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ALGORITHM FOR THE OPTIMAL DESIGN OF PLUS - ENERGY BUILDINGS

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Abstract. The paper presents an algorithm for the optimal design of plus - energy buildings. It explains the need for designing such type of buildings. The aim of this article is to create a hypothetical plus-energy building. The study presents a calculation for electricity from renewable sources: solar and wind energy. The calculations take into account the climatic conditions in a particular area of Poland. The final part of the article provides a comparison of the number of solar collectors, photovoltaic panels and wind turbines required to meet the energy needs of the building. Detached houses were placed in two different climatic regions of Poland.

Introduction

A plus - energy building is a building that produces in a year more energy than it consumes [1]. A great emphasis on plus - energy buildings is placed by the Directive 2010/31/EU. Under this directive, from 2020 all newly created buildings will be buildings of nearly zeroenergy consumption. The Directive 2010/31/EU aims to reduce greenhouse gas emissions, therefore buildings of nearly zero energy consumption will use the energy from renewable sources [2]. Environmental pollution and depletion of fossil fuels are the main reasons for which the emphasis is put on renewable sources of energy [3]. By 2020, 20% of the energy consumed by EU countries should come from renewable sources. Buildings consume approximately 40% of total energy demand in the European Union. It has a significant impact on the long - term energy consumption. New buildings must be characterized by low energy consumption and they should use modern technology [2]. But there is a problem: What to do with the existing buildings? Is it possible that a building which has existed for many years, could be made environmentally friendly?And whether an existing building can be a plus - energy building? In order to answer these questions, a detached house which has existed for several years was adopted for the calculation.Two climatically different cities in Poland were selected: Czestochowa and Leba [4]. Then the identical detached houses were located in those cities. Energy consumed by the buildings came from two renewable sources: solar energy and wind energy.

1. Algorithm of calculations

The algorithm of calculations included the determination of energy produced throughout the year:

- from the sun - the energy was produced by photovoltaic panels and a solar collector,
- from the wind - the energy was produced by a wind turbine.

Then the number of the above-mentioned devices which are needed to ensure the total energy demand of the building has been calculated.

1.1. The amount of energy obtained from the sun

The data taken from the Ministry of Transport, Construction and Maritime Economy [5] and a model of the heat pipe solar collectors with an area 2 m^2 [6] and polycrystalline photovoltaic panel were adopted for the calculations [7]. The amount of energy produced by solar collectors and photovoltaic panels was calculated using the formula [8]:

$$E_s = R_s \cdot S_a \cdot e_{opt} \cdot e \tag{1}$$

where E_s [kWh] is the energy produced by the solar collector or photovoltaic panel, R_s [kWh/m^2] is the solar radiation for a given surface (horizontal surface/30°/45°/60°/90°), S_a [m^2] is the active area of the absorber, e_{opt} [-] is the optical efficiency of the collector or photovoltaic panel and e[-] is the monthly utilization rate of efficiency.

The energy demand for the domestic hot water [9]:

$$E_{te} = \frac{V_{hw} \cdot N_p \cdot h_w \cdot d_w \cdot (T_{hw} - T_{cw}) \cdot m_c \cdot t_{ui}}{3600} \tag{2}$$

where E_{te}[kWh] is the total energy demand for heating water, V_{hw} [m^3/d] is the unitary daily hot water consumption, N_p [-] is the number of people using the installation, h_w [kJ/kg·K] is the specific heat of water, d_w [kg/m^3] is the density of water, T_{hw} [°C] is the temperature of hot water in the inlet tap, T_{cw} [°C] is the cold water temperature taken as 10°C, m_c [-] is the correction multiplication factor, t_{ui} [d] is the time of using the installation.

1.2. The amount of energy obtained from the wind

The data taken form the Ministry of Transport, Construction and Maritime Economy [5] and a model of the wind turbine with a nominal power 5.8 kW were adopted for the calculations [10]. The amount of energy produced by a wind turbine was calculated using the formula [11, 12]:

$$E_w = \frac{c_f \cdot n \cdot 0{,}5 \cdot \rho \cdot A \cdot t \cdot v^3}{1000} \tag{3}$$

where: E_w [kWh] is the energy produced by a wind turbine, c_f[-] is the conversion factor of wind energy into mechanical energy, n [-] is the product of mechanical efficiency of the rotor gearbox and auxiliary machinery and electrical equipment efficiency, ρ [kg/m^3] is the air density, A [m^2] is the area swept by the rotor blades, t [h] is the time of wind average speed measurement, taken as one hour, v [m/s] is the hourly average wind speed calculated at the height of the wind turbine. The value of v was calculated from the formula [12]:

$$\mathrm{v} = \mathrm{V_a} \cdot \left(\frac{\mathrm{h}}{\mathrm{h_a}}\right)^{\mathrm{b}} \tag{4}$$

where: V_0 [m/s] is the velocity measured at the height h_a, v [m/s] is the velocity calculated at the height h, h_a[m] is the position height of the anemometer, h [m] is the height for the calculation of the velocity v, b [-] the exponent of terrain roughness factor.

1.3. Optimal selection of number of solar collectors, photovoltaic panels and wind turbines for the selected building

An optimal selection of a number of devices has been chosen in such a way that the selected quantity of these devices can produce enough energy to satisfy the total energy demand of the building.While selecting the devices, the geographical location of the building and the climatic conditions in the are awere also taken into account [8, 12]:

$$n_c + n_p + n_t > t_d \tag{5}$$

where: n_c [kWh] is the energy produced by the calculated number of solar collectors, n_p [kWh] is the energy produced by the calculated number of photovoltaic panels, n_t [kWh] is the energy produced by the calculated number of wind turbines, t_d [kWh] is the total energy demand of the building.

2. Solar energy

The average annual insolation in Poland is about 1000 kWh/m^2. Its maximum value reaches about 1200 kWh/m^2 in Lublin while its minimum value is about 900 kWh/m^2 and can be found in the northern part of the country [13]. In this paper, two climatically different cities in Poland were selected: Czestochowa and Leba (Fig. 1). The total insolation for Czestochowa is 1082 kWh/m^2 during a year, while for Leba it is 911 kWh/m^2, for the angle 45°of the sun rays [5].

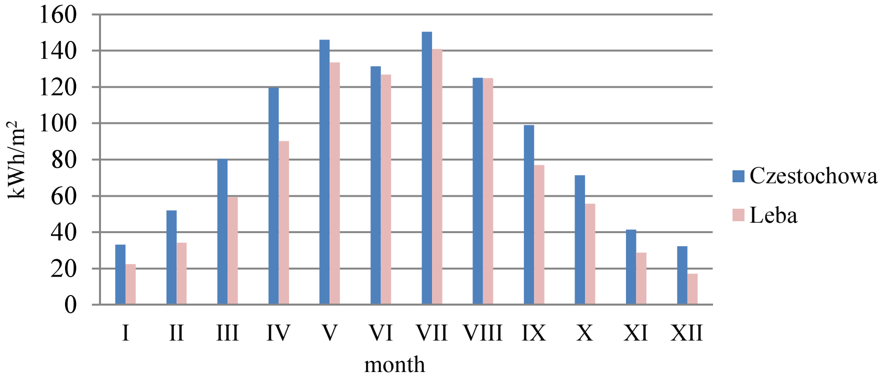

Fig. 1. Total insolation in each month in Czestochowa and in Leba. The data for the angle 45° of the sun rays [5]

Table 1

The insolation values for different angles of the sun rays in Czestochowa and Leba [5]

Angle of the sun rays	0°	30°	45°	60°	90°
Czestochowa [kWh/m^2]	990	1080	1082	1056	933
Leba [kWh/m^2]	847	908	911	896	815

Solar collectors have been used for heating utility water. In the article it is assumed that five people live in the building. The hot water requirement has been calculated on the basis of the Standard: PN-EN 15316-3:2007, while the hot water tank with a capacity of 300 liters has been properly selected [8]. Having information about the insolation and the hot water demand, a proper number of solar collectors has been adopted. Five solar collectors have been optimally selected (Fig. 2). Hot utility water is to be heated up with other sources of heat in winter.

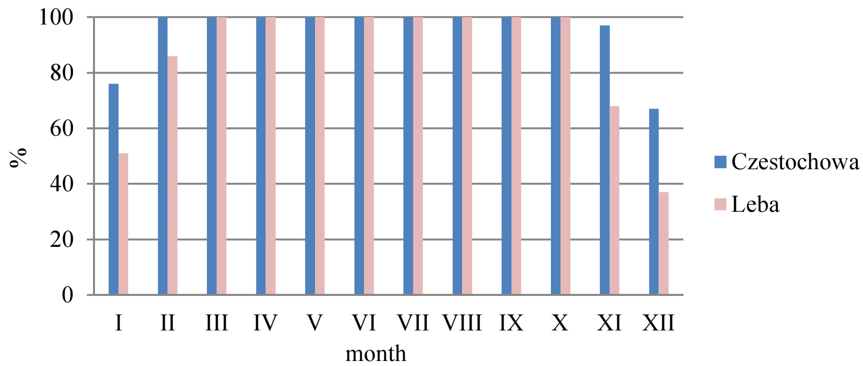

Fig. 2. Coverage of the energy requirements for heating hot water in each month. The energy produced by five solar collectors [own calculations]

Additional heating of hot utility water requires annually about 735 kWh in Czestochowa and about 913 kWh in Leba (Fig. 3).The water is reheated with the use of electricity generated by the photovoltaic panels or wind turbines [own calculations].

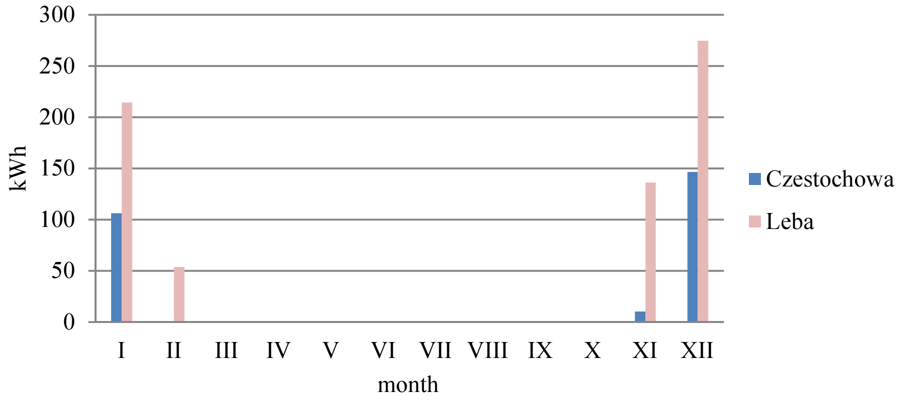

Fig. 3. Additional energy consumption to heat water in each month [own calculations]

Photovoltaic panels are used to generate electricity under the influence of sunlight. In the present case, solar panels were set at the angle of 45°, at which point the largest amount of energy is generated in Czestochowa and in Leba (Fig. 4). The photovoltaic panel has produced 277 kWh of energy per year in Czestochowa and the identical photovoltaic panel has produced 233 kWh of energy per year in Leba [own calculations].

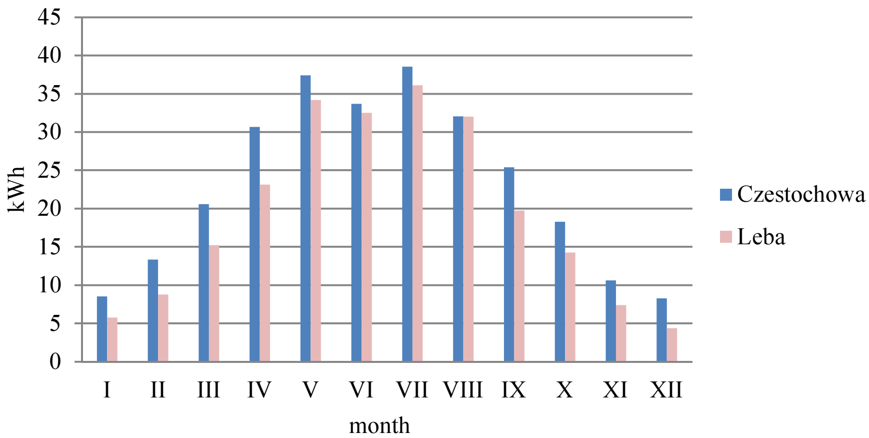

Fig. 4. Electrical energy generated by a single photovoltaic panel within a month in Czestochowa and Leba [own calculations]

3. Wind energy

Wind power is unevenly distributed in Poland. Czestochowa has relatively poor wind resources in strong contrast with Leba [12].

Wind energy is calculated from the formula (3) which is exact for low wind speed. For higher wind speeds a limit of error should be adopted, because the values are inaccurate [14]. Manufacturers usually provide a wind turbine power graph (Fig. 5). Basing on this graph, we can read the dependence of power generated from the wind speed. Knowing the average hourly wind speed we can do the reading from the graph of power, and then by summing the values obtained, we can calculate the amount of energy produced by the wind turbine per year.

The paper compares the amount of energy calculated from the formula (3) and the amount of energy read from the graph given by the manufacturer.

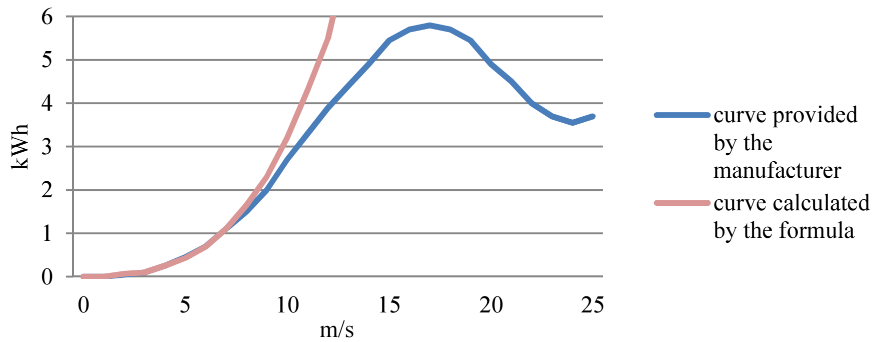

Fig. 5. Wind turbine power, read from the graph given by the manufacturer, compared with the power calculated by the formula [10-12]

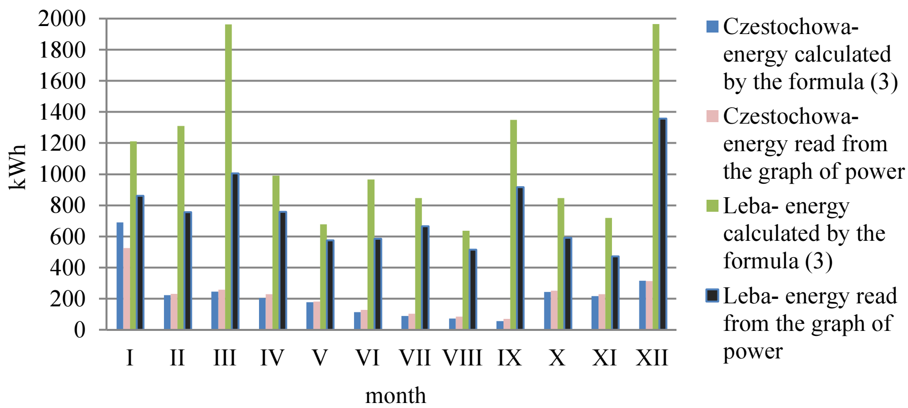

Fig. 6. The amount of energy produced by a single photovoltaic panel in Czestochowa and in Leba. The amount of energy calculated from the formula (3), compared with the amount of energy read from the graph of power [own calculations]

The wind speed is low in Czestochowa, so the value read from the graph is approximate to the value of energy calculated by formula (3). The wind speed is high in Leba, so the value read and the value calculated are different (Fig. 6). For higher wind speed, formula (3) is not accurate, because the wind speed is raised to the third power in the formula. Due to the fact that the value of the energy read from the graph is more accurate than the value calculated from formula (3), the value of the reading has been adopted for further calculations.

4. Optimal selection of number of wind turbines and photovoltaic panels, depending on the geographic location of the building

Five solar collectors were used to heat the hot water in the buildings in Czestochowa and in Leba. The additional energy to heat the water, shown in Figure 3, was added to the column "The total energy demand".

Table 2

Optimal selection of number of wind turbines and photovoltaic panels for Czestochowa [own calculations]

month	Electric energy produced by:			The total energy demand	The energy given / taken (-) from the network
	1 wind turbine	1 photovoltaic panel	5 wind turbines and 22 photovoltaic panels		
	[kWh]				
I	525.9	8.5	2816.6	3149.8	−333.2
II	230.3	13.3	1444.7	2726.2	−1281.5
III	257.5	20.6	1740.2	1954.7	−214.5
IV	228.9	30.7	1819.1	1497.2	322.0
V	181.7	37.4	1731.2	677.8	1053.4
VI	127.7	33.7	1379.1	355.2	1023.8
VII	102.5	38.5	1359.9	362.7	997.2
VIII	83.9	32.1	1124.9	333.5	791.4
IX	71.2	25.4	914.0	725.2	188.9
X	251.6	18.3	1659.8	1544.1	115.6
XI	229.4	10.6	1380.0	2510.2	−1130.3
XII	313.1	8.3	1747.4	2973.8	−1226.4
sum	2603.3	277.3	19116.7	18810.4	306.3

Table 3

Optimal selection of number of wind turbines and solar panels for Leba [own calculations]

month	Electric energy produced by			The total energy demand	The energy given/ taken (-) from the network
	1 wind turbine	1 photovoltaic panel	2 wind turbines and 5 photovoltaic panels		
	[kWh]				
I	860.2	5.7	1748.9	3190.7	−1441.8
II	756.6	8.8	1557.2	2729.8	−1172.6
III	1005.6	15.2	2087.2	1978.3	108.9
IV	757.7	23.1	1630.9	1506.0	124.9
V	575.3	34.2	1321.6	678.9	642.7
VI	584.3	32.5	1331.1	355.2	975.9
VII	664.7	36.1	1509.9	362.7	1147.2
VIII	514.6	32.0	1189.2	329.6	859.6
IX	916.3	19.7	1931.1	722.8	1208.3
X	590.3	14.3	1252.1	1565.0	–312.9
XI	472.7	7.4	982.4	2531.0	−1548.6
XII	1357.0	4.4	2736.0	3038.6	–302.6
sum	9055,1	233,5	19277,6	18988,6	289,0

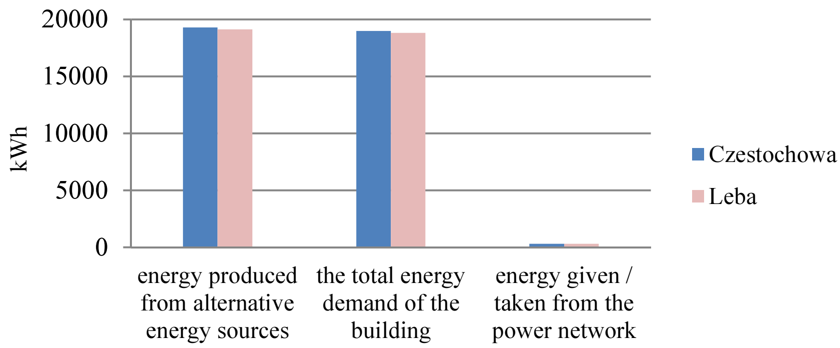

Fig. 7. The annual energy balance of the building - Czestochowa and Leba [own calculations]

Conclusions

A plus-energy building meets the requirements of the Directive 2010/31/EU and is environmentally friendly. The algorithm for the optimal design of plus-energy buildings consists in making series of calculations, as a result of which the total building energy demand is fulfilled with the energy generated from renewable sources. It is important to choose the right number of devices for the production of energy from renewable sources. The selection of the devices usually depends on the climatic conditions prevailing in the area. Any existing building can be a plus - energy are on the condition that it will use the energy from renewable sources. The surplus of energy produced can be sold to the power network.

Acknowledgments

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