvos, "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations", *Solar Energy* 83 (5), 614–624 (2009).

[38] I. Tetsuyuki and M. Atsushi, "Annual degradation rates of recent crystalline silicon photovoltaic modules", *Progress in Photovoltaics: Research and Applications* 25, 953–967 (2017).

[39] I. Staffell, and R. Green, "How does wind farm performance decline with age?", *Renewable Energy* 66, 775–786 (2014).

[40] P. Terlikowski, J. Paska, K. Pawlak, J. Kaliński, and D. Urbanek, "Modern financial models of nuclear power plants", *Progress in Nuclear Energy* 110, 30–33 (2019).

[41] J. Paska, *Economics in electrical power engineering*, Publishing House of Warsaw University of Technology, Warsaw, 2007, [in Polish].

[42] The Ministry of State Assets in Poland, Polish energy policy until 2040 – project (2019), https://www.gov.pl/web/aktywa-panstwowe/polityka-energetyczna-polski-do-2040-r-zapraszamy-do-konsultacji1 [in Polish].

[43] Lazard, Levelized Cost of Energy Analysis – ver. 13.0, 2019, https://www.lazard.com/perspective/lcoe2019 (Accessed: 10.12.2019).

[44] NEA, IEA, OECD, Projected Costs of Generating Electricity (2015) https://www.oecd-nea.org/ndd/egc/2015/

[45] HomerPro User Manual, https://www.homerenergy.com/products/pro/docs/3.13/index.html (Accessed: 10.05.2019).