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Environmental benefits and economic feasibility of a photovoltaic assisted heat pump water heater

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ABSTRACT

This work presents a techno-economic study which evaluates the environmental benefits and the economic feasibility of a photovoltaic assisted compact heat pump water heater. The system heats water for domestic consumption in a 190 litres tank. The heat pump is simultaneously powered by the grid and PV panels, although the system was designed to prioritize the PV energy supply. The system does not use batteries and does not feed electricity to the grid.

Based on experimental measurements during one year, the study analyses the efficiency of the system for a 4 family members domestic hot water (DHW) consumption. The experimental data shows that the system is friendly to the grid, showing low peak loads and not feeding to the grid.

A techno-economic analysis which considers the lifetime cost of the system as well as its environmental benefits has been carried out. The techno-economic analysis shows the benefits of this system when it is compared to: a DHW heat pump without PV, an electrical heater, a boiler and a boiler + solar thermal collectors. The total annualized cost of the system, for a period of 25 years and an electricity price of 0.2 €/kWh, has been quantified at 337 €/year. Furthermore, the system has been found to reduce the non-renewable primary energy consumption by 79% and the CO_2 emissions by 82% in comparison with a boiler.

Finally, experimental correlations of the system performance are proposed, so that the results of this work can be extended to other locations with similar climates.

1. Introduction

The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C.

The EU efforts in relation to progress towards the goal set in the Paris Agreement are clearly established for the building sector in recently approved Directives (2018/2001/EU; 2018/844/EU). The pathway towards the objective of decarbonized buildings by the year 2050 is established in the 2018/844/EU. It implies that current fossil fuel equipment (boilers) for DHW production will be replaced by environmental friendly solutions, probably involving heat pumps. In addition, the EU has set a binding target to reduce emissions by at least 40% below 1990 levels by 2030.

The promotion of the use of energy from renewable sources like heat pumps, geothermal, solar photovoltaic and solar thermal systems will be one of the key ways to achieve these challenges (2018/2001/EU). Last but not least, Directive 2018/2001/EU states that Member States should try to minimize the overall cost of decarbonized systems.

In this framework, the application of efficient heat pumps with the possible support of solar thermal or photovoltaic energy is presented as a solution to be considered in future nearly zero energy buildings. In residential buildings, from the design point of view, the DHW demand cannot be reduced and the hot water can be accumulated (water tanks). Therefore, solar-assisted compression heat pumps SACHP for the production of domestic hot water are very suitable systems to operate depending on the availability of solar thermal or photovoltaic energy.

Much research on SACHP water heaters has been carried out during the last 20 years. Most of it is focused on solar thermal energy use in the evaporator of the compression heat pumps. Two types are considered: direct expansion solar heat pumps (DX-SAHP) when refrigerant flows through the solar collector or indirect expansion solar heat pumps (IDX-SAHP) when there is a heat exchanger between the refrigerant and the fluid that flows through the solar collector. Many of these works are presented in Wang et al. (2017) and Mohanraj et al. (2018) reviews, where it is found that air heat pumps in the application of domestic hot water at present have typical SPF (seasonal COP) between 2.5 and 3.5

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Nomenclature

E_{HP}	electricity consumption by the heat pump
E_{PV}	photovoltaic production
$E_{PV,HP}$	part of the photovoltaic production which is consumed by the heat pump
$E_{PV,RES}$	part of the photovoltaic production which is consumed by the resistance inside the DHW tank to directly heat the DHW
E_{GD}	electricity consumption from the grid (by the heat pump)
$\bar{\eta}$	average seasonal efficiency
FSAV	fraction savings.
I	solar irradiation
P	power
nRPE	non-renewable primary energy
PEF	primary energy factor
PER_{nRE}	primary energy ratio defined as the nRPE consumed by a system over the nRPE consumed by the reference system
Q_{TOT}	total thermal energy provided by the system to the water inside the tank
Q_{DHW}	useful thermal energy for domestic hot water production
Q_L	water tank thermal losses
Q_{HP}	thermal energy produced by the heat pump
Q_{RES}	thermal energy produced by Joule effect at the electrical resistance
SC	solar contribution
SPF	seasonal performance factor. It is the efficiency of a device or system, calculated as the ratio of the heat provided by the device/system and its total electric energy consumption over a period of time

Subindices

boiler	*boiler* system
CO_2	refers to CO_2 emissions
EL	electricity
GD	electrical grid
HP	heat pump
HP + PV	heat pump powered by photovoltaic panels and the grid
NG	Natural Gas
nRPE	non-renewable primary energy
PV	photovoltaic panels
RES	resistance
ref	reference system
TH	thermal energy

when water preparation temperature is below 50 °C, and this performance can be improved to 6–9 by adding a solar contribution to the system.

In recent years, photovoltaic solar energy has also been considered in the behavior of SAHP. The recently published review of Mohanraj et al. (2018) includes a section about Solar photovoltaic assisted heat pump water heaters. Some works like Chow et al. (2010) and Fang et al. (2010) are focused on DX-SACHP with PVT evaporators that improve at the same time the COP of the heat pump and the efficiency of the PV panels. Anyway, in a real application it should be considered that when the SACHP is stopped, PVT efficiency is usually lower than standard PV. In these works, photovoltaic electricity is exported and not considered to be a part of the system.

Indirect expansion solar heat pumps IDX-SACHP with PVT have also been studied. Wang et al. (2015) investigated the efficiency of an IDX-SACHP with a PVT of water recirculation. The installation accumulates the water heated by the PVT, being able to combine better with the heat pump through a water/coolant exchanger. To overcome the difficulties remaining in the existing PVT technologies, Zhang et al. (2013) and Li and Sun (2018) propose to use heat pipes as part of the PVT panels. They obtained an overall coefficient of system performance much higher than traditional heat pump systems and the photovoltaic efficiency was also improved.

A different approach to the efficiency of the system should be carried out when photovoltaic energy cannot be exported or when the benefits of this excess electricity are not obtained. The last revision of the European EPBD directive established a new *Smart Readiness Indicator* as a parameter to measure the capacity of buildings to adapt their operation to the needs of the occupants and the grid and to improve the energy efficiency and overall performance of buildings. In this research line, Kato and Suzuoki (2014) carried out simulations to demonstrate that it is possible to use heat pump water heaters (HPWH) in homes to improve the operation of the electricity network in residential areas with many photovoltaic installations. Their proposal was an autonomous scheduling of HPWH so that the aggregated electricity consumption by a number of HPWHs follows the daily change in power supply of the photovoltaic system. Their study focused on the electrical analysis of the system, making an energy balance, but without considering the possible requirements of the DHW demand (possible problems of low temperature and discomfort). Sichilalu and Xia (2015) developed a scheduling model for heat pump water heater (HPWH) in order to optimize the energy control of a grid-tied photovoltaic. They asses that the collective effort required to turn a new or existing building into a NZEB involves proper selection of an appropriate technology, application of optimal control in energy demand. Poulet and Outbib (2015) analysed hybrid systems using renewable energy sources without any connection to an electrical network. After their experience, they came to the conclusion that the optimal design consisted of photovoltaic panels + air/water heat pumps with improved control which includes strategies based on the weather forecast.

Thygesen and Karlsson (2014) studied the performance of PV solar assisted heat pump water heaters with two different storage systems: a battery and a hot water tank. They concluded that thermal storage and eventually a PV controlled heat pump is the most cost effective system, since the objective should be to reduce the purchase of electricity.

The approach of the authors (Aguilar et al., 2016) focused on improving the performance of a photovoltaic assisted heat pump for domestic water heating applications. The photovoltaic panels are connected directly to the unit and the photovoltaic electricity is only consumed in the system: either in the compressor or in the electric heater. The heat pump analysed is an ON/OFF unit with a nominal heating capacity of 1.5 kW and a nominal electrical consumption of 470 W (nominal COP = 3.19). The system has a thermal storage of 190 litres and no batteries.

Mohanraj et al. (2018) pointed out that in solar assisted compression heat pumps (SACHP), further research is needed on some specific topics like *Techno economical feasibility evaluation of SACHP systems for different applications*.

Poppi et al. (2018) reviewed techno-economic studies of hybrid renewable energy systems that combine ST (solar thermal) and/or PV with heat pumps for residential heating applications (space heating and DHW production). In their study, the payback was shown to be dependent on solar irradiance and heating degree-days. Moreover, they pointed out that the inclusion of PV into heat pump systems further complicates the analysis in order to clearly define where the system boundary must be for a transparent energetic and economic assessment of solar assisted heat pumps. In fact, they proposed the building boundary level to better understand energetic and economic potential of PV heat pump systems (the surplus PV energy was not considered).

Payback of PV and heat pump systems can vary significantly according to metering policies in place (Thygesen and Karlsson, 2013). They analyzed 3 solar assisted ground source heat pump systems and concluded that the conjunction with a PV-system is the most effective system with regards to energy and economics.

Li and Sun (2018) found that compared with a traditional heat pump water heater, although extra $368.2 should be paid for the initial cost of the PVT system, about 29.6% of life cycle cost could be saved.

In this context, this work presents a detailed technical and economic study of the system that was experimentally measured by the authors in Aguilar et al. (2016). Correlations of the system performance are provided so that the results can be extended to other locations. The boundary for the energetic and economic assessment is considered to be the system itself, since all the PV energy is consumed in the water heater. An economic analysis which considers the lifetime cost of the system has been carried out. The proposed system is compared to other 5 widely spread water heater systems in terms of primary energy consumption and economic savings. In addition, the interaction of the system with the network, its peak loads and its adjustment with the photovoltaic production have also been analysed.

2. Experimental setup

The system under study ($HP + PV$), depicted in Fig. 1, consists of a compact heat pump connected simultaneously to two PV panels of 235 Wp each (see Table 1) and to the electrical grid. An MPPT micro-inverter connected to the PV panels converts direct current (24–30 VDC) to alternating (230 VAC).

The coupling between the heat pump, the photovoltaic panels and the electrical network is carried out by means of a network current inhibitor. This device prioritizes the PV energy supply over the one from the grid, in order to maximize the use of solar energy. Consequently, if PV production is sufficient to power the heat pump, no grid electricity is consumed. Electricity consumption from the grid is only required when the PV panels' production is not enough to completely feed the heat pump. In this case, the grid will provide the difference between the panels' production and the heat pump consumption. When the heat pump is OFF and the PV panels produce electricity, this energy is consumed by an electrical resistance inside the water tank. In any case, the total energy produced by the PV panels is used by the system for DHW production (by the heat pump or by the electrical resistance). The objective of this configuration is to minimize electricity consumption from the grid.

Fig. 1 also shows the energy flows (thermal and electrical) within the HP + PV system. From them, the equations describing the system may be defined. Eq. (1) describes that the electricity produced by the PV panels can be used to power the heat pump and/or to feed the electrical resistance inside the water tank.

Table 1
Technical data of the compact heat pump and the photovoltaic panels.

(a) Compact heat pump model: MIDEA Compak KHP 15 190.

Parameter	Value	Units
Heating capacity	1500	W
Compressor electrical power	470	W
Coefficient of performance*	3.19	–
Electrical heater power	2000	W
Refrigerant	R134a	–
Evaporator fan power	30	W
Tank volume	190	L

(b) Technical data of the photovoltaic panels.

Parameter	Value	Units
Nominal power	235	Wp
Efficiency	13.74	%

* Manufacturer test conditions: Input/output water of 15 °C/55 °C. Outside wet/dry bulb of 15 °C/20 °C.

$$E_{PV} = E_{PV,HP} + E_{PV,RES} \quad (1)$$

Besides, the heat pump can be powered with electricity from the PV panels and/or from the grid.

$$E_{HP} = E_{PV,HP} + E_{GD} \quad (2)$$

The thermal energy Q_{TOT} is provided to the water by the heat pump Q_{HP} and the electrical resistance Q_{RES}, and it is used for DHW production Q_{DHW} and to compensate por energy losses Q_L.

$$Q_{TOT} = Q_{HP} + Q_{RES} \quad (3)$$

$$Q_{TOT} = Q_{DHW} + Q_L \quad (4)$$

Furthermore, the following indicators, which evaluate the performance of the system, have been defined. On the one hand, the seasonal performance factor of the heat pump is defined as the coefficient between the thermal energy provided by the heat pump and its electrical consumption in real working conditions throughout a year.

$$SPF_{HP} = \frac{Q_{HP}}{E_{HP}} \quad (5)$$

On the other hand, the solar contribution has been defined as the ratio between the heat produced by the heat pump or the electrical resistance using electricity from the PV panels and the total heat produced.

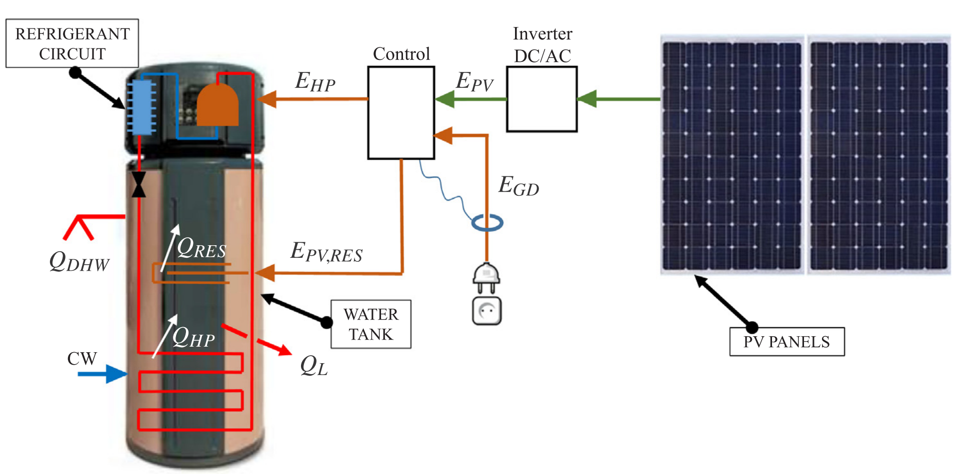


Fig. 1. Sketch of photovoltaic assisted heat pump for domestic hot water production ($HP + PV$ system).

$$SC = \frac{Q_{PV}}{Q_{TOT}} = \frac{Q_{RES} + Q_{HP}(E_{PV,HP}/E_{HP})}{Q_{RES} + Q_{HP}} \tag{6}$$

A deeper analysis of the HP + PV system in relation with the aforementioned performance indicators was presented in a previous work by the authors (Aguilar et al., 2016).

The use of energy of the system can be better observed in Fig. 2, where one day results are shown. The light grey area corresponds to energy produced by the PV panels which is consumed by the heat pump $E_{PV,HP}$. The area in dark grey belongs to energy from the electrical grid which is consumed by the heat pump E_{GD}. Lastly, middle grey has been used to color the energy produced by the PV panels which is consumed by the electrical resistance inside the DHW tank $E_{PV,RES}$, directly used to heat water ($Q_{RES} = E_{PV,RES}$).

2.1. Experimental facility

In order to test the described system during one year, an experimental facility was built on the roof of the university research laboratory, located in Elche (Southeast of Spain).

Fig. 3 shows the facility, where subsystems A (heat pump and DHW tank) and B (power sources) have already been described. In subsystem B, the solar panels are facing South with an inclination of 45°. In order to emulate domestic hot water consumption without wasting water, subsystem C has been used. It has an auxiliary tank which receives hot water at 55–60 °C from the heat pump and a water chiller which cools it down to 12–15 °C.

Besides, several probes and measuring instruments have been installed along the facility in order to measure: meteorological data, refrigerant cycle temperatures and pressures, water flowrate and power consumption (from the grid and from the PV panels). All the instruments and probes are connected to an HP 34970A data acquisition unit, which makes recordings every minute.

The facility has been used to emulate the consumption of a 4 member family. For this number of people, a daily consumption of 132 litres at 55 °C has been estimated in agreement with the Spanish regulation (CTE DB-HE4) and the standard UNE-EN 16147. In an effort to imitate the consumption in a real dwelling, where hot water is consumed throughout the morning, the afternoon and the evening, 6 water tappings of 22 litres each have been programmed every day. Each one has been carried out at 4 L/min with a duration of 5.5 min at the following local times 7:30, 8:15, 10:00, 13:45, 21:00, 22:00.

The heat pump has been configured to start operation at 10:00 a.m. (solar time) and stop when the DHW preparation temperature of 55 °C has been reached.

Electrical measurements uncertainties on voltage and current are lower that 1% for 95% of confidence level. They yield to a power measurement uncertainty of less than 1.5% and an uncertainty lower than 2% in the calculated solar contribution, *SC*, (JCGM 100:2008).

Further details of the experimental setup have been provided in a previous work (Aguilar et al., 2016).

3. Results

As has been mentioned before, the aim of this work is to verify and highlight the benefits of the system under study for domestic hot water (DHW) production. Such benefits can be summarised as:

1. The use of electricity as a better energy source than the direct use of fossil fuels (decarbonization).
2. The reduced impact of the system on the electrical grid (grid friendly system).
3. The reduction in primary energy consumption as well as CO_2 emissions.
4. The reduced annualized cost of the system.

The following subsections analyse each of the former points. Additionally, the tools to extend the results of this section to different regions around the world with Mediterranean climate conditions have been included in Section 3.5.

3.1. Decarbonization

The first argument has been pointed out by the European Union as an effective way of reducing CO_2 emissions, together with a higher percentage of renewable energy production in the grid. In fact, the European Union has set the goal of full decarbonization of buildings before 2050. It can be stated that heat pumps for domestic hot water production will play a key role in achieving this.

The consumption of hot water in homes can be increased by adding the water consumption of household appliances: washing machine and dishwasher.

In future nZEB homes, where heating and cooling demand will be reduced, the optimization of the DHW production system will be very important to reach the goal of decarbonisation. The design of the heat pumps must be carried out in such a way that they should work taking into account the available renewable energy: usually photovoltaic solar energy. The heat pump can operate in sunny hours and store the thermal energy in the tank: hence the importance of the design and dimensioning of the system.

In this sense, this study shows the results of a year of operation of a compact heat pump of 1.5 kW (thermal) with a tank of 190 liters, operating for a typical DHW consumption of a family of 4 members. The system only consumed 317.6 kWh of electricity from the grid in one year (cost of about 50 €/year).

3.2. Impact of the system on the grid

In order to evaluate the impact of the system on the grid, Fig. 4 has been plotted. It shows the heat pump electricity consumption, the PV panels' production and how much electricity is consumed from the grid. This data is plotted throughout one week for three different periods of the year: January, April and June.

As can be observed, the starting time of the heat pump (10:00 a.m., solar time) has been selected in order to maximize the use of PV electricity. The results also show that the electricity consumption peak could reach a maximum of about 600 W, on the rare occasions when there is no PV production at all. Furthermore, if there is good photovoltaic generation, the maximum grid electricity consumption is about 300 W. In any case, consumption peaks are very low by using this system, which is a significant advantage in comparison for example with an electric heater. Moreover, the photovoltaic electricity surplus does not feed the grid but a resistance inside the DHW tank (Fig. 2), and thus unplanned and potentially problematic electricity supply from the

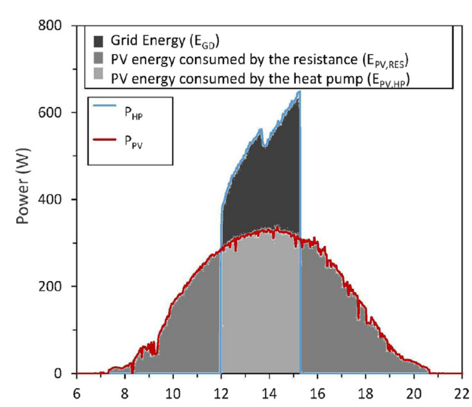


Fig. 2. Energy flows within the experimental setup during one day of operation.

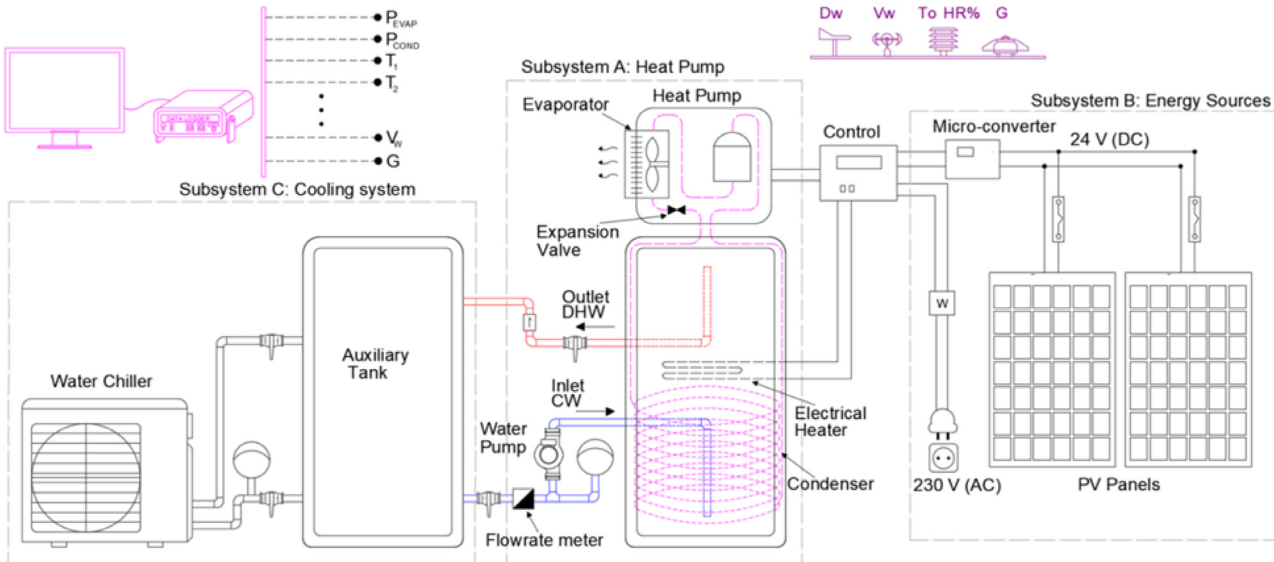


Fig. 3. Experimental facility.

PV panels to the grid is avoided.

3.3. Environmental analysis

In this section, primary energy consumption and CO_2 emissions of the system under study will be evaluated. To that aim, its performance will be compared to five alternatives which are commonly used for DHW production. Thus, the comparison considers a total of six systems:

- *HP + PV*. This is the system under analysis which has been described in Section 2. It consists of a 1.5 kW_{TH} compact heat pump which heats water within its 190 litre water tank (Table 1(a)). The

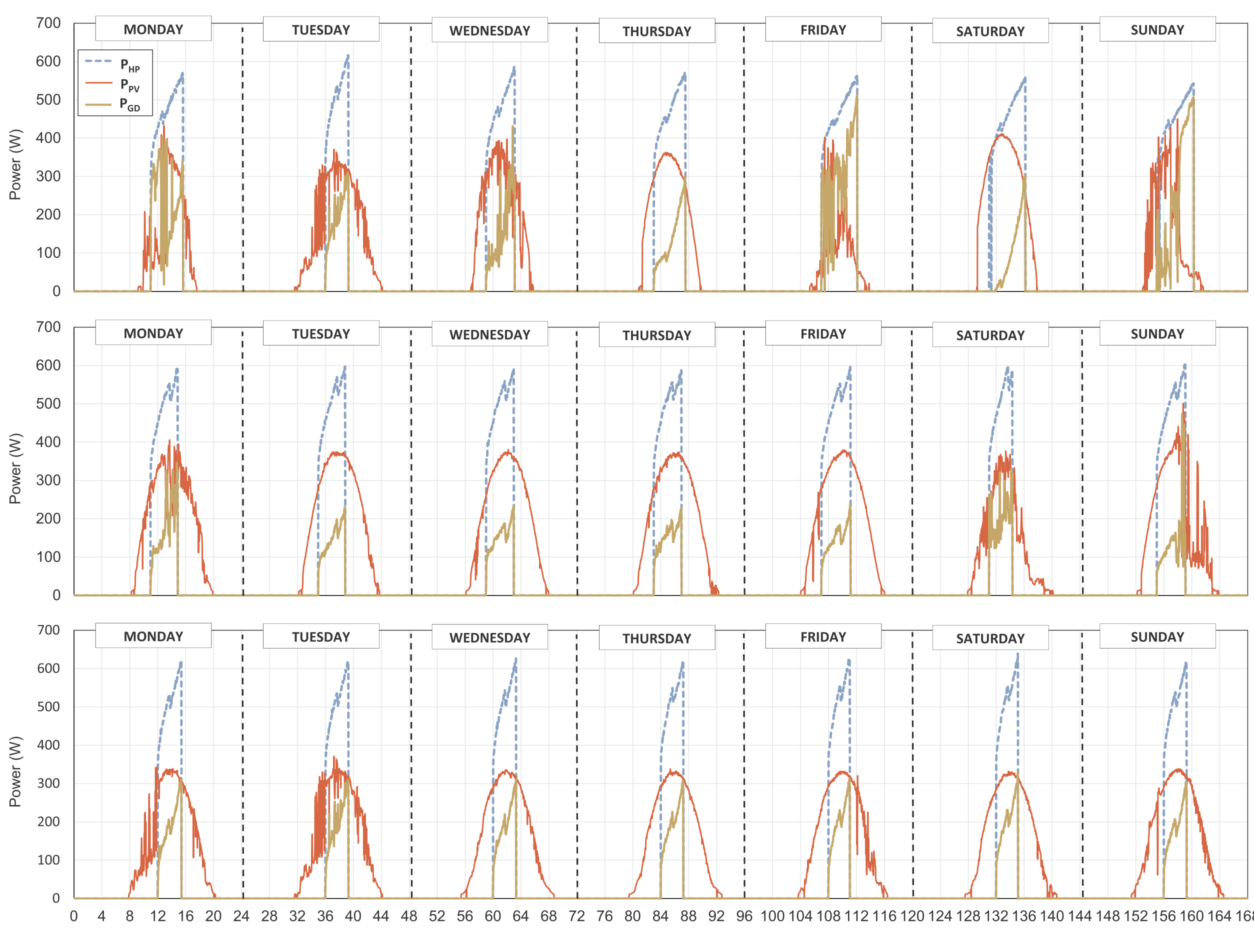


Fig. 4. Electricity production and consumption during one week of January (top), April (middle) and June (bottom).

heat pump is powered by two 235 Wp photovoltaic panels (Table 1(b)) and the grid. Besides, if the heat pump is OFF, the PV production is used to power an electric resistance within the tank.

- *HP*. It consists of the same heat pump which is powered only by the grid (the electric heater is not used).
- *Boiler*. A natural gas boiler with a seasonal efficiency of 92%. This system will be considered the reference one for comparison purposes.
- *Boiler + ST*. A natural gas boiler with a seasonal efficiency of 92% and solar thermal panels with a solar contribution of 60% of the thermal demand.
- *Heater*. An 80 litre water tank with a 1.5 kW electric resistance.
- *Heater + PV*. An 80 litre water tank with a 1.5 kW electric resistance powered by 4 PV panels (a total of 940 Wp).

Sketches of the three systems under comparison, which use solar energy, are depicted in Fig. 5.

The *HP + PV* system has been experimentally studied during one year. The DHW demand results in an energy demand of 2247.6 kWh_{TH} throughout the year according to the measurements. Besides, the 190 litre water tank losses have been experimentally estimated at 596.7 kWh_{TH}, resulting in a total thermal demand of 2844.3 kWh_{TH}. In order to cover such a demand, the *HP + PV* system has been found to consume 317.6 kWh of electricity from the grid, while the rest (514.1 kWh) has been provided by the PV panels.

The *SPF* of the *HP + PV* system is defined as the fraction between its thermal heat production over its electricity consumption from the grid in real working conditions throughout a year:

$$SPF_{HP+PV} = \frac{Q_{TOT}}{E_{GD}} \tag{7}$$

The total thermal, electrical and/or natural gas demand of the other systems have been estimated from the data obtained for the *HP + PV* system. The results are summarized in Table 2.

The *HP* system would have the same total thermal demand as the *HP + PV* one. Its seasonal performance factor is considered to be $SPF_{HP} = 3.42$ (obtained from the experimental measurements), resulting in an electricity consumption from the grid of 831.7 kWh.

In the case of the *Boiler*, as there are no water tank losses, the total demand (2247.6 kWh_{TH}) is lower than in the previous cases. The seasonal efficiency of the boiler (*Boiler* has been estimated at 92% and its electrical consumption at 2% of the total demand. Consequently, the natural gas consumption results in 2443 kWh.

For the *Boiler + ST* system, the same considerations as in previous system have been made regarding: the total demand, the boiler efficiency and its electrical consumption. The solar thermal facility has been calculated by using the f-chart method to cover 60% of the total demand, resulting in a system with a 120 litres water tank and a 2.2 m^2 thermal solar panel. Besides, a 30 W circulation pump has been estimated to work 5 h a day. The results show a natural gas consumption of 977.2 kWh and an electricity consumption of 72.7 kWh.

In the case of the electrical heater (*Heater* system), the water tank losses have been calculated by means of the AISLAM software (IDAE, 2007), resulting in a 60% of the ones of the *HP + PV* system, due to its smaller size. The result is a total demand of 2605.6 kWh_{TH} which requires the same amount of electricity (100% efficiency).

If the *Heater + PV* system is considered, the water tank losses would be the same as with the *Heater* system. Although the electricity consumption of the heater is the same in both cases (2605.6 kWh), only 1038.6 kWh is consumed from the grid, as the difference is provided by the PV panels. The contribution of each PV panel has been obtained from the experimental measurements of electricity production per panel within the *HP + PV* system.

From the final energy consumption, the non-renewable primary energy consumption and CO_2 emissions have been obtained by applying the conversion factors in Table 3. In order to obtain the non-renewable primary energy consumption and CO_2 emissions by square metre, a surface of 90 m^2 has been estimated for a 4 member family dwelling.

If the *Boiler* system is taken as the reference system, the following ratios may be defined. On the one hand, the *savings fraction* of non-renewable primary energy, indicates the percentage of non-renewable primary energy consumption which is saved by the system under consideration.

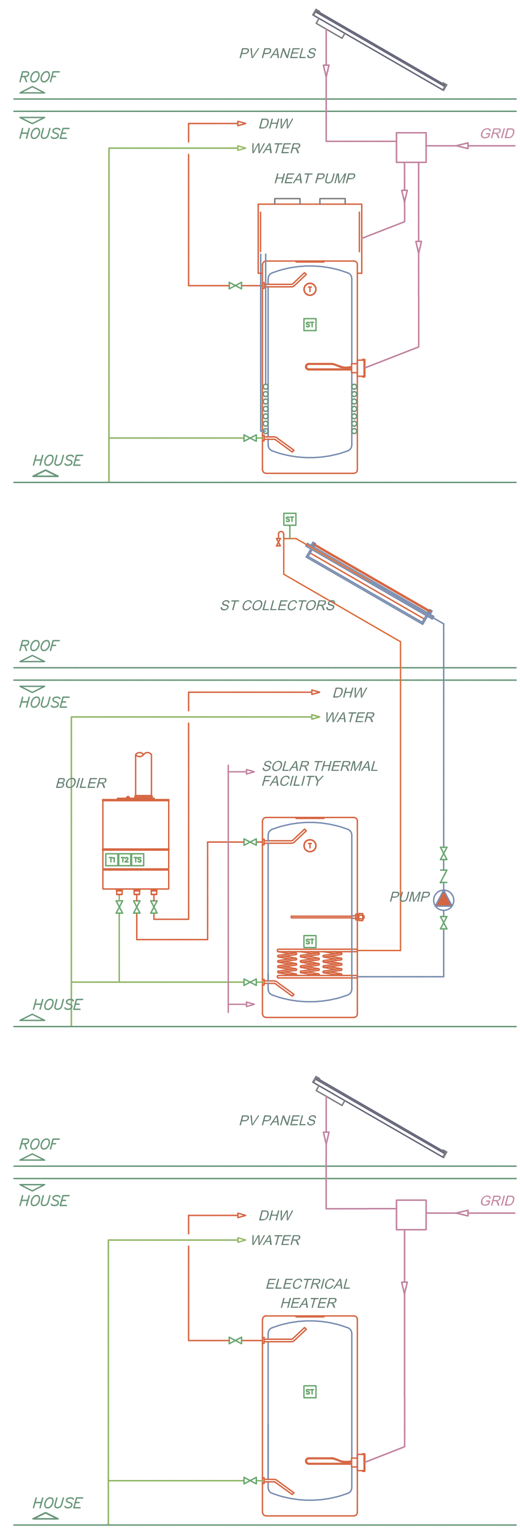


Fig. 5. Sketch of the facilities of the comparison which use solar energy. Top: *HP + PV*. Middle: *Boiler + ST*. Bottom: *Heater + PV*.

Table 2
Annual energy consumption and CO_2 emissions for the systems under consideration.

	Units	HP + PV	HP	BOILER	BOILER + ST	HEATER	HEATER + PV
DHW demand	kWht	2,247.6	2,247.6	2,247.	2,247.6	2,247.6	2,247.6
Water tank heat loss	kWht	596.7	596.7	0.0	0.0	358.0	358.0
Total demand	kWht	2,844.3	2,844.3	2,247.6	2,247.6	2,605.6	2,605.6
Grid electricity consumption	kWh	317.6	831.7	45.0	72.7	2,605.6	1,038.6
Natural Gas consumption	kWh	0.0	0.0	2,443.0	977.2	0.0	0.0
Non-renewable primary energy	kWh	635.2	1,663.3	3,021.6	1,318.1	5,211.2	2,077.2
Non-renewable primary energy (*)	kWh/m^2	7.1	18.5	33.6	14.6	57.9	23.1
FSAV nRPE	–	79.0%	45.0%	0.0%	56.4%	−72.5%	31.3%
Ratio nRPE	–	4.76	1.82	1.00	2.29	0.58	1.45
CO_2 emissions	kg CO_2	113.4	296.9	631.7	272.2	930.2	370.8
CO_2 emissions (*)	kg CO_2/m^2	1.3	3.3	7.0	3.0	10.3	4.1
FSAV CO_2 emissions	–	82.1%	53.0%	0%	56.9%	−47.3%	41.3%
Ratio CO_2 emissions	–	5.57	2.13	1.00	2.32	0.68	1.70

* For a dwelling surface of 90 m^2.

Table 3
System efficiencies and energy conversion factors for Spain (IDAE, 2016).

	Value	Units
SPF_{HP+PV}	8.96	
SPF_{HP}	3.42	
$\bar{\eta}_{Boiler}$	0.92	
PEF_{EL}	2.0	kWh$_{nRPE}$/kWh
PEF_{NG}	1.2	kWh$_{nRPE}$/kWh
Electricity emissions	0.357	gCO_2/kWh
Natural Gas emissions	0.252	gCO_2/kWh

$$FSAV_{nRPE}(\%) = \frac{nRPE_{ref} - nRPE_{sys}}{nRPE_{ref}} \tag{8}$$

On the other hand, the Primary Energy Ratio (PER_{nRE}) indicates the relation between the non-renewable primary energy employed by the reference and by the analysed system for the same energy demand.

$$PER_{nRE} = \frac{nRPE_{ref}}{nRPE_{sys}} \tag{9}$$

Equivalently, similar savings factor and ratio can be defined for CO_2 emissions between the system under consideration (*sys*) and the reference system (*ref*).

$$FSAV_{CO_2}(\%) = \frac{CO_{2,ref} - CO_{2,sys}}{CO_{2,ref}} \tag{10}$$

$$PER_{CO_2} = \frac{CO_{2,ref}}{CO_{2,sys}} \tag{11}$$

As can be observed in Table 2, the lowest CO_2 emissions and non-renewable primary energy consumption correspond to the *HP + PV* system. With this system, the annual primary energy savings in comparison with the reference is $FSAV_{nRPE} = 79\%$, which means it is 4.76 times more efficient in the use of primary energy than the reference system. Furthermore, the annual CO_2 emissions savings factor is even higher, $FSAV_{CO_2} = 82.1\%$, being 5.57 times more efficient than the reference system regarding emissions.

The heater presents the worst annual performance of all the systems, consuming more primary energy ($FSAV_{nRPE} = -72.5\%$) and emitting more carbon dioxide ($FSAV_{CO_2} = -47.3\%$) than the reference, which is the second worst system in both parameters. The rest of the systems perform better than the reference, being the boiler with solar thermal panels the best option among them ($FSAV_{nRPE} = 56.4\%$ $FSAV_{CO_2} = 56.9\%$).

Quite significant for a system is the non-renewable primary energy consumption per dwelling surface area (Fig. 6). This value is usually limited within the E.U. countries, so that high primary energy consumptions are not allowed. The sum of non-renewable primary energy consumption for the services of air conditioning, heating and DHW is typically limited to values up to 15 to 40 kWh$_{nRPE}$/m^2 (E.U.Recomendation of 29 July 2016). This means that using an electric heater (57.9 kWh$_{nRPE}$/m^2) or a boiler (33.6 kWh$_{nRPE}$/m^2) for DHW production is not an option. In this way, the real consumption of a heater with PV panels (23.1 kWh$_{nRPE}$/m^2), a heat pump (18.5 kWh$_{nRPE}$/m^2) or a boiler with solar thermal panels (14.6 kWh$_{nRPE}$/m^2) may be valid options depending on the applicable limitation, being the boiler with solar thermal panels the solution with the lowest primary energy consumption among them. Once again, the system under study (*HP + PV*) beats the other systems of the comparison by far, consuming only 7.1 kWh$_{nRPE}$/m^2.

3.4. Economic analysis

This study is aimed at analysing the economic viability of the heat pump water heater powered by photovoltaic panels and the grid (HP + PV) in comparison with conventional DHW systems. The same systems as in the previous section have been chosen for the comparison.

The economic analysis, whose results are shown in Table 4, takes into account the annual costs for investment, maintenance, residual value, replacement and energy cost during the system lifetime. The annualized cost for a system is calculated by means of the annuity method.

The lifetime of each system component is estimated to be: PV panels: 25 years; Inverter and inhibitor: 12.5 years; Solar thermal collectors and tank: 20 years; Heat pump, boiler and electrical heater: 18 years (according to the ranges proposed on Annex D of EN 15459-1:2018). The initial cost and the annual maintenance cost are determined from real prices provided by three companies that use to work at local level. The provided costs were finally discussed and agreed with the three companies to be a good approach to the real prices offered at present in Spain.

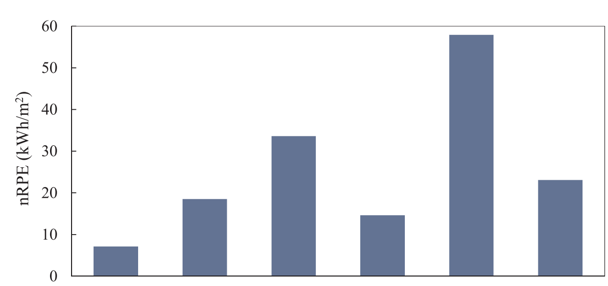


Fig. 6. Annual non-renewable primary energy consumption for a 90 m^2 dwelling.

Table 4
Techno-economic study results for a 25 year lifetime (Energy cost 0.15 €/kWh).

	HP + PV	HP	BOILER	BOILER + ST	HEATER	HEATER + PV
INVESTMENT	€	€	€	€	€	€
PV panels	400.0	0.0	0.0	0.0	0.0	800.0
Inverter + Inhibitor	300.0	0.0	0.0	0.0	0.0	600.0
Solar thermal collectors	0.0	0.0	0.0	1,300.0	0.0	0.0
Heat Pump	1,200.0	1,200.0	0.0	0.0	0.0	0.0
Boiler	0.0	0.0	1,200.0	1,200.0	0.0	0.0
Electric heater	0.0	0.0	0.0	0.0	500.0	500.0
TOTAL INVESTMENT MATERIAL	**1,900.0**	**1,200.0**	**1,200.0**	**2,500.0**	**500.0**	**1,900.0**
Design, planning and commissioning	200.0	200.0	60.0	120.0	50.0	200.0
General costs associated to works	380.0	240.0	240.0	500.0	100.0	380.0
Indirect costs and industrial benefits	95.0	60.0	60.0	125.0	25.0	95.0
TOTAL INVESTMENT COST	**2,575.0**	**1,700.0**	**1,560.0**	**3,245.0**	**675.0**	**2,575.0**
REPLACEMENT COST	€/year	€/year	€/year	€/year	€/year	€/year
PV panels (NL = 25 years)	0.00	0.00	0.00	0.00	0.00	0.00
Inverter + Inhibitor (NL = 12,5 years)	11.65	0.00	0.00	0.00	0.00	23.30
Solar thermal collectors (20 years)	0.00	0.00	0.00	12.62	0.00	0.00
Heat Pump (18 years)	18.12	18.12	0.00	0.00	0.00	0.00
Boiler (18 years)	0.00	0.00	18.12	18.12	0.00	0.00
Electric heater (18 years)	0.00	0.00	0.00	0.00	7.55	7.55
TOTAL REPLACEMENT COST	**29.77**	**18.12**	**18.12**	**30.74**	**7.55**	**30.85**
MAINTENANCE COST	€/year	€/year	€/year	€/year	€/year	€/year
PV panels + Inverter + Inhibitor	30.00	0.00	0.00	0.00	0.00	40.00
Solar thermal collectors	0.00	0.00	0.00	60.00	0.00	0.00
Heat pump	60.00	60.00	0.00	0.00	0.00	0.00
Boiler	0.00	0.00	60.00	60.00	0.00	0.00
Electric heater	0.00	0.00	0.00	0.00	20.00	20.00
TOTAL MAINTENANCE COST	**90.00**	**60.00**	**60.00**	**120.00**	**20.00**	**60.00**
OPERATION-ENERGY	€/year	€/year	€/year	€/year	€/year	€/year
Energy Cost (Electricity or Gas)	63.52	166.33	155.56	73.17	521.12	207.72
Power Cost (Electricity or Gas)	40.00	40.00	60.00	60.00	80.00	80.00
TOTAL ENERGY COST	**103.52**	**206.33**	**215.56**	**133.17**	**601.12**	**287.72**
ANNUALIZED COSTS	€/year	€/year	€/year	€/year	€/year	€/year
Investment	118.95	78.53	72.06	149.90	31.18	118.95
Replacement	29.77	18.12	18.12	30.74	7.55	30.85
Maintenance	87.38	58.25	58.25	116.50	19.42	58.25
Energy (Electricity or Gas)	100.50	200.32	209.28	129.29	583.62	279.34
TOTAL ANNUALIZED COST	**336.61**	**355.23**	**357.72**	**426.45**	**641.77**	**487.40**

The maintenance cost for the PV panels has been quantified as 30 €/year for two panels and 40 €/year for four panels. This same cost has been quantified at 60 €/year for the solar thermal collectors. For the heat pump and the boiler, a maintenance cost of 60 €/year is considered, while 20 €/year is used for the electric heater.

The period under consideration for the study is 25 years. An inflation rate of 3% and a market discount rate of 3% have also been considered. Besides, the units are paid with a 5 year credit at an interest rate of 5%. On the one hand, the energy cost of electricity is considered to be 0.20 €/kWh and its power cost 40 €/year for the heat pump

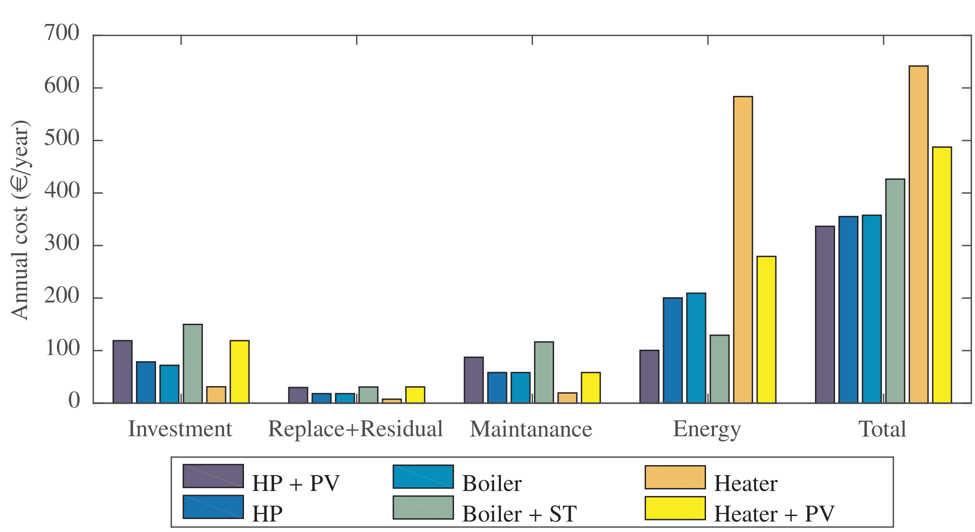


Fig. 7. Individual annual cost contributions and total cost of the systems.

systems (*HP* and *HP* + *PV*) and 80 €/year for the systems with electrical heaters. On the other hand, the energy and power cost of natural gas are 0.06 €/kWh and 60 €/year, respectively, for the systems using boilers. The prices are based on official published data (CNMC, 2019; CNMC, 2018).

If focusing on the investment cost, the results in Table 4 show that the cheapest alternative for DHW production is, by far, the electric heater. Buying a heat pump and two photovoltaic panels for the same use would be almost 4 times more expensive. This may trick consumers into making this choice, however, when all lifetime costs are considered, the electric heater becomes the worst choice and the heat pump with PV panels the best one. The main reason is that the electric heater is much less efficient than a heat pump, leading to higher energy consumption. Furthermore, the difference in price between the natural gas and electricity, results in lower total annualized costs for the solutions with boilers than for those with electric heaters.

Fig. 7 is the comparison of the individual annual cost contributions and the total cost between the systems.

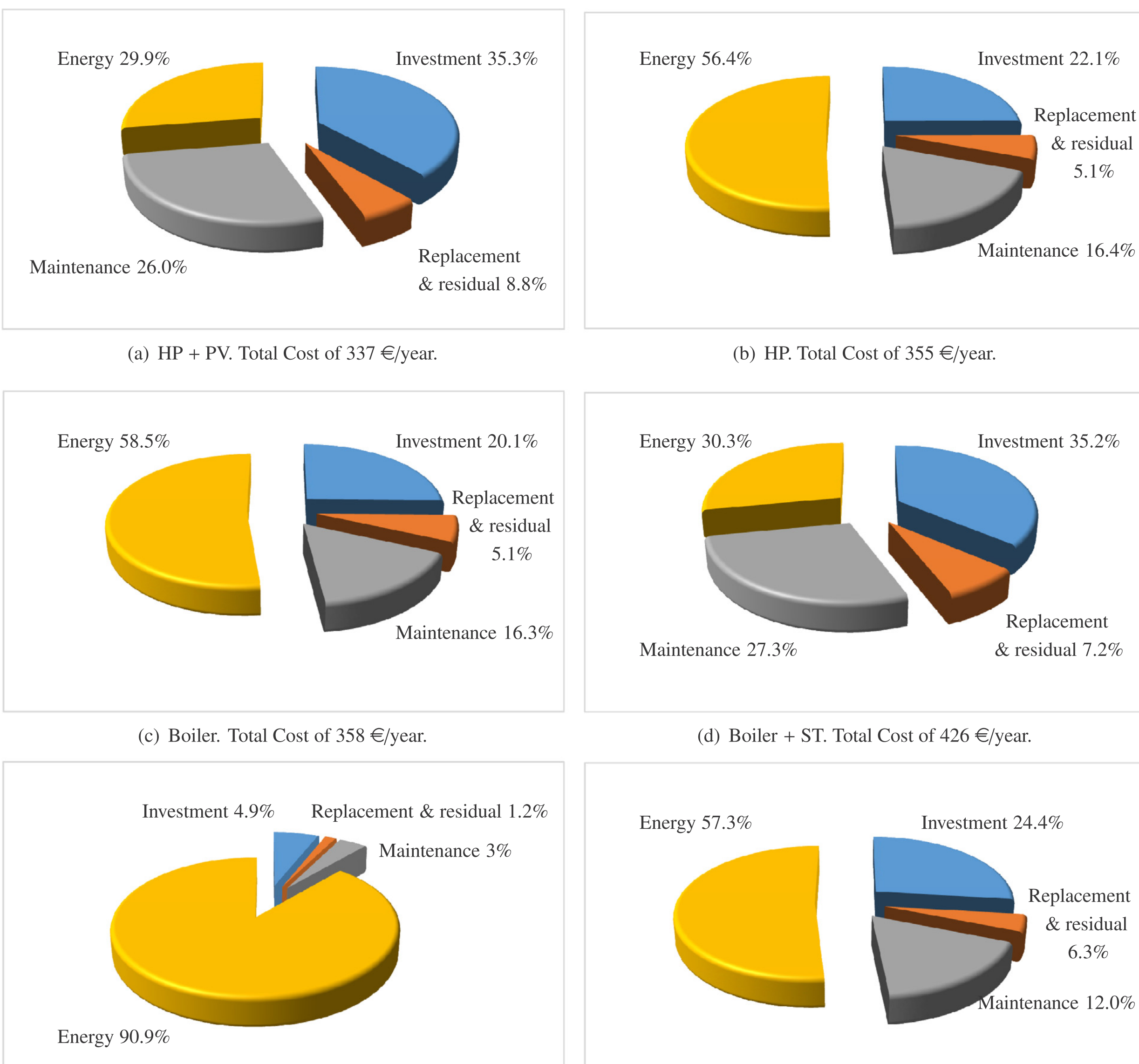
As it can be appreciated, the energy cost for the electric (*Heater*) is huge in comparison with the investment cost, 583.6 €/year vs 31.2 €/year, resulting in a total annualized cost of 641.8 €/year.

If the heater is powered partly by photovoltaic panels (*Heater* + *PV*), the cost of energy drops to 279.3 €/year and the investment cost rises to 119 €/year, resulting in a cheaper choice (487.46 €/year) than the heater alone.

The use of a simple boiler requires an investment of 72.1 €/year, being the total annualized cost of 357.7 €/year significantly lower than for the *Heater* and the *Heater* + *PV*, mainly due to the lower energy costs of natural gas. Its energy cost is 209.3 €/year, the maintenance cost is 58.3 €/year and the replacement and residual cost is 18.1 €/year.

If the *boiler* is combined with solar thermal collectors, the energy expenditure drops significantly to 129.3 €/year, however, it does not compensate for the rise in investment (149.9 €/year), maintenance (116.5 €/year) and replacement and residual cost (30.7 €/year). The result is that using solar thermal collectors makes the total annualized cost higher (426.4 €/year).

The solution with a heat pump (*HP*), if compared with the boiler, implies similar energy (200.3 €/year), investment (78.5 €/year), maintenance and replacement costs, resulting in a slightly lower total annualized cost (355 €/year).



(a) HP + PV. Total Cost of 337 €/year.

(b) HP. Total Cost of 355 €/year.

(c) Boiler. Total Cost of 358 €/year.

(d) Boiler + ST. Total Cost of 426 €/year.

(e) Heater. Total Cost of 642 €/year.

(f) Heater + PV. Total Cost of 487 €/year.

Fig. 8. Total life system cost contributions.

If the heat pump is combined with photovoltaic panels (*HP + PV*), the required investment obviously increases (119 €/year), but the energy requirements are significantly reduced to 100.5 €/year, resulting in similar total annualized cost of 336.6 €/year, which is also the lowest one of the comparison.

Fig. 8, shows the individual weight of each annualized cost in the total cost for the different systems. For example, in the figure, the most significant cost of each system can be appreciated. For the *heater*, the energy cost represents 90.9% and investment is only 4.9%. The energy cost is also significant for the *Boiler* (58.5%), the *heater + PV* (57.3%) and the *HP* (56.4%), but not that important for the *boiler + ST* (30.3%) or the *HP + PV* (29.9%). For the latter options, the investment and maintenance costs are even more important than the energy cost (*HP + PV*, maintenance of 26% and investment of 35.3%, *boiler + ST* maintenance of 27.3% and investment of 35.2%).

From the results, it can then be concluded, that the heat pump with the photovoltaic panels is the cheapest option, although similar to using only a heat pump or only a boiler. However, the results of the economic study depend highly on the energy prices, which can vary in time and from one country to another. Therefore, the same comparison has been carried out for different electricity prices, ranging from 0.1 €/kWh to 0.4 €/kWh.

As can be observed in Fig. 9, if the electricity price is very low (0.1–0.15 €/kWh), the heat pump (without PV panels) would be the economically most interesting choice. If the electricity price is higher, the heat pump with PV becomes more interesting in comparison with the heat pump (without PV panels). It can be also seen that the impact of the energy price on the total annualized cost of the HP + PV system is low. This reduces the uncertainty of this long term economic analysis.

3.5. Results extrapolation tools

In this section, the necessary tools are provided for the extrapolation of the results of this work to other locations with similar climate conditions (Mediterranean climate). To that aim, the experimental results have been used to obtain the correlations of Figs. 10 and 11.

On the one hand, in Fig. 10 there is a representation of the solar contribution (Eq. (6)) versus daily solar irradiation for all daily measurements. It shows that solar contributions of up to more than 80% may be reached on days with high irradiation.

On the other hand, Fig. 11 shows the relation between the daily average seasonal performance factor of the heat pump SPF_{HP} versus the average ambient temperature during its working hours (from 10:00 to 14:00 solar time). It shows a significantly better performance of the heat pump for high ambient temperatures than for low ones.

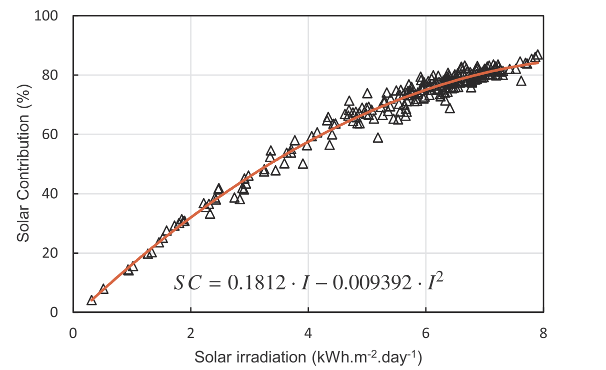


Fig. 10. Solar contribution to the heat pump consumption (*HP + PV system*) as a function of the irradiation on the surface of the PV panels (45°). Correlation in red.

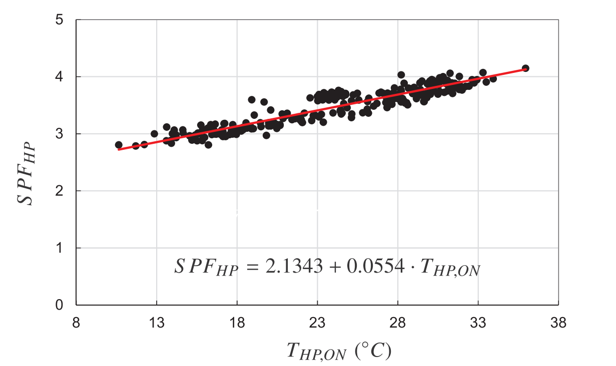


Fig. 11. Seasonal performance factor of the heat pump for one day versus the average ambient temperature during its working time.

From Eqs. (1)–(6), Eq. (12) is deduced, which allows us to obtain the photovoltaic electrical energy consumption of the heat pump.

$$E_{PV,HP} = \frac{Q_{TOT}\cdot SC - E_{PV}}{SPF_{HP}} \tag{12}$$

Finally, in order to determine the grid electricity consumption of the heat pump, Eq. (13) may be used (from Eqs. (2) and (5)).

$$E_{GD} = \frac{Q_{HP}}{SPF_{HP}} - E_{PV,HP} \tag{13}$$

Consequently, once the climate conditions at a different location are known, the energetic needs of the *HP + PV* system can be determined

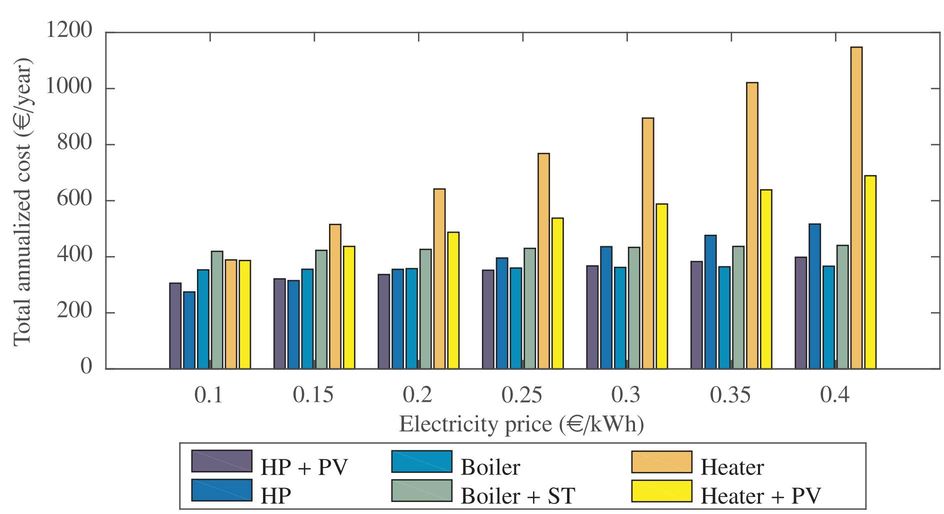


Fig. 9. Influence of the electricity price on the total annualized cost.

as well as its operating cost. Thus, the results of this study can be extrapolated to other locations with similar climate conditions (Mediterranean climate) and domestic hot water demand.

4. Conclusions

This work has analysed the use of a heat pump powered by photovoltaics and the grid for domestic hot water production purposes. The *HP + PV* system does not feed electricity to the electrical grid and does not use batteries.

The economic study has shown that the *HP + PV* solution is competitive for domestic hot water production. In addition, the combination of heat pumps and photovoltaics should be considered as a decarbonized solution for nearly zero energy buildings, since it has a minimal non-renewable primary energy consumption.

The total annualized cost of the proposed solution (337 €/year) is considerably lower than other options in the market and similar to using only a heat pump or a boiler. The environmental study attests that the system under study outperforms by far any other solution: savings in primary energy of $FSAV_{nRPE} = 79\%$ and in CO_2 emissions $FSAV_{CO_2} = 82\%$ vs. a boiler. The boundary of the techno-economic analysis is the system itself.

The low electricity consumption from the grid of the *HP + PV* system, yields to a low dependence of the total annualized cost on the electricity price. This reduces the uncertainty of a long term economic analysis.

The interaction with the electrical grid plays an important role when a heat pump is supported by photovoltaics. The system has been shown to be friendly towards the electrical network:

- PV production is 100% self-consumed by the system.
- The system does not feed electricity to the grid.
- Very low electrical consumption peaks.

This work has provided valuable experimental data for the design and comprehension of the operation of facilities implementing the system under study.

Finally, experimental correlations for the solar contribution and the seasonal performance factor of the heat pump have been obtained. They can be used to extrapolate the results of this work to other locations with similar climatic conditions.

References

Aguilar, F., Aledo, S., Quiles, P., 2016. Experimental study of the solar photovoltaic contribution for the domestic hot water production with heat pumps in dwellings. Appl. Therm. Eng. 101, 379–389. https://doi.org/10.1016/j.applthermaleng.2016.01.127.

Chow, T., F. Fong, K., Pei, G., Ji, J., He, M., 2010. Potential use of photovoltaic-integrated solar heat pump system in Hong Kong. Appl. Therm. Eng. 30, 1066–1072. https://doi.org/10.1016/j.applthermaleng.2010.01.013.

Comisión Nacional de los Mercados y la Competencia (CNMC), 2018. Informe de supervisión del mercado de gas natural en España. Periodo: año 2017. Expediente IS/DE/007/18. Spain.

Comisión Nacional de los Mercados y la Competencia (CNMC), 2019. Boletín de indicadores eléctricos de febrero de 2019. Spain.

European Parliament and Council of the E.U. of 11 December, 2018. Directive 2018/2001/EU, on the promotion of the use of energy from renewable sources. Official Journal of the European Union.

European Parliament and Council of the E.U. of 30 May, 2018. Directive 2018/844/EU, amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. Official Journal of the European Union.

European Union Commission, 2016. Commission recommendation (EU) 2016/1318 of 29 July 2016, on guidelines for the promotion of nearly zero-energy buildings and best practices to ensure that, by 2020, all new buildings are nearly zero-energy buildings. Official Journal of the European Union.

Fang, G., Hu, H., Liu, X., 2010. Experimental investigation on the photovoltaic-thermal solar heat pump air-conditioning system on water-heating mode. Exp. Thermal Fluid Sci. 34, 736–743. https://doi.org/10.1016/j.expthermflusci.2010.01.002.

Instituto para la diversificación y ahorro de la energía (IDAE), 2007. Guía técnica para el diseño y cálculo del aislamiento térmico de conducciones, aparatos y equipos. ISBN 978-84-96680-08-1. Ministerio de industria energía y turismo. Gobierno de España.

Instituto para la diversificación y ahorro de la energía (IDAE), 2016. Factores de emisión de CO2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumidas en el sector de edificios en España. Documento reconocido del reglamento de instalaciones térmicas en los edificios (RITE). Ministerio de industria energía y turismo. Gobierno de España.

JCGM, 100:2008. Evaluation of measurement data - Guide to the expression of uncertainty in measurement. ISO.

Kato, T., Suzuoki, Y., 2014. Autonomous scheduling of heat-pump water heaters for mitigating voltage rise caused by photovoltaic power generation systems. Appl. Therm. Eng. 71, 652–657. https://doi.org/10.1016/j.applthermaleng.2013.10.029. special Issue: MICROGEN III: Promoting the transition to high efficiency distributed energy systems.

Li, H., Sun, Y., 2018. Operational performance study on a photovoltaic loop heat pipe/solar assisted heat pump water heating system. Energy Build. 158, 861–872. https://doi.org/10.1016/j.enbuild.2017.10.075.

Mohanraj, M., Belyayev, Y., Jayaraj, S., Kaltayev, A., 2018. Research and developments on solar assisted compression heat pump systems: A comprehensive review (part-b: Applications). Renew. Sustain. Energy Rev. 83, 124–155. https://doi.org/10.1016/j.rser.2017.08.086.

Poppi, S., Sommerfeldt, N., Bales, C., Madani, H., Lundqvist, P., 2018. Techno-economic review of solar heat pump systems for residential heating applications. Renew. Sustain. Energy Rev. 81, 22–32. https://doi.org/10.1016/j.rser.2017.07.041.

Poulet, P., Outbib, R., 2015. Energy production for dwellings by using hybrid systems based on heat pump variable input power. Appl. Energy 147, 413–429. https://doi.org/10.1016/j.apenergy.2015.03.005.

Sichilalu, S.M., Xia, X., 2015. Optimal energy control of grid tied PV–diesel–battery hybrid system powering heat pump water heater. Sol. Energy 115, 243–254. https://doi.org/10.1016/j.solener.2015.02.028.

Thygesen, R., Karlsson, B., 2013. Economic and energy analysis of three solar assisted heat pump systems in near zero energy buildings. Energy Build. 66, 77–87.

Thygesen, R., Karlsson, B., 2014. Simulation and analysis of a solar assisted heat pump system with two different storage types for high levels of PV electricity self-consumption. Sol. Energy 103, 19–27. https://doi.org/10.1016/j.solener.2014.02.013.

United Nation Framework Convention on Climate Change, Paris, 2015. Tracking country climate pledges.

Wang, G., Quan, Z., Zhao, Y., Sun, C., Deng, Y., Tong, J., 2015. Experimental study on a novel PV/T air dual-heat-source composite heat pump hot water system. Energy Build. 108, 175–184. https://doi.org/10.1016/j.enbuild.2015.08.016.

Wang, Z., Guo, P., Zhang, H., Yang, W., Mei, S., 2017. Comprehensive review on the development of SAHP for domestic hot water. Renew. Sustain. Energy Rev. 72, 871–881. https://doi.org/10.1016/j.rser.2017.01.127.

Zhang, X., Zhao, X., Xu, J., Yu, X., 2013. Characterization of a solar photovoltaic/loop-heat-pipe heat pump water heating system. Appl. Energy 102, 1229–1245. https://doi.org/10.1016/j.apenergy.2012.06.039. special Issue on Advances in sustainable biofuel production and use - XIX International Symposium on Alcohol Fuels - ISAF.