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Performance analysis of a PV driven heat pump system during a heating season in high latitude countries

Bartosz Chwieduk[a], Dorota Chwieduk[a]*

[a] Institute of Heat Engineering, Warsaw University of Technology, Nowowiejska 21/25, Warsaw 00-665, Poland

Abstract

The paper analyzes utilization of a PV system driving the heat pump of a low energy house in Warsaw during winter. Based on the demand for electricity of the considered building for summer conditions the size of the photovoltaic system has been determined. On the basis of meteorological data and technical data of PV modules the energy output for all hours of the year has been calculated. The duration of the heating season and the amount of energy that must be supplied to the heat pump in all the days of the year to keep the indoor air temperature at a constant level have been calculated. After taking into account the heat pump output, an estimation of the time of its operation for all the days of the year has been made. The share of PV energy and energy from the grid towards the total energy supplied to drive the heat pump has been determined. Two cases of PV system configurations have been considered. The first utilizes batteries for storage and all the energy produced by the PV system can be used to drive the heat pump. In the second case, the time of the heat pump operation is coupled to the time of the availability of solar radiation and the PV operation. However, operation of both systems is not coherent all the time. The impact of the PV operation on indices of energy consumption is analyzed. For the considered specific micro scale PV system coupled with a ground heat pump to supply energy for space heating in this low-energy building, the results show that reduction of primary energy consumption is not significant. However, to give a definite answer of how the PV system should be coupled to a ground heat pump to supply heat for the space heating of a low-energy building the optimization of the operation of the heating system based on technical and economic aspects should be performed.

Keywords: ground source heat pumps; solar energy availability; solar gains by PV system; space heating via a heat pump driven by PV system; indices of energy consumption of buildings, low-energy buildings.

1. Introduction

In Poland, as in other European countries, the building sector is responsible for about 40% of energy consumption in the country. Nearly 70% of this 40% is used for space heating in buildings. However, in recent years this share has been gradually decreasing. Strong energy saving policies have given evident results. Buildings are designed, constructed and operated with stress on improving their thermal quality and efficient use and operation of energy systems. According to existing regulations in Poland [1], nowadays indices of primary energy consumption in single family houses and in multifamily apartment buildings cannot exceed 120 kWh/m^2 per year and 105 kWh/m^2 per year, respectively. From the year 2021 these indices will be at level of 70 kWh/m^2

* Corresponding author. Tel.: +48222345227.
E-mail address: dorota.chwieduk@itc.pw.edu.pl; bartosz.chwieduk@itc.pw.edu.pl.

per year and 65 kWh/m^2 per year, respectively.

Reduction of the energy needs of a building can be achieved through good architecture and building construction, including application of appropriate materials and structure of the building. Reduction of energy consumption can be accomplished through utilization of efficient energy systems and their devices. Application of renewable energy technologies is especially recommended, because for such systems primary energy consumption based on fossil fuels is nearly zero (energy based on fossil fuels can be only used to drive auxiliary devices). Ground source heat pumps systems are such a technology and their use is a very good option for operation in high latitude countries, and countries with climatic conditions similar to Polish ones.

2. Selection of a space heating system for low energy buildings

Utilization of renewable energy in buildings can be considered when standard methods of reduction of the energy needs have been already applied. Reduction of the energy needs through well designed architecture and building construction make the utilization of renewable energy systems more efficient and reliable [2].

In Poland, as in other high latitude countries, winters can be cold and solar irradiation low. During heating seasons solar energy can be used, but the share of solar energy to meet the energy needs of a building is small (between 10–20%). However, in summer and even earlier, from April until the end of September, the solar irradiation is high, as well as the ambient air temperature. This is due to the influence of the continental climate. When a building is designed and constructed according to energy conservation rules and especially when it is a low energy building, then there is no need to supply heat for the space heating. Heat for the DHW – Domestic Hot Water system only is needed. A solar thermal system can nearly cover the full DHW heating needs (electric auxiliary system can be used as back up) from approximately 80% in September and April to 100% from May to August [3].

During the heating season solar energy can be used as preliminary energy for the space heating, but most of the space heating load must be accomplished by another source of energy, e.g. by a ground heat pump. Ground source heat pumps can operate as the main energy system. Energy gained by the heat pump from the ground and solar energy gained by the solar collectors can be used directly for the heating needs or can be stored in a storage tank for the later use. The storage tank is the central focal point of the low temperature heating system. Heat from the storage tank can be used for DHW or space heating. Usually the low temperature heating is applied in the form of the underfloor (water) heating. As has been mentioned, the solar thermal system can cover nearly the full DHW needs outside the space heating season, and because of that there is no need to use the heat pump in summer [3].

Coupling a solar thermal system with a ground source heat pump is very good solution for effective operation of the heating system based on renewables for Polish climatic conditions and other countries with a similar climate. During the several sunny months, from spring to autumn, when the ground source heat pump is not used the natural heat recovery of the ground body takes place. The ground medium can come back to its initial thermal state before extracting the heat out of it (at the beginning of the next space heating season). The distribution of temperature of the ground at different depths, where vertical ground heat exchangers are inserted, should be the same at the beginning of the each heating season. This is beneficial for effective operation of the heat pump and the heating system of the building [4].

To make further reductions in fossil fuel consumption by the heating system of a building it would be good to use renewables to supply electricity to drive a heat pump and auxiliary devices, e.g. pumps, fans, etc. One of the possibilities is to use the photovoltaic (PV) modules and this method is considered in the paper. It can be mentioned, that application of heat pumps driven by the PV system is supported by the national Polish financial support mechanism introduced by the National Environmental Fund to promote utilization of renewables.

3. Heating of a low energy building via a ground heat pump driven by a PV system

3.1. Description of the space heating system of the building under consideration

To determine space heating needs of a building it is necessary to formulate the energy balance of a building taking into account all the energy flows into and out of the building at a given time. Modelling of the energy balance of a building can be done in a very detailed way [3], [5] or in a simplified way using for example standard methods for determination of the energy performance characteristic of a building [6] – [8].

The building considered in the paper is an existing low energy single family house of 350 m^2 floor area.

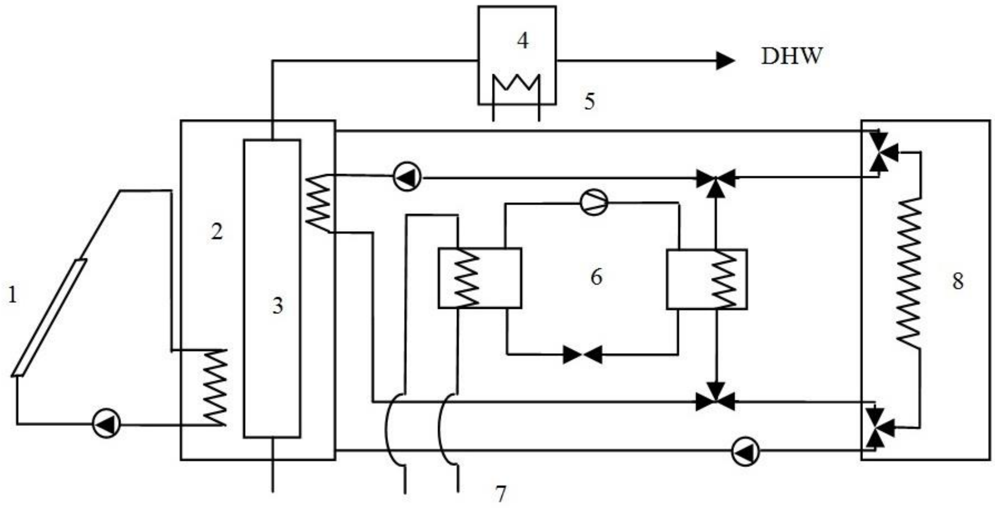
Calculations of the energy needs for the space heating and ventilation, and DHW have been performed according to the standard method applied for determination of the energy performance characteristics of buildings [7] – [8]. Own simulation code developed to determine energy demands of buildings has been applied. Some results of calculations of the monthly energy balance components of the considered building are presented in Table 1. Due to the well planned architecture (solar house concept) and construction of the building (not described in the paper) the monthly heat demand is small in winter, and in March and October can be even neglected.

Table 1. Total monthly heat losses due to the heat transfer through envelope and ventilation, heat gains (internal and solar), heat demand

Monthly components of energy balance	Total heat losses (*kWh*)	Total heat gains (*kWh*)	Heat demand (*kWh*)
January	3827	2245	1582
February	3406	2298	1111
March	2787	3598	17
…			
October	2081	2839	6,8
November	2966	1800	1167
December	3455	1668	1787

Results of calculations included in the energy performance certificate of the considered building show that the indices of the final and primary energy consumption are very low. They are equal to 22,56 kWh/(m^2 a) and to 25,58 kWh/(m^2 a), respectively. So they are much lower than limit indices introduced by the Polish regulations [1] and the building under consideration is really a low energy building.

Heating of the considered building is accomplished by a ground source heat pump coupled with a solar heating system [9]. The operation of the solar thermal collectors and the heat pump is not directly connected. Both devices operate in parallel. They can operate at different time of a day, but they can also supply heat at the same time. It is also possible to supply heat directly from the heat pump to the underfloor heating system (without charging the storage tank). A simplified scheme of the heating system is shown in Fig.1. Six flat plate solar collectors of 10,92 m^2 aperture area supply heat to the main buffer storage tank of 700 liters volume. An antifreeze mixture circulates in the solar collector loop. The ground source heat pump thermal capacity is equal to 8,1 kW (and the compressor capacity is 1.8 kW). There are four with vertical U shaped heat exchangers inserted into four ducts, each of 50 m depth. The vertical tubes are connected together by horizontal collector pipes. An antifreeze mixture circulates through the ground heat exchangers and supplies heat to the buffer storage tank, or directly to the heat pump. The buffer storage tank with water as a storage medium contains a small tank inside. The small tank is used as a buffer tank for the DHW system. Cold water is supplied to the small tank and when the water is heated up it flows out of the tank and is transferred to the other tank, which is the main DHW storage tank (50 liters volume) equipped with an auxiliary electric heater. Space heating of the building is accomplished by the underfloor heating system that is supplied by the heat stored in the big buffer tank or directly by the heat pump. Figure 2 presents the print-screen of a display of configuration and operation of the considered system on 3nd November at 6 o'clock.



1 – liquid solar collectors
2 – buffer storage tank
3 – inner DHW storage tank
4 – main DHW tank
5 – auxiliary electrical heater
6 - heat pump
7 - ground heat source for a heat pump
8 - space heated by underfloor heating system

Fig. 1. Schematic of configuration of a parallel solar assisted ground heat pump system for the space heating and DHW

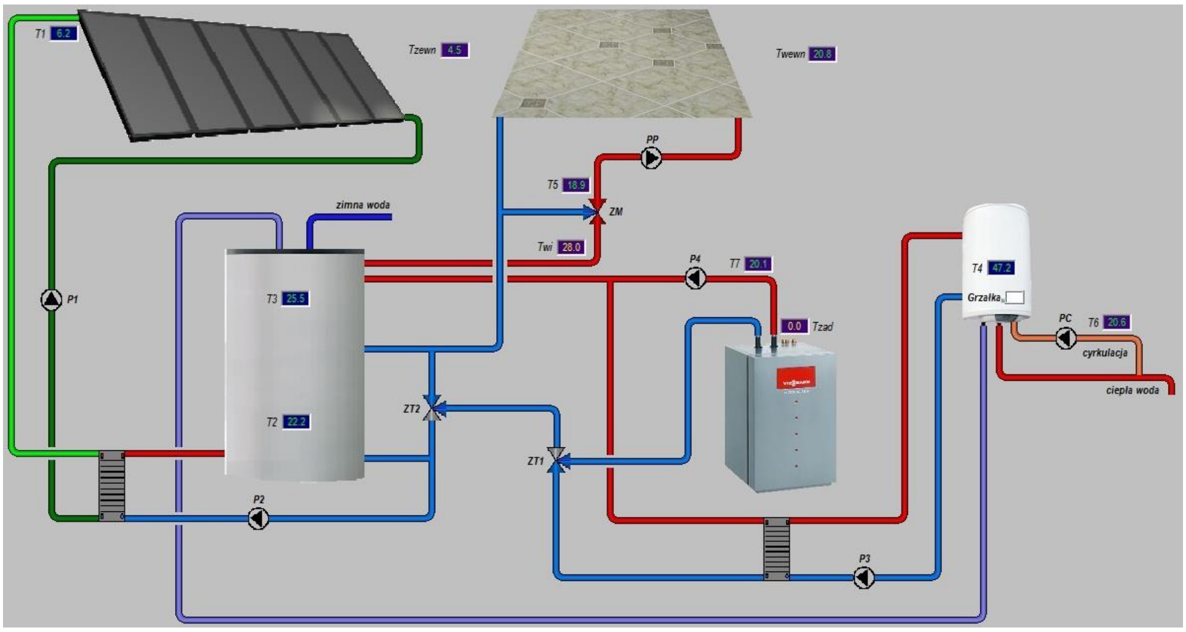


Fig. 2. The print screen of a display of configuration and operation of the ground heat pump system coupled with solar heating system

A heat pump operates only during the heating season in parallel mode with the solar thermal system. After a few years of operation the SCOP (Seasonal Coefficient of Performance) of the heat pump reaches a steady annual mean level of 4.9. Ventilation of the building can be accomplished through the heat recuperation system (with flow rate of 900m^3 per hour), which is mainly used in winter or through natural gravity ventilation system (when the heat recuperation central unit is turned off), which is used in summer. Apart from the solar and ground energy the electricity from the grid is the only other form of energy that is used. The electricity production in Poland is in 85% based on coal (hard and brown) which causes high primary energy intensity of this energy carrier, as a whole energy sector. To reduce fossil fuel consumption the utilization of electricity based on renewables can be taken into account. The paper considers utilization of solar energy through application of PV systems to supply electricity to the house.

3.2. Selection and operation of the PV system supplying electricity to the considered building

To determine the availability of solar radiation on inclined surfaces of PV modules the solar irradiations for every hour of every day of the averaged year have been determined. Solar irradiation has been calculated using the isotropic diffuse solar radiation model proposed by Liu-Jordan [10]. The hourly sums of direct and diffuse solar radiation have been taken from the official meteorological national data set [11]. To size the PV system methods of “the best month” and “the worst month” of the solar radiation conditions have been used. June usually is the month with the highest solar irradiation and December the lowest. In contrast the electricity demand is usually the highest in December (the shortest days of the year and the ambient temperature low) and the lowest in June (the longest days of the year and the ambient temperature high; and no cooling devices electrically driven are applied, as is characteristic for low-energy buildings). Electrical energy needs of all electrical appliances and the heat pump of the building under consideration have been calculated. The results are presented in Fig. 3. These results have been validated against monthly electricity consumption by the real operation of all devices installed in the building. Calculations of hourly solar irradiation of inclined surfaces of the PV modules (inclination – 30^0, orientation - to the south) and energy produced by the PV systems have been performed using our own simulation code.

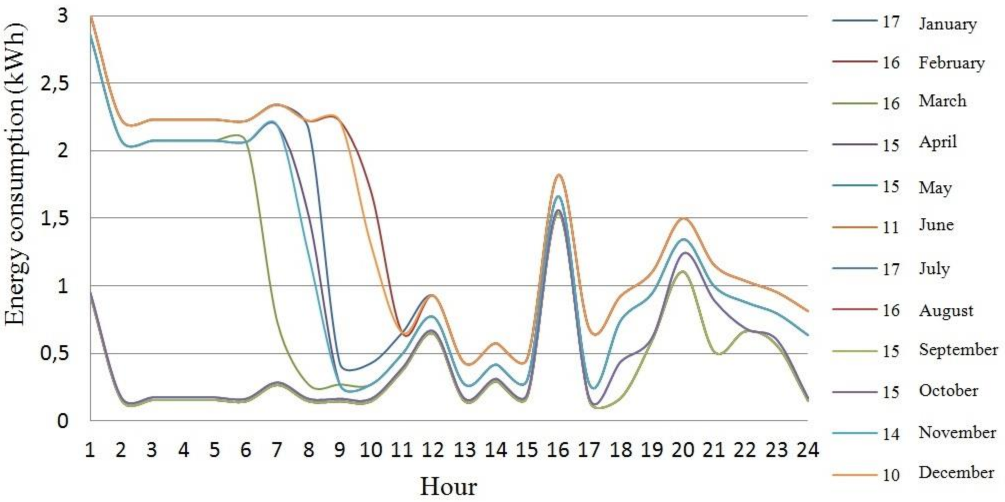


Fig. 3. Electrical energy needs of all electrical appliances and a heat pump of the building under consideration

in the following hours of the year

Taking into account two options mentioned above, “the best month” - June and “the worst month” – December, the installed capacity of the PV system should be 2.7 and 61,5 kW, respectively, if the PV system is designed to cover all electricity needs in these two months [12]. Due to the space (surface area) available on the roof of the considered building and the investment costs of the PV system the first option (small size) of the PV system has been chosen for consideration. Multi-crystalline silicon PV modules of specific operation characteristics [13] have been selected for analysis. The PV module has a size of 1.640m x 0.99m and the peak capacity is equal to 245 $W_{p.}$. Taking into account calculated available solar radiation incident on the PV modules throughout the year and the physical and operational parameters of the modules the useful solar energy gained by the PV systems has been determined. It should be underlined, that calculations of the solar gains of the PV system have taken into account the dependence of the efficiency of the PV module on temperature (NOCT - nominal operating cell temperature is equal to 45ºC and power temperature coefficient is equal to -0,004). Figure 4 and 5 present the results of calculations of the solar gains of the PV system with installed capacity of 2.7 kW operating in Warsaw climatic conditions in the following hours of the year and the following days of the year, respectively. The total annual electrical energy gained by the selected PV system is equal to 2859 kWh.

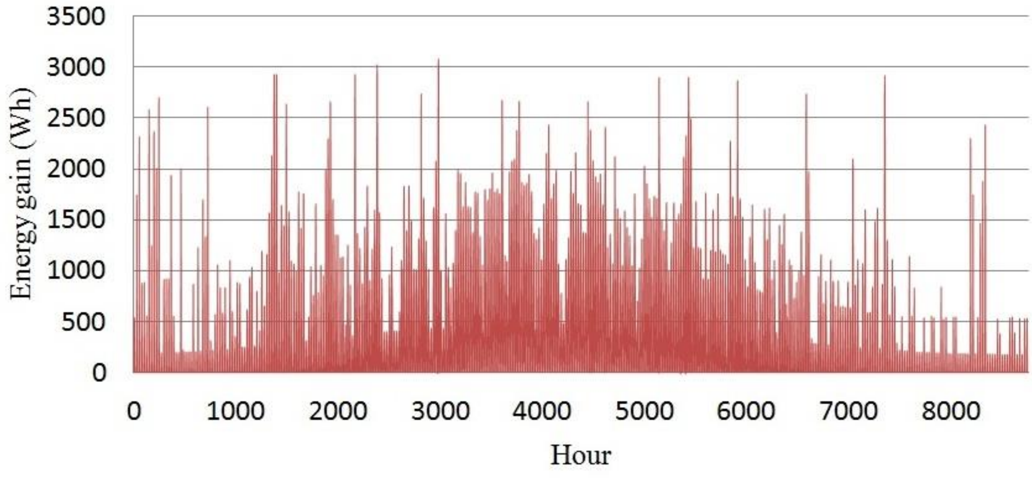


Fig. 4. Solar gains of the selected PV system in the following hours of the year

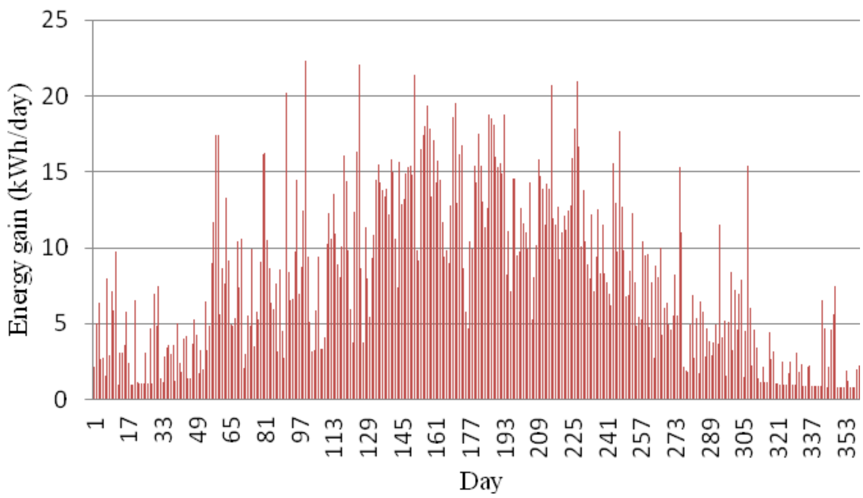


Fig. 5. Solar gains of the selected PV system in the following days of the year

Analyzing distribution of the solar gains presented in Fig. 4 and Fig. 5 it can be seen that summing up the hourly gains for every day of the year gives a somewhat different view of solar energy availability.

3.3. Operation of the heat pump supplying heat to the space heating system

As a result of the space heating demand calculations based on the standard methodology determining the energy characteristics of buildings the period of the space heating season for the considered building has been evaluated to be from 20th of October to 15th of March (see data in Table 1). This period is in accordance with the electricity bills that have been paid in that time. The heat pump does not operate continuously. On the basis of installed capacity of the heat pump compressor and the calculated values of the hourly energy consumption by the heat pump during every day of the heating season the total daily time of operation of the considered heat pump has been determined. The results of calculations are presented in Fig. 6. The total annual (space heating season only) energy required to drive the compressor of the heat pump is equal to 2185 kWh.

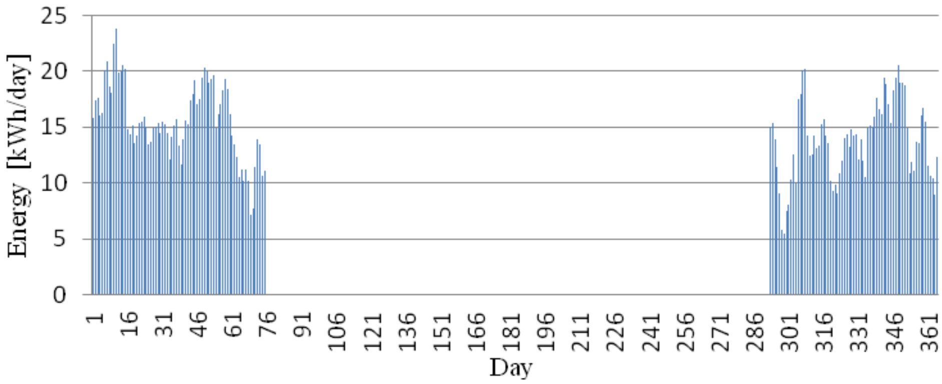


Fig. 6. Daily electrical energy needed to drive a heat pump for space heating of the considered building

Knowing the energy needs of the heat pump throughout the heating season and ability of the PV system to provide energy the coherency and complementarity of such energy systems, that can be called "the user" (a heat pump) and "the energy producer" (energy source), can be evaluated.

3.4. Compatibility of the heat pump operation supplying heat to the space heating system and PV system providing heat to drive the heat pump

Two options of the PV system configuration and operation have been considered. The first configuration assumes that the PV system is equipped with batteries. All the energy gained by the PV modules is used to drive the heat pump: directly or through the solar batteries (accumulated energy is used to drive the heat pump, when the PV modules cannot operate – no solar radiation or solar irradiance is too low). When there is no energy available directly from the PV modules or from the batteries, the heat pump is driven by electricity from the grid. In the second case the PV system contains inverters only and it can supply electricity only directly to the heat pump. When the PV modules do not operate electricity from the grid is used. In the last case the time of the heat pump operation is correlated to the operation of the PV modules (i.e. when PV modules operate than the heat pump operates, too).

Taking into account the two options mentioned above, in the first case the heat pump can use 100% of energy gained by the PV system (from modules and accumulators) during the heating season, which is equal to 559 kWh and gives 25% of the total electrical energy needed to drive the heat pump. In the second case 495,6 kWh of electricity produced by the PV during heating season can be used, which corresponds to 88,6% of the total energy produced by the PV and to 23% of the total electrical energy needs of the heat pump. It can be noticed, that the share of energy supplied by the PV system in two considered cases of its configuration do not differ a lot, and so because of higher investment costs in a case of the system with batteries (see Table 2), the second option is analyzed further.

Table 2. Investment costs of on-grid PV system and off-grid PV system (with batteries)

Type of PV system	Without batteries	With batteries
PV modules	1830 EUR	1830 EUR
Inverter	1370 EUR	1370 EUR
Batteries	-	11430 EUR
PV charge controller	-	230 EUR
Installation	1370 EUR	1370 EUR

Sum	4570 EUR	16230 EUR

Figure 7 presents the energy produced by the photovoltaic system for every day of the heating season for the second case of configuration of the system. When the energy produced by the PV system is not needed by the heat pump the surplus energy is sent to the grid, being equal to 63.4 kWh per heating season. Figure 8 presents the electrical energy from the grid used to drive the heat pump for every day of the heating season.

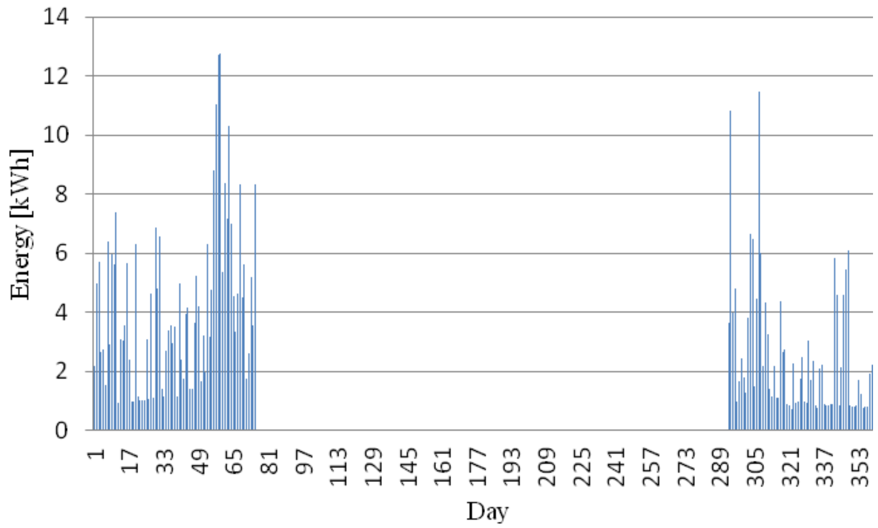


Fig.7. The energy produced by the photovoltaic system during the heating season

It is known, that solar energy availability is the lowest when the space heating demand is the highest. So the results of the calculations performed are not unexpected. The share of solar electricity (solar energy converted into electrical energy) gained by the considered micro PV system to drive a heat pump used to provide space heating in the low energy building is not very big. However, looking at the problem from the other side the reduction of 23 - 25% of energy supplied by fossil fuels is not small. However, energy efficiency aspects should be coupled with the economic analysis to give a full recommendation for application of PV driven heat pumps in low energy buildings.

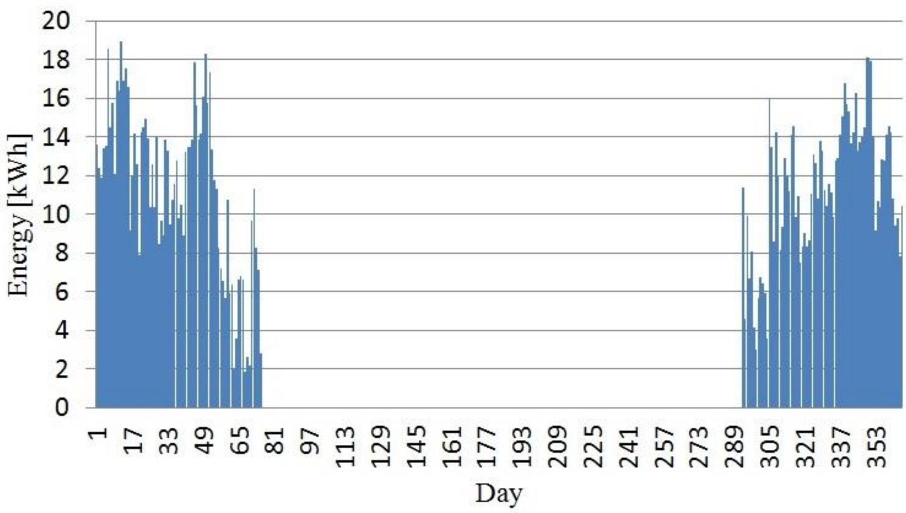


Fig.8. The energy from the grid used to drive the heat pump during the heating season

4. Summary and Conclusions

As has been already mentioned the building under consideration is a low energy building. It means that the energy needs of the building have been reduced a lot thanks to good (thought-through) architecture and its civil engineering design. What is more, the energy consumption of the building is also reduced a lot due to the application of modern energy efficient heating systems, including the solar thermal system and the ground source heat pump. The indices of the final and primary energy consumption are really very low comparing standards for buildings in similar climatic conditions. In the building under consideration, as it has been already mentioned, the indices of final and primary energy consumption are equal to 22.56 kWh/(m^2 a) and to 25.58 kWh/(m^2 a), respectively (according to the national regulation in Poland from the year 2012 a nearly zero – energy building cannot consume more than 70 kWh/(m^2 a)). For further reduction of primary energy consumption (based on fossil fuels) the application of a PV system driving a heat pump during a heating season has been proposed.

The PV system taken for final analysis is a micro system and its capacity of 2,7 kW_p has been determined on the basis of the "best month" method, when the solar radiation is the highest and electricity consumption is the lowest. The results show that energy provided by the PV system can cover about 23%- 25% of the total energy needed to drive a ground source heat pump for the space heating of the building. Because of this the indices of the final and primary energy consumption for the all heating energy needs (including DHW energy) can decrease accordingly to 20.11 kWh/m^2 (with solar batteries) and to 20.28 kWh/m^2 (without the batteries) per year. Then the primary energy consumption indices can be at level of 21.22 and 21.72 kWh/m^2 per year, accordingly. It means, a reduction of 4.36 and 3.86 kWh/m^2 per year respectively in comparison to the present energy consumption. It does not look too much. However, taking into account the percentage of the primary energy reduction, it looks much better. The energy reduction corresponds to 17% and to 15% of the primary energy. To summarize the indices of annual final and primary energy consumption for the all heating energy needs for three cases of the heating system applied in the building under consideration are presented in Table 3. Case 1 corresponds to existing heating system with solar collectors and a heat pump driven by electricity from the grid. In case 2 the difference is in using a heat pump driven partly by the PV system with batteries and partly by the electricity from the grid. In case 3 the PV system has the same PV modules but it does not contain batteries.

Table 3. Indices of final and primary energy consumption for the all heating energy needs for three cases of the heating system

Indices of annual energy consumption	Final (*kWh/(m^2a)*)	Primary (*kWh/(m^2a)*)
Case 1	22.56	25.58
Case 2	20.11	21.22
Case 3	20.28	21.72

It can be concluded, that to give the definite answer how (size and configuration) the PV system should be coupled to a ground heat pump to supply heat for the space heating of a low-energy building the optimization of the operation of the heating system should be performed. In the optimization procedure the technical – energy efficiency as well as the economic aspects should be taken into account.

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