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Research Paper

Experimental study of the solar photovoltaic contribution for the domestic hot water production with heat pumps in dwellings

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HIGHLIGHTS

- Experimental study of a photovoltaic solar heat pump (PV+HP) working to produce domestic hot water.
- A fully monitored experimental facility is described in detail.
- Seasonal results from an entire year of study are presented.
- Some key performance indicators to show the system efficiency have been proposed and calculated.
- The annual performance factor of the system (PV + HP) is 8.92 while the average solar contribution (SC) is 61.7%

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ABSTRACT

The present paper describes experimental work, carried out during an entire year on a heat pump used for domestic hot water (DHW) production, which is powered from photovoltaic panels and the grid simultaneously. The system was designed and controlled to give priority to the renewable source to reach the maximum solar contribution.

The aim of the study was to analyze the real possibilities of using photovoltaic energy to produce DHW with heat pumps in dwellings. The system developed (heat pump + PV) works without batteries and therefore the energy storage is carried out by the hot water accumulated in the tank.

The design of the system was carried out in order to optimize the solar contribution. Some key aspects of the design are: the heat pumps' power, the water storage volume, the control strategy and a device to derive the excess of PV electricity to a secondary heater.

The system was tested for typical DHW production of a typical family of 4 residence: 130 liters at 55°C, about 6.2 kWh a day. Tests were carried out in the university laboratory located in Alicante (Spain). The results during a year of study demonstrates that the annual average efficiency of the heat pump (SPF_{HP}) could be close to 3.5 and the annual average efficiency of the whole system would be near 9, while the solar contribution would be higher than 60%.

1. Introduction

There is important concern in our current society about climatic change and the low level of traditional energy resources; thus, it is necessary to develop new, more environmentally friendly technologies that require a minimum level of contribution from fossil fuels.

Energy consumption in buildings in the European Union is about 40% of the total energy consumption. The European Directive 2010/31/EU [1] is focused on the reduction of energy consumption and the integration of renewable energies, instead of fossil fuels, with the final aim of to reduce greenhouse gas emissions.

Currently, the main technologies that make use of renewable energy, which have a direct application in buildings, are thermal solar energy for heating and/or domestic hot water (DHW) production [2] and photovoltaic solar energy for electrical energy production [3]. Other techniques focus on the combination of both thermal and photovoltaic solar energy. In this regard, Buker and Riffat [4] presented a review with several applications of solar thermal collectors combined with PV panels. In this kind of technology, known as photovoltaic-thermal or "PV-T", solar energy is simultaneously converted into electricity and heat [5]. The heat dissipated by the PV panel is absorbed by a thermal fluid (air, water or refrigerant) and used for heating or DHW production. A large amount of

Abbreviations: PV, Photovoltaic; DHW, Domestic hot water; HP, Heat pump; HT, Electrical heater.

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research on PV-thermal (PV-T) collectors has been carried out in last couple of decades. Zondag [6] presents an overview of these researches.

Several researches [7,8] show the idea of the combination of a heat pump and solar energy, which is called a solar-assisted heat pump (SAHP) system, where the solar thermal collector replaces the conventional evaporator in a heat pump so the evaporation temperature of the refrigeration increases and the heat pumps efficiency improves. This could be an attractive solution in cold regions where higher evaporation temperatures are necessary. In this regard, Chow et al. [9] described a solar assisted heat pump (SAHP) for indoor swimming pool space and water heating.

On the other hand, the PV solar assisted heat pump (PV-SAHP) combines the systems previously described with photovoltaic panels [10]. In this case, the cooling effect of the refrigerant decreases the PV panels temperature so its efficiency is higher. Gang et al. [11] presented experimental research about an application of a photovoltaic solar assisted heat pump (PV-SAHP) in China.

Omojaro and Breitkopf [12] summarize various investigations and analyze the use of direct expansion solar assisted heat pump systems, where SAHP and PV-SAHP are taken into account.

However, the most common technology in buildings is, undeniably, the flat plate solar thermal system.

For the last years, there have been lots of developments in solar thermal technology. Currently, a solar thermal installation can reach efficiencies between 45 and 55% with a typical solar contribution between 30 and 70% depending, obviously, on the collector's surface area, energy demand, solar insolation, etc. These values are more typical in tertiary or industry sector, where the installations have a high maintenance level.

Unfortunately, the experiences in solar thermal energy in dwellings have not been very successful, due mainly to the usually deficient maintenance or a complete absence of it, the consequence being a much lower saving of energy than what was expected. In these cases the conventional energy consumption in the backup heater tends to increase to supply the domestic hot water demand. Furthermore, stagnation and overheating are common problems in this kind of installation, and both of them were analyzed by Quiles et al. [13] and Frank et al. [14]. These problems can decrease the useful life of the solar thermal systems.

The production of domestic hot water with a heat pump powered by PV energy could be an interesting solution especially in family homes. In this configuration, the backup energy comes from the grid, while the PV installation acts as renewable energy source.

In the last few years, heat pump water heaters are being used in many countries. A lot of manufacturers are including this equipment in their catalogs, mainly due to their great performance and compact appearance. An experimental and simulation study was carried out by Morrison et al. [15] about different types of heat pump water heaters and the results showed that the average COP's were between 2.5 and 4.5, depending on the outdoor temperature and the thermal load. Guo, Wu, Wang, and Li [16] reached similar results with an experimental study about heat pump water heaters installed in Shanghai. These results could be better if part of the electrical energy consumption came from a renewable source such as a PV installation and/or wind generator. Poulet and Outbib [17] show this kind of installation as an alternative to the solar thermal energy, mainly in applications where solar water heaters cannot be optimized.

The current paper describes experimental work, carried out during an entire year, focused on a domestic hot water heat pump that is powered from photovoltaic panels and from the grid, simultaneously. The design of the system has been carried out to reach the maximum solar contribution working the following strategy:

Fig. 1. Photography of the experimental facility.

1. The heat pump works 3 to 5 hours a day in order to use the solar energy.
2. The water tanks volume is higher than those used in standard systems in order to store the thermal energy needed during 24 h.
3. The control system has been developed specially to obtain the maximum solar contribution.
4. The excess photovoltaic electricity is derived to a heater installed in the tank.

This study can help to select the design parameters of the system in function of the DWH demand and climatic conditions in order to optimize the solar contribution.

Furthermore, it allows us to compare the advantages of both technologies, conventional thermal energy and heat pump water heaters powered by PV panels.

2. Experimental method

The heat pump analyzed is an ON/OFF equipment with a nominal heating capacity of 1.5 kW and a nominal electrical consumption of 470 W (nominal COP=3.19). Two photovoltaic panels with a total peak power of 470 Wp are connected to a micro-converter, which is connected to the equipment at 230 Vac. The experimental set-up was installed on the roof of the University's research laboratory located in Elche (Spain). Fig. 1 shows a photograph of the facility.

Table 1 shows the technical characteristics of the heat pump for DHW, while table 2 shows the technical characteristics of the photovoltaic installation.

Tests are carried out under real climatic conditions, while a recirculation circuit is used to simulate water consumptions. The facility simulates 6 domestic-hot-water consumptions of 20–23 liters each one. The heat pump equipment heats the water to 55°C and it keeps

Table 1
Technical characteristics of heat pump.

Kaysun Compak KHP 15 190	Simb.	Unit	Economical model
Thermal capacity	Q_{HP}	W	1500
Electrical power of the compressor	$P_{E\text{-}COMP}$	W	470
Coefficient of performance	COP	%	3.19
Electrical heater power	Q_{ELEC}	A	2000
Refrigerant	–	–	R134a
Evaporator fan power	$P_{E\text{-}FAN}$	W	30
Tank volume	V	L	190

Table 2
Technical characteristics of photovoltaic panels.

Eurener 235	Simb.	Unit	Nom.
Nominal power	$P_{N,PV}$	W	235
Panel surface area	A_{PV}	m^2	1.67
Efficiency	$Eff_{,PV}$	%	13.74
Short circuit current	I_{SC}	A	8.25
Open circuit voltage	V_{OC}	V	37.08
Nominal current	$I_{N,PV}$	A	7.66
Nominal voltage	$I_{N,PV}$	V	30.01

the water temperature higher than 50°C. The water inlet temperature is between 12 and 15°C.

The average energy needed to heat the domestic hot water consumption of 129.5 liters with a mean water temperature increase of 41.0°C is Q_{DHW}=6.26 kWh a day. The average tank energy loses are estimated to be Q_{LOSS}=1.63 kWh, therefore the average total energy needed is $Q_{U,TOT}$ = 7.78 kWh a day.

Fig. 2 shows schematically how the heat pump equipment is connected. The domestic hot water (DHW) energy demand is supplied by the heat pump and by an electrical heater. The photovoltaic energy is used in the heat pump when it is ON, while if it is OFF, the photovoltaic energy is derived to the electrical heater. The electricity taken from the grid is only used to support the heat pump (never in the electrical heater).

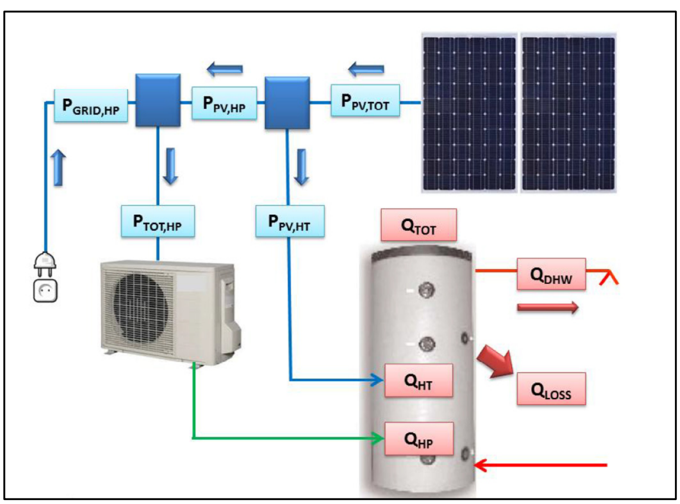

Fig. 2. Schematic graph of the energy flows involved.

2.1. The experimental set-up

To track the equipment's behavior, a monitoring facility has been built. Fig. 3 shows the experimental facility where the subsystem "A" consists of the analyzed DHW heat pump equipment. This equipment is connected, simultaneously to the mains 230 V 50 Hz electric power and to a micro-converter connected directly to the photovoltaic solar panels.

The total energy produced by the PV panels is consumed in subsystem A, in the heat pump if it is ON and in the electrical heater if the heat pump is OFF. The energy from the grid is only necessary if the PV energy is not enough.

During the whole study, the heat pump was switched ON at 11:30 am. Its switch OFF hour depends on the moment when the maximum temperature (55°C) is reached, although it tends to work between 3 and 4 hours. Thus, the working hours are close to the hours of maximum solar radiation; therefore, the solar energy support is maximized.

The photovoltaic solar energy production comes from the subsystem B, which consists of two photovoltaic solar panels (235 W peak power), connected in parallel to the micro-converter with an efficiency of 97%. The panels are placed on the flat roof of the building, facing South with an inclination of 45°.

Finally, the subsystem "C" is the system used to simulate domestic hot water consumptions. The air to water chiller keeps the auxiliary tank temperature constant at 12–15°C. The domestic hot water consumptions are simulated by switching on a pump: 6 times a day, 250l/h during 4–5 minutes at 6:30, 7:30, 9:00, 12:45, 20:00 and 21:15.

Several probes and measuring instruments are installed along the entire installation to determine the efficiency of the equipment (heat pump) and of the entire system (heat pump + PV panels). All the instruments and probes are connected to a HP 34970A Data Acquisition Unit, which recorded all the measurements every 2 minutes. Table 3 shows the 20 experimental data recorded every measurement as an example of the used methodology.

The currents $I_{PV,TOT}$ and $I_{GRID,HP}$ are determined from a value of voltage drop produced in a shunt resistance, calibrated to the passage of electric current. The electric power consumed by the heat pump from the grid ($P_{GRID,HP}$) and from the photovoltaic panels ($P_{PV,HP}$) are measured by two "Class A" wattmeters (1% accuracy).

Electrical energy measurements are tested with a network analyzer Chauvin Arnoux CA8332B. The solar contribution produced

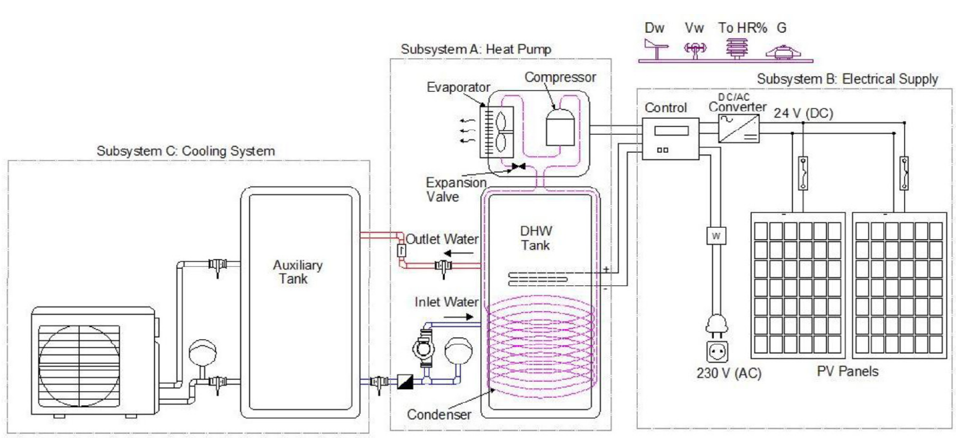

Fig. 3. Experimental setup.

Table 3
Measurements taken and recorded every 2 minutes, June 23th, 13:06.

Description	Simb.	Value	Units
Inlet water temperature	$T_{W,IN}$	40.41	°C
Outlet water temperature	$T_{W,OUT}$	40.95	°C
Mass flow rate of water	m_W	0.00	kg/h
Refrigerant temperature in the compressor's inlet	T_1	17.80	°C
Refrigerant temperature in the compressor's outlet	T_2	71.12	°C
Refrigerant temperature in the condenser's outlet	T_3	50.19	°C
Refrigerant temperature in the evaporator's inlet	T_4	17.25	°C
Refrigerant condensing temperature	T_{COND}	56.43	°C
Refrigerant evaporating temperature	T_{EVAP}	16.79	°C
Grid voltage	V_{GRID}	225.73	V
Current from the grid	I_{GRID}	1.47	I
Power from the grid	P_{GRID}	329.58	W
PV panels voltage	V_{PV}	26.59	V
Current from the PV panels	I_{PV}	13.03	I
Power from the PV panels	P_{PV}	346.46	V
Solar irradiance	Irr	875.34	W/m^2
Outdoor ambient temperature	T_{OUT}	28.23	°C
Relative humidity	HR	56.42	%
Wind speed	V_{WIND}	2.11	m/s
Wind direction	D_{WIND}	158.31	°

by the photovoltaic panels is, therefore, perfectly measured from electrical measurements.

2.2. Calculation of the thermal energy produced by the heat pump

The total useful thermal energy produced ($Q_{U,TOT}$) is determined by two different methods simultaneously, in order to have more reliability in the results.

The first method is a "direct method", where the total heat produced by the system is calculated from measurements in the DHW tank. The total thermal energy can be separated into two components: useful energy for DHW (Q_{DHW}) production and tank losses (Q_{LOSS}).

The DHW useful energy is determined by measuring the flowrate and water temperatures in the inlet and the outlet during the 6 periods of water consumption that are simulated by switching the recirculating pump on. An electromagnetic Siemens MAG 1100 F flowmeter is used to measure the domestic hot water flowrate, and the inlet and outlet DHW temperatures are measured by two RTD PT100 Class B submerged probes. This measurement is considered to be very accurate and an uncertainty lower than 2% is expected. Since the important measurement is the temperature difference, the probes are previously calibrated together.

Tank losses cannot be measured; nevertheless, a good estimation can be made. During one week, the tank temperature is forced to be constant at 50°C with an electrical heater. This measurement is used to calculate the tank's overall heat transfer coefficient. Using the described method, the tank's losses are calculated to be: 1.9 W/°C. To take into account the wind influence on the tank's losses a small correction factor is also considered.

The second method applied is an "indirect method" [18], where the total useful thermal energy produced by the unit ($Q_{U,TOT}$) is calculated from the sum of two following values. The first one is thermal energy produced by the heat pump ($Q_{U,HP}$) that is calculated from measurements in the refrigerant thermodynamic cycle. The second one is the thermal energy produced by the electrical heater ($Q_{U,HT}$). This second value is determined using electrical measurements and applying a conversions factor of 1 between thermal and electrical energies.

In this method, it is necessary to measure the electrical energy consumed by the heat pump's compressor. This measurement, previously carried out, showed that the heat pump fan and the control system only consume 40 W, therefore the compressor consumes:

$$P_{COM} = P_{HP} - 40 \quad (1)$$

The compressor is also insulated; thus it is considered that 93% of the electricity consumed by the compressor goes to the refrigerant and 7% are energy losses by heat transfer.

The following temperatures are measured by small K-type thermocouples located on the surface of the refrigerant circuits pipe: 4 main temperatures of the thermodynamic cycle. Condensing and evaporating refrigerant pressures are measured by highly accurate pressure transducers. These measurements allow us to determine the refrigerant enthalpies in the 4 characteristic points of the refrigerant circuit.

The refrigerant mass flow is obtained applying the following equation:

$$0.93 \cdot P_{COM} = m_R \cdot (h_2 - h_1) \quad (2)$$

In order to have conservative calculations, the temperature in the compressor outlet is considered to be the higher value between the measured data (from discharge pressure and temperature) and from an isentropic efficiency of:

$$\eta_{ISO} = 0.775 - 0.05(p_{COND}/p_{EVAP}) \quad (3)$$

The differences between both direct and indirect methods have been lower than 5% in 95% of the 248 measured days. The methodology is considered therefore to be well tested.

2.3. Measurement uncertainties

The experimental uncertainty was calculated by the following (JCGM 100: 2008) [19]. Electrical measurements are very accurate. Uncertainties on voltage and current are in all measurements lower that 1% for 95% of confidence level. These uncertainties yield to uncertainties in the power measures lower than 1.5% and in the calculated solar contribution (SC) lower than 2%.

The useful thermal power given by the heat pump is determined directly by the DHW production and tank losses and indirectly by the "refrigerant method" as has been explained in the previous section. The estimation of the total useful thermal power Q_{TOT}, calculated by both methods showed differences lower than 5% in 95% of the measured days.

3. Experimental results

The experimental study was carried out during one year in order to establish seasonal results. Results are going to be presented in two levels:

- Detail level: data were taken every 2 minutes (720 data of every variable measured a day). These data were processed in order to get results of every analyzed day.
- Seasonal level: 248 days were analyzed (at least 15 days every month). These results were used to obtain conclusions about the system seasonal behavior.

In the following subsections, detailed and mean results are presented.

3.1. Detailed results: measurements during one day

Fig. 4 shows the electrical power produced by the photovoltaic panels ($P_{PV,TOT}$) as an example of the measurements carried out for 248 days. Measurements show that the example day was a cloudy one (August 24th).

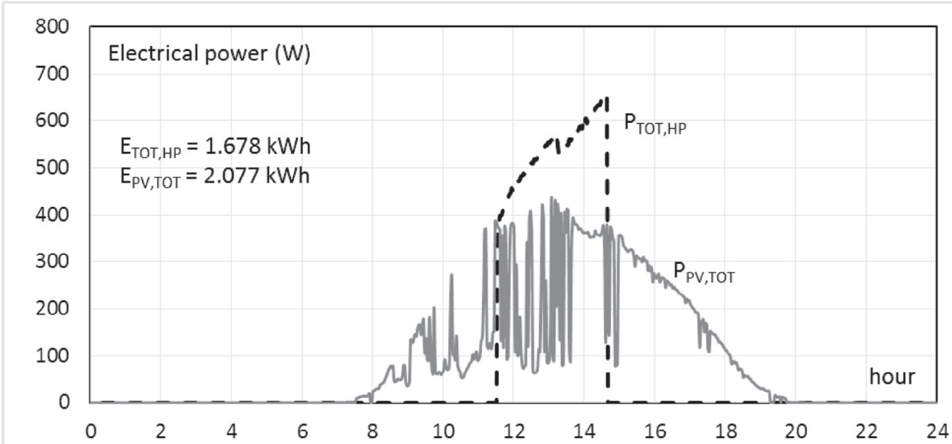

Fig. 4. Electricity produced by the PV panels ($P_{PV,TOT}$) and electrical power consumed by the heat pump ($P_{TOT,HP}$). August 24th.

As the DC/AC converter had an efficiency of 97% (this data were given by the manufacturer and were tested that the value was correct) the electrical energy produced by the photovoltaic panels ($E_{PV,HP}$) is given by the following equation:

$$E_{PV,TOT} = \sum_{1}^{720} P_{PV,TOT}(1/30) = \sum_{1}^{720} 0.97 \cdot \frac{V_{PV,TOT} \cdot I_{PV,TOT}}{1000} \cdot (1/30) \quad (4)$$

The electrical energy produced by the PV panels during the example day was $E_{PV,TOT} = 2.077$ kWh.

Fig. 4 also shows the electrical power consumed by the heat pump ($P_{TOT,HP}$). It can be observed that the heat pump only switched on once a day. Once the control of the heat pump turned it on, it worked until the DHW tank temperature reached 55°C.

Since the storage energy in the tank is high (the water temperature in the whole tank is 55°C or higher), the system guaranteed a DHW temperature higher than 48°C during all scheduled consumptions (temperature stratification in the tank also plays a key role in this situation).

The total electrical power consumed by the heat pump ($P_{TOT,HP}$) is directly measured with an electrical meter. Thus, the total electrical energy consumed in 24 hours ($E_{TOT,HP}$) is known as the sum of each measurement, following the equation:

$$E_{TOT,HP} = \sum_{1}^{720} P_{TOT,HP} \cdot (1/30) \quad (5)$$

The total electrical energy consumed by the heat pump on the analyzed day was $E_{TOT,HP}$ =1.678 kWh, lower than the PV energy produced ($E_{PV,TOT}$), previously calculated. In the study, neither the electrical exchanges with other building installations nor the exchanges with the grid are considered.

In this facility, part of the electricity consumed was supplied from the grid when the heat pump was ON, this is because the solar power was not enough, as shown in Fig. 5. Thus, the following relation can be established when the heat pump is ON:

$$P_{TOT,HP} = P_{PV,HP} + P_{GRID,HP} \quad (6)$$

On one hand, during the analyzed day, the electrical energy taken by the heat pump from the grid was $E_{GRID,HP} = 0.836$ kWh. The electrical energy consumed by the heat pump from the PV panels was therefore $E_{PV,HP} = 1.678–0.836 = 0.842$ kWh.

On the other hand, the PV energy produced when the heat pump was OFF was delivered to the electrical heater asextra thermal energy supplied to the DHW tank. So, the electrical energy consumed by the heater was $E_{PV,HT} = 2.077–0,842 = 1.235$ kWh. It should be taken into account that an electronic device was used to derive this electricity to the heater. This device modified the voltage in order to adjust the inlet and outlet energy.

As previously, an equation can be defined when the heat pump is OFF.

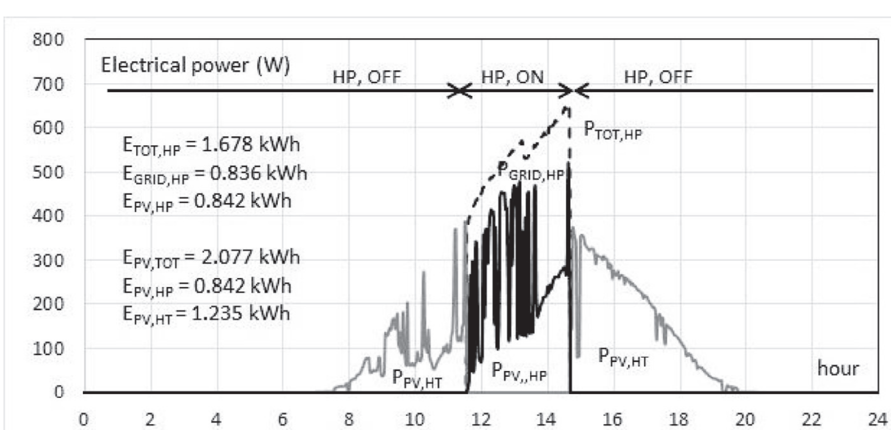

Fig. 5. Electricity produced by the PV panels that is consumed by the electrical heater (PPV,HT), electricity consumed by the heat pump (PTOT,HP) and electricity consumed by the heat pump from the grid (PGRID,HP). August 24th.

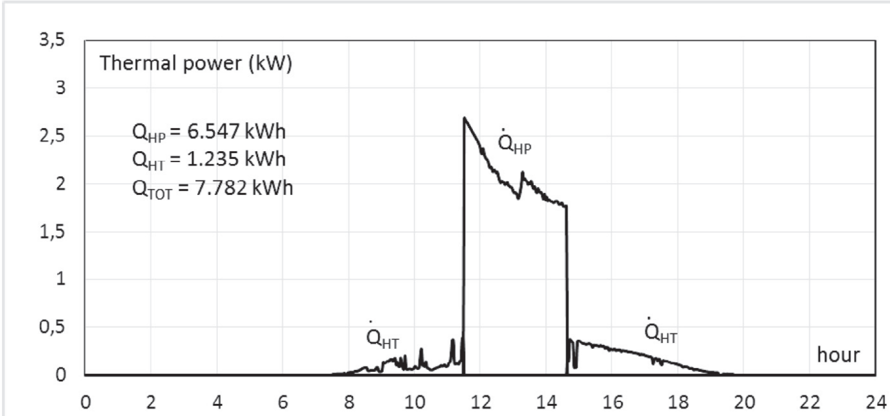

Fig. 6. Thermal energy produced by the heat pump Q_{HP} and by the electrical heater Q_{HT}.

$$P_{PV,TOT} = P_{PV,HT} \tag{7}$$

The thermal flow in kW that both the heat pump and the electrical heater gave to the DHW tank is shown in Fig. 6.

When the heat pump is ON, the thermal power given by the heat pump Q_{HP} is determined by applying the "refrigerant method" detailed in Section 2.2.

When the heat pump is OFF, it is considered that all the electrical energy consumed by the heater is transformed to heat, so: $\dot{Q}_{U,HT} = P_{PV,HT}$, and therefore $Q_{U,HT} = E_{PV,HT} = 1.235$ kWh.

The thermal energy produced by the heat pump $Q_{U,HP}$ is calculated applying the refrigerant method as:

$$Q_{U,HP}(kWh) = \sum_{1}^{720} \dot{Q}_{HP}(kW) \cdot (1/30) \tag{8}$$

For the analyzed day in this example, the thermal energy produced by the heat pump was $Q_{U,HP} = 6.547$ kWh. The thermal energy that the DHW tank received from the heat pump and from the electrical heater calculated by the "refrigerant method" is:

$$Q_{U,TOT}(kWh) = Q_{U,HP} + Q_{U,HT} = 6.547 + 1.235 = 7.782\,\text{kWh}.$$

The COP of the heat pump has been determined and it is shown in Fig. 7. It can be seen that the instantaneous COP depends on the tank temperature, more precisely, the tank temperature on the bottom third part of the tank, where the condenser of the refrigeration circuit is located. Condensing and evaporating pressures are shown in Fig. 8. Compressor pressure ratio ($t = p_{CON}/p_{EVA}$) increases from $t = 1.9$ at the beginning, where the tank temperature in the bottom is about 20°C to $t = 3.8$ at the end, where the tank temperature in the bottom is 55°C.

Also, the total thermal energy given to the tank ($Q_{U,TOT}$) is also calculated applying the "direct method" as the sum of the thermal energy needed for DHW (Q_{DHW}) production and the tank losses (Q_{LOSS}).

The water consumption is produced 6 times a day, where a water consumption of about 22 liters in 5 minutes is produced each time. The energy consumption is showed in Fig. 9.

The thermal energy needed for DHW production is calculated by

$$Q_{DHW}(kWh) = \sum_{1}^{6} Q_{DHW}(kWh) \tag{9}$$

For the analyzed day, $Q_{DHW} = 6.603$ kWh

The tank losses cannot be measured but they can be estimated with a certain degree of accuracy. A measurement of the energy losses produced during $7 \times 24 = 168$ hours was carried out and the UA coefficient was estimated: UA = 1.9 (W/°C). This coefficient has been used to estimate energy losses. For the analyzed day, the energy losses in 24 hours were $Q_{LOSS}(kWh) = 1.152\,kWh$

Tests were carried out to be sure that the tank's energy at the beginning and at the end of the day were the same.

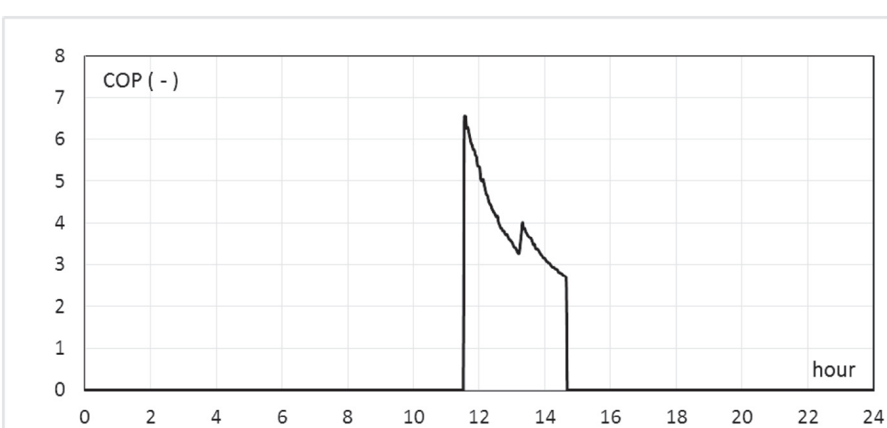

Fig. 7. Coefficient of performance of the DHW heat pump.

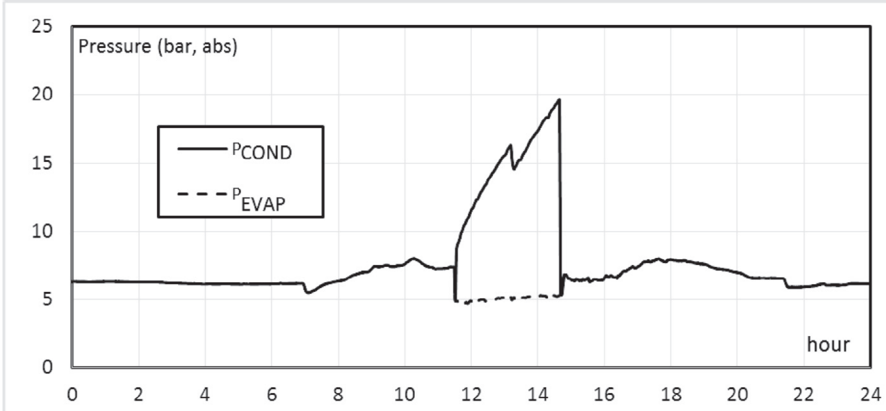

Fig. 8. Condensing and evaporating pressures.

The total thermal energy produced by the DHW production system was:

$$Q_{U,TOT}\,(kWh) = Q_{DHW}\,(kWh) + Q_{LOSS}\,(kWh) = 6.603 + 1.152 = 7.755\ \text{kWh}$$

The difference between both used methods is only 0.32% (7.755 vs 7.782 kWh). This value is very small, since a deviation of 5% was obtained for a 95% of the analyzed days.

3.2. Key performance indicators

As an example of the methodology employed for the system analysis, some Key Performance Indicators have been proposed. All of them have been applied following the same methods as the example day previously analyzed.

The Seasonal Performance Factor of the heat pump (without taken into account the PV contribution), SPF_{HP} is:

$$SPF_{HP} = \frac{Q_{U,HP}}{E_{TOT,HP}} = \frac{6.547}{1.678} = 3.90 \tag{10}$$

When the whole system is considered (HP + HT + PV), the seasonal performance factor of the system SPF_{SYS} is defined as the relation between the total heat given to the system $Q_{U,TOT}$ and the energy taken from the grid, $E_{GRID,HP}$.

$$SPF_{SYS} = \frac{Q_{U,TOT}}{E_{GRID,HP}} = \frac{Q_{U,HP} + Q_{U,HT}}{E_{GRID,HP}} = \frac{6.547 + 1.235}{0.836} = 9.30 \tag{11}$$

The primary energy ratio is calculated for the monitored installation as the ratio between useful heat and/or cold in relation to the non-renewable primary energy consumption. The primary energy factor for PV equipment is 0 and for grid electricity is considered to be 2, resulting

$$PER = (1/2.0) \cdot SPF_{SYS} = \frac{9.30}{2.0} = 4.65\ kWh_{TH}/kWh_{PE} \tag{12}$$

Solar contribution of the heat pump:

$$SC_{HP} = \frac{E_{HP,PV}}{E_{HP,TOT}} = \frac{0.842}{1.678} = 50.2\% \tag{13}$$

Solar Contribution of the system:

$$SC_{SYS} = \frac{Q_{U,HT} + Q_{U,HP} \cdot SC_{HP}}{Q_{U,HT} + Q_{U,HP}} = \frac{1.235 + 6.547 \cdot 0.502}{1.235 + 6.547} = 58.1\% \tag{14}$$

Photovoltaic production factor. In this facility, the maximum electricity production of the panels is measured directly ($E_{PV,TOT}$= 2.077 kWh). This parameter tries to consider how well the PV electricity is used: the best way is to use it in the heat pump. To calculate this parameter, a standard efficiency of SPF_{ST} =2.8 for a “typical” heat pump is considered.

$$PPF(\%) = \frac{E_{PV,HP} + E_{PV,HT}/SPF_{ST}}{E_{PV}} = \frac{0.842 + 1.235/2.8}{2.077} = 61.8\% \tag{15}$$

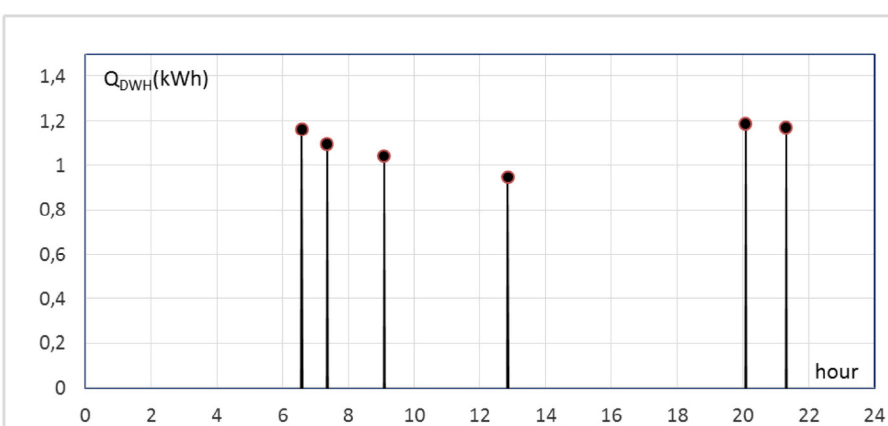

Fig. 9. Energy consumed on every one of the 6 water consumptions.

Table 4
Energy measurements: monthly mean values of electrical and thermal energy.

Month	Q_{DHW} kWh	Q_{LOSS} kWh	$Q_{TOT,D}$ kWh	$E_{TOT,HP}$ kWh	$E_{GRID,HP}$ kWh	$E_{PV,HP}$ kWh	$E_{PV,TOT}$ kWh	$E_{PV,HT}$ kWh	Q_{HP} kWh	$Q_{TOT,I}$ kWh
January	5.56	2.15	7.71	2.30	0.90	1.40	2.02	0.61	6.94	7.55
February	5.67	2.02	7.42	2.28	0.98	1.43	2.18	0.75	6.90	7.65
March	5.55	1.89	7.46	2.12	1.01	1.17	2.08	0.91	6.65	7.56
April	6.69	1.74	8.51	2.05	0.68	1.37	2.59	1.22	7.51	8.74
May	6.38	1.71	8.08	1.96	0.87	1.09	2.19	1.10	7.17	8.27
June	6.53	1.36	7.89	1.77	0.81	0.97	2.21	1.24	6.48	7.72
July	6.69	1.19	7.88	1.68	0.71	0.98	2.39	1.41	6.39	7.80
August	6.66	1.14	7.82	1.64	0.76	0.88	2.23	1.35	6.43	7.78
September	6.42	1.20	7.62	1.67	0.80	0.87	2.14	1.27	6.34	7.61
October	6.31	1.44	7.77	1.80	0.76	1.04	2.19	1.15	6.41	7.56
November	5.74	1.77	7.53	2.03	1.13	0.89	1.62	0.72	6.54	7.26
December	5.67	2.03	7.70	2.23	1.04	1.20	1.92	0.72	6.78	7.50
Average	6.16	1.63	7.78	1.96	0.87	1.11	2.14	1.04	6.71	7.75

This parameter shows that, although 100% of the electricity produced by the PV panels is used in the facility, the use of this electricity in an electrical heater ($E_{PV,HT}$ = 1.235 kWh) has a low efficiency.

3.3. Reference conditions

Some of the key performance indicators calculated in the last section depend on climatic conditions and water tank temperatures. These data are also provided in order to compare the behavior of this system with a system tested at other conditions.

- Mean outlet temperature in 24 hours: $T_{M,24h}$ = 26.5°C.
- Mean outlet temperature when the heat pump is ON: $T_{M,HP,ON}$ = 29.9°C
- Solar insolation in the PV panels: G = 5.85 kWh/m^2
- Mean water temperature in the inlet: T_{IN} =10.8°C
- Mean water temperature in the outlet: T_{OUT} =53.8°C

3.4. Seasonal results

The monthly average values have been obtained directly as the average of the daily average values (more than 20 analyzed days per month, 248 days in total). Table 4 shows the mean values obtained for every month.

The key performance parameters calculated in the previous section for a specific day have been calculated for the more than 20 days for every month and these results are shown in Table 5.

When mean data are shown in graphics, it is easier to find the influence of climatic conditions on the calculated Kpi. Fig. 10 shows the mean outlet temperature, calculated during 24 hours and calculated during the period that the heat pump is on. It is clear that when using a heat pump for DHW production where the objective is to use as much of the solar energy as possible, the heat pump should work during sunny hours, where the external temperature is higher: $T_{M,HP,ON}$ is 4–5°C higher than $T_{M,24h}$. Moreover, the heat pump should never work in the coldest hours of the day, so defrosts are avoided or are minimized in winter.

The key of the system's performance consists on having enough energy storage in the water tank in order to be useful for the consumers during the whole day without connecting the heat pump. The optimization of the control system of these equipment is vital for their correct behavior.

Fig. 11 shows the mean daily solar insolation on the photovoltaic panels inclined 45° and orientated south. The data of radiation during the month of April appears atypical. This result was obtained because only 5 of 30 days within this month were cloudy: The rest, 25 days, were sunny.

The seasonal performance factor of the heat pump is clearly a function of the outdoor temperature when the heat pump is working. The obtained values were very high because the heat pump mainly worked at temperatures above 6–7 °C. Thus, the eventual defrosts were avoided. The equipment only defrosted on 5 days throughout the whole year. The SPF of the equipment nearly reached the value of 4 on the hottest days. This value was less than 3 on the coldest days (if the equipment defrosts the SPF value does not reach 2.5). Fig. 12 shows that the SPF of the heat pump is relatively high, but it always worked at temperatures above 15°C. The efficiency obtained was similar to the one declared by the equipment's manufacturer.

The Solar Contribution System basically depends on the system's design and on the selected control strategy. Within the previous section it was shown that the system's Solar Contribution yielded 58.1% on a day that the equipment's consumption was $E_{TOT,HP}$ = 1.678 kWh and the photovoltaic installation produced $E_{PV,TOT}$ = 2.077 kWh.

Table 5
Key performance parameters: monthly mean values.

Month	SPF_{HP} (–)	SPF_{SYS} (–)	SC_{HP} (%)	SC_{SYS} (%)	PPF (%)	$T_{M,24h}$ (°C)	$T_{M,HP,ON}$ (°C)	G_{SOL} (kWh/m^2)	Vol. (L)
January	3.01	8.38	60.9	64.1	80.5	11.40	16.83	5.20	123.5
February	3.03	7.81	59.3	63.3	77.9	13.66	16.29	5.16	131.7
March	3.14	7.49	53.7	59.2	71.9	15.61	19.37	6.17	133.3
April	3.67	12.81	66.7	71.4	69.7	19.73	23.78	6.77	128.2
May	3.67	9.54	55.7	61.6	67.8	19.53	24.16	5.88	125.7
June	3.65	9.56	54.5	61.8	63.9	23.79	27.98	5.90	130.8
July	3.80	11.07	58.1	65.7	62.1	26.34	30.32	6.53	133.6
August	3.92	10.24	53.7	61.7	61.1	26.80	30.75	6.23	133.6
September	3.81	9.56	52.2	60.2	61.8	25.76	29.85	5.86	130.0
October	3.55	9.92	57.8	64.2	66.3	22.12	26.92	5.92	129.3
November	3.23	6.41	44.1	49.7	71.3	16.09	20.29	4.14	129.1
December	3.04	7.23	53.6	58.1	75.9	12.02	16.82	4.88	125.9
Average	3.42	8.92	55.9	61.7	69.1	19.43	23.65	5.73	129.5

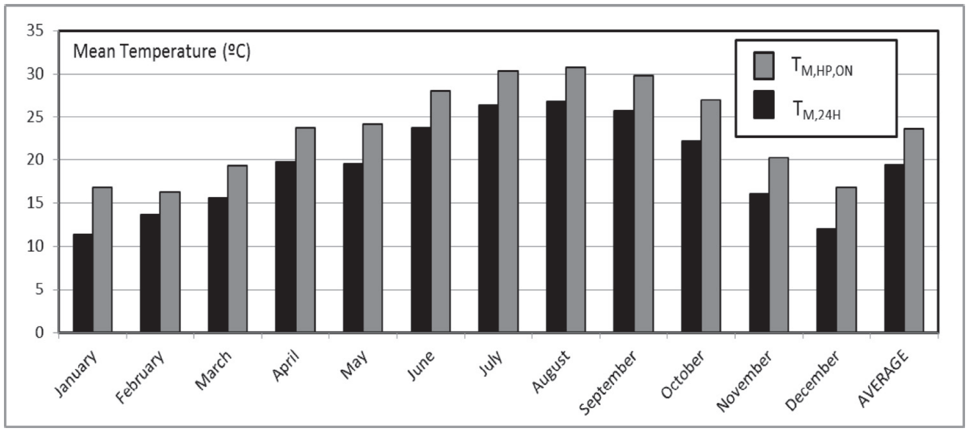

Fig. 10. Mean outlet temperature during 24 hours and during the hours that the heat pump is on.

Fig. 13 shows the Solar Contribution obtained according to Equation 12's definition. This equipment incorporates and electronic device that leads the electric energy from the solar panels to the electric resistance when the heat pump is not working.

The maximum electric energy yield produced by the photovoltaic panels is better shown by the photovoltaic performance factor (PPF%). The system makes use of the 100% of the energy produced by the solar panels and makes the solar panels work at their point of optimal performance. The "loss of opportunity" is produced because the electric energy should be used in the heat pump since it has a high SPF. For the purpose of this study, when the electric energy is directly consumed by the resistance it is considered as a loss. Fig. 14 shows the monthly medium data of the PPF (%) calculated according to the Equation (15).

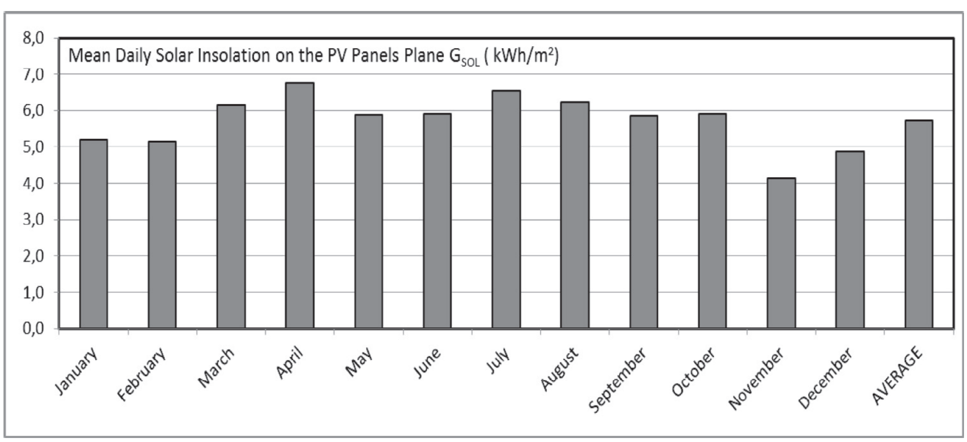

Fig. 11. Mean daily insolation on the PV panels plane. Monthly values.

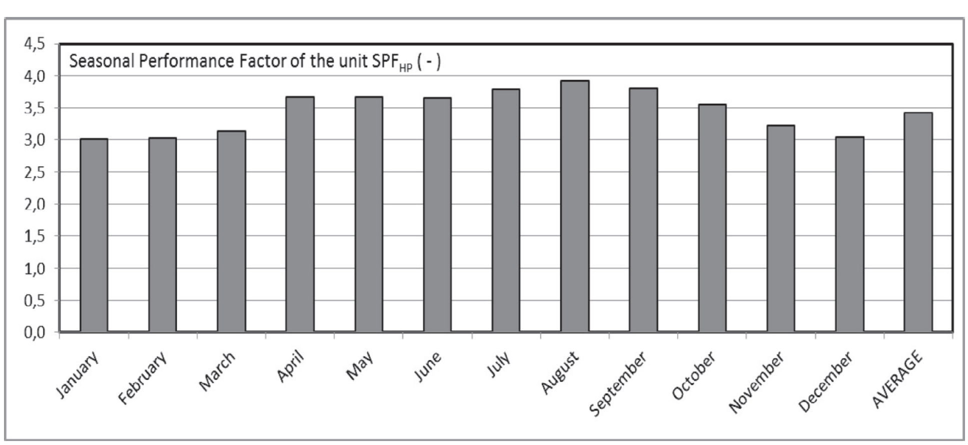

Fig. 12. Seasonal performance factor of the heat pump, $SPF_{HP}(-)$. Monthly values.

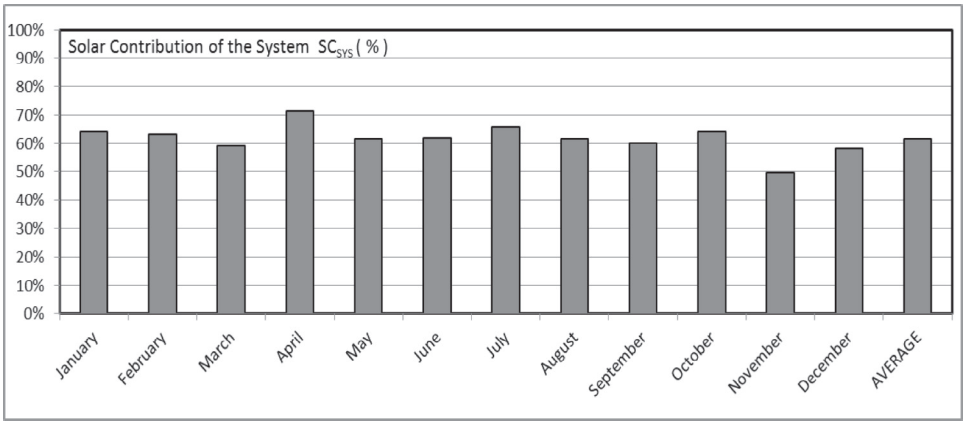

Fig. 13. Solar contribution of the system, SC_{SYS}(%). Monthly values.

The annual value obtained of PPF = 69.1% shows the possibilities for optimizing the HDW system with solar photovoltaic energy in the future. Moreover, for summer months the factor (60%) is lower than the one for winter months (80%) when the solar panels have a 45° inclination.

Finally, the seasonal performance factor of the system SPF_{SYS}(−) is the parameter that relates the produced thermal energy with the electric energy consumed from the grid. Fig. 15 shows the typical average monthly values of the SPF_{SYS}. The value for April stands out as it is an atypical month as far as the insolation values are concerned.

From the energetic efficiency point of view the annual average value of SPF_{SYS} = 8.92 indicates that the average daily production is 7.75 kWh and a grid energy consumption of 0.87 kWh. The annual primary energy ratio calculated according to Equation (12) results PER = 4.46 kWh_{TH}/kWh_{PE}.

4. Final discussion and conclusions

An experimental analysis of a DWH production system consisting of a heat pump driven by PV panels and by the grid has been carried out during a year.

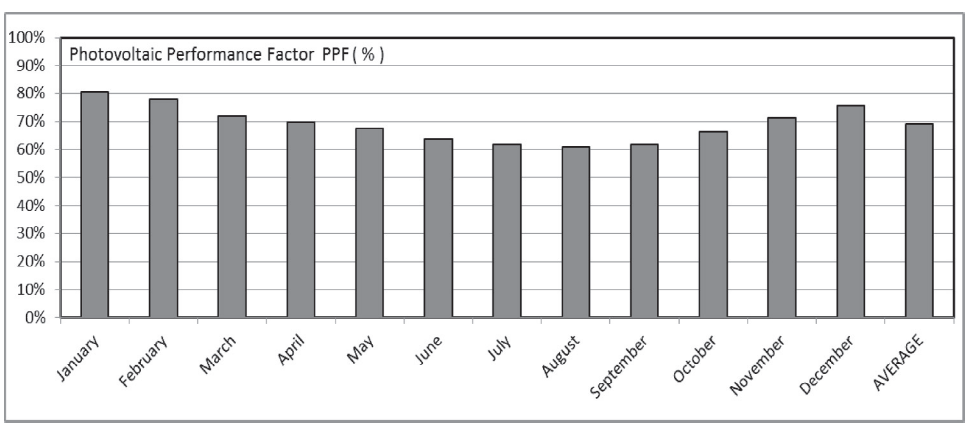

Fig. 14. Photovoltaic performance factor PPF(%). Monthly values.

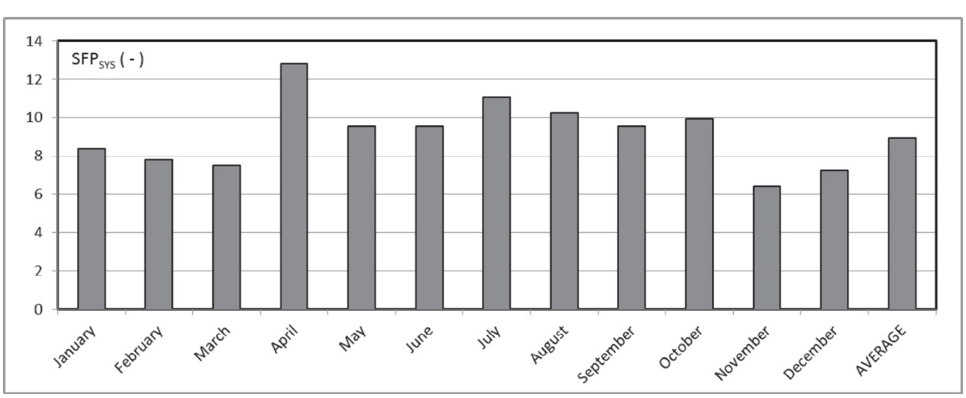

Fig. 15. Seasonal performance factor of the system SPF_{SYS}(%). Monthly values.

In the annual results, we can see that the average useful energy is 7.78 kWh/day: 6.16 kWh/day are for DHW production and 1.62 are for the tank losses. The energy demand is covered with an average energy consumption of 3.01 kWh/day: 0.87 from the grid and 2.14 kWh/day from the PV panels. The results show that the heat pump produces DHW at 55°C and has a very high average seasonal efficiency ($SPF_{HP} = 3.42$).

The average solar contribution is higher than 60% and the average efficiency of the system is SPF_{SYS}=8.92. For a family of 4 living in Spain, this means that their DHW demand can be covered with about 0.11 €/day, (40 € a year).

The non-renewable primary energy consumption has been PER = 4.46 kWh_{TH}/kWh_{PE}, 1.74 kWh_{PE}/day (0.87 kWh_{E}/day from the grid, using a conversion factor of 2 kW_{PE}/kWh_{E}). If a solar thermal energy installation with a natural gas boiler (CF = 1.19 kW_{PE}/kWh_{NG}) is defined as a point of reference, seasonal average performance of 92% and a solar contribution of 60%, the non-renewable primary energy consumption would be 4.17 kWh_{PE}/day, much higher than the real value reached with the heat pump + PV system.

The obtained data show that the DHW production by means heat pumps supported by solar photovoltaic energy is very interesting. The system's design is crucially important to get a good efficiency, considering the following aspects as essential:

- The DHW demand, ambient temperature and solar insolation
- The peak power of the solar panels that must be related with the power of the heat pump
- Type of heat pump: ON/OFF or inverter.
- Thermal accumulation volume, electric accumulation in batteries?
- Control strategy, ON, OFF, solar irradiation adjustment.

Despite already being very favorable, the results can be improved. Around half the energy produced by the panels is used by the heat pump, the other half being "misused" by the electric resistance.

The key to the optimization of the design lays in the maximum transfer of PV electrical energy from the resistances (1.04 kWh) to the heat pump. Thus the grid electricity consumption will be lower. This aspect will be developed within future works.

Nomenclature

COP	Coefficient of performance [–]
E	Electrical energy [kWh]
G	Daily solar insolation in the PV panels angle [kWh/m^2]
h	Refrigerant enthalpy [kJ/kg]
I	Electrical current [A]
IRR	Solar radiation [W/m^2]
m	Mass flow [kg/s]
P	Electrical power [W]
p	Pressure [bar]
PPF	Photovoltaic production factor [%]
$\dot{Q}$	Thermal power produced by the heat pump [kW]
Q	Thermal energy produced by the heat pump [kWh]
SC	Solar contribution [%]
SPF	Seasonal performance factor [–]
T	Temperature [°C]
V	Electrical voltage [V]
Vol	Water volume [L]

Subscripts

1	Compressor's inlet (refrigerant thermodynamics cycle)
2	Compressor's outlet (refrigerant thermodynamics cycle)
3	Between the condenser and the expansion valve
4	Between the expansion valve and the evaporator
COM	Compressor
DHW	Domestic hot water
D	Direct method
E	Electrical
GRID,HP	Electrical consumptions by the heat pump from the grid
HP	Heat pump
I	Indirect method
LOSS	Energy losses produced in the tank
M,24h	Average value during 24 hours
M,HP,ON	Average value during heat pump working hours
OUT	Outside (ambient)
PE	Primary energy (non-renewable primary energy)
PV,HP	Electrical consumptions by the heat pump from the photovoltaic panels
PV,HT	Electrical consumptions by the electrical heater from the photovoltaic panels
PV,TOT	Total electricity produced by the photovoltaic panels
R	Refrigerant of the unit (R134a)
SYS	Whole system (heat pump + photovoltaics)
TH	Thermal
TOT,HP	Total electricity consumed by the heat pump (photovoltaic + grid)
U,HP	Useful thermal energy produced by the heat pump [W]
U,HT	Useful thermal energy produced by the electrical heater [W]
U,TOT	Total useful thermal energy produced by the unit (HP+HT) [W]

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