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Optimising the selection of batteries for photovoltaic applications

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Summary. Methods were developed for determining the amount of energy generated by a PV module and for establishing an optimum battery capacity for applications in autonomous solar systems. The methods were applied for selection of batteries operating with the PV module with polycrystalline structure. Based on the analysis for a selected meteorological station, the optimum capacity of the battery to operate with the polycrystalline module was determined. Also, the unit cost of energy storage as a function of the battery depth of discharge was determined.

Key words: battery capacity, autonomous solar system, photovoltaic module, battery depth of discharge.

FOREWORD

The climate package adopted in 2008 by the EU Member States assumes, among others, increasing by 20 % electrical energy production from the so called "clean energy sources" [3]. One of the forms of energy production is direct processing of solar radiation into electricity in photovoltaic cells. Electrical energy generated in this way can be used to supply, e.g. street lights operating in the so called autonomous systems. In Poland, for road and street lighting around 1.8 TWh of electrical energy is used [17]. This results in CO_2 emission of ca. 1.3 M tons. Therefore, using this type of systems may have measurable benefit in reducing energy consumption and the resultant reduction of carbon emissions. Due to the nature of autonomous lighting systems, which rely solely on the energy supplied from solar cells, it is necessary to store the produced energy. This involves an appropriate selection of energy storage, i.e. battery capacity, which will have to operate in various weather conditions, with an uneven distribution of solar radiation thorough the year and the resultant varying consumption of energy by the consumer. There are elaborate literature sources on the selection of photovoltaic cells for the systems [15,18,8,6], however, the subject of energy storage received little attention. Most of the scholars describe extensively the methods for selecting starting and traction batteries [1,16,9,2], the methods for selecting battery capacity depending on the equipment power [5], yet nothing is said about the methods for selecting capacities of batteries for photovoltaic systems in terms of cooperation with the energy source.

OBJECTIVE

In view of the apparent lack of literature on the optimisation of selecting battery size to photovoltaic applications, this paper aims to develop methods allowing an optimum capacity determination for photovoltaic systems operating as autonomous power supply sources. Also an application example of battery selection is covered, in relation to 1 m^2 of the reception area of a photovoltaic panel made of polycrystalline silicon for a selected meteorological station.

RESEARCH METHODS

The main issue in a correct selection of a battery for photovoltaic systems is to determine the amount of energy the battery should store. The solar radiation energy may be determined based on the meteorological data on insolation, published at the website of the Ministry of Transport Construction and Maritime Economy [www.transport.gov.pl]. With this data source, the monthly amount of energy can be calculated from the formula [10,11,12].

$$E_m = \sum_{i=1}^{n} I_i \cdot g_i, \qquad (1)$$

where:

I_i – solar radiation intensity $W \cdot m^{-2}$,

g_i – number of hours in a month with ith radiation intensity h.

Calculations of monthly sums are made for various inclination angles of the receiving plane. Based on those monthly radiation sums for all-year applications, such module inclination is decided at which the variability of sums in a year is the lowest possible. Afterwards, the amount of energy delivered by a photovoltaic module is determined in relation to 24 hours, for the least favourable month as can be determined from the formula (2):

$$E_{sd} = \frac{E_{m\,min}}{d}, \tag{2}$$

where:

$E_{m\ min}$ – solar radiation energy $W \cdot h \cdot m^{-2}$,

d – number of days in a month in which there is minimum E.

The calculated E_{sd} value forms the basis for selection of a photovoltaic system for supplying a receiver in the all-year autonomy and determining the total operating autonomy period. The prerequisite for a battery selection is that it could store the total energy produced during the day in the best possible conditions. For this, yet in relation to the maximum insolation, the formulas (1) and (2) will be used. Capacity of the battery can be derived from the energy balance (3):

$$E_{dmax} \cdot \eta_{(T,I)} = q \cdot U \cdot z_{(n)} \cdot \eta_a, \tag{3}$$

where:

$E_{d\ max}$ – maximum 24-hour energy of solar radiation $W \cdot h \cdot m^{-2}$;

$\eta_{(T,I)}$ – effectiveness of the photovoltaic module, depending on the radiation intensity and operating temperature [20,13,6];

q – battery capacity in Ah,

U – battery rated voltage,

z(n) – battery depth of discharge depending on the number of cycles,

η_a – energy storage effectiveness in a battery, depending on the temperature, charging system and battery itself.

The last stage is to calculate the autonomy period of the supply source, which can be expressed as the ratio of energy produced by a photovoltaic module during the day, in maximum insolation $E_{d\ max}$, to the average 24-hour energy E_{sd}:

$$W_a = \frac{E_{dmax} \cdot \eta_{1(T,I)}}{E_{sd} \cdot \eta_{2(T,I)}}, \tag{4}$$

where:

$E_{d\ max}$ – maximum 24-hour energy of solar radiation $W \cdot h \cdot m^{-2}$,

E_{sd} – 24-hour energy of solar radiation $W \cdot h \cdot m^{-2}$,

$H_{1(T,I)}$ – photovoltaic module effectiveness depending on the radiation intensity and operating temperature in extreme conditions,

$H_{2(T,I)}$ – photovoltaic module effectiveness depending on the radiation intensity and operating temperature in average conditions.

The methodology presented above was applied to select a battery for an autonomous photovoltaic system, in which photovoltaic cells with polycrystalline structure were used (the most popular in the market) [19], installed in a selected location.

ANALYSIS

While developing the method for selecting the battery capacity to operate in a solar autonomous system, meteorological data on the solar radiation distribution was applied, selecting a meteorological station located in south-east Poland in Podkarpackie province. The data refers to hour parameters of the total intensity of solar radiation on a surface for a typical meteorological year, calculated based on EN ISO 15927:4. Based on this data, total insolation was determined, depending on the inclination angle (0°, 30°, 45°, 60°) of the receiving surface oriented south in individual months of the year, as shown in the plot in Fig. 1.

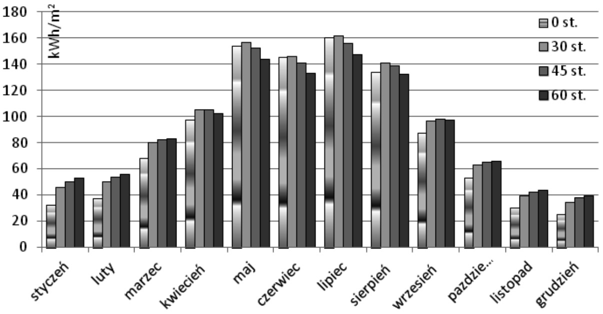

Fig. 1. Insolation distribution depending on the inclination angle of the receiving surface in a monthly configuration

The insolation is characterised by great variability in individual months and varies from 35 kWh/m² in December to 160 kWh/m² in July (Fig. 1). The value of insolation is affected by the inclination of the receiving area. An optimum inclination for the autumn and winter time (from October to March) should be 60° and 30° for other months. In the annual scale, considerable difference in the insolation is no longer observed, see Table 1.

Table 1. Annual insolation figures

Inclination angle	Insolation $kWh \cdot (m^2a)^{-1}$
0°	1026
30°	1118
45°	1122
60°	1096

An important parameter regarding the operation (effectiveness) of photovoltaic cells is also the insolation distribution, depending on the solar radiation density [5,6], which, for the area in question, is shown in Figure 2.

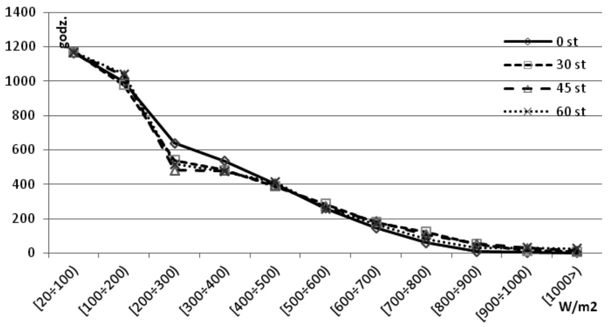

Fig. 2. Insolation distribution for selected inclination angle of the receiving surface versus insolation

The above graph allows determining the insolation figure vs. insolation, and it is shown by the area below the graph. As shown in the graph (Fig. 2), in over 50 % of the time of the average day length, the earth surface receives a stream of radiation with the density up to 200 W/m^2. With such a low solar energy stream, lower efficiency of the photovoltaic conversion should be considered [6,14].

Considering the effectiveness change of a solar cell [20] [11,12] with polycrystalline structure, the amount of energy was determined, which the cell is able to generate in a month. Bearing in mind the all-year autonomy of the system, the optimum inclination angle of the cell surface is 60^o since it delivers most energy (Figure 3) in the autumn and winter time, and the least in the spring and summer period.

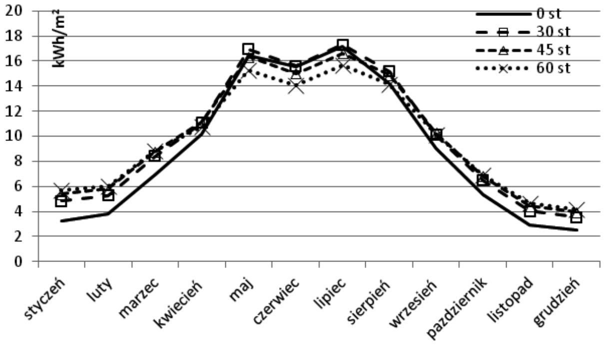

Fig. 3. Electricity production by a photovoltaic polycrystalline module

Assuming, in further calculations, the inclination angle of module plane of 60^o, the average daily production of electricity was calculated together with the degree of use in the all-year autonomy system (Fig. 4). The graph is useful for determining parameters of a receiver supplied by an autonomous PV source.

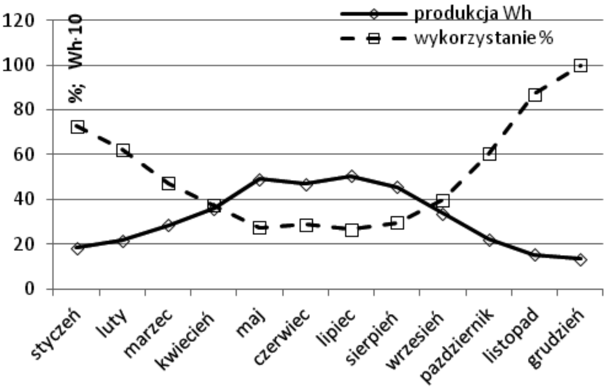

Fig. 4. Daily production of electricity from PV, and degree of use in the all-year autonomy system

A battery operating with a PV source should have optimally selected capacity, for the minimum cost of energy storage, ensuring, at the same time, storage of the energy delivered from the module.

To perform practical calculations of the cost of energy storage in a battery, data from commercial offers from various companies were used. Batteries with available technical documentation, specifying their life vs. depth of discharge, were chosen. The analysis of unit cost of energy supplied from a battery was started from determining the amount of energy per cycle (5):

$$E = \frac{q \cdot U \cdot z_c}{10^3}, \tag{5}$$

where:
E – energy output in a cycle [kWh],
q – battery capacity [Ah],
U – voltage at battery terminals [V],
z_c – battery depth of discharge per cycle.

The unit cost of energy supplied from a battery was determined from the relationship 6:

$$K_j = \frac{c \cdot 10^3}{E \cdot n(z_c)}, \tag{6}$$

where:
Kj – unit cost of energy [PLN/kWh],
c – battery market price [PLN],
E – energy output in a cycle [kWh],
$n(z_c)$ – number of cycles as a function of depth of discharge.

The relationships 5, 6 were adopted to simulate the unit cost of energy delivered by five different battery models with capacity above 200 Ah, and the results are shown in Fig. 5. Due to significant differences in the achieved results, the solar batteries were divided into two groups “a” and “b”, without specifying the manufacturers.

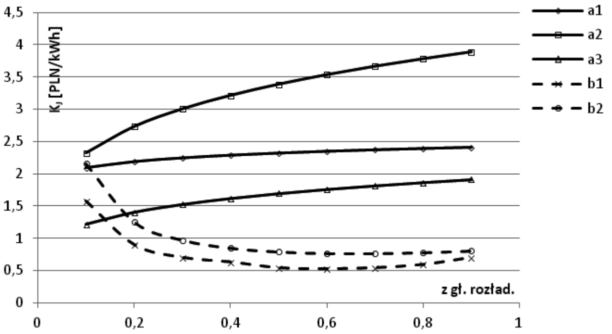

Fig. 5. Unit cost of energy storage as a function of the battery depth of discharge

Group “a” includes batteries for which the unit energy cost increases along with the depth of discharge. The lowest unit cost of energy from a battery in this group is with discharge to 10 %, and varies from 1.2 to 2.3 PLN/kWh, which is a few times higher than that of the energy from the power grid. Energy buffer of 10 % of the battery capacity is definitely too low for applications in autonomous solar systems. Therefore, 20 % depth of discharge was assumed for batteries in this group. For the “b” group batteries, however, the minimum unit cost can be found at the depth of discharge of 60 %. It has to be stressed that, for an optimum depth of discharge for this group, the unit energy cost varies from 0.5 to 0.75 PLN/kWh and is comparable with that of the energy from the power grid.

While designing battery capacity, it was assumed that the daily energy produced in the most effective solar conditions should be completely stored in the battery, at the optimum depth of discharge. Therefore, the maximum energy production by a PV in the best solar conditions was determined for further analysis of the system with all-year autonomy (Fig. 6).

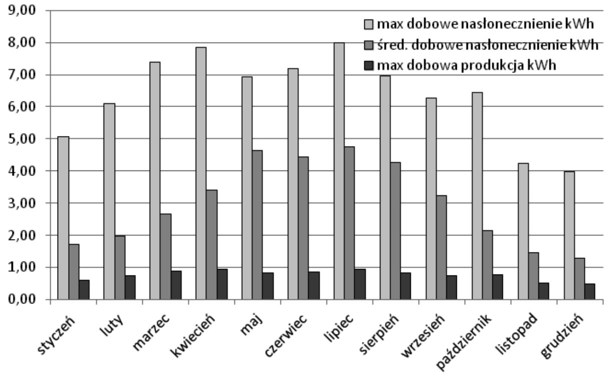

Fig. 6. Daily insolation: a) maximum, b) average, c) max energy production by a polycrystalline module; the values specified refer to 1 m^2 of the receiving area

From the relationship 3, battery capacity in two variants was determined, i.e. with the all-year and half-year autonomy, for the optimum depth of discharge, with the division into the “a” and “b” groups. The results of the battery capacity q calculations in relation to 1 m^2 of the receiving area are shown in the plot (Fig. 7).

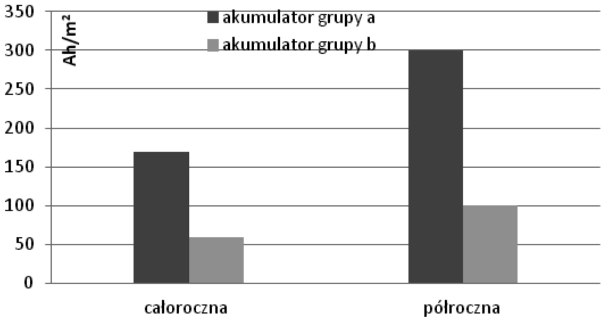

Fig. 7. Battery capacity

Legend: akumulator grupy a: group ‘a’ battery
akumulator grupy b: group ‘b’ battery
całoroczna: all-year
półroczna: half-year

Analysing the obtained results, it can be stated that for systems with all-year autonomy, the optimum battery capacity should be 60 Ah/m^2 for the “b” group batteries, and 170 Ah/m^2 for the “a” group batteries. For systems operating in the half-year autonomy (March-September), the capacity should be increased by 65 % for the “b” group and by 75 % for the “a” group respectively. For the battery capacities decided this way, the autonomy index W_a is 3.5 days for the all-year autonomy and 3 days for the half-year autonomy system, respectively.

CONCLUSIONS

The methods presented herein allows for the determining of the amount of energy generated by a PV module and establishing an optimum battery capacity for applications in autonomous solar systems. The methods developed were applied for selection of batteries operating with the PV module with polycrystalline structure. They can also be applied for other cell types in solar systems. Analysing the selected meteorological station, the optimum battery capacity operating with a polycrystalline module was established, which is 60 Ah/m^2 with the depth of discharge of 60 % and 170 Ah/m^2, with the depth of discharge up to 20 %. Also the unit cost of energy storage as a function of the battery depth of discharge was determined. The cost is from 1.2 to 2.3 PLN/kWh for the group of batteries marked as “a” and from 0.5 to 0.75 PLN/kWh for the “b” group. The very cost of energy storage in the batteries, in the best case, is comparable to the energy from the power grid, hence, at present, they are not a competitive alternative to the energy supplied from the power grid. It may be an alternative supply solution in places when no power grid supply is available.

The presented methods for selection of battery capacity allow for the achievement of 3.5 day-autonomy in the all-year operation, on condition that the energy drawn from the solar source will not exceed the average daily figures delivered by the PV module in the month with the lowest insolation.

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OPTYMALIZACJA DOBORU AKUMULATORÓW DO ZASTOSOWAŃ FOTOWOLTAICZNYCH

Streszczenie. Opracowano metodykę pozwalającą na określenie ilości energii produkowanej przez moduł PV, oraz na określenie optymalnej pojemności akumulatora do zastosowań w autonomicznych układach solarnych. Metodykę wykorzystano przy doborze akumulatorów współpracujących z modułem PV o strukturze polikrystalicznej. Na podstawie analizy dla wybranej stacji metrologicznej określono optymalną pojemność akumulatora współpracującego z modułem polikrystalicznym. Określono również koszty jednostkowe magazynowania energii elektrycznej w funkcji głębokości rozładowania akumulatora.

Słowa kluczowe: pojemność akumulatora, autonomiczny układ solarny, moduł fotowoltaiczny, głębokość rozładowania akumulatora.