Chapter

Optimization of Stand-Alone Hybrid Solar-Wind System by Using General Morphological Analysis

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Abstract

At the beginning of this chapter is a brief introduction to the issue of renewable energy sources. Next, aspects that should be considered when choosing a location of both solar photovoltaics panels and wind turbines are discussed. Afterwards, there is a brief theoretical introduction to the General Morphological Analysis (GMA), followed by practical application of GMA to optimize the structure of hybrid solar-wind system, which is preceded by a description of the adopted design assumptions. At the end of the chapter is a numerical model of a hybrid solar-wind system developed in the MATLAB/Simulink environment and analysis of the results of numerical simulations.

Keywords: wind turbine (WT), solar photovoltaic (PV) module, hybrid renewable energy system, global horizontal irradiance (GHI), direct normal irradiance (DNI), general morphological analysis (GMA), cross-consistency assessment (CCA)

1. Introduction

Over the past few years, renewable energy sources have been on everyone's lips—especially those who are a little closer to the topic of energy sources. There's no wonder in this, because sooner—thanks to legislation of the developed countries—or later, through the total exhaustion of conventional sources of energy, renewable sources of energy will play a major role in energetics. In addition, continuous expansive use of nonrenewable energy sources by man causes global climate change and increases pollution of the Earth's atmosphere. The use of renewable energy sources by installing micro-installations by individual customers (single-family houses, small farms, small companies) is one of the ways to reduce the effects of excessive exploitation of fossil deposits. However, micro-installations using renewable energy sources due to their specificity, e.g., dependence on the time of day and year, and weather or geographical location, cannot be the main source of energy in the current state development of technology. In many cases they must be supported by traditional energy sources (gas, oil, or coal). An alternative idea is to use more efficient hybrid solutions, i.e., based on at least two renewable energy sources. Solar-wind micro-installation is the most common hybrid system in non-conventional power plants. This is because these two renewable energy sources complement each other perfectly.

2. Criteria for choosing a location for hybrid solar-wind system

2.1 Criteria for choosing a location for wind turbine

In selecting the location for wind turbine, it is necessary to consider a lot of criteria. The most important of them is wind condition analysis. The wind characteristics of the certain area can be determined by carrying out at least 12-month measurements at a height of 40–50 m. This allows to calculate the average annual wind speed and determines its dominant directions. This data is necessary to estimate the profitability of investment. To reduce investment costs, you can use data from local meteorological station (e.g., see [1]) or Global Atlas for Renewable Energy from [2] or [3].

Another factor which must be considered is the distance between wind turbine and residential building. In order to reduce the so-called turbulences, it is important to consider the shape of the area and to identify all obstacles such as trees or houses. It can be assumed that within the approximate radius of 20 times heights of obstacle, in this case height of wind turbine, the wind can be turbulent, thus lowering operating efficiency. Additionally, wind turbine cannot exceed the permissible noise standards. According to the analysis of the principles contained in [4, 5] adopted in 24 countries, German lands and Canadian provinces [6], it follows that minimal distance between buildings and wind turbines is in the range from 500 up to 1000 m. The most rigorous criterion is in Scotland, where this distance is 2000 m. Maximum noise level of wind turbine in residential places (measured outside of this buildings) in most countries ranges from 30 up to 50 dB. Wind turbine works silently, so resultant noise is related to rotation of the blades and control devices. Wind turbine should be also placed away from human settlements to mass or construction dimensions and its flickering [7]. Shadow length depends on the height of wind turbine and the angle of sunlight. Additional factors that affect the intensity of flickering are, inter alia, rotor diameter, cloudiness, the presence of trees between wind turbine and living buildings, and the arrangement of windows in buildings [8, 9].

Environmental factors also play an important role; therefore decisions on investment and location conditions should be obtained. For Poland, these guidelines are contained in [10]. Wind turbine placement on legally protected areas, such as national parks, nature reserves, landscape parks, and area of "Natura 2000," is strictly limited [11]. Placement of wind turbine on the area of national parks and nature reserves according to the law is prohibited. Localization of wind turbine in less restricted areas such as landscape parks is possible when the project gets a positive opinion of the park's director and positive environmental impact assessment. The wind turbine location in the area of "Natura 2000" is possible only with a positive environmental impact assessment and a natural compensation condition. It should be taken into account that a wind turbine project in a valuable place due to flora and fauna resources may be rejected by local authorities at the stage of making environmental decisions [10–12].

Due to the high cost of constructing the wind turbine, many economic aspects should be taken into account. In choosing a location for the wind turbine, the price of land, road infrastructure, distance from power grid, and possibility of connecting to it should be considered. Wind turbine requires connection to the power grid for start-up and further operation; therefore, the project must take this into account. Single wind turbines may be connected to a medium voltage line through the transformers mounted directly on power poles, while big wind farms require the use of Main Supply Point (GPZ-MSP) that converts produced energy into higher voltage level to bring it to the high voltage transmission network.

GPZ-MSP should be localized near wind farm due to capital-intensive and time-consuming preparation of energy connection. Additionally, wind turbines should not be built in areas exposed to mining damage, with high seismic activity, or in areas at risk of eruptive river. Except localization, economic criteria should take into account cost of investment itself, where the biggest expense is cost of the wind turbines. Other expenses that will take place are the cost of design and preparatory works, cost of road infrastructure, cost of the earthworks, and cost of connection to several utilities. Also, there are also some operating costs during wind turbine normal operation. There are taxes, insurance payments, technical service, environmental fees (they appear to be sometimes very high), and possibly some other depending on location and other aspects.

When choosing a location, social conditions should be taken into account. It must be estimated how much wind turbine construction may improve or worsen the comfort of life for residents of nearby towns and villages. Before starting a project, consultations should be carried out with local authorities, to recognize city development plan and provide information about the scale of the investment and social, economic, and environmental consequences. Local authorities usually accept investments in wind turbines, because they see the chance to increase budget income from local taxes. At the same time local communities are afraid of the influence of such wind turbines on their health and surrounding landscape. Therefore, during the preparation and construction of wind turbine, educational activities should be carried out to provide relevant information about project wind energy among the public [12].

2.2 Criteria for choosing a location for solar system

When calculating revenues from investments in solar energy, the first parameter to consider is latitude. Let us suppose that the Earth is round (a sphere). This causes the rays from the sun to hit the Earth's surface at different angles, ranging from 0° (when the sun is above the horizon) to 90° (when the sun is perpendicular to the Earth). The angle of incidence of sunlight depends on geographic location, the time of year, and the time of day. The power of the rays from the sun describes such quantities as solar radiation, Global Horizontal Irradiance, Direct Normal Irradiance, Diffuse Horizontal Irradiance (DIF), and insolation. Solar radiation, often called the solar resource, is a general term for energy emitted from the sun in the form of electromagnetic waves. There is also defined GHI which is the ratio of the total amount of shortwave radiation falling horizontally on ground from outer space. This is the value that best describes the parameters for solar installations and includes both DNI and DIF parameters. Most energy radiated from the sun hits the Earth's surface when the sun is perpendicular to it. The smaller the angle, the more the rays from sun dissipate, providing less energy. Therefore, the amount of energy acquired from the Sun is usually determined by DNI parameter, which means the amount of solar radiation received per unit area by a given surface measured on a flat plane perpendicular (or normal) to the rays from the sun. This is one of the most important parameters that should be considered in order to maximize the efficiency of photovoltaic panels. The DHI means a quantity of energy received per area unit by a surface (which is not subjected to any shade) that does not arrive in a direct path from the sun but is scattered by molecules and particles in the atmosphere and comes potentially from all directions [13–15].

According to [16], uncertainty reduction related to the insolation in each area directly implies increasing the predictability of energy production capabilities. Insolation measures the solar energy and is the resultant on a specified area over a period of time and is expressed in two ways. The first one is watt-hours per square meter (Wh/m^2) measured per day which represents the average amount of energy hitting the area each day. The second way represents the average amount of power hitting the area over the entire year and is expressed in watts per square meter (W/m^2) [13, 14].

When defining solar photovoltaic module for project there are needed data that describes insolation. To know the values for each region, the required and proper surface area of solar panels can be calculated. In order to acquire reliable and objective values that describe solar efficiency, their measurements should be carried out for a period of 5 years and take the mean value from this period to compute solar effectiveness. This long period for observations is caused by the varied weather conditions that may occur during these years, where the number of sunny and cloudless days changes. Those values may also be obtained from solar resource map © 2019 Solargis [17]. It is very important to remember about uneven distribution of sunlight that results from meteorological (number of sunny days) and geographical (variable day length) conditions. In winter sunlight may be up to seven times weaker than in summer. In Poland between May and July, the Sun allows to produce near 200 kWh/m^2, but in winter—between December and January—it is no more than 32 kWh/m^2; solar energy resources in Poland are characterized by high variability throughout the year. Up to 77% of the year's solar energy is available in 6 months of spring–summer period (April–September).

Apart from the sunshine conditions discussed above during solar panel selection, there are more conditions that have to be taken into account such as air pollution and precipitation. Temperature, air pollution, and dirt factors of PV module reduce the conversion efficiency of the solar plant equipment. Oberlander in his BSc thesis [18] showed that dirty PV cells in damp climates cause significant losses of output power. He showed that there is a 9% loss greater in PV module efficiency from 12 g/m^2 polluted area than previously reported efficiency losses in other literature. Experimental researches presented in [19] showed that dirt settling from construction pollutants (plaster, cement, and borax) in the form of layer of weight of 10 g reduces performance of the PV panels by over 25.8%. Xiaoyuan et al. showed in their work [20] that aerosol pollution in China reduces the production on optimally tilted fixed PV panels by up to 1.5 kWh/m^2 per day, incurring a high percentage decrease (25–35%) in polluted northern and eastern China. Etim et al. in [21] showed also that solar energy decreases as relative humidity and high rainfall increase.

Additionally, a factor that has an impact on investment in solar energy decisions is refunding. As part of EU policy, companies can receive funding for renewable energy sources. In Poland the National Fund for Environmental Protection and Water Management offers loans and subsidies and other forms of refunds for local governments, public organizations, and social organizations as well as for individuals.

3. Theoretical and methodological foundations of GMA

Nowadays, more and more engineering problems are related to innovation and optimization of production processes, and analytical methods used so far do not provide ready algorithms for their solution. Here we are talking about creative problems, in which when solving, synthesis is more important than analysis, intuition than logical thinking, and subconsciousness than consciousness. The answer to demand formulated this way was the development of creative-thinking methods that support best or optimal result search. Optimization methods are used when the solution concept is known for mechanical device or service. On the other hand, during search of solution for innovative solutions and original idea, where the main role plays unlimited human ingenuity, creative solving methods are used, called also inventive methods. GMA is one of inventive methods. According to method's creator Zwicky, morphological analysis is the method for identifying, indexing, and investigating the total set of relationships or "configurations" contained in multidimensional, non-quantifiable complex problem [22–25]. GMA is often called the method of producing inventions, because the way of processing according to its principles forces ordering temporary and potential solution proposals at the beginning and next joining them into new potential solution proposals. This method allows or even imposes joining new value of two or more proposals, solutions, and conceptions although on the beginning it seems to be absurd or even impossible. The basic rules of methodical conduct according to are described below GMA.

Precisely identifying and defining parameters (or dimensions) of the complex problem are the starting point of GMA application. Identified parameters (or dimensions) are called fundamental variables. These variables represent the considered meta-model research in the initial problem space called the morphosphere. Please note that a morphological model contains only discrete variables, even if variable in morphosphere looks like a continuous variable (e.g., product mass or construction dimensions); it is treated as discrete and evaluated in this way. Next, for each parameter (fundamental variable), should be define the set of value. These values represent possible, appropriate states or conditions that each parameter can adopt. In this way, a set of ideas is developed, which can be separate solutions or cases. Then for each of these variables, a range of relevant values or conditions is assigned. In the next step, a multidimensional matrix is being created called a morphological box or "Zwicky's box." The morphological box is created by setting all considered variables together with their features, values, states, etc. Each cell of the morphological box contains one particular "value" or condition from each of the fundamental variables. Internally it is a typological field containing all the possible involved relationships. A graphic interpretation of the typological field is a physical space assuming that it does not exceed three variables. When there are more variables, graphical interpretation becomes hyperspace. In such cases its creation is omitted by combining variables within each other [22–26].

In the next step, the formal configurations or potential morphotypes are determined, i.e., all combinations between individual ideas for all parameters. Every element of the formal configurations becomes a potential solution, so it requires further analysis. By the term morphological analysis, we mean searching for a subset r-connections in a given formal configuration. All r-connections or part of them may be chosen using morphological research: by systematic enumeration, by limited enumeration, by randomization, by random walk method, and by similarity methods or sequentially.

Depending on the enumeration method, r-connection different varieties of morphological method can be obtained in result. In morphological method searching for creative solutions takes place in a specific cycle (**Table 1**).

The first stage of morphological analysis involves recognizing the problem and proceeds in two phases. First phase involves setting boundaries of problem. The main purpose of this phase is to define the full shape of a given problem. The natural tendency to narrow the problem should be overcome, but on the other hand, it is necessary to define boundary points, which further help to define problem precisely and to realize the second phase of this stage.

Further in the second phase, the range of these variables is determined. Therefore, ideas are sought to implement fragment of the problem, as if it did not exist as a whole. This assumption has a significant impact on the number and quality of ideas, because during searching for a solution of a problem, we are not limited by the requirements

Stages	Phases	The most commonly used supportive methods
Recognition of the problem	• Determining the limits of the problem • Defining the problem	Teratological method
Analysis of the problem	• Identification of problem parameters • Search for possible parameter states	Brainstorm Synectic techniques
Problem synthesis	• Construction of the morphological box or morphological field • Reduction of morphospace	Monte Carlo method Moles' discovery matrix

Table 1.
Procedure of GMA.

and conditions forced by the whole problem. In this way it is easier to break away from existing solutions and the same way to prepare new ground for new proposals.

Third stage, depending on the number of variables, begins with construction of morphological box or morphological field. Each coordinate of morphological box represents certain parameter or states. "Coordinate measure" represents the next idea. By multiplying the "measures," a morphological product is obtained. In this way a very rich set of potential solutions that include original solutions arises. Thanks to methodical requirements, it can be combined into new value ideas which previously appears impossible to aggregate. Normative elements are introduced after creating the morphological product. At this stage a lot of solution variants are developed. Some of them are solutions known to public, simple, and used for a long time, and therefore they are rejected. Some others are rejected because of contradictions or senselessness. However, there are a lot of combinations that give many features to new and innovative solutions.

Finding new solutions requires reducing the size of the morphological box or morphological field. Various selection techniques are used for this purpose, but in sequential study, the discovery matrix is appropriate, a tool proposed by Moles [27, 28]. In the morphospace any pair of parameters is selected—fundamental variables—and their ranges are listed in two-dimensional matrixes. The next step is to compare these pair of parameters. It is assessed whether—or to what extent—a given pair of parameters can coexist, i.e. represent a coherent relationship. If not—pair of parameters is eliminated from further analysis. In this way, only pairs of parameters that are not logically contradictory or empirically limited are subject to further analysis. Selected morphological products are then paired with the next parameter—variable—in order to get new discovery matrix, and new morphological products from this matrix are treated the same way as in the initial matrix. As a result, the morphological space is reduced from many to several solutions, but which of them becomes basis to specific projects is determined by criteria defined in problem definition phase.

The synthesis and evaluation of ideas are carried out repeatedly, until the researchers are convinced that all the possibilities of obtaining a new idea are exhausted. The work ends with the development of several reasonable proposals, from which the best ones are selected. It is usually recommended to develop at least five proposals and then choose the best optimal solution from them.

4. Application of GMA for optimization of hybrid solar-wind system

The purpose of the morphological analysis was to optimally select the components of an ecological energy source. The following problem parameters were considered:

P1	P2	P3	P4	P5	P6	P7	P8
P1.1	P2.1	P3.1	P4.1	P5.1	P6.1	P7.1	P8.1
P1.2	P2.2	P3.2	P4.2	P5.2	P6.2	P7.2	P8.2
P1.3	P2.3	P3.3		P5.3	P6.3	P7.3	P8.3
	P2.4	P3.4		P5.4	P6.4	P7.4	P8.4
	P2.5			P5.5	P6.5		
	P2.6			P5.6			

Table 2.
Segment of morphological field—One is shown.

type of energy used (P1), photovoltaic cell type (P2), place of installation of PV panels (P3), wind turbine assembly location (P4), type of wind turbine (P5), number of turbine blades (P6), wind turbine blade material (P7), and type of battery (P8). Then, for each parameter, its states, attributes, or values were specified. In this way, an 8-parameter field in morphological format was developed. This field contains 8 parameters and 69,120 possible (formal) configurations, one of which is shown in **Table 2**.

Considering the design assumptions, the following attributes and values of individual parameters were considered:

- For P1: wind energy (P1.1), solar energy (P1.2), and wind and solar energy simultaneously (P1.3)
- For P2: monocrystalline cells (P2.1), polycrystalline cells (P2.2), amorphous silicon cells (P2.3), CIGS cells (P2.4), CdTe cells (P2.5), and dye-sensitized solar cells (P2.6)
- For P3: ground surface (P3.1), vertical wall of the building (P3.2), slanting roof of the building (P3.3), and flat roof of the building (P3.4);
- For P4: vertical (P4.1) and horizontal wind turbine (P4.2)
- For P5: one-blade turbine (P5.1), two-blade turbine (P5.2), three-blade turbine (P5.3), three-blade turbine with diffuser (P5.4), four-blade turbine (P5.5), and multi-blade turbine (P5.6)
- For P6: carbon fiber (P6.1), glass fiber (P6.2), aluminum (P6.3), wood-reinforced epoxy resin (P6.4), and steel (P6.5)
- For P7: ground surface (P7.1), vertical wall of the building (P7.2), slanting roof of the building (P7.3), and flat roof of the building (P7.4)
- For P8: classic acid (P8.1), gel (P8.2), absorbed glass mat (P8.3), and lithium ion (P8.4)

The next step in the analysis-synthesis process was the reduction of morphological field. This was done in cross-consistency assessment process [25]. For this purpose, all of the parameter values in the morphological field were compared with all others, in the form of a discovery matrix. The first discovery matrix compares the first two parameters (**Table 3**).

Due to, that system which bases only on one renewable energy source is completely dependent on unpredictable weather factors, this approach was rejected.

	P1.1	P1.2	P1.3
P2.1.	x	x	x
P2.2.	x	x	
P2.3.	x	x	x
P2.4.	x	x	
P2.5.	x	x	x
P2.6.	x	x	x

Table 3.
The first discovery matrix.

Solutions based on one renewable energy source make continuous production of electrical energy impossible. There is naturally inverse correlation between solar and wind energy generation. During long sunny days, insolation is high and wind speed is usually low, whereas during shorter days, during winter, wind speeds are high and insolation is low. As mentioned earlier, differences in weather conditions are also visible between day and night as well as between the seasons. Therefore, in areas with seasonal climate, hybrid solution should be the best, because neither photovoltaic panels nor wind turbines can meet the daily demand on electricity. Therefore, in the first discovery matrix, only hybrid solutions were approved. Next, the basic electron device used to change solar energy into electricity using the photovoltaic effect was considered. Depending on the material used and its structure, several types of solar cells can be distinguished. Between all solar cells of the first generation, best efficiency (18–22%) is achieved by monocrystalline cells. However, cells of this type are quite expensive, so the ratio of costs incurred to better performance is economically inefficient. Therefore, solutions that use this type of solar cells are rejected. Nowadays, in Poland polycrystalline panels are most often used. These cells have lower efficiency than the previous (14–18%) and lower price for modules. However, they are less energy-intensive in production in comparison to monocrystalline cells, and both types have a lifetime of 25 year. In addition, in latitude where Poland is located, there are different sunlight conditions. Polycrystalline cells during operation apart from direct sunlight capture much more reflected and refracted sunlight than monocrystalline cells. Polycrystalline panels work stably throughout the year. In addition, the price-performance ratio is more favorable for them. For this reason, they were accepted. The next stages describing P2 are three cells of the second generation: amorphous silicon, CIGS, and CdTe cells. A characteristic feature of these cells is a very small thickness of semiconductor layer that absorbs light. These cells are cheaper in production than cells of first generation, and production process is more automated. Such solar cells can be produced by a method similar to printing, which is very efficient and does not require large amounts of energy. They are interesting alternative to photovoltaic development. However, the performance of these solar cells is lower than that of the first-generation cells and is, respectively, for amorphous silicon, 6–10%; CIGS, 12–15%, and CdTe, 10–12%. Amorphous cells and CdTe cells due to its lowest efficiency were rejected, while CIGS cells were accepted. The last taken into account type of solar cells are cells of third generation, dye-sensitized solar cells. They are characterized by simple construction, the lowest price, and very low efficiency. In the future, these cells are expected to be more efficient because their work will take place in a wide spectrum of radiation, so that energy production will occur even in areas that are not exposed to sunlight. It seems that in the future it will be an ideal solution in Poland. But at present, cells

	P1.3.P2.2	P1.3.P2.4
P3.1.	x	x
P3.2.		
P3.3.		
P3.4.	x	x

Table 4.
The second discovery matrix.

of this type should be rejected. Todays in Poland the first-generation cells perform best. However, if within a few years nothing new appears in the production of silicon cells and the production of the third generation cell will gain momentum and the efficiency of their work will increase, they will probably be an ideal tool for generating green energy from solar radiation in Poland. Thus, combinations in gray cells in **Table 3** go on to the further CCA process. These combinations were combined with the third parameter, as shown in the second discovery matrix, in **Table 4**.

Installing PV panels on the ground requires more space because of the need to place them at a distance from each other to avoid mutual shading. In addition, when the PV installation is located too low, its shading occurs in the morning and evening hours and thus the inability to obtain the maximum amount of energy. For this reason, ground PV systems should be raised to a height of about 1.5–2.5 m, which will not look too esthetically. Therefore, the option of installing a PV system on the ground was rejected. The optimal installation place for PV panels is a pitched roof facing south (possibly east and west) with an angle of inclination of 30–35°. A deviation of 15° to the vertical or horizontal from this angle will not cause losses greater than 4%. For flat roofs or roofs with a different degree of inclination, special arrangement correction frames are used, on which the panels are mounted. In addition, the location of the panels on the roof hinders vandalism and theft. Therefore, this solution was accepted. Installing PV panels on a flat roof was rejected because of the design assumptions. PV systems are rarely mounted on building walls due to the appearance of the facade. On the other hand, however, the panels that will be mounted on the south wall of the property are very efficient and easy to clean and maintain. The vertical arrangement of the panels eliminates the problem of snow which, in the case of roof and ground panels, limits the access of sunlight. That's why this solution was accepted. Thus, combinations in cells marked gray in **Table 4** go on to further CCA process. These combinations were combined with the next parameter, as shown in the third discovery matrix, in **Table 5**.

Horizontal axis wind turbines are most often used. They have high performance (efficiency, small fluctuations in torque) in strong wind conditions. They are also characterized by high reliability, ease of service, and low cost. The main advantage of these turbines over a vertical axis turbine is efficiency. The latter have low efficiency and much larger their dimensions are needed to produce the same amount of energy as a horizontal axis wind turbine. Therefore, this type of turbine has been rejected. Thus, combinations in cells marked gray in **Table 5** go on to further CCA process. These combinations were combined with the next parameter, as shown in the fourth discovery matrix, in **Table 6**.

Increasing the number of wind turbine blades results in a higher drive torque but a lower rotational speed. In turn, smaller number of blades increases the turbine speed. The use of single-blade and double-blade turbines results in a low weight of the rotor, which theoretically translates into a lower cost of its implementation. However, due to the high-speed indicator and the high rotational speed of the

	P1.3.P2.2.P3.2	P1.3.P2.2.P3.3	P1.3.P2.4.P.3.2	P1.3.P2.4.P.3.3
P4.1.	x	x	x	x
P4.2.				

Table 5.
The third discovery matrix.

	P1.3.P2.2.P3.2. P4.2	P1.3.P2.2.P3.3. P4.2	P1.3.P2.4.P.3.2. P4.2	P1.3.P2.4.P.3.3. P4.2
P5.1.	x	x	x	x
P5.2.	x	x	x	x
P5.3.				
P5.4.				
P5.5.	x	x	x	x
P5.6.	x	x	x	x

Table 6.
The fourth discovery matrix.

monoplane turbines, they are quite noisy. Turbine noise, which increases as the speed increases, should be considered. Therefore, single-blade and double-blade turbines were rejected. Three-blade turbines are currently used most often due to a very good balance of aerodynamic forces, as well as high stability of work by balancing gyroscopic forces and uniform torque. Three-blade turbines are characterized by high efficiency, and it was decided to be accepted. Three-blade turbines with a diffuser are also noteworthy. The use of a diffuser results in less sensitivity to turbulence, greater structural integrity, better fatigue strength, greater torque at low wind speeds, lower load fluctuations that act on turbine blades, quieter turbine operation, and higher allowable rotational speed. Therefore, this solution was also accepted. The aerodynamic efficiency of the turbine increases with the number of rotor blades. However, this relationship is not linear, and the addition of each subsequent blade increases performance. Multi-blade turbines deliver high torque at low wind speeds. For the purposes of the project, it will be more desirable to achieve high speed but with less torque. Increasing the number of blades will cause a reverse reaction; therefore, four- and multi-blade turbine concepts were rejected. Thus, the combinations in cells marked gray in **Table 6** go on to further CCA process. These combinations were combined with the next parameter, as shown in the fifth discovery matrix, in **Table 7**.

The vast majority of wind turbine blades are made of fiberglass reinforced with epoxy resin or polyester. There are also solutions using carbon fiber, but they are very expensive, and their use in this case is economically unjustified. Turbines made of wood reinforced with epoxy resin have not gained much popularity so far. Turbines of very small sizes, in turn, can be made of steel or aluminum blades, but they are quite heavy and susceptible to material fatigue. Thus, combinations in cells marked gray in **Table 7** go on to further CCA process. These combinations were combined with the next parameter, as shown in the sixthth discovery matrix, in **Table 8**.

The wind turbine should be mounted above the roof of the building, which is usually the biggest obstacle to wind. Therefore, installing the turbine on the ground involves the necessity to erect a high-altitude tower (approx. 12 m), which increases investment costs. Placing the turbine on the roof of the building will save on the

	P1.3. P2.2. P3.2. P4.2. P5.3	**P1.3. P2.2. P3.2. P4.2. P5.4**	**P1.3. P2.2. P3.3. P4.2. P5.3**	**P1.3. P2.2. P3.3. P4.2. P5.4**	**P1.3. P2.4. P.3.2. P4.2 P5.3**	**P1.3. P2.4. P.3.2. P4.2. P5.4**	**P1.3. P2.4. P.3.3. P4.2. P5.3**	**P1.3. P2.4. P.3.3. P4.2. P5.4**
P6.1.	x	x	x	x	x	x	x	x
P6.2.								
P6.3.	x	x	x	x	x	x	x	x
P6.4.	x	x	x	x	x	x	x	x
P6.5.	x	x	x	x	x	x	x	x

Table 7.
The fifth discovery matrix.

	P1.3. P2.2. P3.2. P4.2. P5.3. P6.2	**P1.3. P2.2. P3.2. P4.2. P5.4. P6.2**	**P1.3. P2.2. P3.3. P4.2. P5.3. P6.2**	**P1.3. P2.2. P3.3. P4.2. P5.4. P6.2**	**P1.3. P2.4. P.3.2. P4.2 P5.3. P6.2**	**P1.3. P2.4. P.3.2. P4.2. P5.4. P6.2**	**P1.3. P2.4. P.3.3. P4.2. P5.3. P6.2**	**P1.3. P2.4. P.3.3. P4.2. P5.4. P6.2**
P7.1.	x	x	x	x	x	x	x	x
P7.2.	x	x	x	x	x	x	x	x
P7.3.								
P7.4.	x	x	x	x	x	x	x	x

Table 8.
The sixth discovery matrix.

cost of the tower and long electrical cables. Undoubtedly, the option of installing a wind turbine on a vertical wall of the building should be rejected. Also, due to the adopted design assumptions, among which the roof pitch is 35°, the flat roof is rejected. Therefore, guided by the costs, only the pitched roof was accepted. Thus, combinations in cells marked gray in **Table 8** go on to further CCA process. These combinations were combined with the next parameter, as shown in the seventh discovery matrix, in **Table 9**.

If the system is not connected to the network, it is necessary to use batteries to ensure continuity of power supply to the receivers. Four types of batteries were considered. Acid batteries are classic batteries in which the electrolyte in liquid form fills the cell. When designing PV installations, classic batteries with armored positive plate are recommended. The disadvantage of this type of battery may be the need to buy additional equipment and gas recombinators, due to the possible release of harmful sulfuric acid fumes. These batteries have relatively the lowest lifetime and poor performance at high discharges. In turn, the advantage of these batteries is their low price. The undoubted advantage of gel batteries is the high charging efficiency, having no effect of electrolyte stratification during charging, and lower ventilation requirements. Due to the fact that the PV system battery will work cyclically, at this stage acid batteries are rejected. In gel batteries intended for PV installations, full recovery from deep discharge is possible, as well as an increased number of deep charging and discharging cycles thanks to the use of positive armor plates in the electrodes. In addition, gel batteries are more resistant to shocks, vibrations, and high temperatures than acid or AGM

	P1.3. P2.2. P3.2. P4.2. P5.3. P6.2. P7.3.	P1.3. P2.2. P3.2. P4.2. P5.4. P6.2. P7.3.	P1.3. P2.2. P3.3. P4.2. P5.3. P6.2. P7.3.	P1.3. P2.2. P3.3. P4.2. P5.4. P6.2. P7.3.	P1.3. P2.4. P.3.2. P4.2 P5.3. P6.2. P7.3.	P1.3. P2.4. P.3.2. P4.2. P5.4. P6.2. P7.3.	P1.3. P2.4. P.3.3. P4.2. P5.3. P6.2. P7.3.	P1.3. P2.4. P.3.3. P4.2. P5.4. P6.2. P7.3.
P8.1.	x	x	x	x	x	x	x	x
P8.2.								
P8.3.	x	x	x	x	x	x	x	x
P8.4.	x	x	x	x	x	x	x	x

Table 9.
The seventh discovery matrix.

batteries. Their lifetime and the number of charging and discharging cycles are definitely the longest. Gel batteries best tolerate variable temperature fluctuations that occur in temperate climates. Unfortunately, they are the most expensive. In battery based on AGM technology, the possibility of electrolyte leakage from a mechanically damaged battery has been eliminated. Accumulators of this type have a one-way pressure valve, which, with an excessive increase in pressure of accumulated gases, opens, eliminating the problem of incorrect charging and discharging performance. This design will ensure high efficiency of the internal recombination process. Advantages of this battery are the ability to install in any position and to reduce the initial costs compared to gel batteries. However, these batteries have the shortest service life and the fewest charge and discharge cycles. Therefore, they will certainly not be taken into account. Despite the low price, they are characterized by short life and low efficiency at high discharges. On the basis of the pros and cons analysis, the gel battery was selected, and the AGM battery was also rejected. In addition to the mentioned batteries, there are also lithium-ion batteries that are characterized by long life, reliability, a wide range of operating temperatures, low internal resistance, and higher efficiency than lead-acid batteries. Lithium-ion batteries save space and weight when accumulating the same amount of energy. Their disadvantage is undoubtedly the price, because in relation to lead-acid batteries, they are much more expensive. Therefore, this solution was also rejected.

Performing morphological analysis using the Moles discovery matrix method allowed to obtain 8 optimal solutions from 69,120 possible combinations. They are:

- Hybrid solar-wind system consisting of PV panels made of polycrystalline cells and mounted on vertical wall of the building, three-bladed (made of fiberglass) horizontal turbine mounted on slanting roof of the building, and gel battery

- Hybrid solar-wind system consisting of PV panels made of CIGS cells and mounted on vertical wall of the building, three-bladed (made of fiberglass) horizontal turbine mounted on slanting roof of the building, and gel battery

- Hybrid solar-wind system consisting of PV panels made of polycrystalline cells and mounted on slanting roof of the building, three-bladed (made of fiberglass) horizontal turbine mounted on a slanting roof of the building, and gel battery

- Hybrid solar-wind system consisting of PV panels made of CIGS cells and mounted on slanting roof of the building, three-bladed (made of fiberglass) horizontal turbine mounted on a slanting roof of the building, and gel battery

- Hybrid solar-wind system consisting of PV panels made of polycrystalline cells and mounted on vertical wall of the building, three-bladed (made of fiberglass) horizontal turbine with diffuser mounted on a slanting roof of the building, and gel battery

- Hybrid solar-wind system consisting of PV panels made of CIGS cells and mounted on vertical wall of the building, three-bladed (made of fiberglass) horizontal turbine with diffuser mounted on a slanting roof of the building, and gel battery

- Hybrid solar-wind system consisting of PV panels made of polycrystalline cells and mounted on slanting roof of the building, three-bladed (made of fiberglass) horizontal turbine with diffuser mounted on slanting roof of the building, and gel battery

- Hybrid solar-wind system consisting of PV panels made of CIGS cells and mounted on slanting roof of the building, three-bladed (made of fiberglass) horizontal turbine with diffuser mounted on slanting roof of the building, and gel battery

5. Numerical model of hybrid solar-wind system

Based on GMA, a hybrid solar-wind system consisting of PV panels made of polycrystalline cells and three-blade horizontal axis wind turbine mounted on the slanting roof of the building and gel battery was selected for numerical testing. This installation has the task of supporting the supply of a 250 m^2 single-family house in electricity. The house is located in the temperate climate zone, in Poland in the Silesian Voivodeship. Data regarding the value of insolation and wind maps for the selected location come from [2, 7]. The average monthly demand for electricity was estimated on the basis of data taken from [29]. The block diagram of the designed hybrid system is presented in **Figure 1**. On its basis, a model will be developed in MATLAB/Simulink software.

In order to carry out example numerical simulations, a hybrid system was modeled consisting of:

- Upwind three-blades wind turbine with the following parameters: max power 500 W; rated voltage 12 V; start up, cut in, and cut out wind speed 2, 3.5, and 30 m/s, respectively; and rotor diameter 2.5 m. It is equipped with a mechanical locking system and a three-phase asynchronous motor. The generator's efficiency is 96%.

- Eight PV panels with 330 W for each connected in parallel. Their parameters are maximum power 33 W, maximum power voltage 58 V, maximum power current 5.7A, open-circuit voltage 69.7 V, efficiency 19.8%, and size 1590 × 1053 × 35.

- Four batteries with maximum capacity 150 Ah each and nominal voltage 12 V.

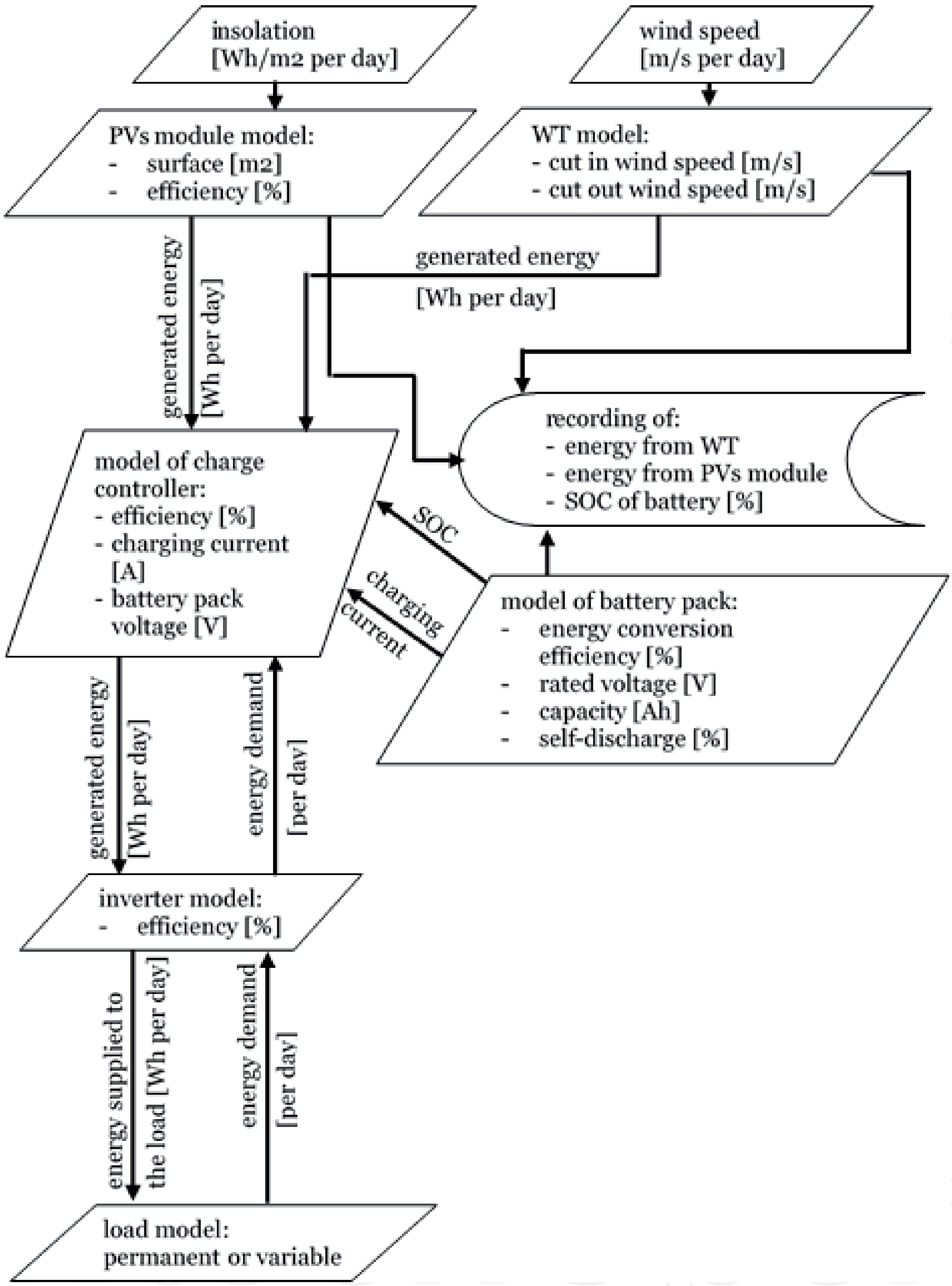

Figure 1.
The block diagram of the designed hybrid system.

The graph of daily insolation, estimated on the basis of data taken from [17], and graph of average daily wind speed, estimated on the basis of data taken from [2] are shown in **Figure 2**, on (a) and (b), respectively.

Capabilities of modeled hybrid system are shown on **Figure 3**. These capabilities should be understood as energy that could be transferred without restrictions to the power grid, assuming inability to store surpluses.

The waveform demanded by household energy value during the day and battery charge status are shown on **Figure 4**.

How many times per year this system cannot cover energy demand may be shown by comparing household monthly demand on energy with energy produced by the hybrid system (**Figure 5**).

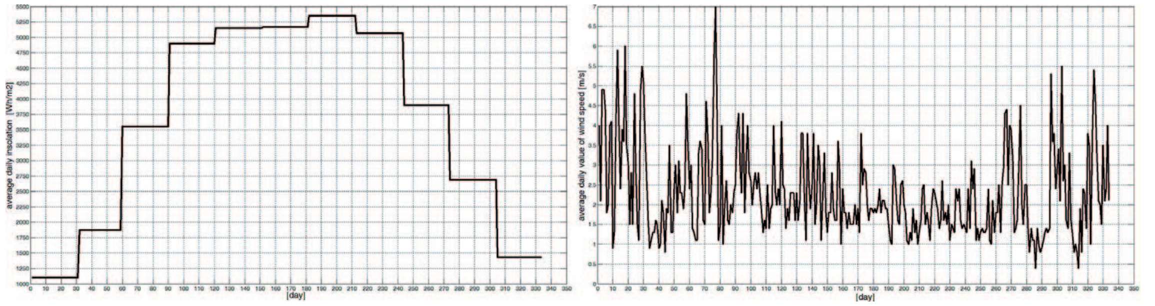

Figure 2.
The graph of average daily (a) insolation [Wh/m²] and (b) wind speed [m/s].

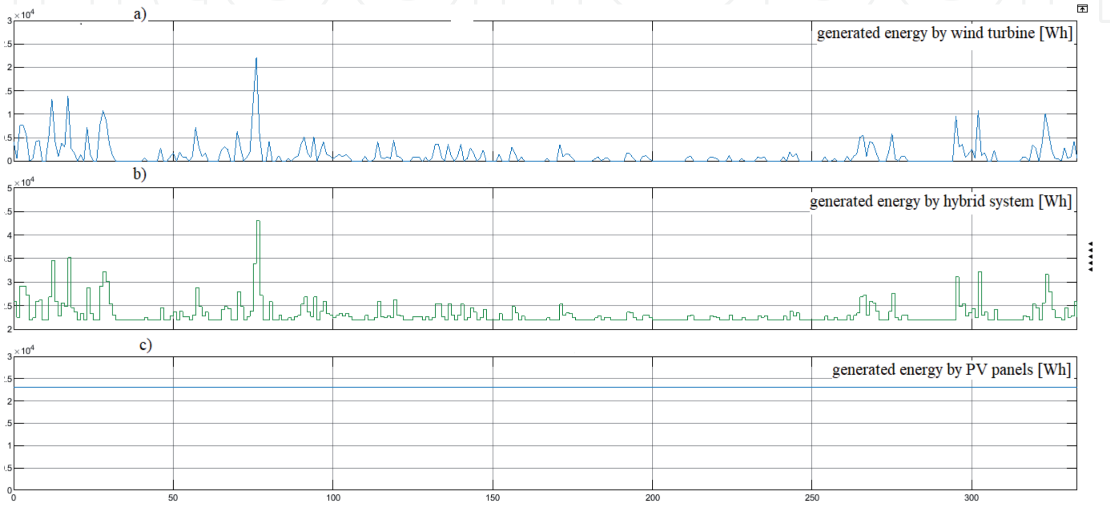

Figure 3.
Generated energy by (a) wind turbine, (b) hybrid system, and (c) PV panels.

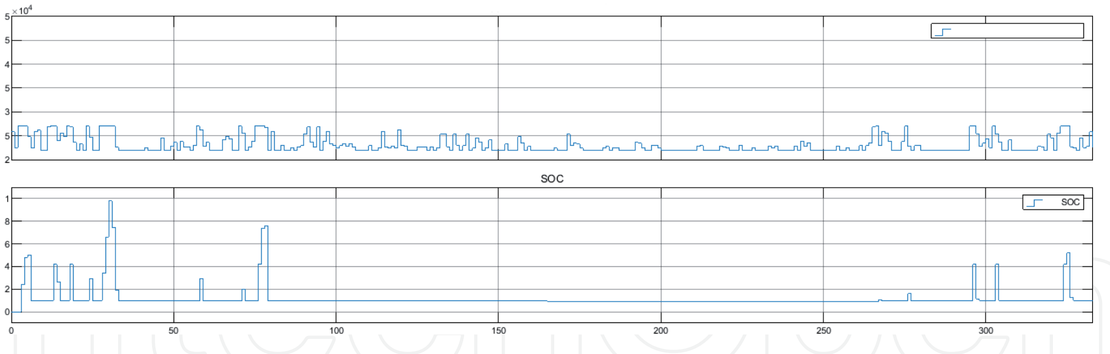

Figure 4.
Waveform demanded by household energy value during the day and battery charge status.

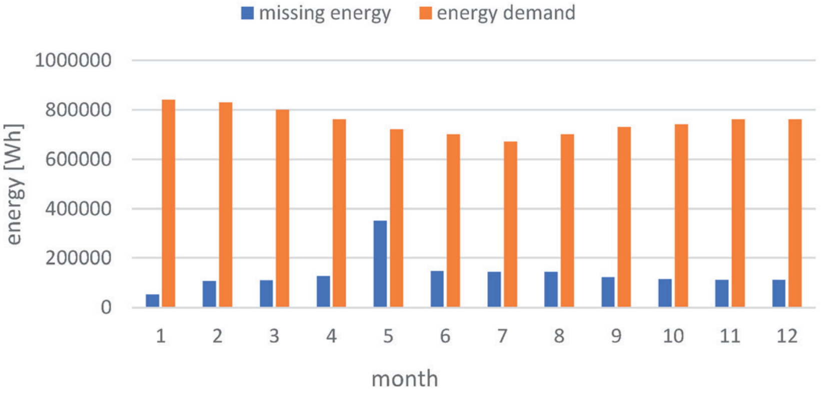

Figure 5.
Comparison of energy demand with the amount of missing Wh per month.

6. Conclusions

At the beginning of this chapter, a brief introduction to the issue of energy sources is given. Further text discusses aspects that should be considered when choosing a location of both solar system and wind turbines. Text also provides arguments for a need to replace the nonrenewable energy sources with renewable ones. Then large part of the text discusses climatic, environmental, social, health, and ecologic aspects that should be considered during choosing a location for both solar panels and wind turbines. The next part of the chapter briefly introduces theory to General Morphological Analysis. Next, the practical application of GMA was described to optimize the structure of hybrid solar wind farms, preceded by a description of the adopted design assumptions.

At the end of the chapter, the developed numerical model of a hybrid solar-wind system in the MATLAB/Simulink environment was presented. Based on the data resulting from the simulations carried out for the adopted model of a hybrid solar-wind power plant supplying the household, it can be concluded that the amount of missing energy, i.e., the difference between the demand and the energy generated by the modeled system, amounting to 15.67%, is a very satisfactory result. Therefore, observing the further development of solar cells and batteries, such energy sources for countries without very favorable climatic conditions, for example, in Poland, should be treated as a cost-effective alternative to nonrenewable energy sources.

At present, energy storage is a very expensive solution and for the analyzed configuration did not bring satisfactory results. The batteries for the input data used have reached the state of charge only a few times, while the stored energy has been used very quickly. Such operation causes very fast battery wear. Energy surplus could easily be stored in other ways, e.g., in water tanks, which would be a cheaper and definitely more ecological solution. Abandoning the storage of surplus in batteries would not bring significant losses in this case.

Conflict of interest

The author declares that there is no conflict of interest.

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