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Research Paper

Experimental analysis of an air conditioner powered by photovoltaic energy and supported by the grid

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HIGHLIGHTS

- An experimental study of a photovoltaic solar air conditioning unit (PV + AC) working in cooling mode is presented.
- The experimental facility of the system (PV + AC) fully monitored is described.
- Seasonal results from more than one hundred days of study are presented.
- Some key performance indicators to show the system efficiency have been proposed and calculated.
- The seasonal average EER of the system (PV + AC) is 14.54 while the average solar contribution (SC) is 64.6%.

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ABSTRACT

The present document describes experimental work carried out on an air conditioning unit which has been powered using both a photovoltaic installation and the grid simultaneously. This document exposes the information gathered during an entire year of data collection. The control system has been designed to give priority to the renewable energy source in order to maximise solar contribution.

The aim of the study is to analyse any real possibilities and the viability of the use of photovoltaic systems to supply energy to air conditioning equipment without batteries or regulators. In this case, the conventional energy source has been used to supply energy when the PV energy is insufficient.

The main elements of the experimental setup were; an air conditioning unit with a nominal cooling capacity of 3.52 kW, and a photovoltaic installation with three 235 W_p panels connected directly to the equipment at 24 Vdc.

The equipment has been monitored during the 12 h of daily usage (from 8 to 20 h), to condition an office with 35 m^2 in Alicante (Spain). The results during a cooling period of 6 months have demonstrated that the average EER could be close to 15. Both the solar contribution and the production factor are close to 65%. Experimental correlations are given in order to extend the obtained results to simulate other climatic conditions and demands.

1. Introduction

Capable to chill, to heat and even to ventilate the indoor spaces of buildings, air conditioning equipment has become one of the most important devices in the Mediterranean.

If the heating, ventilation and cooling (HVAC) systems were considered as a luxury years ago, currently they are considered as necessary in any new building as the illumination, plumbing, or telecommunication installations.

One of the biggest problems with this kind of installation is the high energy consumption. In Spain it can be between 40 and 60 kWh/m^2-year in dwelling and higher in the tertiary sector [1]. This consumption is due to the long working time and not to a high power demand, thanks to the increasingly more efficient equipment being developed.

According to European Commission [2] buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU. A large part of that consumption goes to the HVAC systems. In [3] European Commission said that in 2007 the overall electricity consumption of the EU-27 air-conditioning stock was around 17 TWh for both the residential and the tertiary sector. It also said that Spain represented the most important market of air condition-

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Nomenclature

E	energy (electrical or heat) (kWh)
EER	energy efficiency rating (–)
G	daily solar insolation in the PV panels angle (kWh/m^2)
h	refrigerant enthalpy (kJ/kg)
I	electrical current (A)
LF	load factor (%)
m	mass flow (kg/s)
P	electrical power (W)
PF	production factor (%)
Q	useful thermal power (W)
SC	solar contribution (%)
T	temperature (°C)
V	electrical voltage (V)

Subscripts

1	in the compressor's inlet (refrigerant thermodynamics cycle)
2	in the compressor's outlet (refrigerant thermodynamics cycle)
3	between the condenser and the expansion valve
4	between the expansion valve and the evaporator
COM	unit's compressor
GRID, UNIT	electricity consumed by the unit from the grid
OUT	outside (ambient)
PV, GRID	electricity produced by photovoltaic panels connected to the grid
PV, UNIT	electricity consumed by the unit from the photovoltaic panels
R	unit's refrigerant (R410a)
SYS	the whole system (Unit + photovoltaic)
TOT, MAX	maximum electricity consumed by the unit at 100% load (1 kWh/h)
TOT, UNIT	total electricity consumed by the unit (photovoltaic + grid)
U	useful energy produced by the unit (cool) (W)

ing equipments with 37% of total EU sales for residential use in 2005.

In this sense, M. Izquierdo et al. [4] showed energy consumption data for Spain, where CO_2 emissions per capita in 2009 came to 9.5 t, reaching 350 million tonnes of CO_2. In specific, the energy consumption of the residential and commercial sector was almost 25% of the final energy consumption, where the air conditioning in summer was one of the most important parts of the total energy consumption.

The general concern for the shortage of energy resources, as well as the increasingly pronounced effects of climate change, requires the development of technologies that are more environmentally friendly and that are guaranteed substitutes for the current use of fossil fuels.

In this regard, it has been observed that for certain applications, mainly the tertiary sector, such as offices, hotels or hospitals, the main thermal demand of buildings has a direct relationship with the hours of solar radiation it receives and the thermal energy demand goes in parallel of the available solar irradiance. This suggests that the use of air conditioning systems that take advantage in one way or another of the solar radiation and use it as the primary source of energy may return great results. Particularly, in countries of southern Europe where days are longer and solar irradiance is higher, a solution with solar energy could be very beneficial.

For years, several solutions where solar energy and refrigeration systems are combined have been studied, some of them have been developed commercially and others have not. Perhaps, the most widespread technologies have been the absorption and the adsorption systems, although their costs are much higher than conventional air conditioning systems. There are several studies [5–8] where these technologies are exposed and developed with Flat Plate Solar Collectors and Solar Vacuum Tubes as a solar caption surface. In [9] a review of different absorption cooling systems which use solar collector as energy source was presented. On the other hand, in [10] state of the art solar refrigeration units were investigated.

One of the other documented technologies, commonly called "PV-Thermal or PV-T", focuses on the use of a hybrid photovoltaic and thermal system, where the heat dissipated by the PV panel is absorbed by a thermal fluid (air, water or refrigerant) and used for HVAC purposes. The cooling effect of the refrigerant allows the PV modules to work at lower temperature and so its photovoltaic efficiency is improved, while the heat pump efficiency increases, too. Ji Jie et. al. [11] showed a PV solar assisted heat pump, where a kind of PV evaporator was presented. More technologies with hybrid PV-T systems were presented in [12–17]. This would be an attractive solution in cold regions where an increase in the evaporation temperatures is necessary.

Another option is to use photovoltaic panels to produce the electricity that powers the compressor in an air conditioning unit [18]. The work detailed in [19] described, among other things, a water condenser cooling system that works by means of a cooling tower, using fan-coil units indoors and solar energy to drive the compressor. This report demonstrates that the use of absorption and photovoltaic refrigeration systems have the largest energy saving potential for buildings in subtropical cities.

In [20] a comparison was made between different cooling systems that used solar energy. In this case the comparison was made between PV panels with batteries, regulators and inverter controllers, versus a thermal system. The lower catchment area required when using photovoltaic technology together with the downward trend in the price of photovoltaic panels is of special importance, presently plunging below the 1 €/W_p mark.

Perhaps one of the most interesting solutions to the use of solar energy for air conditioning systems could be the use of photovoltaic panels. Singh [21] showed the different applications and benefits of PV systems: their high efficiency, great reliability and low maintenance costs are exposed. In addition, the PV system price reduction of around 75% in less than 10 years has brought the solar power close to cost competitiveness in several countries and market segments. The European Photovoltaic Industry Association [22] explained that the cost of PV systems continued decreasing in 2014, so system prices below 1 €/W_p (for utility scale PV above 1 MW) are now common in several European countries.

This paper describes experimental work carried out on an air conditioning unit which has been powered using both a photovoltaic installation and the grid simultaneously. This document exposes the information gathered during 6 months of data collection. The control system has been designed to give priority to the renewable energy source in order to maximise solar contribution. The PV energy has only been used to drive the AC's compressor. The conventional energy source is only used to supply energy when the PV energy is insufficient.

2. Experimental method

The Air-Conditioner analyzed is a unit with a nominal cooling capacity of 3.52 kW (EER = 4.09). Three photovoltaic panels with a total peak power of 705 Wp are connected directly to the unit at 24 Vdc.

The PV panels have been directly connected to the 24 V connection of the air conditioning unit. There is a solar converter inside the unit that changes the DC voltage from 24 V to 200–300 V. This high voltage direct current is internally connected to the DC point in the frequency converter. Here, the energy from the grid and the energy from the PV panels are summed.

Fig. 1 shows schematically how the mentioned system works. Table 1 shows the technical characteristics of the Air Conditioner Unit.

Tests have been carried out under "real" conditions in a 35 m^2 office located in Alicante (Spain). This office is on the second floor, in this case top floor, of an offices building. It has only one external façade which is north facing and has a length of 4.5 m. It has a window of 3×1.5 m^2 with Climalit double glazing and sunscreen slats for sun protection. The ceiling height is 2.8 m. The indoor unit is working inside the office, while the outdoor unit has been installed on the building's roof, just above the office.

The analysed performance profile is focused on typical office hours, from 8 to 20 h. The indoor temperature was set to 23 °C in cooling mode. The relative humidity was not controlled. Values of outdoor relative humidity between 50 and 80% were measured during the study, always with an absolute humidity between 8 and 14 g water/kg dry air. Thus, the cooling and dehumidification effects of the unit resulted in indoor humidity ratios between 35 and 50%.

2.1. Experimental set-up

The designed system (FV-AC) is composed of the air conditioning unit with two electrical connections (PV panels and grid) and the PV installation. The whole system has been monitored to register its behaviour under real working conditions. Fig. 2 shows the experimental setup where subsystem "A" consists of the inverter air conditioner unit. This unit was connected both to the conventional grid (220 AC) and to the PV panels (24 DC). Both energy sources work in parallel and they are summed in order to supply the total electrical energy demanded by the air conditioning unit. So, this air-conditioner has always enough energy to work properly, regardless of the solar irradiance variations.

This unit has an inverter that transforms grid energy from 220 V AC to 200–300 V DC to drive a compressor at different angular velocities. The PV energy integration occurs before connection to the compressor through another inverter that operates between 24 V DC and 200–300 V DC. While PV energy output is sufficient and due to the difference in impedance between the two energy sources (PV and the grid), PV energy becomes the lead energy source. Grid energy is only absorbed once PV energy levels are insufficient.

The photovoltaic solar energy production comes from the subsystem B, which consists of three photovoltaic solar panels connected in parallel (705 Wp, 24 V). The panels have been placed on the flat roof of the building, facing 15° south with an inclination of 30°. Table 2 shows the technical characteristics of the PV panels.

Finally, subsystem C was composed of three photovoltaic panels with the same characteristics as the previously mentioned. However, these ones were connected to the grid through conventional inverter (DC/AC) equipment, which worked using the maximum power point (MPP) of the PV panels. The influence of the behaviour of the air-conditioning unit over the energy production of PV panels of subsystem B could bring a "solar energy loss". This "loss of opportunity" has been determined and analysed too.

Several sensors and measurement equipment were used throughout the entire installation to record data. The currents $I_{PV,UNIT}$ and $I_{PV,GRID}$ have been determined measuring the potential difference produced by a shunt resistance calibrated for the measurement of an electric current, as shown in Fig. 2. The measurement of the compressors electric power consumption (P_{COM}) is done using a Chauvin Arnoux CA8334 network analyser. The meteorological data measured were: solar irradiation, ambient temperature, humidity and wind speed and direction. The following parameters of the air conditioners thermodynamics were measured: condensing and evaporating pressure of the refrigerant (410 A) and the temperatures in the 4 distinctive points of the cycle.

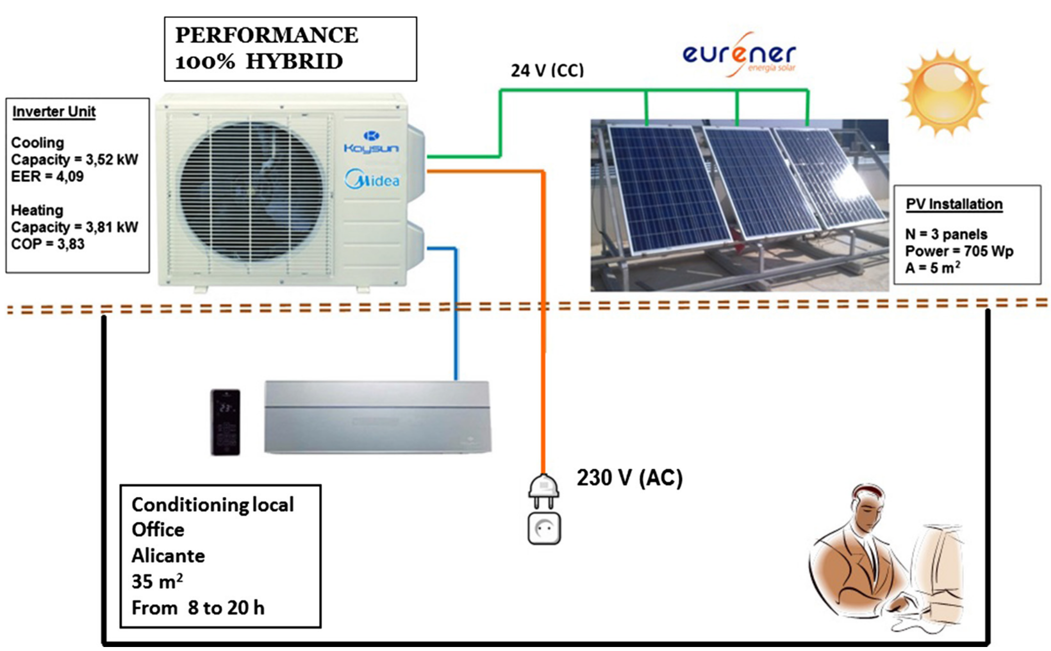

Fig. 1. Air conditioner unit.

Table 1
Technical characteristics of the air conditioner.

Kaysun suite solar 3D	Unit	Min.	Nom.	Max.
Cooling capacity	kW	0.95	3.52	4.15
Cooling power supply	kW	0.19	0.86	1.18
EER	–		4.09	
Refrigerant	–	R410A		

In order to measure the temperatures of the refrigerant accurately the thermocouples were installed inside the refrigerant pipes. Sockets with a female M8 thread were installed on both the suction and discharge pipes and the condenser outlet and evaporator outlet.

In the interior of these sockets, a sheath made of 310 Stainless Steel of only 1 mm diameter for fast response, containing a mineral insulated Type 'K' Thermocouple were installed. These sheaths come prepared for such applications, and screw into the M8 sockets previously mentioned and are fixed in place with their corresponding locknuts, guaranteeing no refrigerant leakage.

Data of the 17 measured parameters was taken every 5 min and recorded by an HP Agilent 34970A data-logger. Table 3 shows the results taken on July 14th at 14:00, as an example of the measurements.

2.2. Measurement uncertainties

The experimental uncertainty was calculated by following [23]. Electrical measurements are very accurate. Voltage and current uncertainties for all our measurements are lower than 1% with a 95% confidence level. This translates in an uncertainty in our power measurements lower than 1.5% and in the calculated variables for Solar Contribution and Production Factor lower than 2%.

The useful thermal power given by the unit was determined by the "refrigerant method" [24] that will be explained on the following section. This value has been calculated indirectly since it needs to estimate the compressors thermal losses.

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

Table 3
Example of the measures recorded every 5 min.

Description	Symbology	July 25th 14:00 h	Unit's
Compressor inlet temp.	T_1	7.89	°C
Compressor discharge temp.	T_2	74.51	°C
Condenser outlet temp.	T_3	39.75	°C
Evaporator inlet temp.	T_4	5.24	°C
Outside temp.	T_O	36.80	°C
Local temp.	T_I	25.50	°C
Evaporating pressure	P_E	6.78	bar
Condensing pressure	P_C	26.54	bar
Absorbed power network	P_{GRID}	458.09	W
PV current equipment	I_{PV}	20.55	A
PV voltage equipment	V_{PV}	24.67	V
PV current network	$I_{PV,GRID}$	21.42	A
PV voltage network	$V_{PV,GRID}$	25.21	V
Solar irradiance	G	962	W/m^2
Relative humidity	HR	53.1	%
Wind speed	V_w	1.41	m/s
Wind direction	D_w	43	°

Table 4 lists the uncertainties of the independent and dependent variables. The uncertainties of the dependent variables (specific enthalpies, refrigerant mass flow and useful thermal power) were determined using EES. The uncertainty values were calculated when the unit was working under different ranges of capacity. Some significant values of the useful thermal power

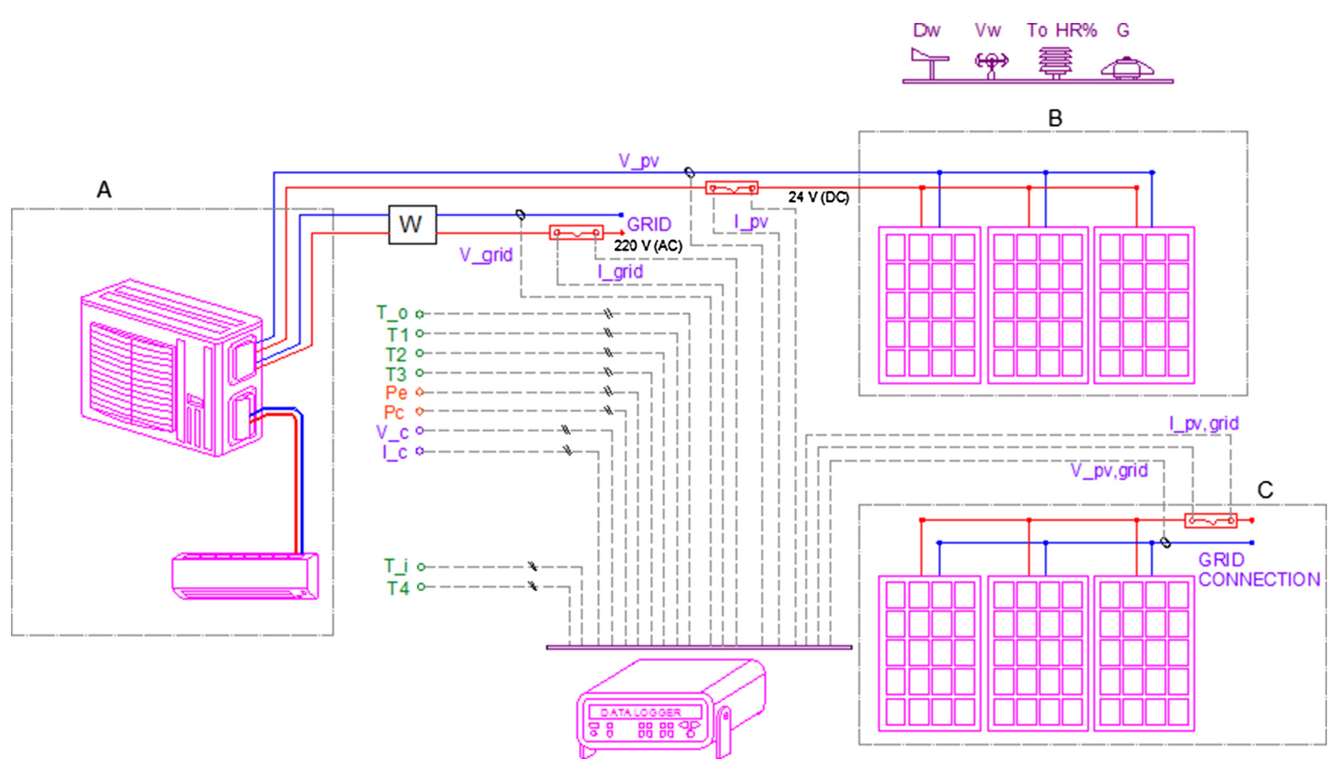

Fig. 2. Experimental facility.

uncertainty (95% confidence level) were: 9.54% when the air-conditioner operates at 25% of its capacity; 5.75 at 50% of its capacity; 4.20% at 75% of its capacity; and 3.72% when the air-conditioner operates at full capacity. In this case, the highest uncertainties were lower than 10% in both refrigerant mass flow and useful thermal power.

3. Results

The experimental study was focused in summer months to establish seasonal results in cooling conditions. In this sense, the results are going to be presented in two levels:

Firstly, in detail: Data is taken every 5 min (144 data sets recorded a day). These data have been processed in order to get results for every analysed day.

Secondly, at a seasonal level: Data from more than a hundred days of the study were analysed (at least 20 days every month). These results were used to obtain conclusions about the seasonal behaviour.

3.1. Detailed results. Methodology

The air conditioner's solar power consumption has been calculated as:

$$P_{PV,\,UNIT} = I_{PV,\,UNIT} \cdot V_{PV,UNIT} \tag{1}$$

The power taken from the grid, P_{GRID}, has been measured using a watt meter.

The air conditioner's total power consumption is derived from the sum of the two previous power indicators as:

$$P_{TOT,\,UNIT} = P_{PV,\,UNIT} + P_{GRID,\,UNIT} \tag{2}$$

As previously explained, the compressor's power consumption P_{COM} was measured with a network analyser (C.A. 8332). The relationship between P_{COM} and $P_{TOT,UNIT}$ in Watts has been defined from several days of simultaneous measurements. The following equation describes that relationship:

$$P_{COM} = 0.921 \cdot P_{TOT,UNIT} - 70 \tag{3}$$

The power produced by the solar PV panels connected to the grid $P_{PV,\,GRID}$ is calculated using the same product as for P_{PV}.

$$P_{PV,GRID} = I_{PV,GRID} \cdot V_{PV,GRID} \tag{4}$$

The energy supplied by the grid, the energy supplied by the PV panels and the energy produced by the PV panels connected to the grid has been calculated using the measured power and the time passed between each recording Δt, using the following equations:

Table 4
Uncertainties of the independent and dependent variables (95% confidence level).

Independent variables	Units	Uncertainty	Range
Refrigerant high pressure side	bar	±0.17	30 bar, class 0.5
Refrigerant low pressure side	bar	±0.14	25 bar, class 0.5
Refrigerant side temperature	°C	±0.6	
Power consumption	W	±11.5	1000 W, class 1
Compressor efficiency	%	±2	
Dependent variables	Units	Uncertainty 25% capacity	Uncertainty 100% capacity
Specific enthalpy, Compressor inlet	kJ/kg	±0.7	
Specific enthalpy, Compressor outlet	kJ/kg	±0.8	
Specific enthalpy, evaporator inlet	kJ/kg	±1.1	
Refrigerant mass flow	g/s	±0.98 (9.48%)	±0.64 (3.60%)
Useful thermal power	kW	±0.17 (9.54%)	±0.11 (3.72%)

$$E_{PV,UNIT} = \sum P_{PV,UNIT} \cdot \Delta t \tag{5}$$

$$E_{GRID,UNIT} = \sum P_{GRID,UNIT} \cdot \Delta t \tag{6}$$

$$E_{PV,GRID} = \sum P_{PV,GRID} \cdot \Delta t \tag{7}$$

The total energy consumed by the unit was known as follows:

$$E_{TOT,UNIT} = E_{PV,UNIT} + E_{GRID,UNIT} \tag{8}$$

The solar contribution is the ratio between the energy produced by the solar panels and the total energy consumed by the equipment. It was calculated as:

$$SC(\%) = 100 \cdot \frac{E_{PV,UNIT}}{E_{TOT,UNIT}} = 100 \cdot \left(\frac{E_{PV,UNIT}}{E_{PV,UNIT} + E_{GRID,UNIT}}\right) \tag{9}$$

The production factor takes into account the photovoltaic energy losses due to the fact that the PV panels connected to the air conditioning unit are not always working at their MPP. This parameter is calculated as the ratio between the power supplied by the PV panels connected directly to the system and the PV panels connected to the grid, as:

$$PF(\%) = 100 \cdot \frac{E_{PV,UNIT}}{E_{PV,GRID}} \tag{10}$$

It is also interesting to know the daily load factor on the unit during this analysis. This is calculated as follows:

$$LF(\%) = 100 \cdot \frac{E_{TOT,UNIT}}{E_{TOT,MAX}} \tag{11}$$

The parameter $E_{TOT,MAX}$ corresponds to the energy consumed on the hottest day, where the air conditioning worked at 100% during the 12 h test period. This value was very close to 12 kWh, so it was taken as a constant value of 12 kWh.

In order to calculate the efficiency of the air conditioner, the useful thermal energy supplied by the unit to the office has been calculated. To carry out this study the temperatures and pressures of the refrigerant circuit were used as follows.

Firstly, the mass flow of refrigerant m_R was calculated as the ratio between the compressor's power consumption and the specific work, obtained from the difference in the fluid's enthalpy between the input and output of the compressor. The compressor's losses were 5% as recommended by the manufacturer.

$$m_R = \frac{0.95 \cdot P_{COM}}{h_2 - h_1} \tag{12}$$

Once the mass flow of refrigerant is known, the useful thermal power is calculated as the product of said mass flow and the enthalpy differences between the evaporator's inlet and outlet. Fig. 3 shows the points where the refrigerant's (R410A) conditions have been measured.

$$Q_{UNIT} = m_R \cdot (h_1 - h_4) \tag{13}$$

The software (EES 2012), which includes a database of refrigerants and their properties, was used to redo the previous operation for each registered point. The useful thermal energy (E_U) supplied to the office during a typical day was calculated as the sum product of the output power by the time elapsed between readings of data, according to the following expression.

$$E_U = \sum_{i=1}^{144} Q_{U_i} \cdot \Delta t \tag{14}$$

The energy efficiency of the air conditioning unit EER_{UNIT} was calculated using the (Eq. (15)). The energy efficiency of the system (PV + AC) EER_{SYS} was obtained from the expression (16), considering, in this case, only the consumption of the non-renewable energy source.

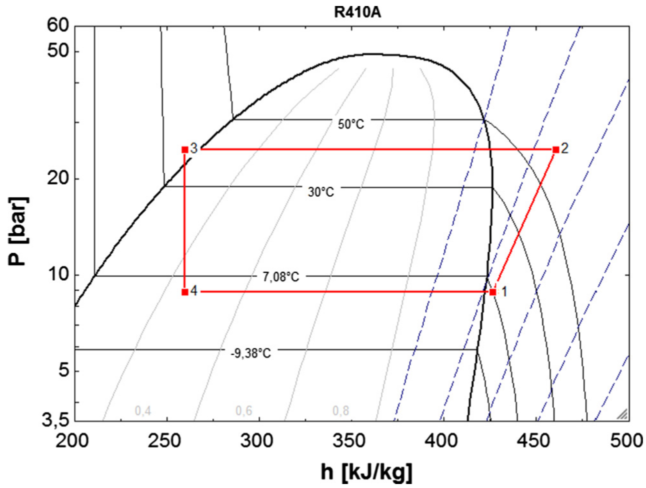

Fig. 3. Representative point taken on the property plot of R410A (July, 31th).

$$EER_{UNIT} = \frac{E_U}{E_{TOT,UNIT}} \quad (15)$$

$$EER_{SYS} = \frac{E_U}{E_{GRID,UNIT}} \quad (16)$$

3.2. Daily results

As an example of the measurements and to show how the unit works, data sets from 2 days are shown in this section.

Fig. 4 shows the weather conditions during the working hours for the two selected days, one of them in July and the other one in September. Outdoor temperature, Relative Humidity and Solar Irradiance over the PV panel surface have been included.

Fig. 5 shows the behaviour curves of the system for a day of the study in July with a high energy demand. This day the total electrical energy consumed by the unit was 8.36 kWh, thus the load factor was 69.9%.

The power from the PV panels and the power from the grid have also been included in Fig. 5. If both curves are integrated, it can be known that the energy supplied by the PV panels is 4.00 kWh and the energy supplied by the grid is 4.36 kWh. If these values are introduced in (Eq. (9)), the solar contribution can be calculated (47.8%).

Lastly, the performance of both PV installations - the PV installation connected directly to the AC unit and the PV installation connected to the grid - is compared. Obviously, the PV panels that work with the air conditioner do not follow the MPP, so their performance is lower than the other ones. The reached production factor was 94.3%, close to 100% because the energy demand was high and thus the PV panels were optimized. This situation was different in the next shown day.

Fig. 6 shows the measurements on a September day where the weather conditions were good (Fig. 4b) and the building's thermal load was low, thus the energy demand was not too high. From the point of view of the Solar Contribution it can be said that the results were good (SC = 73.3%). The energy consumption of the unit was 3.35 kWh, of which 2.45 kWh came from the PV panels and only 0.90 kWh came from the grid. However, the PV production was 2.45 kWh, much lower than expected, this is because the PV panels worked following the unit's energy demand instead of the panel's MPP. This day the PV production could have been 3.81 kWh.

Results show that when the demand of electric energy is lower than the productive capacity of the PV panels (Fig. 6), the production of the PV panels connected to the air conditioning unit ($P_{PV,UNIT}$) is lower than the production of the PV panels connected to the grid ($P_{PV,GRID}$), thus the Production Factor is lower (PF = 2.45/3.81 = 64.5%).

As it is shown in the Fig. 6 the power peak consumed from the grid does not decrease though the amount of consumed energy from the grid is lower when the air conditioner unit is fed with photovoltaic energy. This fact is due to the frequent increments of the power of the compressor required to distribute the oil through the cooling circuit.

The thermal demand variations, the weather conditions and the available solar irradiance means that there are important differences between the results for each day, for this reason ample testing year round is necessary.

3.3. Seasonal results

One hundred days have been processed following the previously described method, with the unit working from 8 to 20 h, and with the unit functioning in naturally varying working conditions, depending on the weather, thermal load, solar irradiance, etc. The following figures show the average result of each analysed day. These results will be studied in order to reach conclusions about the systems behaviour. At the end, seasonal results will be calculated.

In Fig. 7 the average daily outdoor conditions have been plotted, including the outdoor temperature and the average daily insolation on the PV panel's plane in kWh/m^2. The fact that the experimental facility was installed in the southeast of Spain must be taken into account and that the climatic area is classified as V according to [16], where the average insolation is usually high.

Fig. 8 shows the load factor obtained for 100 days in cooling mode. It was calculated that the mean load factor in cooling mode was only 34.5%. Indifferently, the unit was not oversized since during many hours the office needed 100% of its capacity to maintain comfort conditions.

The previously indicated averages have been used to define the typical behaviour of the analysed system. In this sense, Fig. 9 shows how the load factor of the unit, LF(%), depends on the external temperature and on the solar insolation. Since the unit worked under real conditions, the thermal load for each day was different; this is due to the number of people, the kind of work and other factors that changed from day to day.

Fig. 10 shows the solar contribution obtained for the 100 analysed days. The average value obtained for these days was 64.6%.

Fig. 11 shows how solar contribution is dependent on the daily insolation and the AC unit's load factor. Considering the days where the unit's load factor is between 20 and 35%, a linear influence between daily insolation and solar contribution (indicated with circles on Fig. 11) can be observed. This line goes from solar contributions of 50% on cloudy days, where the insolation is about 3 kWh/m^2, to solar contributions of 80% on sunny days (7 kWh/m^2). Finally, one can observe that the days with high thermal demand (load factor higher than 35%) have got the lowest solar contribution, but, even in these conditions, it is expected to be higher than 40%.

As said, the production factor takes into account the energy taken from the three PV panels connected to the unit in comparison to the energy produced by three PV panels connected to the grid. Fig. 12 shows the calculated results, where the mean value of the measurements in cooling mode was found to be 65.1%.

Fig. 13 shows how the production factor slightly depends on daily insolation. This factor depends much more on the facility's load factor.

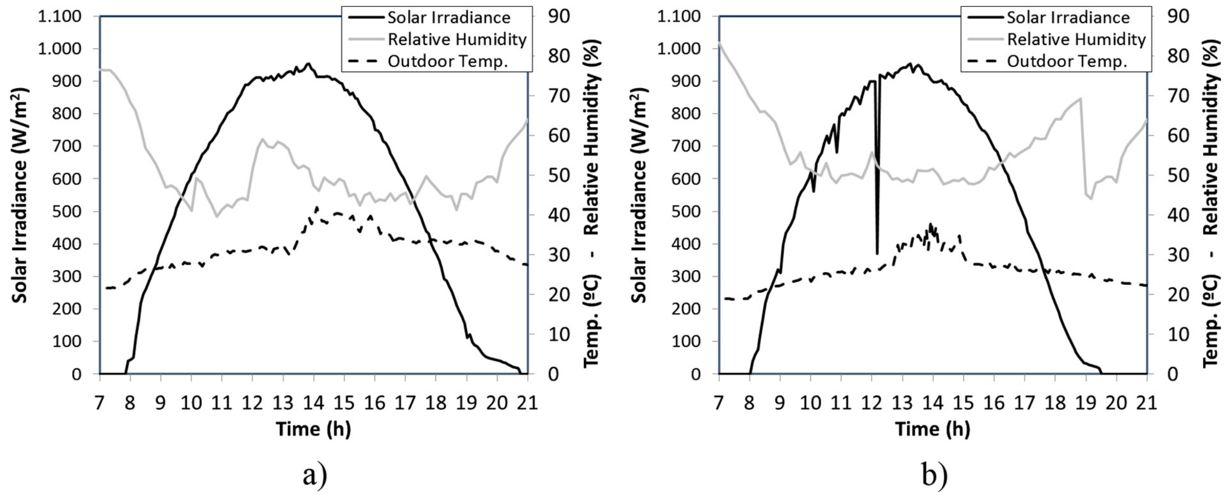

Fig. 4. (a) Weather conditions registered along one day in July; (b) Weather conditions registered along one day in september.

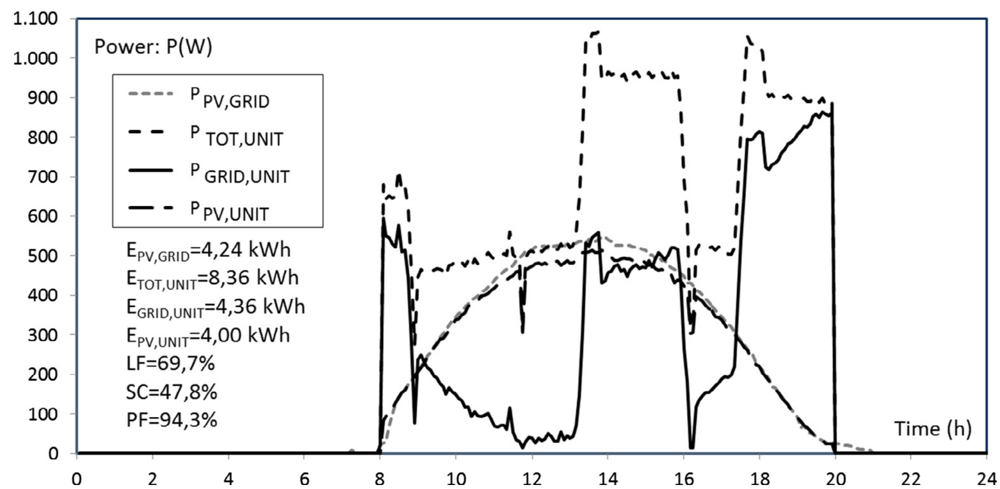

Fig. 5. Electrical curves registered along one day in July, where the demand was high: (T_{OUT} = 32.4 °C, G = 6.95 kWh/m^2, LF = 69.7%).

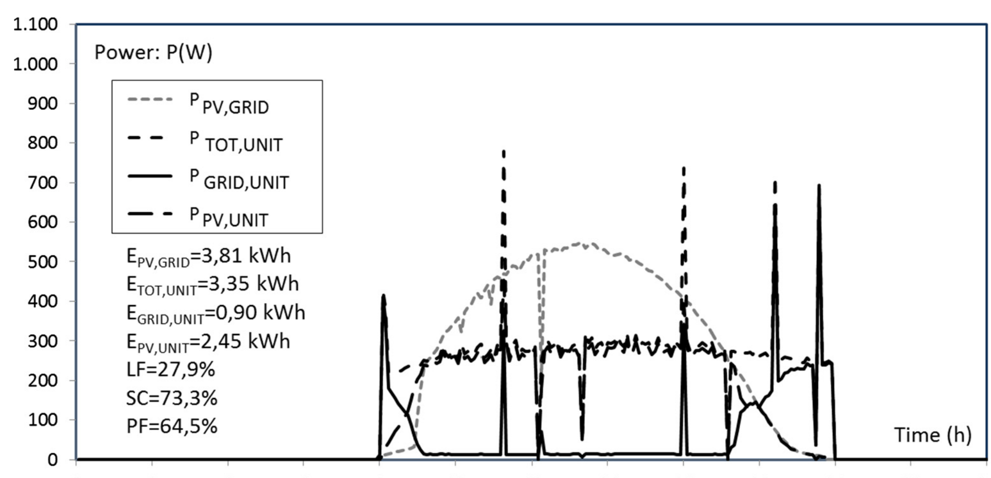

Fig. 6. Electrical curves registered along one day in september, where the demand was low: T_{OUT} = 26.7 °C, G = 6.09 kWh/m^2, LF = 27.9%.

The unit's Energy Efficiency Ratio (EER_{UNIT}) was found to depend on both the load factor and on the outlet temperature (all measurements were carried out at the same inlet temperature). Fig. 14 shows the calculated EER of the unit.

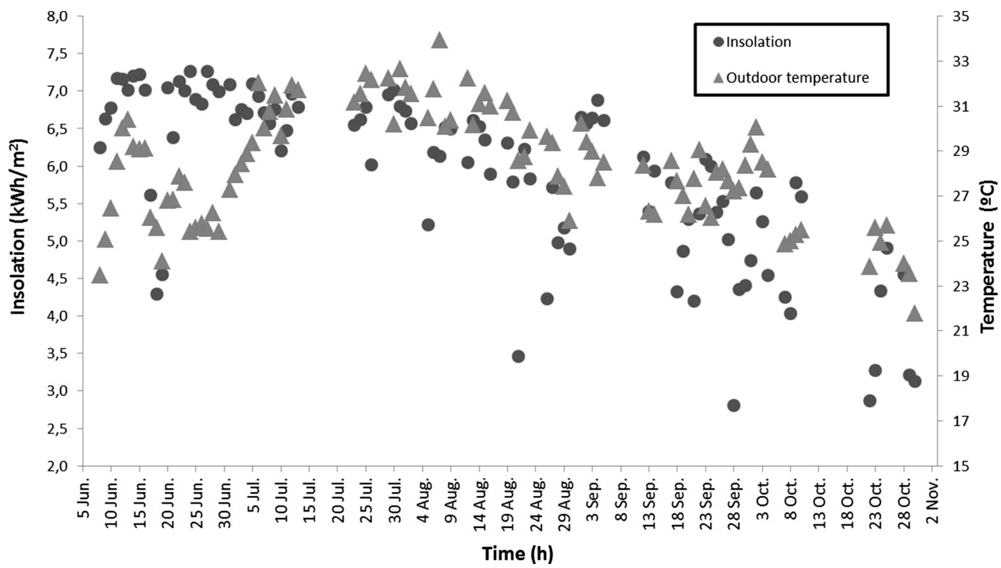

Fig. 7. Average daily outdoor conditions. Data from 100 analysed days.

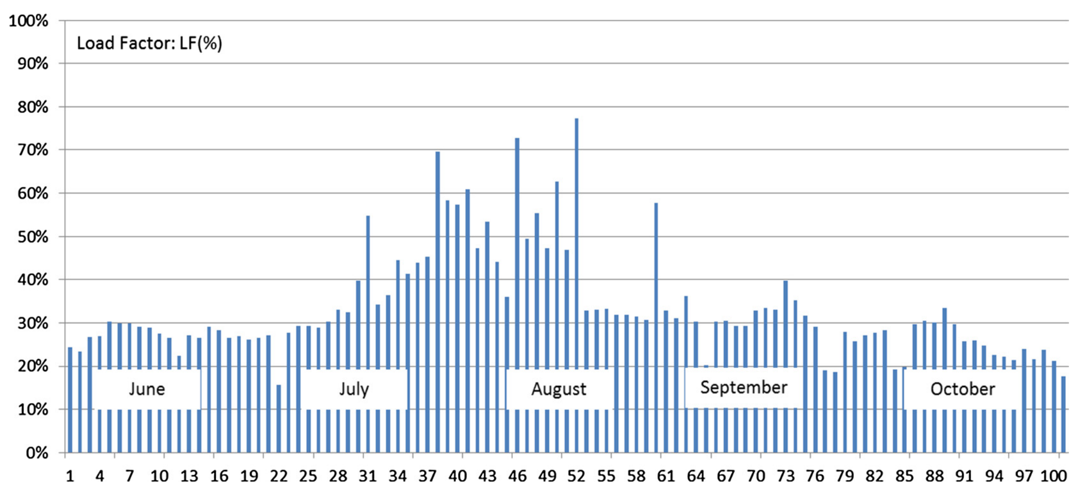

Fig. 8. Daily load factor of the air-conditioner. Data from 100 analysed days.

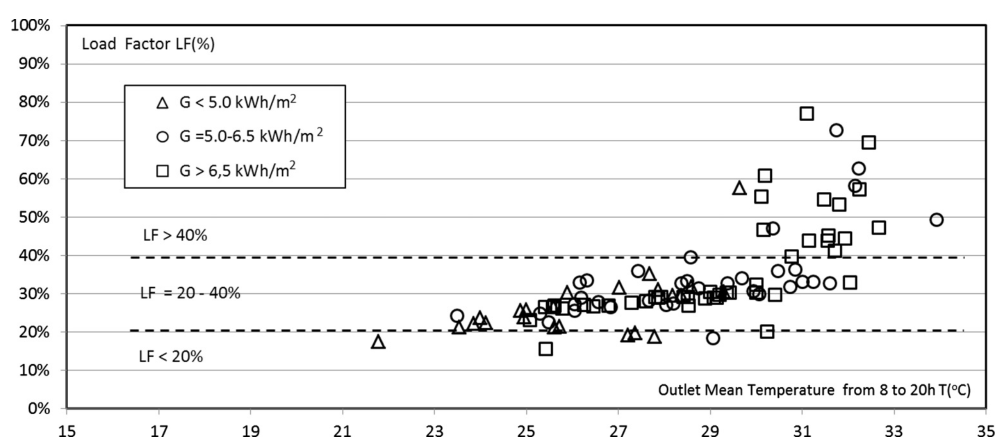

Fig. 9. Daily load factor of the air-conditioner depending on the average outdoor temperature and the solar insolation.

The system's Energy Efficiency Ratio (EER_{SYS}), defined by (Eq. (16)) can also be calculated from the Energy Efficiency Ratio of the unit (EER_{UNIT}) and the Solar Contribution (SC) by:

$$EER_{SYS} = EER_{UNIT} \frac{100 - SC(\%)}{100} \tag{17}$$

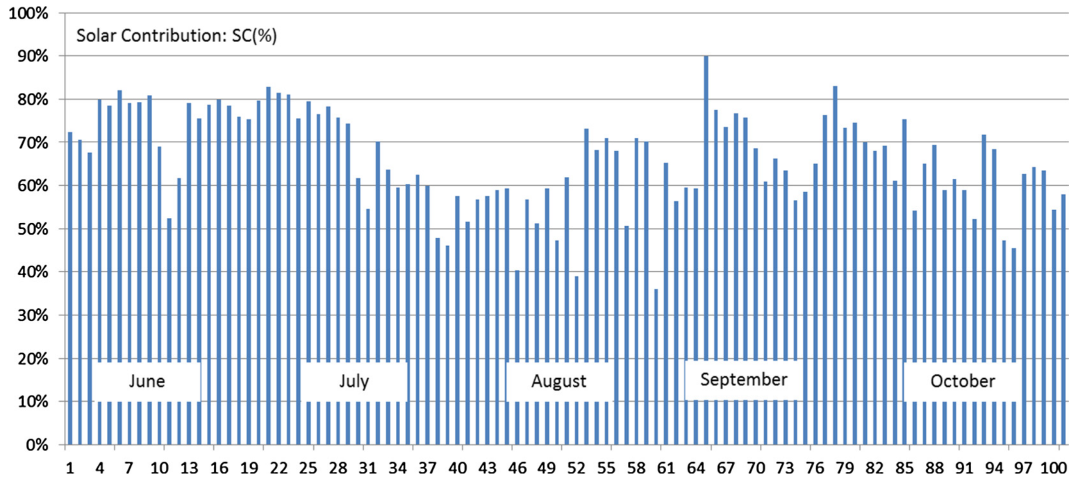

Fig. 10. Daily solar contribution. Data from 100 analysed days.

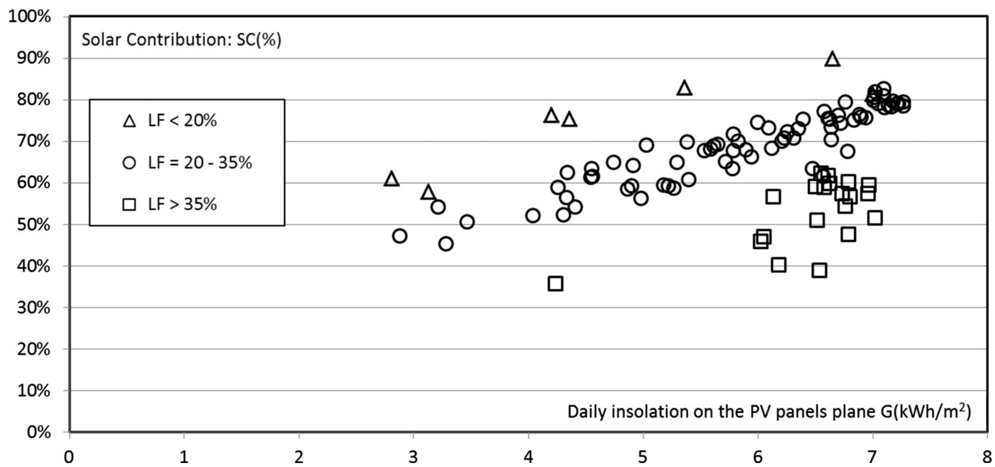

Fig. 11. Daily SC depending on daily solar insolation (G) and load factor (LF).

Fig. 15 graphically shows the system's Energy Efficiency (EER_{SYS}) as a function of the Solar Contribution. This parameter also depends on EER_{UNIT} and therefore on the daily outdoor mean temperature T_{OUT} and the load factor (LF).

3.4 Experimental correlations

Some correlations have been developed to establish the influence of the outdoor temperature, the solar irradiance and the load

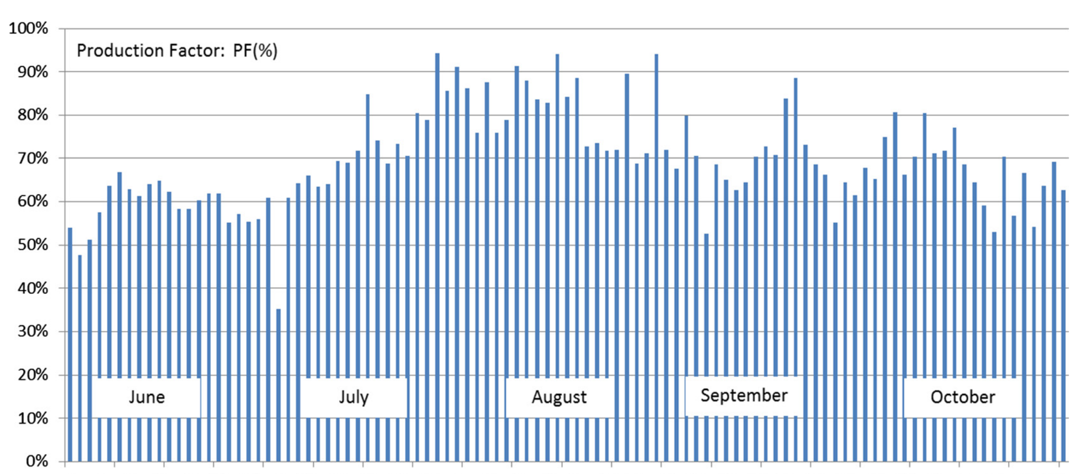

Fig. 12. Measured production factor. Data from 100 analysed days.

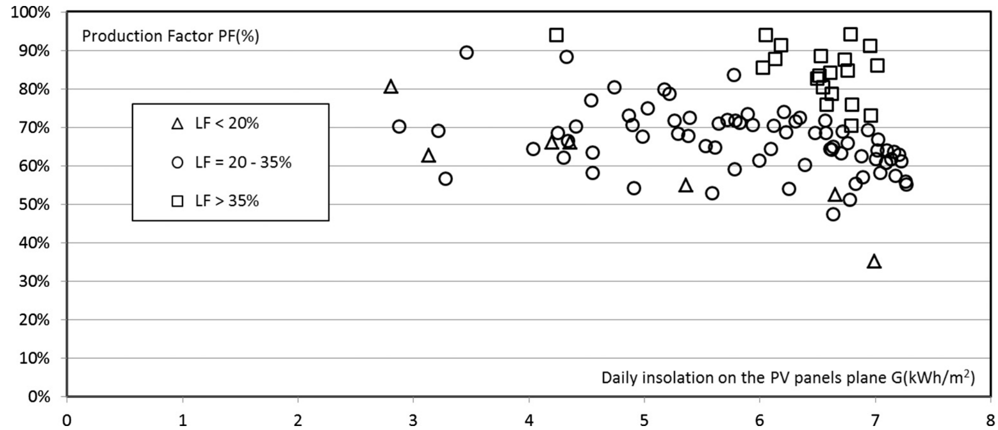

Fig. 13. Production factor (PF) as a function of the daily solar insolation (G) and the load factor (LF).

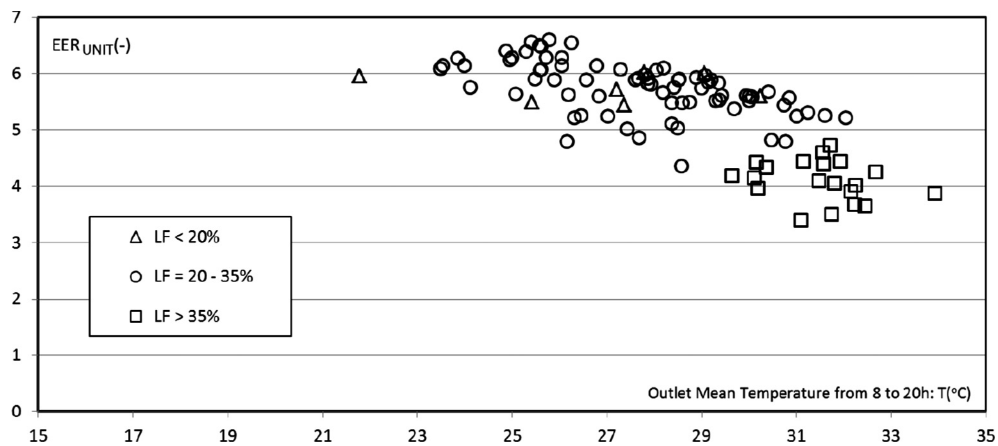

Fig. 14. Energy efficiency of the unit (EER_{UNIT}) as a function of the daily outlet mean temperature and the load factor (LF).

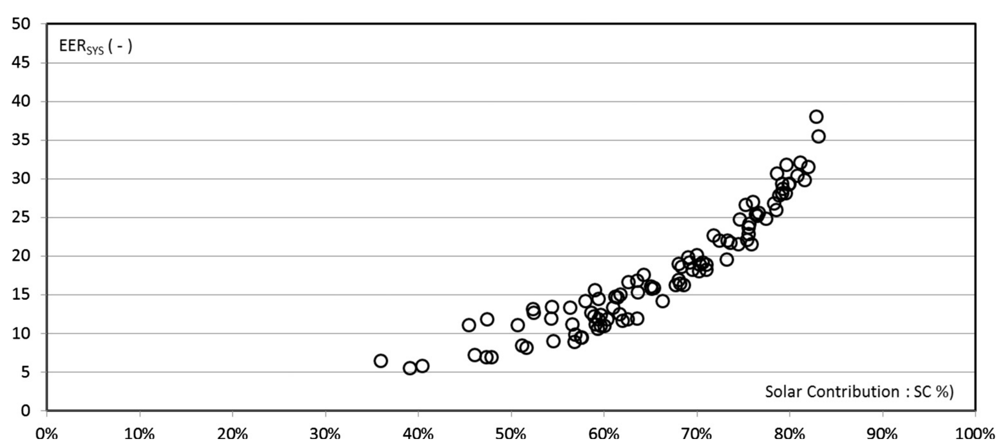

Fig. 15. Energy efficiency of the system (EER_{SYS}) in function of the Solar Contribution.

factor on the system's efficiency. These correlations can be used to extrapolate the obtained results to other locations with a certain level of uncertainty.

The average EER of the unit during one day (from 8 to 20) was shown to be a function of the average outdoor temperature and the load factor. The following correlation was developed with a 14% of uncertainty for 95% of the data:

$$EER_{UNIT} = 8.26 \cdot T_{OUT}^{-0.264} \cdot LF^{-0.395} \quad (18)$$

Fig. 16 represents the correlation in its range of application: daily average outdoor temperature from 24 to 34 °C and unit load factors between 25 and 50%.

It can be said that the most important parameter that needs to be evaluated to determine the possibilities of using solar energy on cooling systems would be the reachable solar contribution.

The daily Solar Contribution (%) was found to be a function of the daily solar irradiance on the PV panel's plane and the load fac-

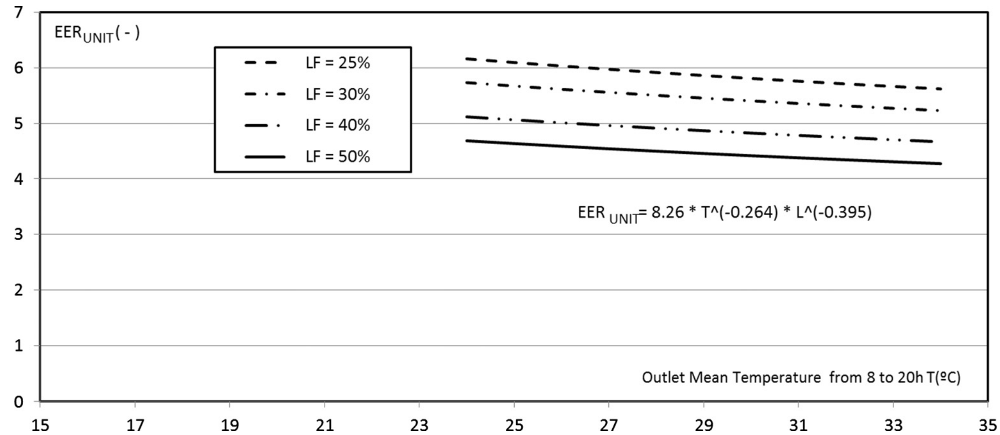

Fig. 16. Graphical representation of (Eq. (18)). Experimental correlation of the energy efficiency of the unit (EER_{UNIT}) as a function of the daily average outdoor temperature and the load factor (LF).

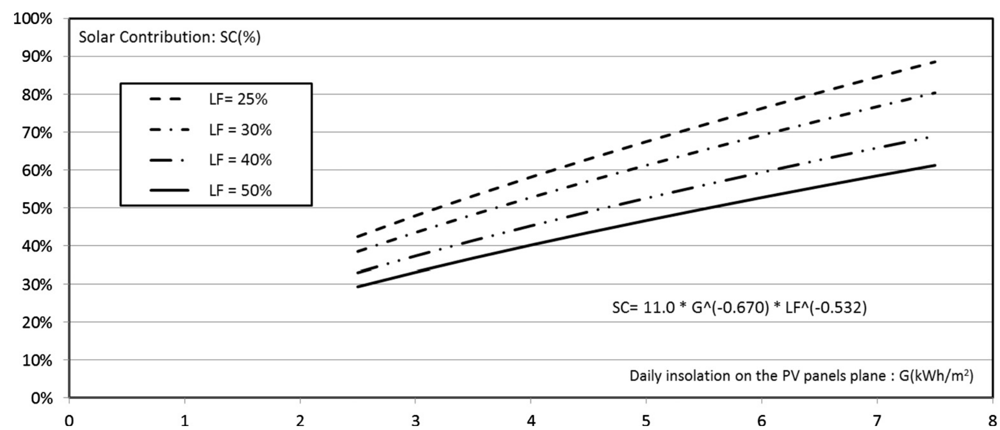

Fig. 17. Graphical representation of (Eq. (19)). Experimental correlation of Daily Solar Contribution (SC) as a function of the daily solar insolation (G) and the load factor (LF).

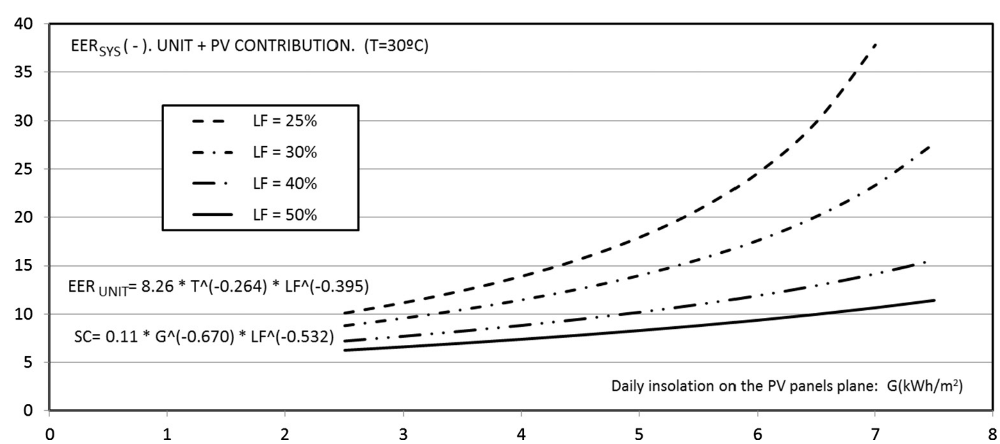

Fig. 18. Graphical representation of EER_{SYS}, calculated by (Eq. (17)), using (Eq. (18)) for EER_{UNIT} and (Eq. (19)) for SC(%).

Table 5
Monthly performance of the unit determined from measures.

Timetable from 8 to 20 h	$E_{PV,UNIT}$ (kWh)	$E_{GRID,UNIT}$ (kWh)	$E_{TOT,UNIT}$ (kWh)	$E_{PV,GRID}$ (kWh)	E_U (kWh)	EER_{UNIT} (–)	EER_{SYS} (–)	SC (%)	PF (%)	T_{OUT} (°C)
May	66.0	25.8	91.8	116.8	519.5	6.50	23.12	82.5	64.9	24.0
June	67.1	18.7	85.7	125.1	514.1	6.00	27.54	78.2	53.6	26.8
July	95.1	75.6	170.7	129.5	720.0	4.22	9.52	55.7%	73.4%	31.1
August	84.8	57.0	141.8	114.7	655.2	4.62	11.49	59.8	73.9	30.6
September	68.2	29.9	98.2	101.0	545.1	5.55	18.21	69.5	67.5	27.8
October	55.4	32.2	87.7	83.6	524.4	5.98	16.26	63.2	66.3	26.1
Cooling	436.5	239.3	675.8	670.7	3478.4	5.15	14.54	64.6	65.1	27.7

tor. The following correlation has been defined with a 12% of uncertainty for 95% of the data:

$$SC(\%) = 11.0 \cdot G^{-0.670} \cdot LF^{-0.532} \quad (19)$$

Fig. 17 represents the SC(%) correlation in its range of application: daily insolation on the PV panels from 2.5 to 7.5 kWh/m^2 and unit load factors between 25 and 50%.

Fig. 18 shows the influence of the insolation on the PV panel's and the load factor on the system's efficiency EER_{SYSTEM}. The curves are presented for an average outdoor temperature of 30 °C.

3.5. Annual results

The unit was working in an office located in Alicante (Spain) during the 6 months of cooling period. Table 5 shows the obtained monthly and seasonal results.

The unit fulfilled a cooling demand of 3478.4 (99.4 kWh/m^2) taking in total 239.3 kWh (6.8 KWh/m^2) of electricity from the grid. If a conversion factor from electricity to non- renewable energy of 2 kWh_{PR}/kWh_E is considered, a primary energy consumption of 13.6 kWh/m^2 would be obtained.

The solar contribution obtained in cooling mode from May to October was 64.5%, while the production factor was 65.1%.

4. Conclusions

An inverter air conditioning unit connected simultaneously to the grid and to 3 PV panels has been analysed to determine its behaviour under real conditions. The experimental analysis has been carried out for cooling conditions, with a working timetable from 8 to 20. The obtained data have been processed in order to define correlations of the unit's performance, which can be used to extend the results to other working conditions.

The performance of the system will depend on the solar radiation, outlet temperature and the unit's load factor. In the analysed office located in Alicante, Spain, the solar contribution obtained in cooling mode from May to October was 64.5% and the production factor was 65.1%.

Finally, the system has demonstrated to be 100% reliable, having undergone no maintenance.

The analysis that we carried out helped us set several technological improvements that could be implemented in the analyzed system in order to optimize its performance. Firstly, we propose the implementation of an adaptative mode control from a set temperature of ±2 °C according to the solar radiation availability or non-availability. Secondly, we propose an optimization method based on an ECO operation mode. Using this type of operation mode the air conditioning unit regulates independently its own operation regime in order to maximize the photovoltaic solar energy input. The aim is to get the maximum coincidence between the demand curve and the photovoltaic production curve.

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