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THE APPLICATION OF PHOTOVOLTAIC CELLS AS AN ALTERNATIVE POWER SUPPLY FOR SMALL HVAC SYSTEMS

ZASTOSOWANIE OGNIW FOTOWOLTAICZNYCH JAKO ALTERNATYWNEGO ŹRÓDŁA ZASILANIA MAŁYCH SYSTEMÓW HVAC

A b s t r a c t

This paper presents selected aspects of an alternative power supply for small HVAC systems. The application of a system based on photovoltaic cells together with energy accumulation in VRLA gel batteries was analysed. The results were obtained using laboratory installation and were compared with the predicted data.

Keywords: *HVAC systems*, *alternative power supply*, *renewable energy*, *photovoltaics*

S t r e s z c z e n i e

W artykule przedstawiono wybrane aspekty alternatywnego zasilania małych systemów HVAC w energię elektryczną. Analizowano zastosowanie systemu opartego na baterii ogniw fotowoltaicznych z akumulacją energii przy użyciu akumulatorów żelowych VRLA. Porównano przykładowe wyniki pomiarów przeprowadzonych na instalacji badawczej z danymi prognozowanym.

Słowa kluczowe: *systemy HVAC*, *zasilanie alternatywne*, *energia odnawialna*, *fotowoltaika*

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1. Introduction

A reliable power supply is known to be the basic requirement for the proper operation of all HVAC (Heating, Ventilation, Air Conditioning) systems. This issue is of particular importance in systems where a power shortage may lead to the failure of devices or a break in operation that can last much longer than the duration of the power failure. Examples of such devices are solar thermal collectors and solid fuel boilers. A loss of power in solar thermal collectors causes an interruption in the reception of heat which consequently results in a very rapid increase in the collector temperature. An increase of fluid volume should be compensated for by the expansion vessel in a well-designed system; however, a design or realisation weakness, or a defect in the expansion vessel, may lead to system damage. Solid fuel boilers are characterised by a long turning off time after failure of the power supply. Interruption of the water circulation in such devices might cause the boiling of water and its partial removing through the opened expansion tank. However, whilst this will not lead to boiler damage, the time required to restore full functionality of the heating system would significantly increase. Another category of devices where an alternative power source is worthy of consideration might be appliances (e.g. mechanical ventilation unit or gas boilers) in which long-term exclusion negatively affects thermal comfort. The problem of the power supply of mechanical ventilation appliances becomes particularly important in modern buildings, so-called ‘passive houses’, which are very airtight. It is noteworthy that the above-mentioned devices are usually characterised by a relatively low power consumption which additionally justifies the use of an alternative power supply.

It is known that the current condition of the electrical grid in Poland is unsatisfactory [9]. Investment expenditures for the expansion and modernisation of transmission lines are not able to compensate for the increasing load. Additionally, the ageing infrastructure (e.g. wooden poles, corroded wires) increases the possibility of failure. Low power quality [12] in some areas might cause further problems. This issue has a particular impact on the proper operation of electronic control and measurement systems. Voltage dips or high THD (total harmonic distortion) values may contribute to the malfunction of the automation components, and thus bring about the breakdown of the whole system.

The aforementioned problems can be avoided through the use of an alternative power source with energy accumulation. In large HVAC systems, diesel generators (usually without batteries) are often used for this role. In the considered small systems (e.g. for houses or hostels) this solution is not popular due to its onerousness. As an alternative, one can consider:

– an uninterruptable power supply (UPS) energy storage system powered by the electrical grid and used only in the case of a power shortage. The uptime depends on battery capacity and the load;
– an alternative power supply which utilises a renewable energy source (photovoltaic panels or wind turbine) with batteries for energy storage and a DC/AC inverter. In such a system, it would be possible to operate the HVAC system during the power failure if favourable weather conditions exist;
– a hybrid system that usually consists of co-operating photovoltaic panels and a wind turbine. Hybrid systems are known to have a higher reliability than single-source systems.

Because of the high investment cost of hybrid systems and insufficient reliability of UPS, further study focused on systems powered by photovoltaic (PV) cells [5, 8].

The main advantage of renewable energy systems (apart from environmental protection issues) is acquiring an additional, independent source of electricity that allows HVAC systems to operate, under favourable weather conditions, even in the case of long-term power grid failure. Moreover, with appropriate design of the PV power system, it is possible to supply the HVAC equipment from the renewable source only. This allows to the reduction of the investment payback time. In the case of excess energy, one can also use the surplus to power other appliances (e.g. refrigerator, lighting). There is also the possibility of selling the excess energy to the national energy grid, but this entails a higher investment cost due to necessity to use a grid-tied inverter. Currently, unfinished legislation regarding renewable energy sources does not encourage investment in systems connected to the grid.

It is noteworthy, that power failures often occur during storms and these are usually preceded by a long period of sunny weather – this allows for a sufficient charge of batteries to be accumulated. Usually, the repair time of such a failure does not exceed a few hours. During this time, it is possible to continue normal operation of the HVAC system. In the winter time, there are often breakdowns involving wire breaks caused by them being laden with snow and ice. Power recovery time after failure of this kind may take several days in particular cases of areas that are hard to reach. In such a situation, the use of an alternative power supply allows for the exploitation of the building at least to a limited extent (depending on battery status and weather conditions).

2. Photovoltaics

In Poland, moderately favorable conditions prevail for the use of solar energy on a large scale due to its geographic location. Depending on the region of the country, the annual sum of total irradiation on a horizontal surface is 930-1070 kWh/m^2 [2]. According to the ‘solar radiation map’ developed by the European Commission [11], it can be found that the annual sum of irradiation on an optimally-inclined surface is 1100–1300 kWh/m^2. Despite this optimistic forecast, which estimated the raise in the installed capacity of PV systems to 24 MW for the end of 2013 [5], the real increase of total power in on-grid systems is proven to be much lower. Based on the report of the Polish Energy Regulatory Office [15], the installed capacity of on-grid photovoltaic systems only reached 1.9 MW by the end of 2013. As can be seen, this represents an insignificant fraction of the total installed capacity of the national energy grid, which is currently estimated at over 38000 MW. Nevertheless, solar energy can be effectively used as an alternative source of power for the relatively small power demand loads in off-grid systems. The above-cited forecast was based on the capacity of panels sold in Poland in 2012 (22.9 MW). Assuming that these panels have been installed, the off-grid systems capacity, which has not been included in the Energy Regulatory Office report, might even exceed the capacity of on-grid systems by a factor of ten. This relationship accurately reflects the current trend in the use of photovoltaic systems.

The monthly distribution of solar irradiation on the selected area might be estimated based on long-term meteorological observations. A significant difference between the data can be seen depending on the applied data sources. To determine the scale of discrepancies between the estimation of the solar irradiation on a flat surface for the location of Krakow--Balice, three different data sources were compared:

– Database Classic PVGIS [14], based on measurements from 1981 to 1990 – this database is included in the PVGIS software [11];
– Database Climate CM-SAF [6], based on measurements from 1998 to 2011 – this database is also available in PVGIS software;
– Database 'typical climate and statistical years for building energy calculation' provided by the Polish Ministry of Infrastructure and Development [10], based on measurements from 1971 to 2000.

The choice of location for comparative calculations was resulted from location of the laboratory installation which was situated in nearby village. The obtained yearly results are summarised in Table 1 while the monthly distribution of irradiation is illustrated in Fig. 1. Further analysis of solar conditions in the vicinity of Krakow is presented in paper [13].

Table 1

Comparison of the annual sum of total irradiation for the location Krakow-Balice

Database	Irradiation [kWh/m^2]
Classic PVGIS	1000
Climate CM-SAF	1110
Typical year, Balice	1045

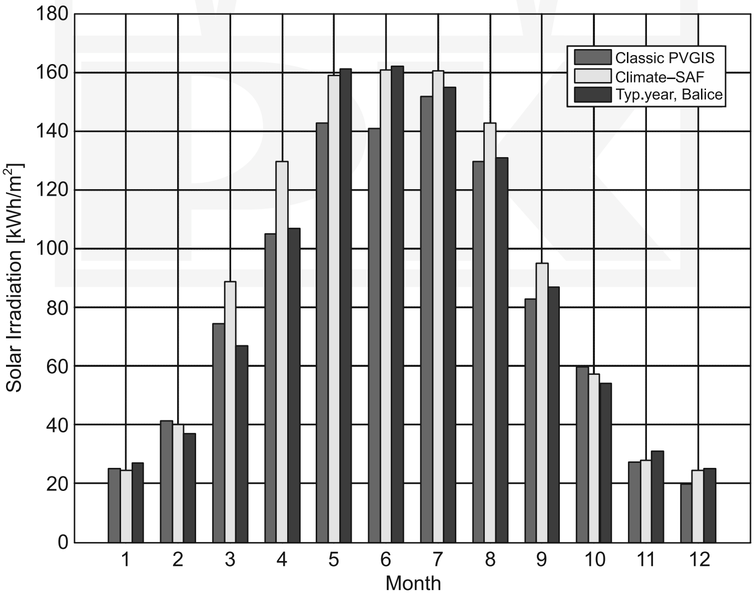

Fig. 1. Monthly sum of total irradiation in Krakow-Balice (according to selected databases)

The efficiency of energy conversion in PV systems is relatively low. Currently, the typical efficiency of the most popular polycrystalline solar panels reaches around 15%; however, this is not a constant value. PV cell efficiency decreases with increases in temperature [3] as well as the age of the cells. According to the forecast provided by the International Energy Agency [7], it is highly probable that the polycrystalline cell efficiency will exceed 20% in the next twenty years. The development of new PV cell technologies is also of particular importance.

In addition to solar irradiance, energy production is heavily dependent upon the operating point of the PV cells. With increasing of the panel load (at a constant irradiance) from open-circuit up to short-circuit, results in reduction of generated voltage: from maximum value in no-load state down to zero when connectors of the panel are shorted. Analysing the voltage characteristics of the PV cell (Fig. 2), one may determine the presence of the point at which the power reaches the maximum (MPP – maximum power point). The maximum operating point tracking (MPPT) is the ability of some devices (charge controllers, DC/AC inverters) to maximisation of the generated power power by control of the load. In practice, the effectiveness of the MPPT in systems with charge controllers will be considerably limited by the batteries' state of charge and the current load of the system. The existence of multiple MPPT algorithms, characterised by a very diverse efficiency [4], is also noteworthy.

Due to the apparent movement of the sun across the sky during different seasons, the amount of electricity generated in PV systems largely depends upon the panels' inclination. The optimal value of this angle is determined by the latitude of the proposed installation. Although there are versions of the systems where the PV panels follow the sun (solar tracking), the higher cost and unreliability of such systems associated with the presence of moving parts as well as the additional consumption of electricity needed to power the actuators and electronics, make this solution less favourable. In southern Poland, the optimal angle of inclination for the maximisation of energy production is 35 degrees. Increasing the inclination to 60 degrees allows the growth of energy production in the winter months at the expense of a decrease in production during the summer.

3. The laboratory installation

In modern HVAC systems, variable speed drives are commonly used for pumps and fans. For this reason, these systems are characterised by their high variability in demand for electricity, depending mainly upon weather conditions and the method of operation. This variability is therefore both seasonal and diurnal. A consequence of this is a difficulty in assessment of demanded capacity of the alternative power supply [1]. The maximum power of all devices powered by photovoltaic systems may only be a guideline that allows for the estimation of the scale of the system. As shown in the characteristics of photovoltaic cells (Fig. 2), aside from weather conditions, the achieved power is also influenced by the load. Therefore, determination of the HVAC system runtime is difficult. Performing measurements on a test installation under conditions similar to typical operation can contribute to a better evaluation of a HVAC system powered by photovoltaic cells.

The laboratory installation used in this study consisted of a gas heating boiler and hot water system using two independent subsystems with solar thermal collectors. The maximum active power drawn by the system is approximately 300W. The power source for this system is the set of two polycrystalline photovoltaic panels with a rated total power of 480 Wp (watt peak). The panels were oriented towards the south and mounted on the roof of the building at an inclination of 35 degrees. Table 2 summarises the essential parameters which characterise the applied panels.

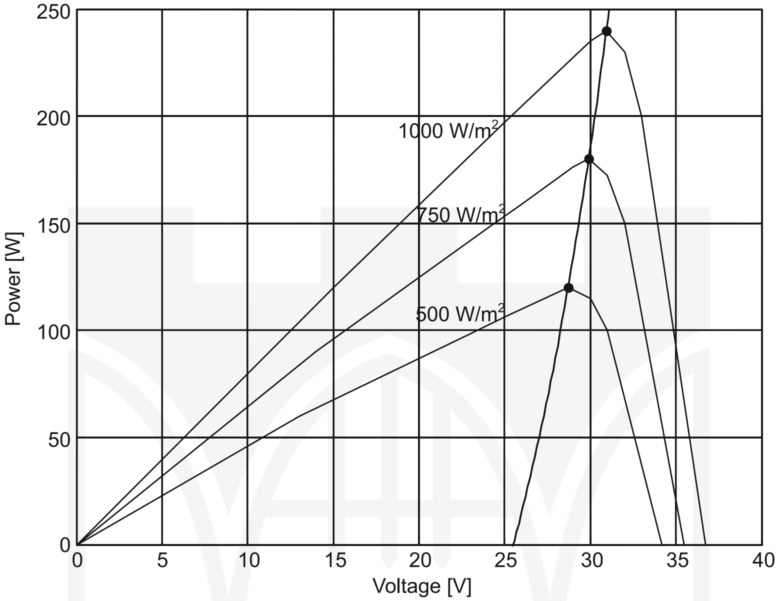

Fig. 2. An example of a voltage – power characteristic of PV panels for different values of irradiance (the dashed line represents MPP)

Table 2

Characteristics of PV panel BS-240-6P-EU1

Nominal power, Pmax [W]	240
Voltage at P_{max}, V_{MPP} [V]	30.95
Current at P_{max}, I_{MPP} [A]	7.75
Short-circuit current, I_{sc} [A]	8.64
Open-circuit voltage, U_{oc} [V]	36.75
Efficiency, η_{PV} [%]	14.4
Panel weight, m [kg]	22
Panel area, a [m²]	1.67
Max power after 10-year period	90% P_{max}
Max power after 25-year period	80% P_{max}

Figure 3 shows an electrical diagram of the PV power supply for the laboratory installation of the HVAC system. Energy produced in photovoltaic panels was stored in VRLA (valve-regulated lead–acid) gel batteries with a capacity of 110 Ah/24 V. A Steca Solarix PRS 2020 charge controller was used to control the charging process and battery protection (U1). Since the electrical appliances (boiler, pumps) are powered with AC, it is necessary to apply a single-phase DC/AC inverter (U2). In the discussed installation, the Victron Phoenix off-grid inverter (350 VA 230 V/50 Hz) was used.

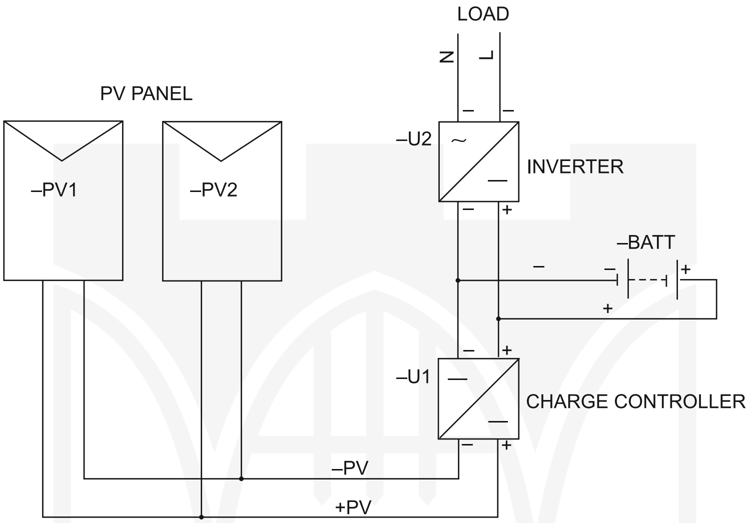

Fig. 3. Electrical diagram of the PV power supply for laboratory installation

In case of deep discharge of the battery, the system provided the possibility to switch to the mains power supply. At present, the system is not equipped with components allowing recharging of the batteries from the mains in case of adverse weather conditions. Due to the requirement of a high level of reliability, these components should ideally allow storage of an adequate amount of energy in the battery.

The system was equipped with elements allowing the measurement of voltage and current generated by the photovoltaic panels and drawn by the connected load. Current shunts were used for current measurement while the voltage was measured using voltage dividers. The acquired signals were converted to a digital form using data acquisition module Advantech ADAM 4017 supported by software written in PHP. The results of measurements were recorded in the database over a period of one minute. The monitoring of the installation commenced in April 2013; however, due to some failures there is no long-term data (e.g. full year) for statistical analysis. For this reason, in the later study, only shorter periods of operation were analysed.

4. Assessment of predicted and actual energy yield

As already mentioned, the statistical data, based on years of meteorological observations, has limited suitability in estimating the possible energy yield in PV systems. Energy production is often estimated using specialised software such as PVGIS, PV*SOL or PVsyst. However, the actual production of electricity depends largely on the current system load as well as the battery charge level. This results directly from the characteristics of the photovoltaic cells (Fig. 2): generated power at a given irradiance is strongly dependent on the cell load. It is noteworthy, that continuous operation with power close to the maximum operating point is not possible even in a system equipped in charge controller with MPPT function. This function operation will only bring a positive effect in the low battery state of charge by limiting the charging current and thus preventing overload of the photovoltaic cells. Likewise, in the case of favourable weather conditions and a high level of battery charge, it is also profitable to power devices other than only HVAC systems. This would increase the energy yield and thus shorten the payback period.

In order to determine the differences between the predicted and actually obtained energy in the considered system, its operation in the months with the highest and lowest total irradiation (respectively: June and December) was analysed. From a set of acquired observations, examples of typical sunny and cloudy days were selected separately for the summer and winter. The maximum reached power and energy yield for selected days were subsequently determined. For comparison, the daily energy yield in the system was estimated using PVGIS software. The obtained results are summarised in Table 3. These results accurately reflect the possible differences in energy yields depending on cloudiness. PV panels can also use diffused radiation, allowing them to produce electricity during cloudy weather; however, the obtained power will be considerably less. Because the amount of consecutive days of cloudy weather cannot be predicted, the forecast of the system uptime, based on statistical data, may be unreliable. It may additionally justify the need to equip the system with devices allowing to recharge the batteries from the mains. While it is impossible to avoid additional loss of energy, the reliability of the considered system should be given priority. Recharging the batteries in the case of a low state of charge should be controlled automatically.

Table 3

Energy yield during typical day – measured and estimated

	Date	Max power [W]	Energy yield [Wh]	PVGIS estimated. [Wh]
Typical sunny day – summer	19.06.2013	390	2227	1727
Typical cloudy day – summer	05.06.2013	130	539	
Typical sunny day – winter	12.12.2013	223	547	234
Typical cloudy day – winter	15.12.2013	36	78	

To show changes in the power available during selected days more accurately, daily charts of generated power levels were created. The graph (Fig. 4) shows a comparison of a typical

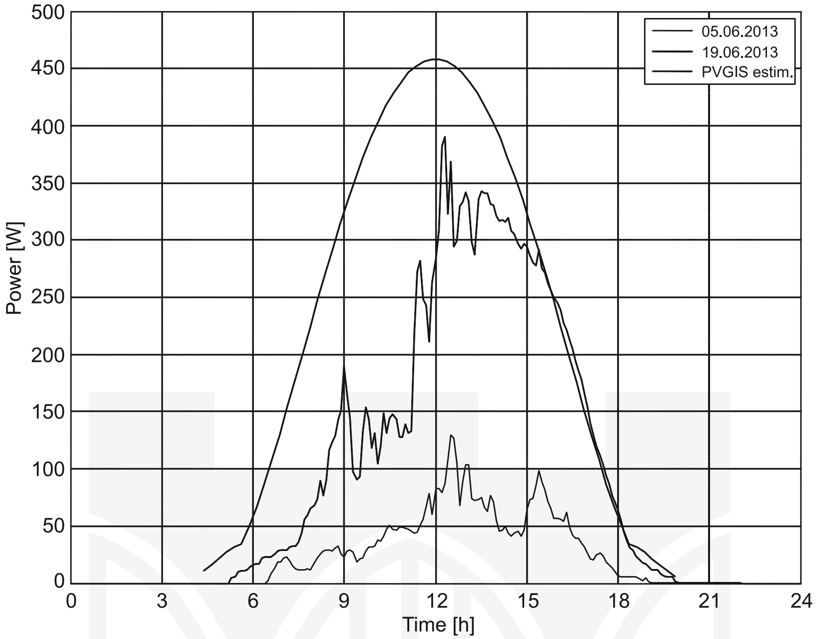

Fig. 4. Comparison of generated power for sample sunny and cloudy days (summer)

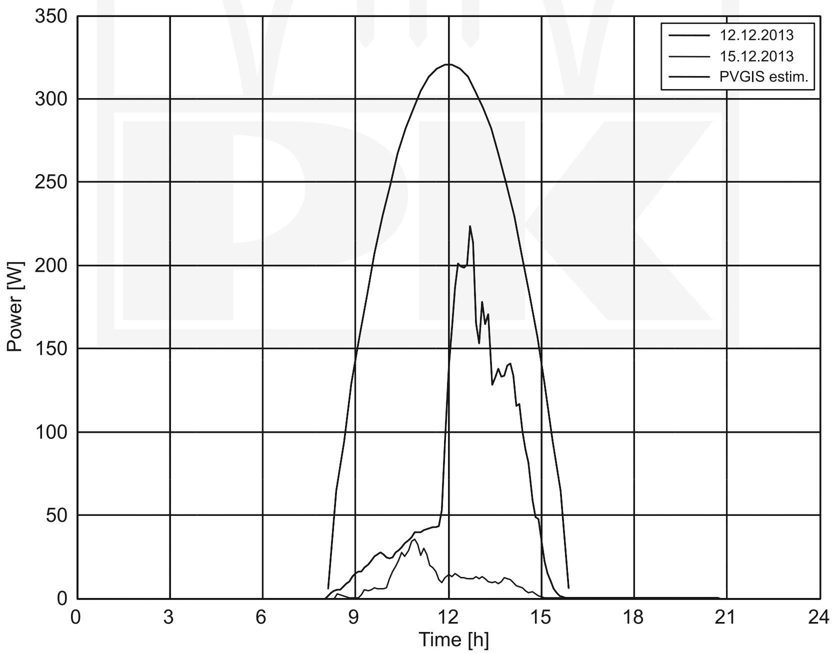

Fig. 5. Comparison of generated power for sample sunny and cloudy days (winter)

sunny and cloudy day during the summer while the graph (Fig. 5) displays similar data for the winter season. Of particular interest may be the comparison of the observed power with the predicted data which is also marked on the charts. The PVGIS software was used to calculate the predicted power assuming a constant efficiency of the PV panels equal to its nominal efficiency.

The predicted power should be interpreted as the power during an average day in a given month (June and December) assuming a clear sky and the PV panel operating at the MPP. The results clearly show the difference between the predicted data and the actual achieved power. Even on a sunny day obtained power is significantly less than the predicted value. The main reason in this case is load mismatch caused by a lack of the MPPT function in the charge controller and thus, under or overload of the PV cells. On cloudy days, the achieved power and energy yields are much smaller. For this reason, unfavourable weather conditions that last a few days, especially in winter, may result in the full discharge of the batteries.

5. Characteristics of electricity use in HVAC systems

As already mentioned, the load of power supply in the HVAC installation is highly variable due to the presence of multiple devices with modulated capacity (pumps, fans, etc.). Since this makes it far more difficult to predict the demand for energy, it is necessary to analyse the operation of individual kinds of load.

Due to the power consumption in small HVAC systems, devices can be divided into:
– equipment with relatively constant power consumption, e.g., controllers or constant speed pumps and fans;
– devices with variable power consumption depending on the solar conditions, such as variable speed pump for solar thermal collectors;
– equipment with variable power consumption depending on other conditions, such as heating boilers or variable speed fans in mechanical ventilation units.

The total power demand during a day is dependent on all kinds of devices, thus the power demand will be dependent on both weather conditions and the plant operation. The graph (Fig. 6) provides an example of the power generated by PV panels and averaged load power. In turn, Fig. 7 contains an additional load power graph, without the averaging, to clearly show actual ‘switching’ character of the load.

Automation components (controllers, measurement transducers) are characterised by their low power consumption of just a few watts. However, these devices operate continuously so their energy requirement represents a significant percentage of the total energy usage. An exemplary system controller for thermal solar collectors, used in the pilot plant, requires about 2W of power. This results in the consumption of electricity at the rate of 1.44 kWh per month. This represents from 3% (in June) to as much as 20% (in December) of the predicted monthly energy production (see Table 3).

Constant speed pumps and fans are characterised by a constant power consumption as long as throttle control components (valves, dampers) do not exist in the system. The presence of such control elements causes a change in power consumption associated with the change of flow. In the laboratory installation, a constant speed pump with a nominal power 45 W

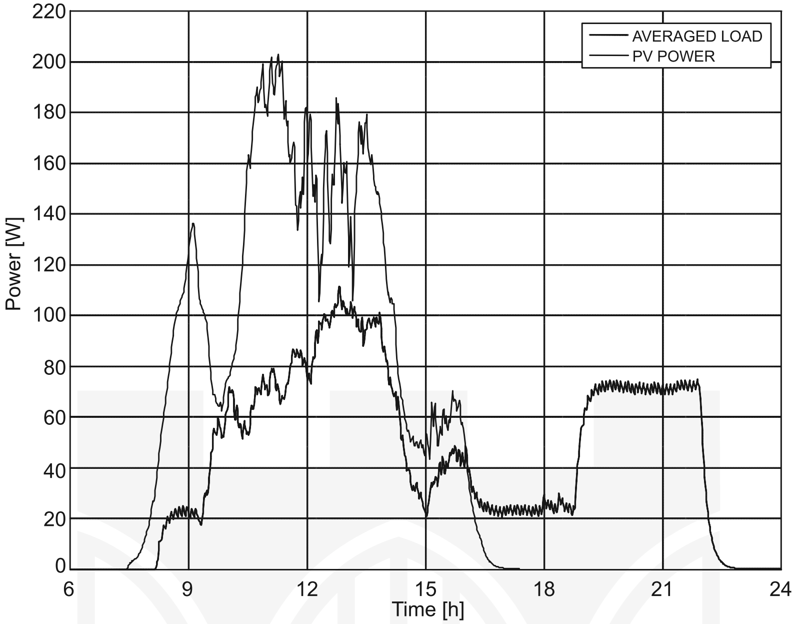

Fig. 6. Example of comparison of the power generated by the PV cells and consumed by the HVAC system

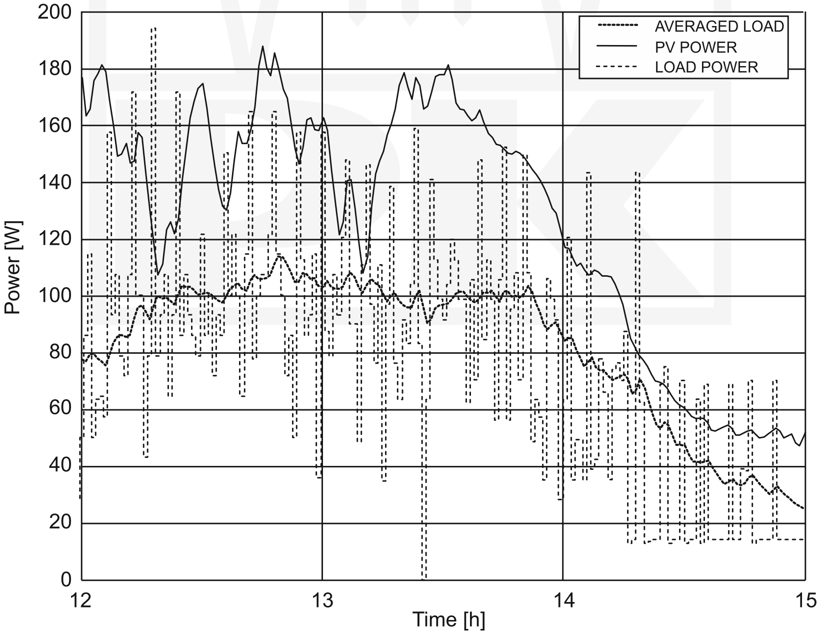

Fig. 7. Pulsed character of load power

was used for discharging the hot water storage tanks in the heating system. In Fig. 6, between 1900 hrs and 2200 hrs, one may notice an increase in power consumption associated with the switching on of the pump.

The variable speed pumps in solar thermal collector circuits are characterised by variable flow and their power demand is dependent upon solar irradiance. This dependence can be seen in Fig. 6, between 0800 hrs and 1600 hrs. The existence of this relationship particularly justifies the application of PV cells to power systems with solar thermal collectors.

Another example of the variable power device is the gas heating boiler. In this case, power consumption is dependent upon the current demand for heat. Subsequent switching of the burner or its heating power modulation causes changes in power consumption which is shown in Fig. 7.

6. Conclusions

The need to ensure continuity of HVAC system operation in many cases enforces the need to consider the use of an alternative or additional power supply. Photovoltaic cells are now willingly considered as an alternative power source for such installations. This is due to the ease of installation of panels, their high reliability and no maintenance requirements. One of the most important advantages of the use of PV panels is also the possibility to continuously power the HVAC system from this source which significantly reduces the payback period.

The optimal selection of the photovoltaic system required to power the HVAC system is stated to be a complex task. An analysis of possible energy yield based on statistical meteorological data for selected location is the basic requirement. As shown, still the obtained results may vary as much as 10% depending on the used database. The total power of installed loads does not give reliable information about the demand for energy and thus it does not allows to estimate the runtime of the system. This is due to the considerable variability in power demand which is entailed by the presence in the modern HVAC systems many devices with modulated power. It was found that an additional difficulty is the unpredictability of the PV cell operating point, particularly in systems that do not use the MPPT.

Given the requirement of power reliability, HVAC systems powered primarily from photovoltaic panels should generally be possible to switch to the mains power supply in case of unfavourable weather conditions. A significant improvement in power reliability can be achieved by equipping the system with devices allowing the automatic recharging of batteries with the power grid.

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