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Techno-economic analysis of an air conditioning heat pump powered by photovoltaic panels and the grid

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ABSTRACT

This work presents an environmental and techno-economic study of an inverter air conditioner simultaneously powered by photovoltaic panels and the grid, without batteries. The unit provides the thermal demand to an office in an administrative building located in Alicante (South East Spain).

In comparison with other systems which also use renewable energy for air conditioning, this one presents significant advantages. It is comparatively simple, reliable, has low maintenance needs and its renewable energy production is entirely self-consumed, which avoids problematic interaction with the grid.

The system has been monitored during one year to measure the thermal energy provided to the room, the electrical consumption of the device and the photovoltaic and grid contribution to it.

Experimental results of some Key Performance Indicators are presented as a result of a one year data collection campaign. The measurements show a solar contribution of 54% to the electricity consumed by the system. As a result, the ratio between the thermal energy and grid electricity consumption during one year is $SPF_{sys} = 9.6$. Consequently, the primary non–renewable energy consumption is drastically reduced to a 26% of the reference system ($SPF_{ref} = 2.5$).

Furthermore, the techno-economic study concludes that in spite of requiring a higher initial investment in the system, the saving produced by the lower electricity consumption, results in an annualized cost of 84% of the reference system cost.

1. Introduction

In 2015 in Paris, the United Nations Framework Convention on Climate Change agreed to keep the increase in global average temperature to well below 2°C above pre-industrial levels, in order to reduce risks and the impacts of climate change. Consequently, the European Union has established the objective of a drastic cut of 80% of CO_2 emissions (referred to 1990) by 2050. Besides, individual goals and pathways have been set for the different energy consuming sectors, the goal for the building sector being a 90% reduction, which includes the total decarbonization of this sector. With this aim, the use of renewable energy and electricity is proposed as substitution for fossil fuels in heating and cooling, which in developed countries accounts for half the energy use in buildings and one fifth of the total national energy use (Pérez-Lombard et al., 2008). Furthermore, the European Union has defined an intermediate general goal for 2030 of a 40% cut in CO_2 emissions, with at least a 32% share of renewable energy.

In addition to the need of emissions reduction, the increasing number of HVAC systems results in an increase of the grid electricity cost due to the high peak demands (Passey et al., 2018). Under these circumstances, there is significant research activity focused on reliable and environmental friendly solutions for HVAC systems. Back in 2007, Balaras et al. (2007) made a review of solar air conditioning systems in Europe and Henning (2007) drew a picture about general issues for using solar thermal energy for the air conditioning of buildings. More recently, Al-Alili et al. (2014) and Zouaoui et al. (2017) focused their works on solar activated solid desiccant cooling technologies. Several authors (Izquierdo et al., 2011; Huang et al., 2011; Allouhi et al., 2015; Al-Ugla et al., 2016) studied the economic feasibility of different types of solar air conditioning systems.

Through a systematic literature research, Sampaio and González (2017) analysed the current situation of photovoltaic solar energy, and pointed out the main advantages which make it a good solution for use in buildings: high reliability, availability, low maintenance needs and its potential to mitigate emissions of greenhouse gases. In fact, solar cooling and heating systems are increasing consistently in number and available technologies (Mugnier et al., 2017). Among them, the use of photovoltaic panels is actively studied. Li et al. (2015) carried out experiments during one day and night in winter and summer to demonstrate that consistent and reliable heating and cooling could be

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Nomenclature

E	energy
LF	load factor
P	power
PnRE	primary non renewable energy
PEF_{EL}	primary energy factor for electricity
Q	thermal energy provided by the air conditioning, including cooling and heating

Key Performance Indicators

SPF_{unit}	seasonal performance factor for the air conditioning unit: ratio of useful heat and/or cold in relation to the electricity consumption needed
SPF_{sys}	equivalent seasonal performance factor for the whole system. It indicates the grid electricity needed for supplying the thermal energy demand
PER_{nRE}	primary non–renewable energy ratio. Relation between the non–renewable primary energy employed by the analysed system and by the reference system for the same energy demand
PF	performance factor of the PV panels connected to the air conditioning unit
FSAV	fraction savings of non–renewable primary energy
SF	solar fraction or solar contribution to the electricity consumed by the air conditioning unit
CR	cost ratio. Ratio between the total annualized cost of the analysed system and that of the reference system for the same space heating and cooling provided
C_{AN}	total annualized cost of the system

Subindex

ref	reference system
PV	photovoltaic panels
GD	grid
unit	air conditioning unit
sys	the whole system including the PV panels and the AC unit
PV, *GD*	refers to electrical energy or power produced by the three PV panels which are connected directly to the grid
PV, *unit*	refers to electrical energy or power produced by the three PV panels connected to the air conditioning unit
GD, *unit*	refers to electrical energy or power consumed from the grid by the air conditioning unit
TOT, *unit*	refers to the total electrical energy or power consumed by the air conditioning unit
TOT, *max*	refers to the maximum total electrical energy or power which would be consumed by the air conditioning unit if it was working at full power during its working time

achieved by a PV and grid powered air conditioner with batteries in the cold winter as well as in the hot summer of Shanghai (China). They also pointed out that this system could be a good solution to reduce the peak loads in the electrical grid during such periods. Huang et al. (2016) studied the operation of small scale air conditioning systems powered by PV and batteries when varying the air conditioning unit model, the number of panels and the battery capacity. The study was made for several typical days. Liu et al. (2017) investigated an air conditioner driven by a quasi grid-connected photovoltaic (PV) system powered during one day in July in Beijing (China). The analysis was carried out for the system with batteries and without them. They quantified the potential energy savings of more than 67% and 77% during summer daytime and night-time. Varga et al. (2017) reported their first experimental results with a small scale solar driven ejector cooling system installed in Porto, Portugal. Xu et al. (2018) applied ice thermal storage air-conditioning and photovoltaic air-conditioning in the refrigeration field. Their analysis showed that it is feasible to use ice thermal storage instead of a battery bank to store solar energy in the field of distributed photovoltaic refrigeration.

A previous work by the authors (Aguilar et al., 2017) tested a heat pump in cooling mode powered by photovoltaic panels and the electrical grid during the hot season in Spain. The cooling system was installed in an office and the solar contribution and the production factor were found to be both 65%. Recently, Opoku et al. (2018) studied the performance of a hybrid solar PV(with batteries)-grid powered air-conditioner for daytime office cooling in hot humid climates (Kumasi, Ghana) during one year. Li et al. (2018) analysed the annual performance of a chiller water plant powered by 1562 PV panels used to provide cooling (April to November) to a 14220 m^2 tertiary building and measured an annual solar fraction of 52%, even when no cooling was generated during the four winter months.

Our literature search has yielded only two experimental works dealing with PV powered air conditioning devices which have been tested throughout one year (Opoku et al., 2018; Li et al., 2018). On the one hand, the study by Opoku et al. (2018) is particular to the hot humid climate in Ghana, as the device only works in cooling mode throughout the year and with a very high demand throughout the day. This situation is very different to the one in an office in Europe, where there are cooling and heating demands throughout the year and the demand varies significantly throughout the day. On the other hand, the work by Li et al. (2018) is focused in a large tertiary building, which is only provided with cooling. The weather conditions of this study are similar to the ones of the mediterranean climate, however, the conclusions of the work would not be applicable to the small tertiary sector working with heat pumps which provide heating and cooling through the year.

Furthermore, the lack of knowledge and economic reasons are pointed out as the main obstacles for a wider spread of this technology (Mugnier et al., 2017).

In view of this situation the present study was undertaken. It presents an experimental study in a real situation, which uses solar energy and grid electricity to provide an office with cooling and heating for one year. By the use of solar energy and an efficient heat pump, the use of primary energy and CO_2 emissions are drastically reduced and, at the same time, the direct use of fossil fuels is avoided. The office is located in Alicante (South East Spain), where the climate is Mediterranean, which is characterised by moderate winters and hot summers. The study, focused on the annual performance of the system, is aligned with the European objective of CO_2 emission reduction, the use of renewable energies, decarbonization and the objective of developing solutions towards nearly zero energy buildings (nZEB). The work analyses parameters such as the solar contribution, the grid electricity savings, the use of non–renewable primary energy and the CO_2 emissions. Besides, the annual cost of the system during its lifetime is quantified and compared to a reference system.

2. Experimental setup

A 35 m^2 office in an administrative building was provided with cooling and heating throughout one year by using a highly efficient heat pump. The working time of the office was from 8 h to 20 h from Monday to Friday and from 8 h to 14 h on Saturday. The characteristics of the air conditioning unit (AC) are detailed in Table 1. For the study, the temperature was set to 23 °C in summer and 21 °C in winter within

Table 1
Air conditioner technical data.

Midea Solar 3D	Unit	Nom.
Cooling capacity	kW	3.52
Cooling power supply	kW	0.86
EER	—	4.09
Heating capacity	kW	3.81
Cooling power supply	kW	0.99
COP	—	3.83
Refrigerant		R410A

the office. The system control was configured to meet the demand.

A sketch of the system (PV panels + AC unit) is shown in Fig. 1. There were three 235 W_p photovoltaic panels located on the roof of the building, with an inclination of 30° (latitude of 38°) and with an azimuth deviation of 15° from South. The AC unit was connected both to the conventional grid (230 V_{ac}) and to the PV panels (24 V_{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 (Fig. 2). So, this air-conditioner has always enough energy to work properly, regardless of the solar irradiation variations. This unit has an inverter that transforms grid energy from 230 V_{ac} at 50 Hz to 200 − 300 V_{dc} to drive a compressor at different angular velocities. The PV energy integration occurs before connection to the compressor through a converter that operates between 24 V_{dc} and 200 − 300 V_{dc}. While PV power output is sufficient and due to the difference in impedance between the two energy sources (PV and the grid), PV power becomes the lead energy source. Grid power is only absorbed once PV power is insufficient.

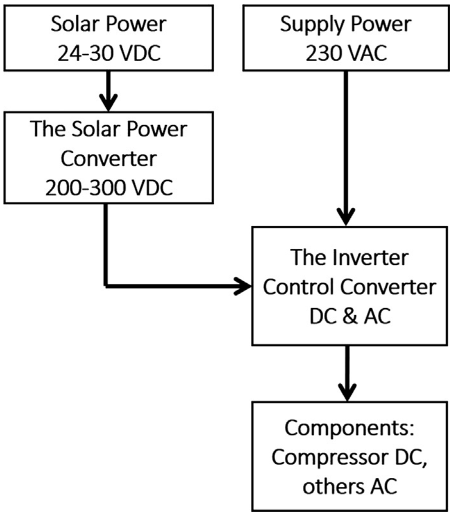


Fig. 2. AC unit power supply connection diagram.

As it can be observed in Fig. 3, three additional and identical PV panels were connected to the electrical grid through a maximum power point (MPP) grid converter. The purpose was to measure the potential maximum production of the panels. Consequently, the influence of the air-conditioning equipment on the PV panels production could be evaluated. The figure also shows details of the data collection carried out by an Agilent 34972A data-logger with a 5 min time step. The room and outside ambient temperatures were measured with type-K thermocouples. The refrigerant cycle parameters were measured by four thermocouples and two nanometers. Two shunt resistances were used to evaluate the current consumed by the air conditioning device both from the grid and from the PV panels, while a third one was used for the PV panels connected to the grid. A network analyser Chauvin Arnoux CA 8334 was in charge of registering power consumption from the compressor. Furthermore, a meteorological station registered humidity, wind, wind direction and solar irradiation.

Further details of this experimental setup and procedure can be

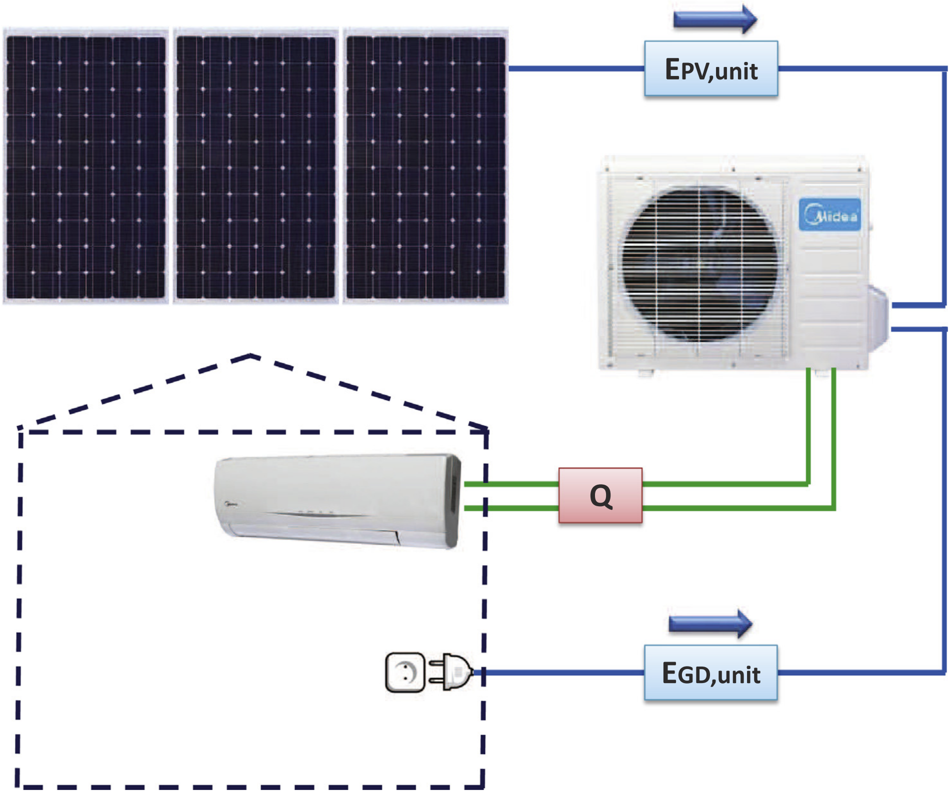


Fig. 1. Sketch of the air conditioning system energy flows.

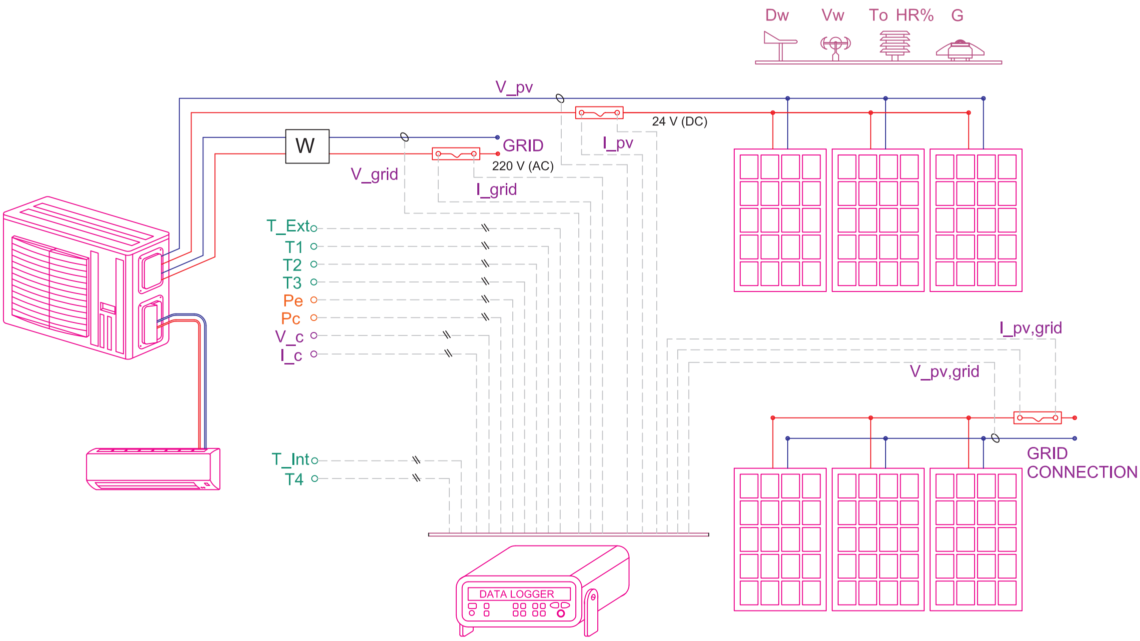


Fig. 3. Experimental setup. Monitorization details.

found in Aguilar et al. (2017), where detailed results in cooling mode are provided.

3. Results

During the experimental campaign, data corresponding to more than two hundred and fifty days (at least 20 days every month) were collected. These results have been used to obtain conclusions about the seasonal behaviour of the system.

3.1. Daily results

In order to understand the behaviour of the system, two typical days, one in cooling and one in heating modes, are described in detail in this section.

Fig. 4 shows the curves of the electrical parameters registered in a day of July, including: the power supplied from the PV panels to the air-conditioning unit ($P_{PV,unit}$), the power supplied from the grid to the unit ($P_{GD,unit}$) and the total power consumed by the unit ($P_{TOT,unit}$), which is the sum of the two previous curves. The 3 reference PV panels were measured and their power curve has been included ($P_{PV,GD}$) in the figure as well.

As it can be seen in the figure, the unit was working for 12 h, between 8 a.m. and 8 p.m. Nevertheless, since the power $P_{PV,unit}$ depends on both the electrical consumption and the solar irradiation, four working points are analysed in the following paragraphs.

At point A, the electrical power consumed by the unit ($P_{TOT,unit}$) was higher than the PV panels potential electricity production, so that the PV power was not enough to feed the AC unit and the rest was supplied by the grid. In this case, the PV panels connected to the unit supplied

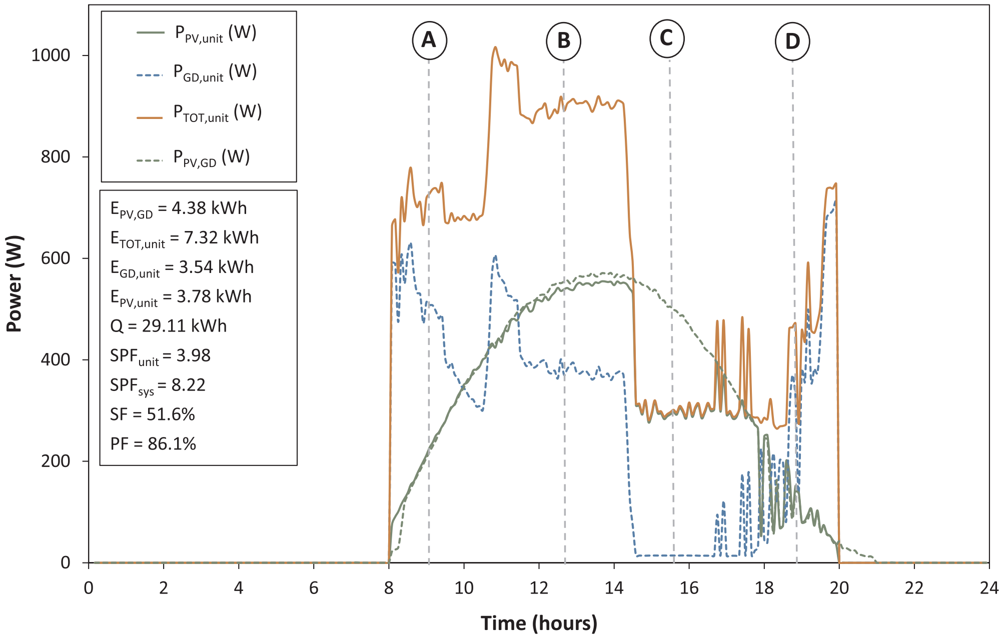


Fig. 4. Electrical curves registered along one day in July: (T_{out} = 30.2 °C, I = 7.61 kWh/m^2, LF = 61.0%).

almost the same power than those connected to the grid. The only power loss was due to the lower efficiency of the unit converter which is not an MPP converter. This power loss can be better appreciated at point B, when the situation was similar to point A.

On the contrary, at point C the electrical power demand of the air-conditioning unit ($P_{TOT,unit}$) was significantly lower than the PV panels potential electricity production ($P_{GD,unit}$). Consequently, the unit converter which controls the PV panels, modified their working point in order to match the electrical power demand ($P_{PV,unit} = P_{TOT,unit}$). It can be seen that the reference PV panels went on working according to the maximum power point, so that the $P_{PV,GD}$ was much higher than $P_{PV,unit}$. In this situation, the power consumption from the grid became almost zero.

Finally, at point D the solar irradiation was decreasing and the system worked as it did at point A.

At 8 p.m. the unit and the PV panels connected to it turned off. However, the PV panels connected to the grid went on working until 9 p.m. because of the available solar irradiation.

The energy supplied by the grid ($E_{GD,unit}$), the energy supplied by the PV panels ($E_{PV,unit}$) and the energy produced by the reference PV panels ($E_{PV,GD}$) have been calculated out of the measured power and the time elapsed between measurements, Δt. The total energy consumed by the unit $E_{TOT,unit}$ is calculated as the sum of $E_{GD,unit}$ and $E_{PV,unit}$. All these results have been included in Fig. 4.

As is explained in Aguilar et al. (2017) the useful thermal energy supplied to the office can be calculated by using the refrigerant method (Tran et al., 2012). In the studied day of July, the useful energy was $Q = 29.11$ kWh.

Fig. 5 shows the curves of the electrical parameters registered in a day of February. As previously, 4 typical working points have been highlighted.

On the one hand, it can be seen that in points E, F and G the system has the same behaviour than in points A, C and D, of Fig. 4, respectively.

On the other hand, in point H both the energy produced by the PV panels connected to the unit and the energy produced by the PV panels connected to the grid is zero because the sunset in winter is before 8 p.m ($P_{GD,unit} = P_{TOT,unit}$).

Several key performance indicators (KPIs) have been defined in order to compare the unit behaviour among the different studied periods. In this section, these KPIs have been calculated for 1 day period.

First of all, the Seasonal Performance Factor of the unit (SPF_{unit}) is defined as the ratio of the useful thermal energy and the total electricity consumed.

$$SPF_{unit} = \frac{Q}{E_{TOT,unit}} \tag{1}$$

The SPF_{unit} represents the performance in the working conditions, of the air conditioning unit only. In order to evaluate the performance of the whole system, including the panels, the equivalent seasonal performance factor for the system has been obtained.

$$SPF_{sys} = \frac{Q}{E_{GD,unit}} \tag{2}$$

So defined, the SPF_{sys} indicates the grid electricity needed for supplying the energy demand. This parameter can be considered like a mean COP or EER of the system, but in working conditions.

The solar fraction is defined as the ratio of the electricity produced by the PV panels and the total consumed by the air conditioner.

$$SF\,(\%) = \frac{E_{PV,unit}}{E_{TOT,unit}} \tag{3}$$

For its part, the Production Factor (*PF*) takes into consideration the solar energy losses due to the fact that the PV panels connected to the air conditioning unit followed its electrical demand instead of using an MPP converter. This KPI is defined as follows:

$$PF\,(\%) = \frac{E_{PV,unit}}{E_{PV,GD}} \tag{4}$$

These KPIs, which have been calculated for these two days, have been included into Figs. 4 and 5, respectively.

Finally, the Load Factor (LF) allows to know the ratio between the real energy consumed by the unit and the maximum energy consumed if the unit was working at 100% power, during the 12 h test period ($E_{TOT,max} = 12$ kWh).

$$LF\,(\%) = \frac{E_{TOT,unit}}{E_{TOT,max}} \tag{5}$$

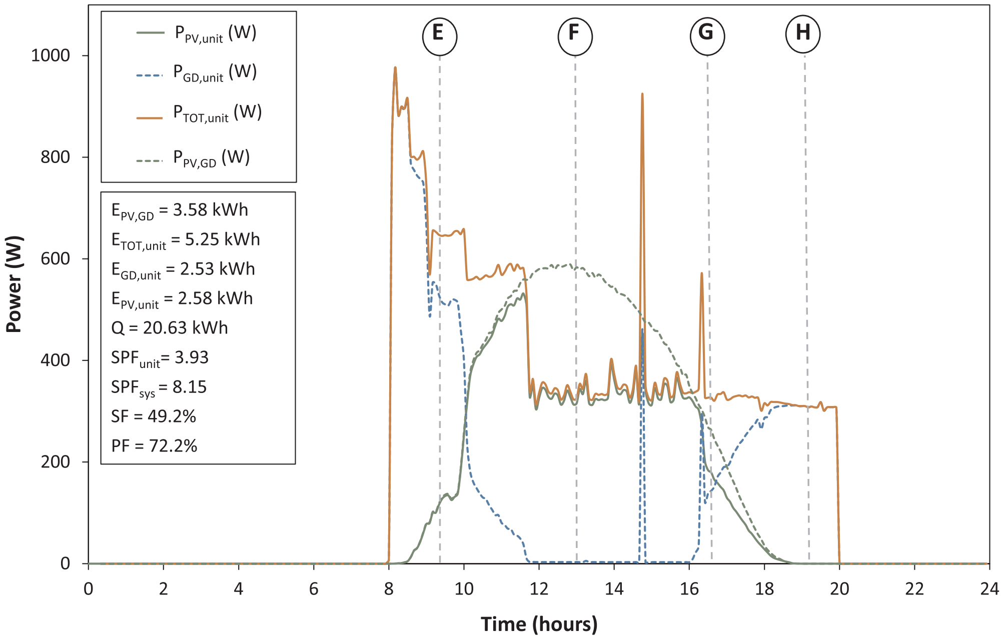


Fig. 5. Electrical curves registered along one day in Feb: ($T_{out} = 12.5$ °C, $I = 5.72$ kWh/m^2, $LF = 43.8\%$).

Table 2

Energy flow data of the HVAC system. All energy values are given in kWh. The unit provides cooling from May to October and heating from November to April.

Nomenc.	EPV, GD	EPV, unit	EGD, unit	ETOT, unit	Q	SPFunit	SPFsys	SF (%)	PF (%)	LF (%)	TEXT (°C)	H (kWh/m^{2}day)
May	116.8	66.0	25.8	91.8	519.5	5.66	20.10	71.9	56.5	27.3	24.0	6.56
Jun	125.1	67.1	18.7	85.8	514.1	5.99	27.50	78.2	53.6	26.2	26.8	7.28
Jul	129.5	95.1	75.6	170.7	720.0	4.22	9.52	55.7	73.4	50.8	31.1	7.35
Aug	114.7	84.8	57.0	141.8	655.2	4.62	11.50	59.8	73.9	42.2	30.6	6.56
Sep	101.1	68.2	29.9	98.1	545.1	5.56	18.20	69.5	67.5	29.9	27.8	6.04
Oct	83.6	55.4	32.2	87.6	524.4	5.99	16.30	63.2	66.3	26.1	26.1	4.91
Cooling	670.8	436.6	239.2	675.8	3478.3	5.15	14.50	64.6	65.1	33.8	27.1	6.45
Nov	56.5	49.4	65.3	114.7	465.2	4.06	7.12	43.1	87.4	35.0	14.9	3.47
Dec	56.4	51.7	89.5	141.2	551.7	3.91	6.16	36.6	91.7	42.0	15.2	3.35
Jan	70.4	61.9	85.0	146.9	575.3	3.92	6.77	42.1	87.9	43.7	15.1	4.15
Feb	75.7	64.0	83.0	147.0	533.0	3.63	6.42	43.5	84.5	47.7	13.6	4.85
Mar	93.0	68.9	72.0	140.9	531.5	3.77	7.38	48.9	74.1	41.9	16.8	5.30
Apr	101.8	58.5	44.8	103.3	387.7	3.75	8.65	56.6	57.5	31.5	19.1	5.93
Heating	453.8	354.4	439.6	794.0	3044.4	3.83	6.93	44.6	78.1	40.3	15.8	4.50
Year	1124.6	791.0	678.8	1469.8	6522.6	4.44	9.61	53.8	70.3	37.0	21.7	5.48

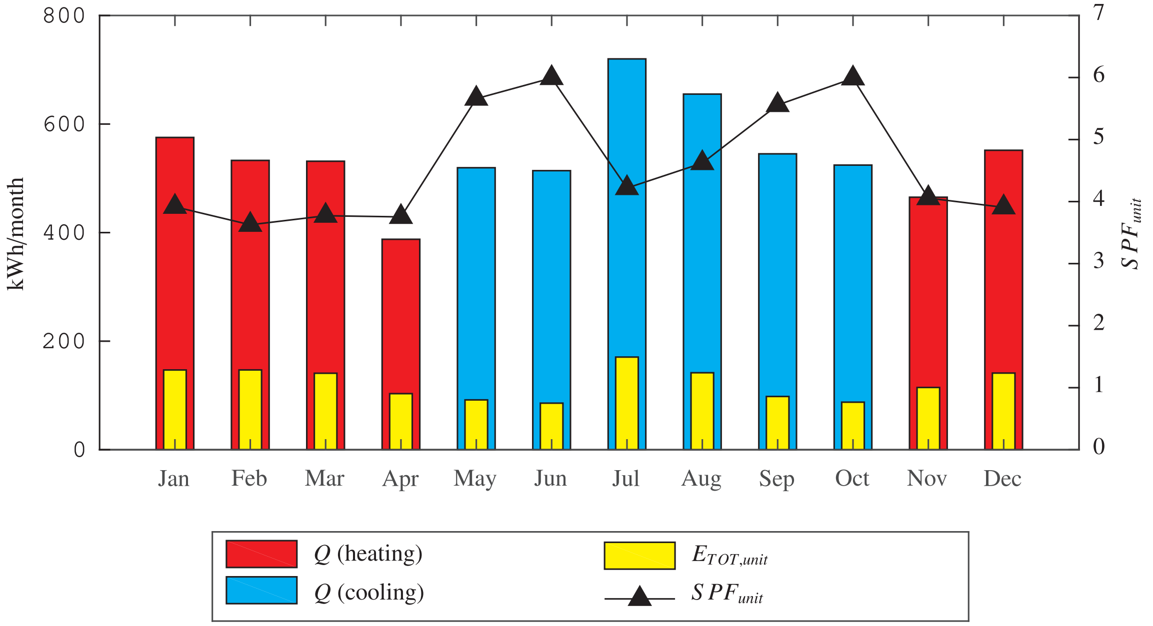


Fig. 6. Total energy consumed $E_{TOT,unit}$ (electrical) and produced Q (thermal) by the air conditioning unit. Seasonal performance factor of the unit (right axis).

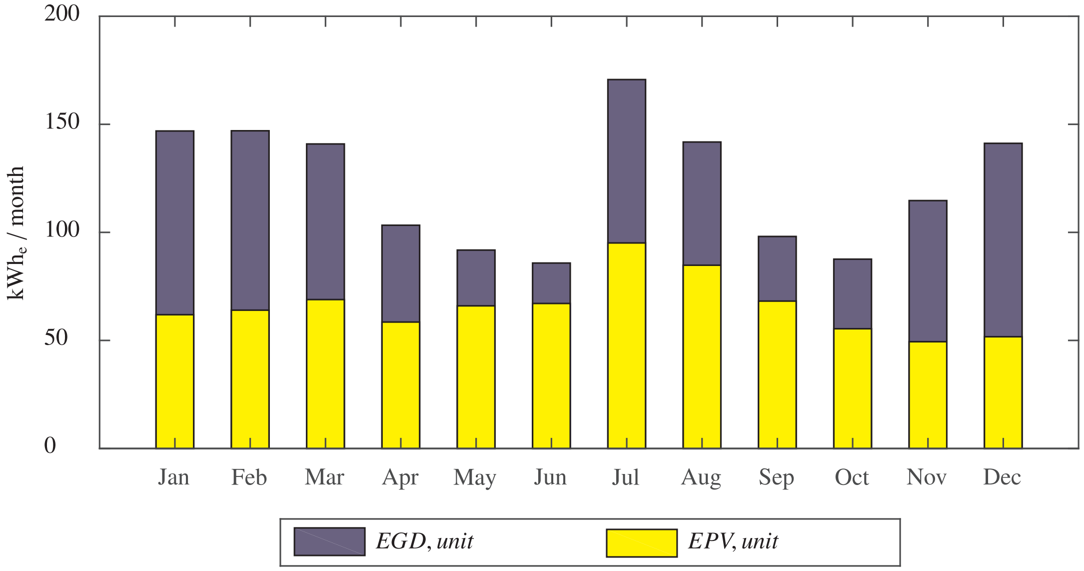


Fig. 7. Electrical consumption ($E_{TOT,unit}$) broken down according to the energy source: the grid ($E_{GD,unit}$) or the PV panels ($E_{PV,unit}$).

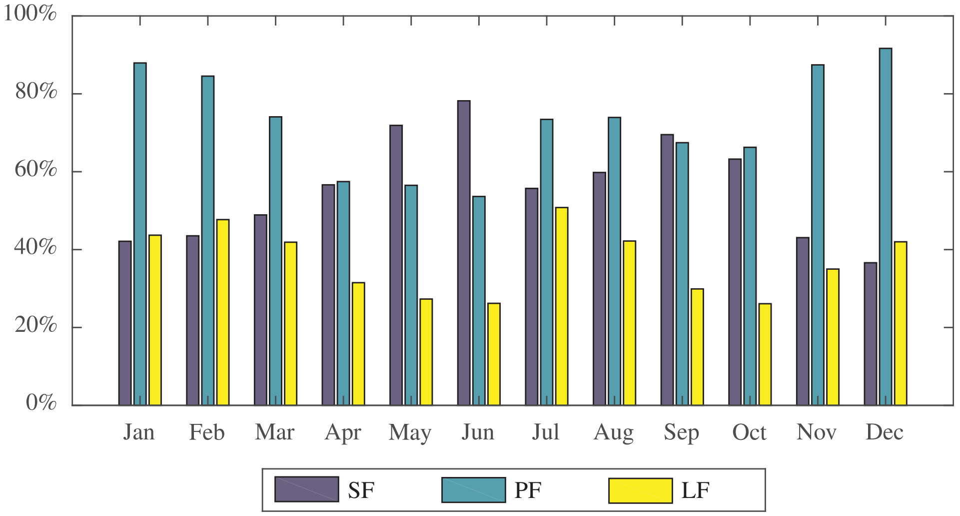


Fig. 8. Solar fraction *SF*, Performance factor *PF* and Load factor *LF*.

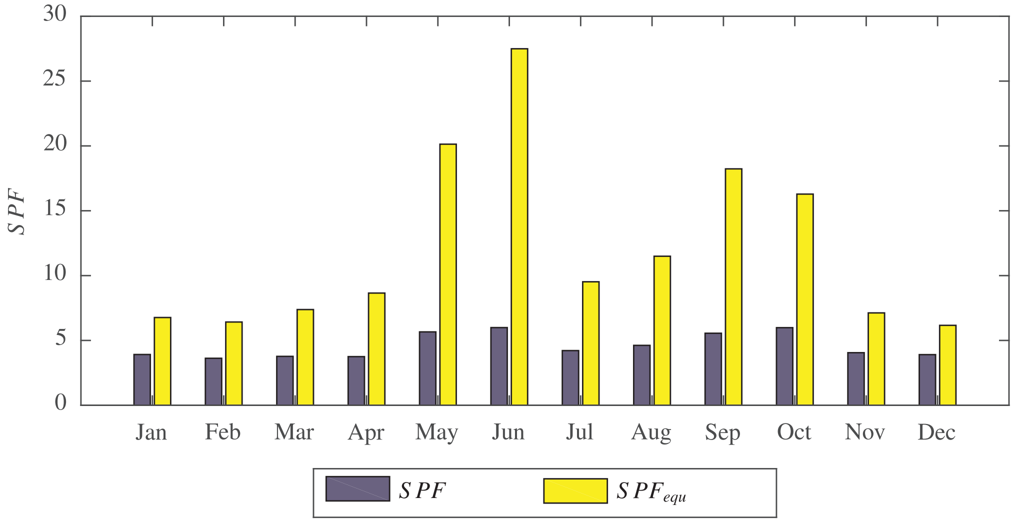


Fig. 9. Seasonal performance factor for the unit (SPF_{unit}) and the system (SPF_{sys}).

Table 3
Reference system efficiency and energy conversion factors for Spain (IDAE, 2016).

	Value	Units
SPF_{ref}	2.5	
PEF_{EL}	2.0	kWh_{PnRE}/kWh_e
Emissions factor	0.357	gCO_2/kWh_e

3.2. Annual results

The results of the system performance throughout one year are analysed in this section. The KPIs defined in previous section will be calculated monthly, seasonally and annually. The unit was working in heating mode from November to April and in cooling mode from May to October, the system control being configured to meet the thermal demand. All the results for this section are detailed in Table 2.

Firstly, the performance of the AC unit is analysed. Fig. 6 shows the total electricity absorbed by the air conditioning unit month by month. The thermal energy (heat or cold) provided to the office is shown in the figure as well. Out of this data, the seasonal performance factor of the AC unit (SPF_{unit}) has been obtained (Eq. (1)) and plotted in the Figure as well.

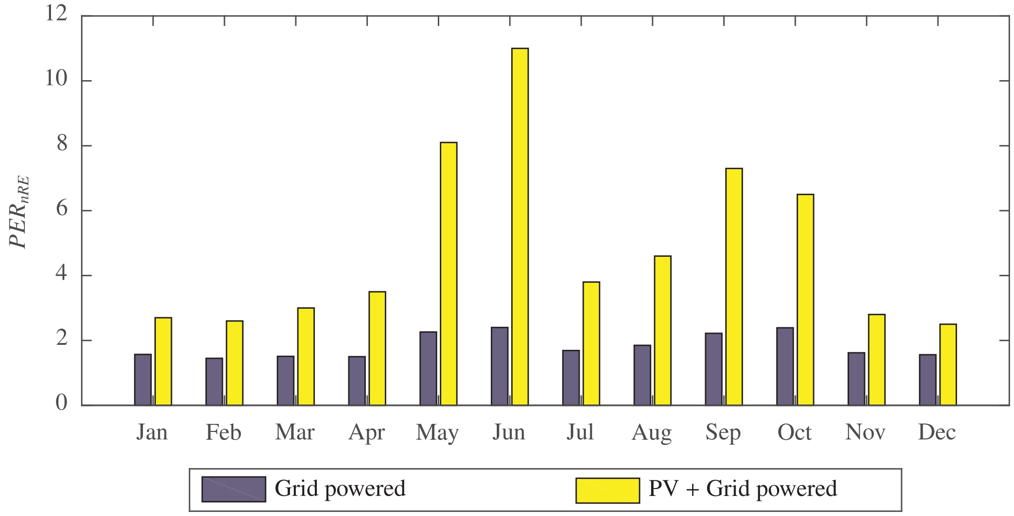
The results show that the highest demand occurs in January in heating mode and in July in cooling mode, as it is expected for this climate. The resulting SPF_{unit} of the air conditioning unit for the year has been 4.44. Better performance of the unit is observed for months with lower demand, when the machine is working at partial loads and the climate conditions are moderate. Besides, the obtained SPF_{unit} of 5.34 in cooling mode is higher than the one in heating mode, 3.84.

The contribution of the PV panels is evaluated next.

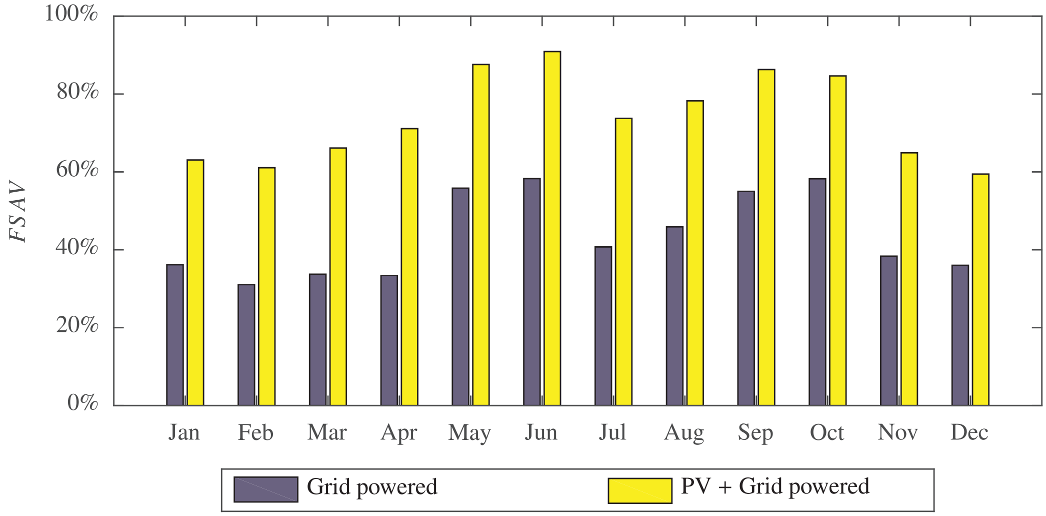
Fig. 7 shows the electricity consumed by the air conditioning unit from the PV panels ($E_{PV,unit}$) and from the grid ($E_{GD,unit}$).

The solar fraction is shown in Fig. 8. The low demand in spring and autumn and moderate solar resource result in solar fractions up to 78% (Table 2). During the hottest months of the year, July and August, the solar fraction drops to 56–59% due to the high cooling demand (high LF), despite being the sunniest months. Lower values of the solar contribution are found from December to March where the thermal demand is also significant (heating) and, besides, the solar irradiation reaches its minimum.

The overall SPF_{sys} for the year, which evaluates the performance of the whole system, including the panels, is 9.61. The results in Fig. 9 show better ratios during months with moderate climate, where the working conditions for the unit are more favourable and the solar fraction is higher. Besides, the SPF_{sys} in heating conditions is 6.93 on



(a) Primary energy ratio.



(b) Fraction savings.

Fig. 10. Comparison of non–renewable primary energy ratios for the systems under study.

Table 4
Primary non–renewable energy consumption and CO_2 emissions for the systems under consideration.

	PV + Grid powered	Grid powered	Reference unit
Produced thermal energy, Q [kWh/year]	6523	6523	6523
Consumed Grid Electricity, ETOT,unit [kWh/year]	678.8	1469.7	2609.0
Seasonal Performance Factor, SPF [–]	9.61	4.44	2.50
Primary non–renewable energy, PnRE [kWh/m^2 year]	38.8	84.0	149.1
CO_2 emissions [kg/m^2 year]	6.92	15.0	26.6
Primary non–renewable ratio, PERnRE [–]	3.84	1.78	–
PnRE Savings Factor, FSAV [–]	74.0%	43.7%	–

average, while in cooling conditions it is 14.54, 110% higher. This difference is partly explained due to the better SPF_{unit} in cooling mode, but also due to the higher solar irradiation available during the hot months, which results in lower grid electricity demand.

As has been commented before, the PV panels connected to the air conditioner do not produce as much energy as if they where connected to the grid.

The results for the performance factor *PF* (Eq. (4)), defined as the ratio between the PV panels energy production and their maximum production if they were connected to the grid, are shown in Fig. 8. The highest performance factor values are obtained from November to February (up to 92%). During this period, irradiation is low and the thermal needs are high enough to make the most of it. In July and August, the thermal needs are high as well, but more irradiation is available during longer periods each day, which results in a higher waste of energy (*PF* between 73% and 74%). However, the highest

Table 5
Techno-economic study results for a 25 years lifetime (Energy cost 0.15 €/kWh).

	PV + Grid powered	Grid powered	Reference
INVESTMENT	€	€	€
PV panels	1200	0	0
Air Conditioner	2600	2500	1500
INVESTMENT MATERIAL	3800	2500	1500
Design, planning and commissioning	200	200	200
General costs associated to works	760	500	300
Indirect costs and industrial benefits	190	125	75
TOTAL INVESTMENT COST	4950	3325	2075
REPLACEMENT COST	€/year	€/year	€/year
PV panels (25 years lifetime)	0	0	0
Air Conditioner (18 years lifetime)	39.27	37.76	22.65
TOTAL REPLACEMENT COST	39.27	37.76	22.65
MAINTENANCE	€/year	€/year	€/year
PV panels (30 €/year)	30	0	0
Air Conditioner (60 €/year)	60	60	60
TOTAL MAINTENANCE COST	90	60	60
OPERATION-ENERGY	€/year	€/year	€/year
Energy Cost of Electricity	101.81	220.46	391.36
Power Cost of Electricity	90	90	90
TOTAL ENERGY COST	191.81	310.46	481.36
ANNUALIZED COSTS	€/year	€/year	€/year
Investment	228.67	153.60	95.85
Replacement	39.27	37.76	22.65
Maintenance	87.38	58.25	58.25
Electricity	186.23	301.41	467.34
TOTAL ANNUALIZED COST	541.54	551.02	644.10
Cost ratio	0.84	0.86	–

waste takes place during months with low thermal needs: April and May (cooling), June and October (heating). The result for the year is an average performance of 70%.

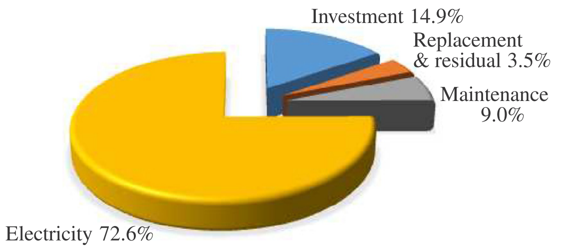
4. Environmental benefits

In this section the environmental benefits of the PV powered air conditioning system are evaluated. With that aim, two different system configurations are studied. One of them consist of an highly efficient AC unit powered by three PV panels and the grid and the other consist of the same unit powered only by the grid. The results will be compared to those of a reference system. Usually, a gas boiler for space heating and an air conditioning unit for space cooling are considered as the reference system. However, this is an expensive solution, which is not often used for offices in the Mediterranean region. Therefore, in this study, the reference system consists in a reversible air conditioner for heating and cooling, which is a very common solution for this climate. The unit is considered to have a seasonal efficiency of 2.5 (cooling and heating). The proposed comparison allows us to evaluate separately the benefits of installing a more efficient heat pump and the PV panels.

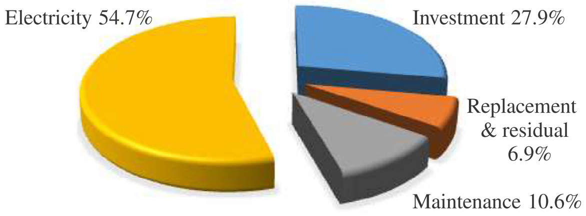
Firstly, the environmental benefits of the analysed systems are evaluated in terms of primary energy consumption and CO_2 emissions reduction.

As electricity is the final energy consumed by all the systems under consideration, their primary non–renewable energy is computed by using the conversion factor for this type of final energy (PEF_{EL} in Table 3):

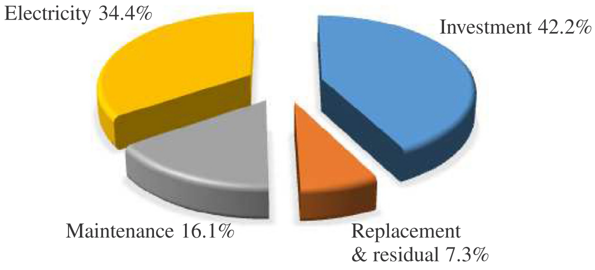
$$PnRE = \frac{Q}{SPF} PEF_{EL} \tag{6}$$



(a) Reference system.



(b) Grid powered system.



(c) PV + Grid powered system.

Fig. 11. Total life system cost contributions.

The *primary energy ratio*, indicates the relation between the non–renewable primary energy employed by the analysed system and by the reference for the same energy demand. For this case, where the final energy consumed by the system and the reference is electricity, the ratio is reduced to the following

$$PER_{nRE} = \frac{PnRE_{ref}}{PnRE_{sys}} = \frac{SPF_{sys}}{SPF_{ref}} \tag{7}$$

The *savings fraction* of non–renewable primary energy, indicates the percentage of non–renewable primary energy consumption.

$$FSAV\,(\%) = \frac{PnRE_{ref} - PnRE_{sys}}{PnRE_{ref}} \tag{8}$$

The results plotted in Fig. 10 show the convenience of using an efficient heat pump instead of the reference system. The annual primary energy ratio for the system without PV panels is 1.78, meaning that the reference consumes 1.78 times more non–renewable primary energy than this system. This results in annual savings of 44% of the primary non–renewable energy. Furthermore, the use of the PV panels boost the savings of primary non–renewable energy. With a PER of 3.84, the system powered with PV panels achieves an annual saving of 74%.

Due to the use of the same final energy for the two systems and the reference, the CO_2 emissions savings in percentage is the same as primary energy: 44% and 74% of the emissions along a year for the systems without the PV panels and with them, respectively. The absolute figures for the CO_2 emissions are shown in Table 4 and they have been calculated with an emission factor for electricity production in Spain (detailed in Table 3). It must be pointed out that PER_{nRe} and $FSAV$ do not depend on the energy conversion factors.

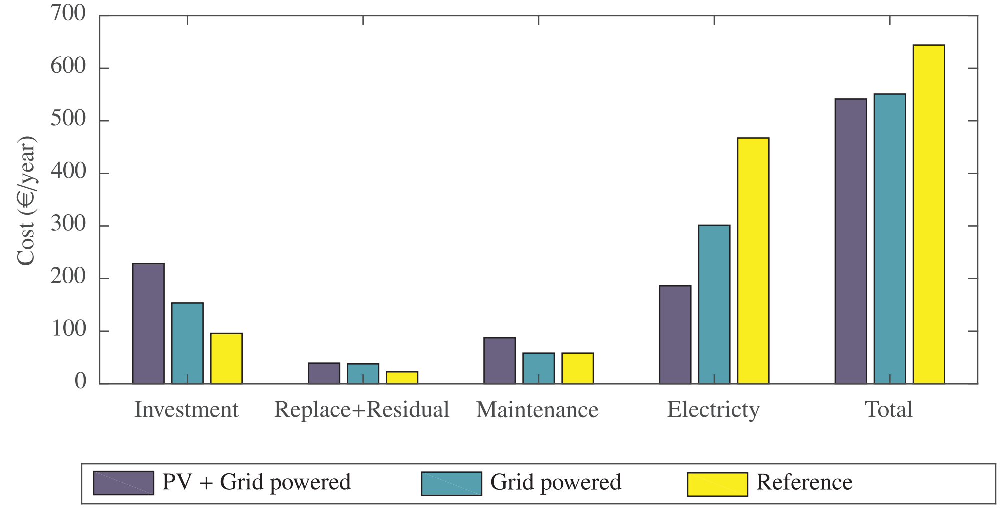


Fig. 12. Individual annual cost contributions and total cost of the systems.

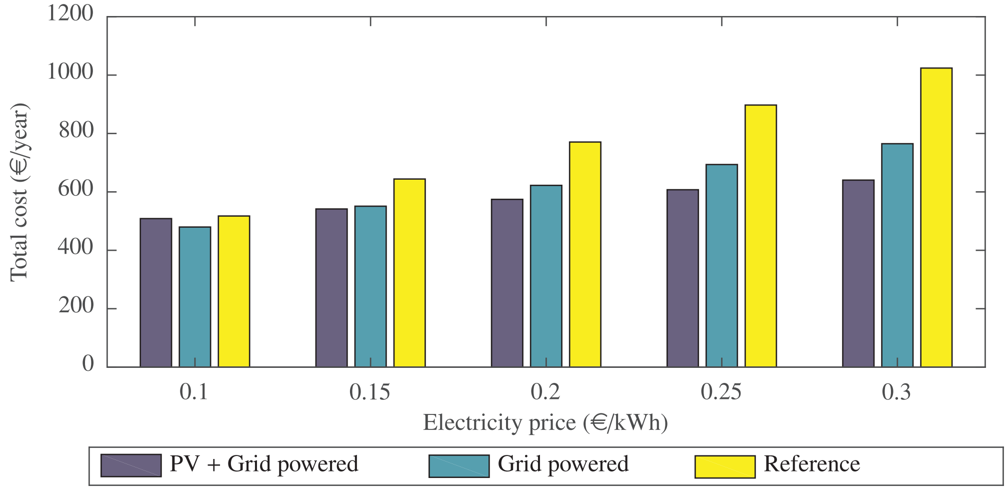


Fig. 13. Influence of the electricity price on the total cost.

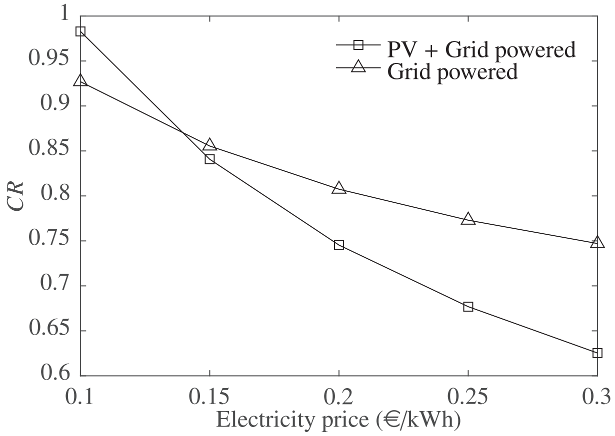


Fig. 14. Cost ratio of the systems as a function of electricity price.

5. Techno-economic analysis

Once the energy savings of both systems have been detailed in the previous section, the cost of the improvements is quantified. Consequently, the systems under study are the same as in the previous section.

The economic analysis takes into account the annual costs for investment, maintenance, residual value, replacement and energy cost during the system lifetime. The annualized costs for the entire system are calculated by means of the annuity method. For each component the estimated lifetime, costs for investment and maintenance are calculated from real prices provided by three companies that work at local level (see Table 5). The maintenance cost for the PV panels has been quantified as 30 €/year, while 60 €/year is considered for the air conditioning unit, both for the reference model and the more efficient one used by the system. The period under consideration is 25 years, which is also the lifetime of the PV panels, while the air conditioning unit is considered to last for 18 years only. An inflation rate of 3% and a market discount rate of 3% have been also considered. Besides, the unit is paid with a 5 years credit with an interest rate of 5%. The energy cost of electricity is 0.15 €/kWh and the power cost 90 €/kW.

Fig. 11 shows the contribution of different concepts to the global cost of a system during its lifetime. For the reference system (less efficient), the highest cost is for the electricity (72.6%), while the investment is 14.9% because the unit is cheaper. An efficient heat pump would require higher investment, which increases investment cost to 27.9% and replacement and residual cost to 6.9% of the total, while the electricity cost is reduced to 54.7% due to lower consumption. If an investment is made to purchase the PV panels, the electricity consumption decreases, but the investment cost and replacement and residual cost raise to 42.2% and 7.3% respectively. The total cost and individual cost contributions for the three systems are depicted in Fig. 12. As can be observed, the total annual cost for the two systems under study is quite similar, the cost of the reference system being about 17–18% higher than them.

Even if there were no economic savings, the investment in the efficient heat pump and the PV panels would be interesting due to the reductions in primary non–renewable energy consumption and CO_2 emissions. Then, the economic savings reinforce this conclusion.

However, the result of the former analysis depends strongly on the electricity price. To overcome this inconvenience, the same study has been carried out for electricity prices ranging from 0.10 €/kWh to 0.3 €/kWh. Fig. 13 shows the total cost of the three systems under consideration versus the electricity cost. Obviously, interest in the reference system increases for low electricity prices, as its higher energy consumption would be cheaper. This can be better observed if the cost ratio, *CR*, is used. It is calculated by comparing the total annualized cost of the system and that of the reference system for the same space heating and cooling energy provided to the room:

$$CR = C_{AN}/C_{AN,ref} \tag{9}$$

As can be observed in Fig. 14, almost no savings are achieved for the lowest energy price by the PV powered efficient heat pump in comparison with the reference. However, for 0.15 €/kWh$_e$, the annual cost of the system is only 84% of the reference system cost, being the more interesting, the higher the energy price.

By comparing the cost ratio for the efficient heat pump with and without the PV panels, their influence is evaluated. As shown in the figure, from the economic point of view, for low energy prices (below 0.15 €/kWh$_e$) the cost of the PV panels becomes slightly higher than the economic savings they produce. Nonetheless, as stated before, the environmental benefits are significant enough to justify this investment for all the prices in the range considered.

6. Conclusions

The work presents an air conditioning solution, consisting of an inverter heat pump powered by PV panels and the electrical grid. The system has been used to meet the thermal demand of an office during one year in a European city in the Mediterranean basin (Alicante, Spain).

Experimental measurements have been carried out during one year. Out of this data, the following working parameters have been quantified for such a period: solar irradiation, PV panels electricity production, PV panels maximum production, electricity consumption of the air conditioning unit from the grid and its thermal production. The results have been summarized as key performance indicators.

The PV panels directly connected to the AC unit have been found to produce 70% of its potential electricity production in comparison to the same model of PV panels connected to the grid. However, this solution does not increase the complexity of the building connection to the grid and avoids potential conflicts with local regulation, by not supplying electricity to it.

The combined use of an efficient inverter heat pump with photovoltaic panels result in a significant reduction of the grid consumption during one year. The seasonal performance factor obtained for the system indicates that for each electrical energy unit consumed from the grid, 9.6 thermal energy units are produced within the office. The solar contribution of the PV panels to the electricity consumption of the AC unit has been quantified as 53.8%.

Environmental and techno-economic studies have been carried out in order to quantify the environmental benefits and to evaluate the feasibility of the system. It has been found to reduce 74% of the primary non–renewable energy consumption and CO_2 emissions in comparison with the reference system. Furthermore its annual cost is 84% of the reference system cost, due to the reduction in electricity consumption.

Moreover, the system provides a simple, feasible, safe and reliable solution based on renewable energy to drastically reduce CO_2 emissions and allow decarbonization within buildings, which is in agreement with the European and international roadmaps to stop the increase in the average Earth temperature.

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