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Bachelor Thesis
Grau en Enginyeria en Tecnologies Industrials

ENERGY EFFICIENCY EVALUATION OF A HYBRID ENERGY SYSTEM

Analyzed in a Mediterranean climate, city of Barcelona

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Abstract

This paper deals with the analysis of a specific hybrid energy system (HYS) from an overall energy efficiency aspect and also from an economical aspect. The hybrid energy system was purposely assembled from standard, market available energy technologies that are presently used in majority of building facilities, particularly in residential ones. Based on the previous aspect, the HYS was assembled using a standard split heat pump system (air-conditioning unit) with an integrated accumulation boiler for hot water preparation and using a small photovoltaic (PV) system. An overall energy efficiency analysis showed the HYS system to be highly energy efficient on average as overall energy efficiency ranged from 50% up to over 300% (the heat pump system acts as a kind of efficiency booster). An economic analysis showed that the HYS produced energy cost ranged from 0.035€/kWh up to 0.15 €/kWh, in investment conditions. A detailed energy efficiency and feasibility analysis showed that the herein analyzed HYS can be a viable option for small or medium building applications in mild climates.

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1. Introduction

The need of heating, cooling and hot water

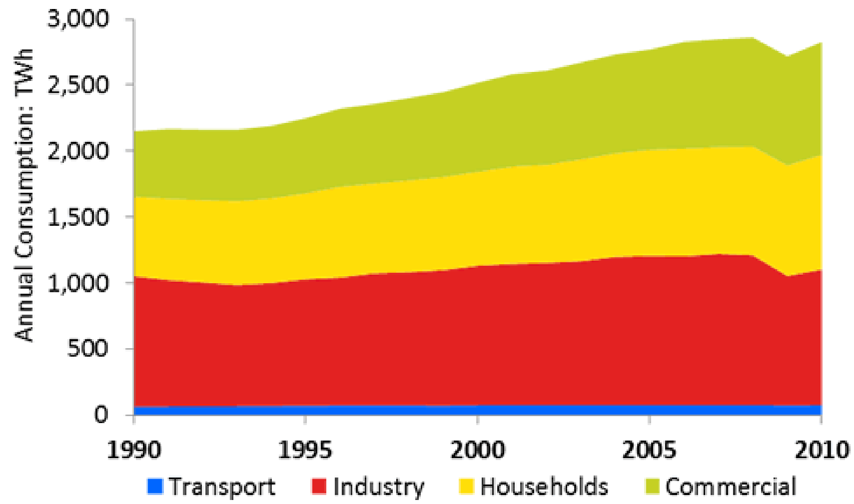
Heating and cooling are processes and systems of raising or decreasing the temperature of an enclosed space for the primary purpose of ensuring the comfort of the occupants; when outside temperatures are low (winter season) or high (summer period), respectively following the human needs. By regulating the ambient temperature, heating and cooling also serve to maintain a building's structural, mechanical, and electrical systems.

The human body uses energy in the form of food, for various vital processes (growth, movement, cell renewal ...) and a residue in the form of heat, which is also used to keep the body at the right temperature so that these processes are developed properly. The heat is dissipated into the environment, but should be dissipated at the same time as our body produces it, in order to keep our corporal temperature. When it does not occur, our losses are higher than heat production, therefore we feel cold, which can produce death by hypothermia in extreme cases. Corporal temperature lost is a real human problem, so there is a strong need to find a solution. There are some alternatives: firstly, temperature can be increased with the clothing insulation and secondly, can be increased by heat production through exercise (as higher energy consumption, more heat excess). When, none of these solutions are possible, you cannot do physical exercise and you cannot increase the wrap dress, heating systems and hot water preparation are the solution.

Heating and cooling systems are installed in enclosed spaces in order to regulate their temperature and other climate conditions. As for any other system, it is necessary to supply energy to run the operation process.

Household electricity consumption

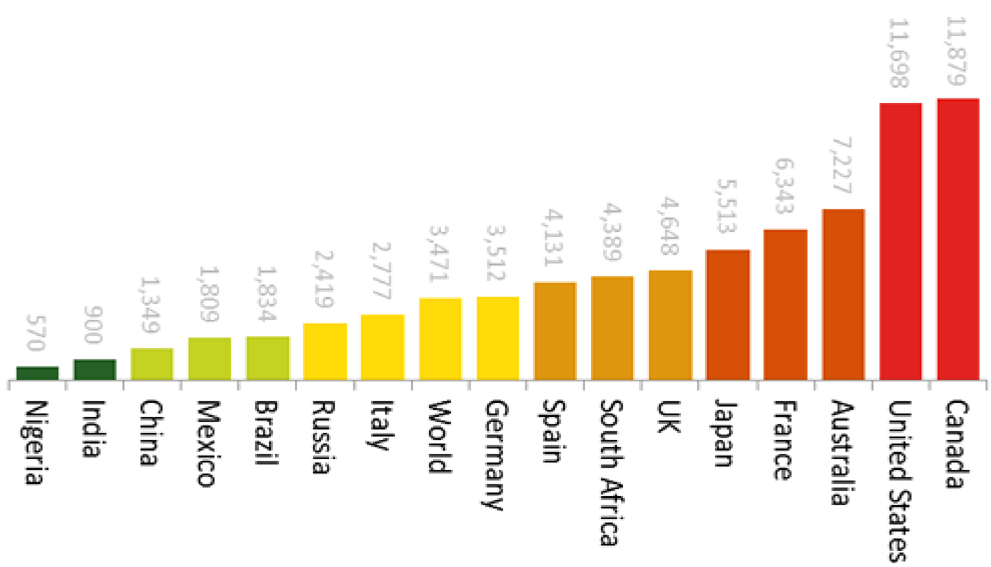
Household electricity use generally makes up about a third of total electricity consumption in most developed countries (see Fig. 1).



Source: EUROSTAT **Fig. 1 EU27 Electricity Consumption by Sector**

Among the twenty-seven countries that make up the European Union electricity is used primarily by industry (36%), households (31%) and the commercial sector (30%), while transport (3%) is a small share. For this purpose the 'commercial' sector includes both private and public services while industry is mostly manufacturing [1].

In Fig. 2 can be seen that average household electricity use varies greatly between countries. It is possible to compare how much electricity the average electrified household uses in different countries.



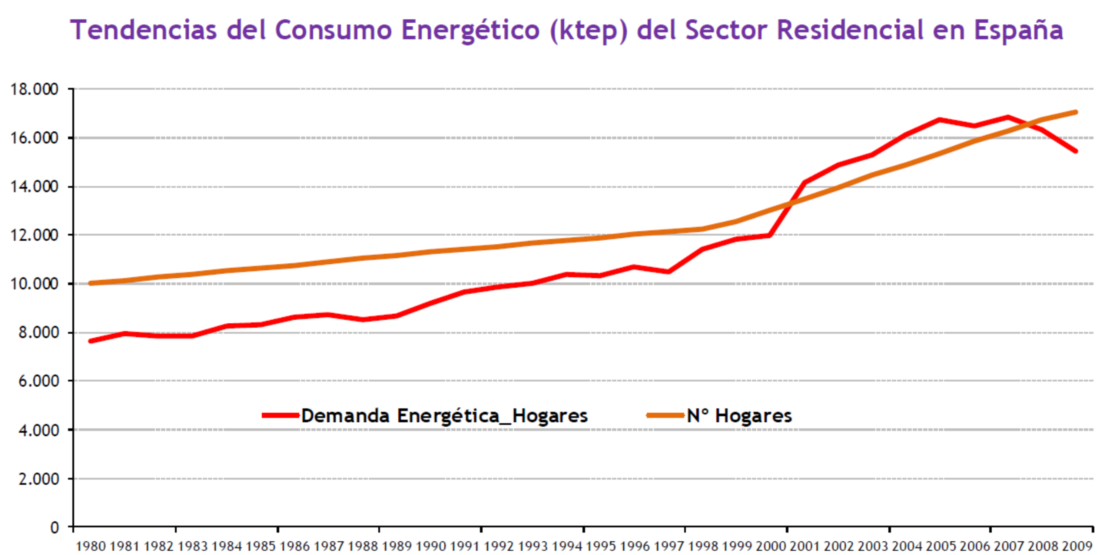
Source: ENERDATA **Fig. 2 Household electricity consumption (kWh/year)**

Across the countries compared household electricity use varies enormously. The average American or Canadian household in 2010 used about twenty times more than the typical Nigerian household, and two to three times more than a typical European home.

But while there are huge differences in household electricity use around the world, all of them tend to use electricity for similar kinds of activity.

Household energy consumption in Spain

The household sector is a key sector in the current Spanish and EU energy context because of the importance of energy demand, in terms of total consumption and electricity consumption amounted respectively to 17% and 25% for Spain, and 25% and 31% at the level of the EU27 [2]. At the national level, various factors such as increased household consumption habits, progressive household equipment, led by increases in purchasing power capacity and improved living standards, provide future rises in the representativeness of the household sector energy demand. The last point is supported by several relevant prospective studies that currently take place in order to facilitate the design and configuration of energy planning policies more in line to cover future demand. Moreover, this sector, in comparison to other end-use sectors in Spain, currently has less consumption, but in relative terms, is one of the sectors which in recent years has recorded higher growth in both consumption (Fig. 3) and energy intensity associated.

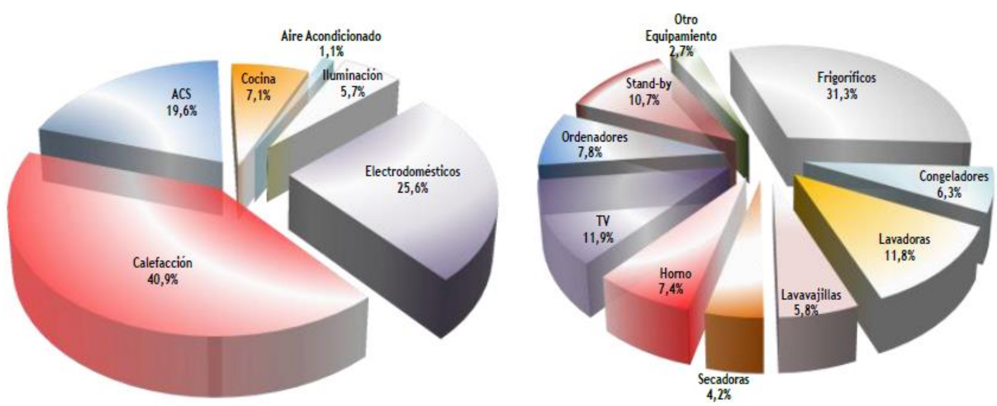


Source: IDAE **Fig. 3 Tend of Spanish energy consumption (ktoe) in household sector**

Significant impacts associated with meeting the energy needs of society and the residential sector in particular in terms of energy dependency, security of supply and environmental impact, require an adequate energy planning based in Spain on three pillars: the Planning of Electricity and Gas Sectors, Planning energy Saving and Efficiency and Renewable Energy Plans [2], which will facilitate the achievement of a more efficient and sustainable energy model.

Breakdown of energy consumption in the Spanish Mediterranean

The climates with high humidity and mild temperatures in winter and very high in summer, affects the structure of energy consumption. The higher consumption, regarding to the national average consumption of refrigeration, balance the lower heating energy requirements. In the following diagram (Fig. 4) is possible to observe the breakdown of energy consumption of Spanish Households with a Mediterranean climate.



Source: IDAE **Fig. 4 Energy consumption according to energetic uses**

In Mediterranean regions of Spain, the major uses of energy are heating (41%), appliances (25%), water heating (20%), kitchen (7%), lighting (6%) and air conditioning (1%).

Regarding consumption for heating in the Mediterranean area are preferred electrical heating equipment as reversible heat pumps, heaters and radiators. The hot water service is present practically in all households. On the other hand, 49% of Spanish households have some type of air conditioning system, basically single. The differences are conditioned by the weather, with the Mediterranean region equipping refrigeration systems in 67% of households. The main system is the reversible heat pump system with a national penetration of 78%, rising to 83% in the Mediterranean region [2].

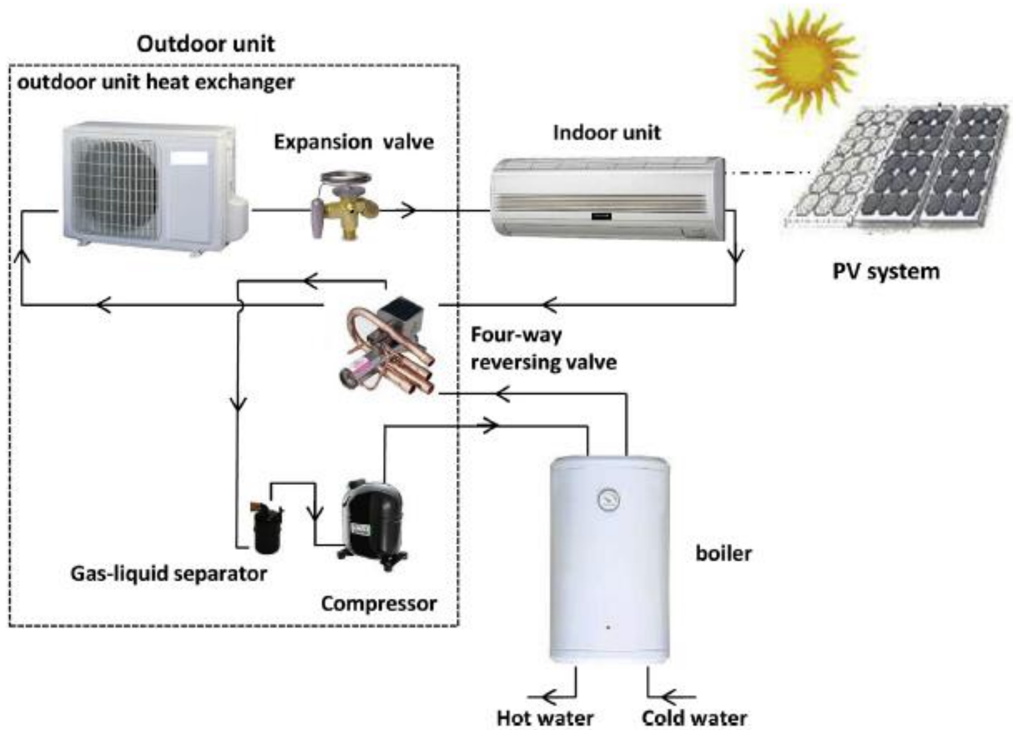
Novel energy systems

As it was said before, the energy policies adopted by developed countries are moving increasingly in the direction to find an efficient and sustainable energetic model, focusing in renewable energies. In this way, hybrid energy systems are an interesting solution due to their more efficient use of renewable energies and their attractiveness from an economic view. Furthermore, the ecological aspect is also an important advantage since this systems enable faster diffusion of renewable energies and a lower use of limited fossil resources. On the other side, the most critical aspect of the implementation of hybrid systems is the high initial investment.

During the last years, a greater amount of research activity has focused on the design, development and testing of hybrid energy systems using renewable energies. In [3] is possible to find some comments about previous novel hybrid energy systems (and its paper's references) until arriving to the system proposed: HYS. This paper's main objective is to analyze the hybrid energy system (HYS) proposed in [3] for the climate conditions of a Mediterranean city like Barcelona.

2. Description of the HYS

The hybrid energy system proposed consist on a standard air-conditioning unit and an integrated boiler for heating water. The system is fuel by a small off-grid photovoltaic plant. The Fig. 5 shows a schematic of the experimental hybrid energy system.



Source: [3] **Fig. 5 Simplified schematic providing an overview of the developed hybrid energy system**

The following points will explain in detail the three main components mentioned.

Heat pump system

The heat pump system consists on a standard air-conditioning split unit, available in the market, adapted for the installation in the HYS. The refrigerant used in the heat pump system is R-410A and the heating/cooling capacity of the air-conditioning unit is 3.7/3.5 KW.

The main difference between a conventional air-conditioning unit and the adapted for the HYS is that in the second one is added a spiral copper heat exchanger between the compressor outlet and inlet of the indoor unit. Therefore, the HYS had two condensers: one located in the outdoor unit (cooling mode) and another one located inside the accumulation boiler for heating water. The rest of the elements of the hybrid energy system: expansion valve, four-way reversing valve, gas-liquid separator) are also components of a standard air-conditioning unit.

The implementation of the system for heating water requires the rebuilding of the electronic regulation of the standard AC unit. The HYS has to provide three different working modes. The first one is a standard heating mode for space heating while water is simultaneously heated in the standard accumulation boiler. The second mode activates a standard cooling mode in which the space is cooled while the water is heated. The main advantages in this second mode is that the rejected heat is recovered using a spiral cooper heat exchanger built inside the accumulation boiler. Finally, the last working mode activates just the water heating.

Accumulation boiler for heating water

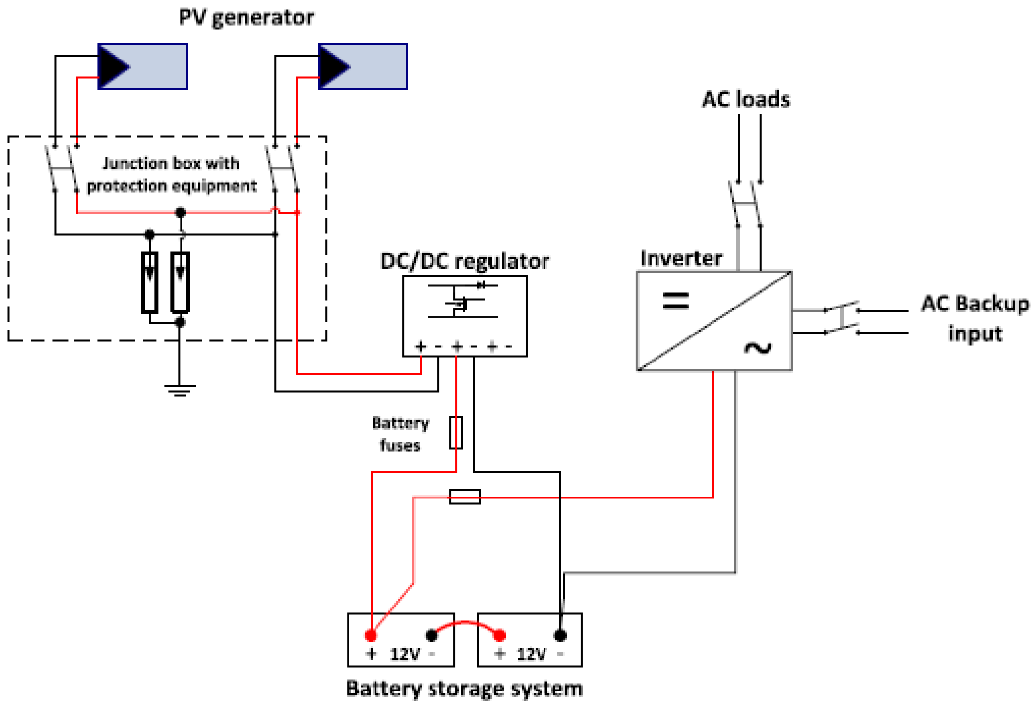
The accumulation boiler consists on a standard boiler with 80L capacity and heat insulation. This boiler, available in the market, requires a modification by installing a spiral heat exchanger inside to heat the water. This heat exchanger consists on a 12 m-long pipe made of copper, with dimensions of 10 x 1 mm.

Refrigerant pressure at the boiler inlet: 22.0 – 25.0 bar
Hot water temperature: 45 – 55 ºC

In case of a problem with the hybrid energy system, the boiler was also equipped with a direct electric heater of 1.2 KW electric power, to ensure the water heating under any circumstance.

PV system

The off grid PV system consists on a conventional stand-alone PV, with additional input for backup power sources running in parallel (see Fig. 6). The backup sources converted the PV system into a hybrid PV configuration, able to store energy in batteries. A diesel generator and power grid are used as backup sources and the battery storage system was designed using four 6-V/330-Ah batteries (Trojan deep cycle J3005) connected in series. When the PV generation is insufficient or the battery SOC (state of charge) is lower than a predefined value, the regulation system activates the backup sources.



Source: [3] **Fig. 6 Simplified electrical wiring diagram of the developed hybrid energy system**

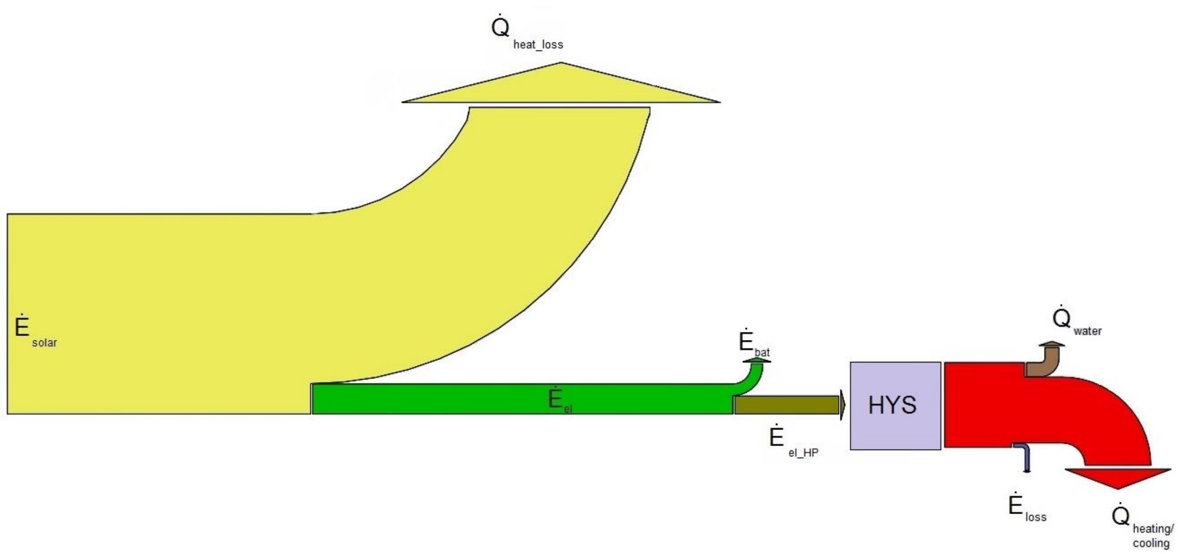
The PV generator is composed of eight PV modules (Luxor solar, LX-195M) arranged in two groups, where each group is connected to its own PWM (pulse width modulation) solar charge controller without an integrated tracking system. The electrical efficiency of the PV modules is 15.4%, in order to the characteristics provided by the supplier (under STC (standard test conditions)-1000 W/m2, 25ºC, AM1.5). In [3] is possible to find the efficiency under real conditions, which was calculated using the STC and environmental parameters with the REF (RetScreen methodology and Evans' formula) for the location analyzed in that manuscript (PV modules were mounted on the flat-roofed faculty terrace using a fixed ConSole mounting system. The PV modules were inclined at 25^{o} and followed the orientation of the FESB faculty building (Split) with an azimuth of 210^{o} (30^{o}).

3. Thermodynamic analysis

As has been commented before, the HYS is basically assembled by to independent energy systems, the photovoltaic system and the heat pump system with waste heat recovery; both integrated into a unique energy system.

Theoretical operating principle

In Fig. 7 is shown the energy flow during the working process of the HYS.



Source: [4] **Fig. 7 General HYS energy flow chart**

From the flow chart it is seen that the incoming solar energy $\dot{E}_{solar}$ is partially converted into useful electricity $\dot{E}_{el}$ although the majority amount of solar energy is transformed into heat loss $\dot{Q}_{heat\_loss}$. Part of the useful energy (or all, depending on the needs) is used to power the modified heat pump system $\dot{E}_{el\_HP}$ and the rest is allocated to recharge the batteries, $\dot{E}_{bat}$. The heat pump system will consume the majority of the energy for heating and cooling spaces, $\dot{Q}_{heating/cooling}$, and the other part will be used for heating water, $\dot{Q}_{w}$, in the integrated boiler. The overall energy loss in the heat pump system, $\dot{E}_{loss}$, is not significant for the analysis, thus it is neglected. The biggest amount of energy loss take place in the copper spiral heat exchanger installed in the boiler, however our analysis will take average measured performance parameters that includes all energy losses in the HYS by indirect way.

From [4], the following equations show the way to obtain the different parameters described before in the flow energy chart.

Energy input into the hybrid energy system incoming from solar energy by the PV panels, i.e. available panel surface, respectively,

$$\dot{E}_{solar} = G_s \cdot A_{PV} \cdot \tau_d \cdot d_m \ , \tag{1}$$

And then the converted energy into electricity equals,

$$\dot{E}_{el} = G_s \cdot A_{PV} \cdot \eta_{PV} \cdot \tau_d \cdot d_m \ . \tag{2}$$

According to [4] electrical efficiency η_{PV} of the crystalline silicon, PV panels can be given as the function of panel (cell) temperature as follows,

$$\eta_{PV} = \eta_0 \left[1 + \beta \left(t_{cell} - 25 \right) \right] . \tag{3}$$

For the used PV modules in our experiment (Luxor, LM-195M), specific parameters in eq. (3) are, $\eta_0 = 15.29\ \%$ and $\beta = -0{,}0045\ ^\circ\mathrm{C}^{-1}$, [4]. Finally, the converted solar energy in the electricity via the PV system can be expressed as the function of incoming solar energy flow $\dot{E}_{solar}$ and operating cell temperature, t_{cell}, respectively,

$$\dot{E}_{el} = 1.56 \cdot G_s \cdot \left[1 - 0.0045 \left(t_{cell} - 25 \right) \right] \cdot \tau_d \cdot d_m \ , \tag{4}$$

where the total area of PV modules for the herein analyzed case was 10.21 m^2.

The HYS is theoretically analyzed for a geographical location with a Mediterranean climate, the city of Barcelona (Spain). The average solar insulation for the city selected is shown in [5] and ranges from 400 W/m^2 to 490 W/m^2 in summer months and between 200 W/m^2 and 300 W/m^2 in winter period. Other general information data such as average air temperature (t_a) [6] and average daily working time of the HYS (τ_d) can also be found in [6].

The average cell temperature can be calculated according to nominal operating cell temperature (NOCT), respectively,

$$t_{cell} = t_a + (\mathrm{NOCT} - 20) \cdot \frac{G_s}{800}, \tag{5}$$

where t_a is the surrounding (ambient) air temperature and the specific PV modules used equals NOCT= $47 \pm 2°\mathrm{C}$, [4].

As it was previously mentioned, the incoming solar energy is partially converted into a useful effect in the form of produced electricity from the PV system and the rest is rejected heat into the environment, according to the energy balance equation it follows,

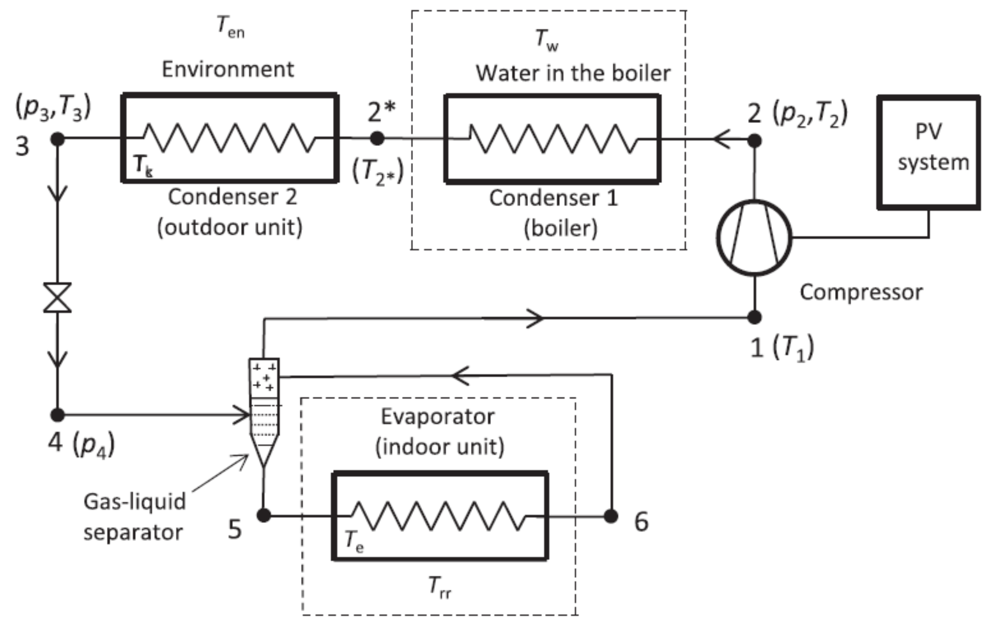
$$\dot{E}_{solar} = \dot{Q}_{heat\_loss} + \dot{E}_{el} \ . \tag{6}$$

After transformation of available solar energy to electricity, one part of it would be used to drive the heat pump system, $\dot{E}_{el\_HP}$ and the rest of it is accumulated into battery storage, $\dot{E}_{battery}$ (however, ratio $\dot{E}_{battery} / \dot{E}_{el\_HP}$ strongly rely on the specific working circumstances), respectively,

$$\dot{E}_{solar} = \dot{Q}_{heat\_loss} + \dot{E}_{bat} + \dot{E}_{el\_HP} \ . \tag{7}$$

Performance analysis

Fig. 8 illustrates the measurement test rig of the hybrid energy system that was developed in detail in [3], which was equipped with temperature and pressure sensors to monitor the refrigerant state values in the different working regimes. The engaged electric power and other electronic parameters, such as the voltage, current, and electricity consumption, were also measured.



Source: [3] **Fig. 8 Simplified measurement test rig scheme**

The measurement test rig was used in [3] to monitor the thermodynamic and electricity parameters of the hybrid energy system in the different working modes. The measured data were used to calculate the critical performance parameters for the hybrid energy system.

Using the first law of thermodynamics (i.e., the energy balance equation for the hybrid energy system), the COP for the heating mode can be expressed as follows:

$$COP_h = \frac{Q_{Hk}}{W_c} = \frac{Q_{k1} + Q_{k2}}{W_c} \qquad (8)$$

where Q_{Hk} is the total heat exchanged in the two condensers, i.e., Q_{k1}, the heat exchanged in the boiler for heating the water (the first condenser) and Q_{k2}, the heat exchanged in the condenser of the outdoor unit (the second condenser).

The same approach can be used to define the COP_c when the hybrid energy system operates in the cooling mode:

$$COP_c = \frac{Q_E + Q_{k1}}{W_c} \qquad (9)$$

where Q_E is the cooling capacity of the evaporator and Q_{k1} is the heat rejected into the boiler.

The heat rejected by the refrigerant to the water in the boiler (condenser 1 in Fig. 8) can be calculated as follows:

$$Q_{k1} = \sum m_w c_{pw}(t_{w2} - t_{w1}) \qquad (10)$$

Where $\sum m_w$ is the total mass of water that was wasted (consumed) during the entire measurement period, i.e., during the water consumption cycles. The water temperature before and after the heat rejection in the boiler, t_{w1} and t_{w2}, in Eq. (3) corresponds to the mean temperature values that were measured during the water consumption cycles.

The heat rejected into the heated space through the indoor unit can be calculated as follows:

$$Q_{k2} = \dot{m}_a c_{pa}(\bar{t}_h - \bar{t}_{sh})\tau \qquad (11)$$

where m_a is the air mass flow from the indoor unit, t_{sh} is the mean temperature at the outlet of the indoor unit, t_h is the mean temperature of the heated space, and τ is the duration of the measurement period.

The heat rejected in the cooling working mode can be expressed as follows:

$$Q_E = \dot{m}_a c_{pa}(\bar{t}_{sc} - \bar{t}_c)\tau \qquad (12)$$

where t_{sc} is the mean temperature of the cooled space and t_c is the mean temperature at the outlet of the indoor unit.

The coefficient of performance for the heating and cooling modes in the equations derived above can be modified as follows:

$$COP_h = \frac{\sum m_w c_{pw}(t_{w2} - t_{w1}) + \dot{m}_a c_{pa}(\bar{t}_h - \bar{t}_{sh})\tau}{\sum W_c} \qquad (13)$$

$$COP_h = \frac{\sum m_w c_{pw}(t_{w2} - t_{w1}) + \dot{m}_a c_{pa}(\bar{t}_{sc} - \bar{t}_c)\tau}{\sum W_c} \qquad (14)$$

In [3], there is a wide study of the hybrid energy system for the cooling working regime tested in the summer. Hence, all the calculated performance data correspond to summer operation, which is the most significant working regime for the potential implementation of the developed energy solution. The hybrid energy system was subjected to different working conditions in the cooling working regime to investigate how these conditions affected the system performance.

Simulation of PV system performance

In order to simulate the PV system performance in the specific geographical location for the analysis of the HYS, has been used the average solar irradiation data [5], the parameters of LX-195M PV panels [7] and with an inclination of the panels to 25º. The results of the simulation according to the specified data are available in Table 1. The column for E_{el} (kWh/month) shows the energy that the PV panels are able to produce for each month, using eq. (2), hence, the annually production reach around 2530 kWh of electricity with an average PV electrical efficiency of 15,1%.

Month	I (kWh/m^{2}day)	τ_d (h/d)	t_a (^oC)	η_{PV} (%)	t_{cell} (^oC)	Gs (W/m2)	E_{el} (kWh/month)
Jan	2,18	10	9,2	15,9	16,6	218	110
Feb	3,14	11	9,9	15,7	19,5	285	141
Mar	4,34	12	11,8	15,4	24,0	362	211
Apr	5,69	13	13,7	15,1	28,5	438	262
May	6,47	15	16,9	14,8	31,5	431	304
Jun	7,1	15	20,9	14,5	36,9	473	315
Jul	7,33	15	23,9	14,2	40,4	489	330
Ago	6,12	14	24,4	14,3	39,2	437	277
Sep	4,78	12	21,7	14,6	35,1	398	214
Oct	3,33	11	17,8	15,1	28,0	303	159
Nov	2,31	10	13	15,6	20,8	231	110
Dec	1,91	9	10	15,8	17,2	212	96

Table 1 PV system performance parameters in HYS

On the other hand, electricity consumed by the heat pump system $\dot{E}_{el\_HP}$ was measured realistically by an energy logger device for a summer and winter steady state in daily and night operation for the city of Split in [4] and as it was previously specified, the engaged electric power ranged from 600

W to 1.100 W in correspondence with the heating/cooling working regime. As Split and Barcelona are cities from a similar Mediterranean climate, this analysis will also take this range of electricity consumption.

In order to compare the energy that the solar panels can produce in front of the demand of energy for every month of the year, has been calculated the amount of energy that the PV is able to produce for every month (Table 2), depending on the climate conditions of the city of Barcelona. As energy demand for the heat pump, has been taken an average absorbed electric power between 600 W in winter (heating regime) to a maximum of 1100 W in summer (cooling regime). The specific demand for each month is presented also in table 2 in accordance with the daily working hours, which, depending on the building facilities, number of occupants, habits and working regime, might range from 4 h up to 12h.

Month	$PV_{produced}$ electricity	operating time-4h	operating time-6h	operating time-8h	operating time-10h	operating time-12h
1	110	136	205	273	341	409
2	141	123	185	246	308	370
3	211	124	186	248	310	372
4	262	96,0	144	192	240	288
5	304	86,8	130	174	217	260
6	315	72,0	108	144	180	216
7	330	74,4	112	149	186	223
8	277	74,4	112	149	186	223
9	214	84,0	126	168	210	252
10	159	99,2	149	198	248	298
11	110	108	162	216	270	324
12	96	136	205	273	341	409
Annual	2528	1215	1822	2430	3037	3644

(All data in kWh)

Table 2. Produced energy and demands for different working hours

Therefore, in order to check the autonomy of the HYS system, has been provided (in Fig. 9) a HYS simulation of the yearly electric demands as the function of the expected operating time.

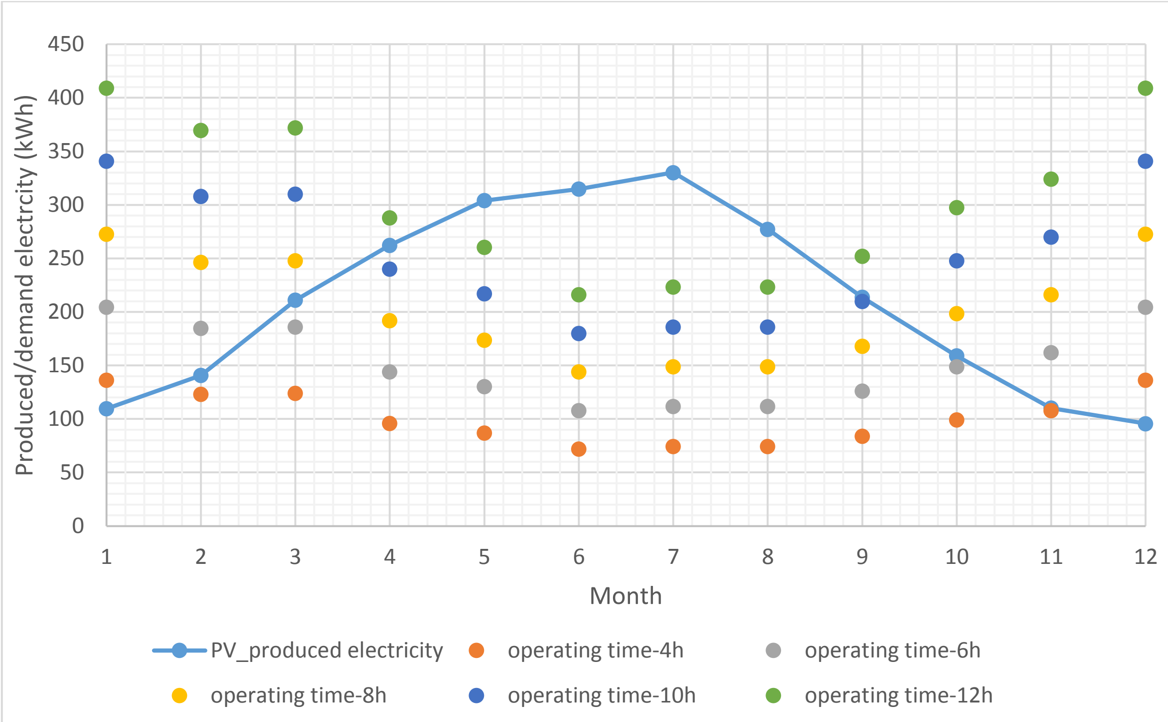


Fig. 9. HYS demands for electricity as the function of estimated daily working time

Taking 8 h/day working time as the average for common households, can be seen in Fig. 9, that the produced energy for the summer months is enough to cover the energy necessities. This means that between April and September the energy produced by the PV panels ensure the supply of energy for the HYS system without having to take electricity from the grid.

On the other side, from October to March the necessities are not covered just with the PV panels. In Fig. 10 it is shown the deficit and surplus of energy per month between energy produced by PV panels and an average demand for 8 hours/day working time. As has been previously specified, during from April to September there is surplus of electricity. The most critical months are December and January with a deficit around 170 kWh. Also not covering demand, November and February present a shortage of 105 kWh and, finally, October and March are almost covering necessities (with 38 kWh lack).

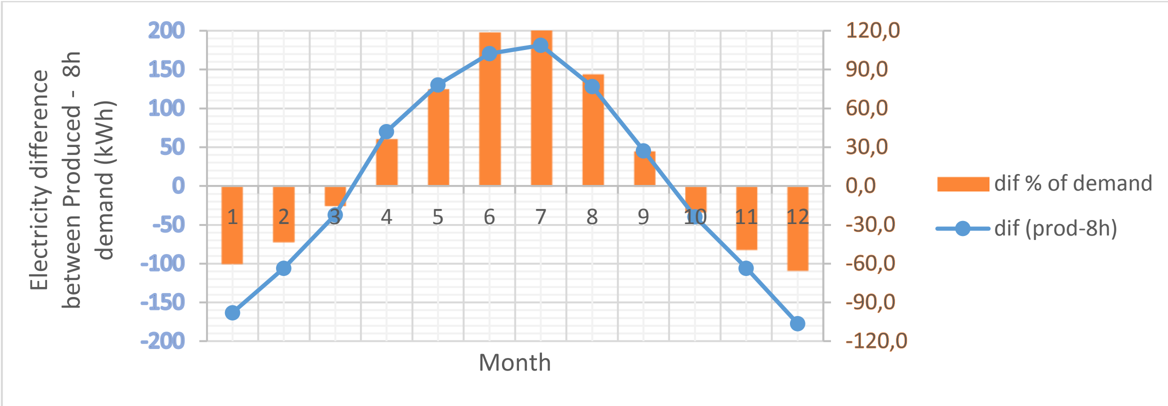


Fig. 10. Deficit and surplus of energy per month

On the right axis it is shown the percentage of the demand covered by the PV panels, presenting a maximum of 65% deficit in the electricity supply for December and January and 45% for February and November.

The deficit of electricity imply a necessity to ensure the total system autonomy. On one hand, it is possible to use the backup sources previously specified, such as grid electricity, to cover the extra demand. On the other hand, it is possible to install extra PV panels in order to increase the production of energy. In this manner, the total electric power of the PV system would be higher.

As it is detailed, the most critical months are December and January, with 65% of the electricity demand not covered; taking an average of 8 hours working per day, which means that it is necessary to increase the PV panels energy production. In order to achieve it, the area of the PV panels would have to be multiplied by 2,85 (10,21 m^2 * 2,85).

As is being taken an average of the daily solar insulation for every month in order to calculate the energy produced per month, is important to consider the possibility of having cloudy days. For that reason, has been added to the system an external electricity storage using 4 batteries, each with a capacity of 330 Ah. Therefore, in case of cloudy days, in which the HYS autonomy can be disturbed, the specified battery storage design can provide a maximum autonomy of 13 hours in summer period and around 7 hours in winter operation (see Table 3). It is important to remember that the system activates the grid electricity supply when the PV generation is insufficient or the battery SOC (state of charge) is lower than a predefined value.

	power needed (kW)	daily demand for 8h/day working time (kWh)	maximum battery storage (kWh)	coverage of the batteries (h)
summer	0,6	4,8	7,92	13,2
winter	1,1	8,8		7,2

Table 3 Electricity coverage of the batteries

HYS energy efficiency

Overall HYS energy efficiency can be calculated according to the known solar energy input and known energy output which is in the form of heating/cooling energy and energy for the hot water preparation [4]. In relation to the possible working regime, overall HYS energy efficiency can be calculated for summer period as follows,

$$\eta_{HYS\_h} = \frac{\dot{Q}_{water} + \dot{Q}_{sc}}{\dot{E}_{solar}}, \qquad (8)$$

And also for winter period,

$$\eta_{HYS\_c} = \frac{\dot{Q}_{water} + \dot{Q}_{sh}}{\dot{E}_{solar}}, \qquad (9)$$

where $\dot{Q}_w$ is the available heat for hot water preparation, $\dot{Q}_{sc}$ space cooling capacity and $\dot{Q}_{sh}$, space heating capacity. An average overall HYS energy efficiency can be expressed as the function of the average $\mathrm{COP_{av}}$ value (for the whole year), with engaged compressor power and incoming solar radiation, respectively,

$$\overline{\eta}_{HYS} = \overline{P}_{comp} \cdot \frac{\mathrm{COP_{av}}}{\dot{E}_{solar}} = \frac{\overline{P}_{comp} \cdot \mathrm{COP_{av}}}{G_s \cdot A_{PV}}, \qquad (10)$$

or in another annotation, expressed as percentage (specific PV area of 10.2 m^2 is included),

$$\overline{\eta}_{HYS}\,(\%) = 9.8 \cdot \frac{\overline{P}_{comp} \cdot \mathrm{COP_{av}}}{G_s} \quad , \tag{11}$$

and where HYS compressor power can be expressed in summer and winter respectively, in the operation as follows,

$$\overline{P}_{comp} = \frac{\overline{Q}_c}{\mathrm{COP_c}} \; , \tag{12}$$

$$\overline{P}_{comp} = \frac{\overline{Q}_h}{\mathrm{COP_h}} \; , \tag{13}$$

Where COP_c corresponds with the common used EER abbreviation, to evaluate the heat pump system efficiency in cooling operation mode.

According to the available solar data for the chosen geographical location, and measured average engaged compressor power, it was possible to calculate overall HYS energy efficiency, its average value $\overline{\eta}_{HYS}$ for the expected COP range (according to experimental experience), it ranges from 4.0 to 6.0). For previous circumstances, calculation results for $\overline{\eta}_{HYS}$ are presented in Fig. 11, average expected values for specific months and expected COP_{av} range value.

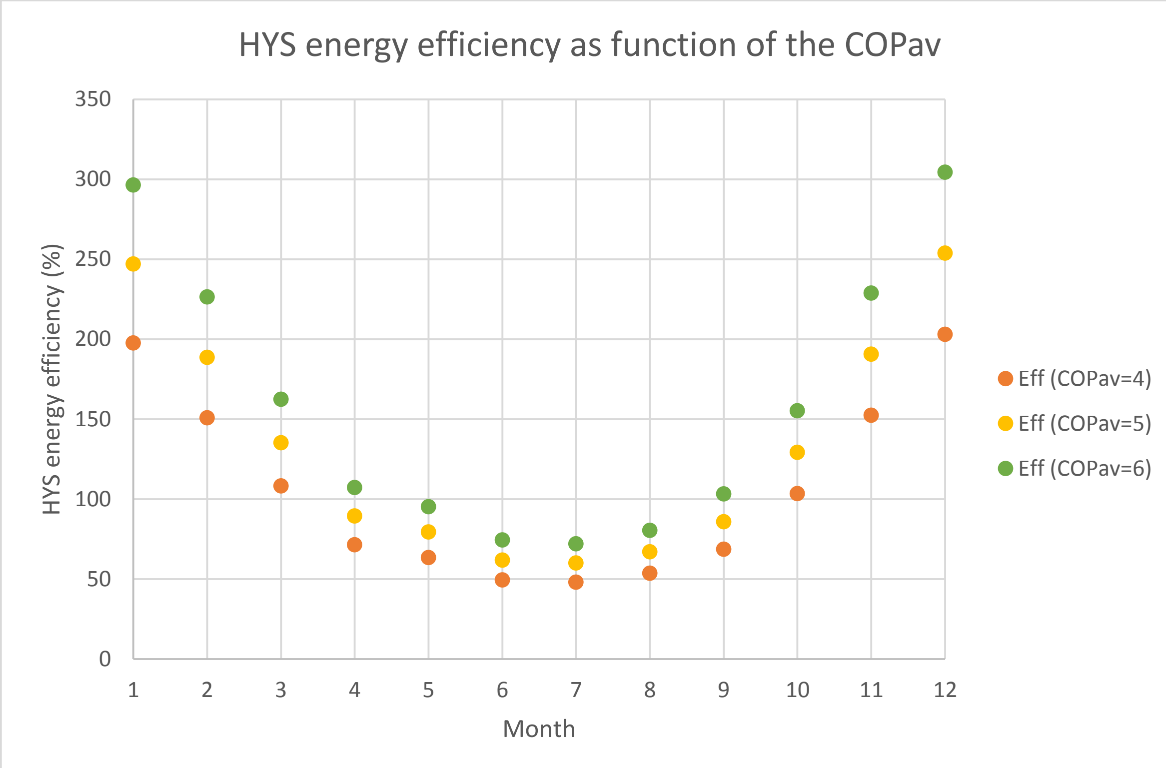


Fig. 11 Yearly overall HYS energy efficiency trend as the function of the COP_{av} value

The graphic above, show the efficiency depending on the expected COP_{av} values. The points represent the efficiency for three different COP_{av} values: 4.0, 5.0 and 6.0, which are the most common values obtained experimentally for the HYS system [3]. As it is represented in Fig. 11, the overall average monthly efficiency ranges between 50% and 100% in summer months and from 100% to 300% during winter period. As has been said in previous sections, the average winter and summer COP_{av} is around 5.0, therefore, taking this value, the HYS monthly efficiency ranges from 60% (in June, July and August) to 250% in December and January. Moreover, the efficiency difference between summer months and winter months is consequence of the higher irradiated solar energy and the higher daily sunlight hours during summer period. This two factors, plus the lower energy demand for summer, imply the lowest efficiency values during summer. On the other side, it is noticed the highest efficiency values are achieved during winter period, due to the lower solar energy input.

As a result, it is useful to integrate a heat pump into the hybrid energy system as it is shown in the previous analysis. Furthermore, it can be concluded that the proposed HYS positively efficient, in terms of energy, for the climate conditions of the location where has been analyzed.

4. Economic analysis

Regarding the possible commercial application of the herein analyzed HYS, its feasibility aspect is crucial. It is also important to emphasize that the upcoming economic analysis is provided for its technical characteristics and working circumstances, which were previously elaborated in this paper. There are a few possible options, the first option is the simplest one: one needs to adjust the existing heat pump split system (standard air-conditioning device), i.e. to add a boiler for hot water preparation and to modify the heat pumps' electronics. Furthermore, in the previous case, the HYS was not driven by a proper PV system; this means that the HYS would be supplied from the grid. In that case, the overall estimated investment to adjust existing installations is approximately 400€ and is the cheapest option for potential users, with respect to the initial cost. However, such an HYS system relies on grid electricity which can be a disadvantage in some situations, as in cases of remote areas and in unstable electrical systems.

As a second option, buying a new HYS system to install it in a particular house suppose an expense of IC = 4400€ [4] taking in account possible bank fees. In case of credit, the interest applied would be 7%. According for the experimental experience in [3] for a Mediterranean climate, the average HYS yearly is COP_{av} = 5.0, where in these circumstances the overall expected average HYS yearly energy output (EO_{HYS}) will be around 12500 kWh/year (which corresponds with average HYS daily operation in the amount of 10 hours/day). Besides that, it will be taken into account an annual PV system degradation of 0.5% which will affect the HYS energy output and a yearly maintenance cost (OM) of 3.6% of the installation cost. For the analysis will be also taken in consideration the standard kWh price in the location of the study (Barcelona, Spain), which average is approximately 0.14 €/kWh [8].

The next table 4 summarize the data for the economic analysis:

LCOE input parameters	
Interest rate (*p*)	7%
Amortization period (*n*)	6/12 years
Installation cost (IC)	4,400€
Operation&Maintenance cost (3.6% of IC per year)	159 €
Annual HYS energy output (0.5% annual PV degradation factor is considered)	12,500 kWh/year
Standard kWh price in Spain	0.14 €/kWh

Table 4 Input parameters economic analysis in HYS

Analyzing the electricity costs for the two mentioned options, taking into account the possible deficit of electricity (showed in Fig. 10) during the winter months and, hence, the payment of the standard grid price. The annual cost of the electricity is showed in table 5:

Month	Option 1 (€)	Option 2 (€)
1	38,192	22,86090612
2	34,496	14,80798874
3	34,72	5,184082408
4	26,88	0
5	24,304	0
6	20,16	0
7	20,832	0
8	20,832	0
9	23,52	0
10	27,776	5,52085078
11	30,24	14,80760777
12	38,192	24,79494226
Annual expense (AE)	340,144	87,97637808

Table 5 Electricity expenditures for each option

Taking in consideration that the annual cost for a normal heat pump system plus the hot water preparation would be the multiplication of the supposed energy output, 12500kWh and the standard 0.14 €/kWh price the result, 1750€/year, shows that the yearly savings are wide.

Proceeding to the calculation of the average kWh price for the overall HYS produced energy (LCOE) in the two options, it will be obtained as follows [4]:

$$LCOE = \frac{AC+AE}{EO_{HYS}} \qquad (14)$$

Where annual cost can be expressed as follows (that includes installation cost, IC and operation maintenance cost, OM),

$$\mathrm{AC} = \mathrm{IC} \times \mathrm{CRF} + \mathrm{OM}, \qquad (15)$$

And where CRF represents the capital recovery factor (i.e. amortization of capital costs), respectively,

$$\mathrm{CRF} = \frac{(1+p)^n \cdot p}{(1+p)^n - 1} \qquad (16)$$

In the previous eq. (16), *n* (years) represents amortization period and *p* represents interest rate.

Once described the formulas, the output values obtained are detailed in the next Table 6:

	Standard Grid	**Option 1**	**Option 2**
IC (€)	0	400	4400
AE (€)	1750	340	88
LCOE 6years (€/kWh)	0.14	0,047	0,094
LCOE 12years (€/kWh)	0.14	0,044	0,064

Table 6 LCOE for each option

From the results obtained above, it can be concluded that the installation of the modified heat pump system plus the boiler for the hot water preparation is certainly profitable against the normal systems. For an amortization time of 12 years the average cost of the electricity would be 0.044 €/kWh for the option 1 and 0.064 €/kWh for the second one, which widely differences from the average retail price for Spain (0.14 €/kWh).

5. Conclusions

The main objective of this study was to analyze the overall energy efficiency of the hybrid energy system. Once simulated the amount of useful solar energy available for the location of the test (city with a Mediterranean climate, Barcelona) and, consequently, the autonomy of HYS, has been able to analyze the overall energy efficiency. Also, taking an average working hours of 8 hours a day, it can be concluded that the system is energy efficient. As it was seen before, the overall average monthly efficiency ranges between 50% and 100% in summer months and from 100% to 300% during winter period, demonstrating that the heat pump system acts as an efficiency booster for the HYS. The efficiency depends on the expected COP_{av} values which were experimentally defined between 4.0 and 6.0 in [3].

Regarding the autonomy of the system, it is concluded that, for an average working time of 8 hours/day, the most critical period was during winter (December and January). The maximum deficit of electricity was 65% of the demand, hence, it was necessary an area of 10,21 m^2 x 2,85 in PV panels to ensure the working process during the winter period and, therefore, during the whole year, for achieving a system independent from backup sources. It was also taken in consideration the possibility of having cloudy days. For that reason, has been considered sufficient the addition of an external electricity storage using 4 batteries, each with a capacity of 330 Ah.

With respect to the economic analysis, it can be concluded that the installation of the modified heat pump system plus the boiler for the hot water preparation is certainly profitable against the normal systems. For an amortization time of 12 years the average cost of the electricity would be 0.044 €/kWh for the option 1 and 0.064 €/kWh for the second one, which widely differences from the average retail price for Spain (0.14 €/kWh).

Furthermore, the proposed HYS is an efficient and ecological renewable energy system using market available technologies. The ideal location for the system would be rural areas using single energy technologies and, going in depth, typical summer destinations with low or useless operation during the winter.

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Nomenclature

A_{PV} - Available surface of the PV panels, m^2

AC - Total life cycle cost, €

AE - Annual electricity expense, €

CRF - Capital recovery factor,

d_m - Number of days in the specific month, days/month

COP_c -Coefficient of performance in cooling mode (corresponds with EER),

COP_h -Coefficient of performance in heating mode,

COP_{av} -Mean value for coefficient of performance for entire season,

EO_{HYS} - Average annual HYS output, kWh/year

$\overline{Q}_c$ - Mean thermal output of HYS in cooling mode (space cooling & water heating), W

$\overline{Q}_h$ - Mean thermal output of HYS in heating mode (space heating & water heating), W

$\dot{E}_{el}$ -Produced electricity from the PV system, Wh/month

$\dot{E}_{el\_an}$ -Annually produced energy, kWh/year

$\dot{E}_{el\_HP}$ -Electricity for heat pump system drive of HYS, Wh/month

$\dot{E}_{bat}$ -Electricity accumulated in the batteries, Wh/month

$\dot{E}_{solar}$ -Incoming solar energy, Wh/month

$\dot{E}_{loss}$ -Overall energy loss from the heat pump system, Wh/month

G_s - Irradiated solar energy, W/m^2

I - Average daily solar irradiation, kWh/m^2dia

IC - Installation cost (overall investment), €

n - Amortization period, years

OM - Operation and maintenance cost, €

$\overline{P}_{comp}$ - Mean compressor power, W

p - Interest rate, % p.a.,

r_m - Maintenance cost, % p.a.,

t_{cell} - Cell temperature, °C

t_a - Ambient temperature, °C

$\dot{Q}_{heat\_loss}$ - Heat loss from the PV panel, Wh/month

$\dot{Q}_{heating/cooling}$ - Heating/cooling capacity of HYS, Wh/month

$\dot{Q}_w$ - Heating capacity for hot water preparation, Wh/month

$\dot{Q}_{sc}$ - Heat capacity for space cooling, Wh/month

$\dot{Q}_{sh}$ - Heat capacity for space heating, Wh/month.

Greek symbols:

β - Temperature coefficent, °C^{-1}

η_{PV} - Electrical efficiency of the PV system,

η_0 - Nominal electrical efficiency of the PV panel at STC,

$\overline{\eta}_{HYS}$ - Average overall energy efficiency of the HYS,

τ_d - Average daily working time of the HYS, h/day