Energy efficiency evaluation of a hybrid energy system for building applications in a Mediterranean climate and its feasibility aspect

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Manuscript highlights:

- An overall energy efficiency analysis was conducted for a specific hybrid energy system (HYS),
- The HYS consists of a split heat pump unit, with waste heat recovery, driven by a PV system,
- Gained results showed relatively high energy efficiency values for the HYS,
- LCOE analysis was conducted to determine HYS economic viability,
- The calculated price of produced energy by HYS is competitive with current prices on the energy market.

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 200% (the heat pump system acts as a kind of efficiency booster). An LCOE analysis showed that the HYS produced energy cost ranged from 0.035€ /kWh up to 0.15 € /kWh, in correspondence with overall working time, the average coefficient performance achieved by the heat pump system and 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.

Keywords: hybrid energy system, heat pump, photovoltaics, energy efficiency, LCOE analysis, renewable energy.

1. Introduction

Hybrid energy systems are a necessity if single renewable energy technologies want to be used in a more efficient way and if they want to be more attractive from an economic standpoint and are therefore crucial in a sustainable energy approach [1-10]. For example, market available photovoltaic technologies are not adequate enough regarding the magnitude of achieved electrical efficiency in real circumstances, but in some cases, if the same technologies are used in forms of hybrid energy systems, it is possible to achieve high overall energy efficiency. It is also important to note that hybrid energy system feasibility is influenced by price on the electricity market. Finally, this means that integrated energy systems (hybrid systems) can have a more favorable economic aspect in comparison with single used renewable energy technologies. Another major advantage is that they can simultaneously ensure different forms of energy, for example electricity, hot water, heating/cooling capacity, etc., which is in general a demand in different types of building facilities. The most critical issue regarding a wider hybrid energy system commercial implementation is their economic aspect as a high initial investment can be expected in most cases. Nevertheless, it can be a viable option in long terms. The ecological aspect (advantage) of it is also important and certainly needs to be taken into consideration regarding present climate issues and the ones that await us. As a result, research activity in recent years has focused on the design and development of novel hybrid energy systems that use renewable energy technologies. Finally, a hybrid energy system enables faster penetration of renewables and a rational usage of limited fossil resources.

This paper's main objective is to analyze and evaluate overall energy efficiency of the specific proposed hybrid energy system (HYS) and its feasibility aspect through a LCOE calculation framework. Furthermore, this paper presents research continuation that was previously reported in [39], where the focus was on the specific hybrid energy system design (and its experimental performance evaluation), that is suitable for applications in a Mediterranean climate (or mild climates in general), as well as other alternative renewable energy concepts [40, 41].

2. State-of-the-art

There have been a large number of experimental attempts and research studies related to hybrid energy systems where the focus has been to establish an optimal techno-economic solution. A short research overview of the latest research findings related to hybrid energy systems will be presented in chapters to follow.

Hybrid photovoltaic-thermal water heating system performance evaluation was elaborated in [11] where experimental results were compared with numerical ones, gained by the Monte Carlo method means. Thermodynamic analysis of a combined PV/T fuel-cell hybrid energy system for residential applications, that can ensure electricity, heat capacity, water purification and hydrogen energy production, was performed in [12]. Hybrid energy PV/T system performance analysis for domestic applications was provided in [13] and the proposed system showed a potential for energy and carbon dioxide savings in UK climate conditions. Ground heat pump systems coupled with solar collectors and their performance parameter analysis was elaborated in [14]. Authors in [15] performed a numerical study on a hybrid heat pump system for existing buildings and concluded that SPF heat pump factor can be increased using a hybrid heat pump system consisting of a retrofitted air-water heat pump. A method was developed in [16] for dynamic testing and evaluation of combined solar-thermal heat pump hot water systems and it was used to determine the COP number for the proposed hybrid energy solution. A novel solar PV/loop-heat-pipe heat pump system was developed in [17] for water heating and this concept was further developed in [18] (the maximal achieved COP value was 8.7). A rooftop wind solar hybrid heat pump system performance analysis was given in [19] and it was possible to achieve a significant reduction in annual carbon dioxide emissions, up to 30 per cent. The development of a hybrid, i.e. absorption/CO2 compression heat pump system was elaborated in [20] and the main goal was to increase heat pump system performance if carbon dioxide is used as a refrigerant instead of conventional refrigerants. A specific design of PV solar-assisted heat-pump/heat-pipe system performance analysis was given in [21]. A hybrid PV heat/pump system was presented in [22, 23] and the system was able to achieve a mean COP value of around 4.0 for UK climate conditions. A solar assisted geothermal heat pump system coupled with a small wind turbine system was studied in [24] and economic viability was proven for the system. Development of a hybrid solar-assisted cooling/heating system was thoroughly elaborated in [25] and the achieved reduction of power consumption ranged from 34.5 % to 81.2%. A hybrid photovoltaic-thermal heat pump system was elaborated in [26] for dynamic modelling where the maximal achieved coefficient performance was at around 8.0. An experimental analysis on a PV-thermal solar heat pump air conditioning system in water heating mode was presented in [27] and the total hybrid system efficiency was improved by a 20% average. A solar hybrid air-conditioning system design and performance for high-temperature cooling applications in a subtropical climate was analysed in [28] and significant reduction in primary energy consumption was established. A hybrid solar energy and ground storage heat pump system study was elaborated in [29] and the proposed energy system was able to reach a mean coefficient performance of around 4.0. A building-integrated photovoltaic/water-heating system design and performance for warm climate applications was elaborated in [30] and the proposed system showed to be more energy efficient than a conventional solar system. A hybrid energy system for medium-sized hotels in Iran was analysed in [31], where a wind-diesel hybrid system option, with battery storage, resulted to be most efficient. A photovoltaic/thermal system in combination with a booster diffuse reflector and vacuum tube for electricity generation and hot water production was analyzed in [32] as well as parametric analysis. A numerical investigtion of the photovoltaic thermal (PV/T) collector was given in [33] for a Tunisian climate. An optimal sizing analysis for hybrid power systems using power pinch was provided in [34] where different scenarios were analyzed. A hybrid approach for efficient renewable energy system synthesis was analyzed in [35] to provide an optimization framework. In general, advancements in hybrid photovoltaic systems are thoroughly elaborated in [36], [37] and different renewable energy options for building applications were analysed in [38].

3. Hybrid energy system considered

As it was mentioned in the introductory section, this paper presents reported research continuation with emphasis being placed on determining overall HYS energy efficiency and its economic viability. A short hybrid energy concept elaboration will be provided as base for further analysis; more details can be found in the reported research [39].

As it is depicted in Fig. 1, the HYS was assembled using a standard split heat pump unit (standard room air-conditioning unit) with additionally integrated a typical commercial boiler for hot water preparation and the whole system was driven by a small PV plant. In summer, the HYS working regime is able to produce cooling capacity and hot water simultaneously, which is basically cost-free (only in terms of operative costs) as waste heat recovery is utilized via an installed copper heat exchanger (inside the accumulation boiler). In winter period, the HYS produces heating capacity and heat for hot water preparation, where water heating cost is quite lower in comparison with direct electric heating.

In general, the HYS operation principle is rather simple and there are three working modes available. According to Fig. 1, refrigerant vapor in winter regime leaves a compressor (that is supplied with electricity from the PV system) with average pressure of around 28.0 bars. The refrigerant first passes through the accumulation boiler (first condenser) and then passes to the indoor unit to ensure space heating capacity (second condenser). After the second condenser, the refrigerant vapor passes towards the expansion valve, where refrigerant pressure is reduced to an approximate 8.5 bar on average. The rest of the process is completely similar to processes in the standard split heat pump systems in case of the winter operation mode. In summer regime, after the compressor, the refrigerant vapor first passes through the accumulation boiler (with an average pressure of 24.0 bars) and then is redirected to the outdoor unit via four-way reversing valve to reject the heat into the surrounding area. Finally, the refrigerant pressure is reduced in the expansion valve to around 10.0 bars so it can obtain space cooling enabled via the indoor unit. The last working regime is pure water heating in the accumulation boiler, where the refrigerant first passes through the accumulation boiler (i.e. spiral copper heat exchanger) and then is directed to the indoor unit (in that case, the indoor unit fan is turned off) and finally goes to the outdoor unit where the refrigerant is then redirected via four-way reversing valve to the compressor inlet.

Based on the previous elaboration, the HYS is a suitable energy option for applications in small (or medium) residential and tourist building facilities in geographical regions with a mild climate (Mediterranean climate).

Fig. 1 The hybrid energy system (HYS) schematic proposed in [39]

The majority of previously mentioned building facilities presently use split heat pump systems (air-conditioning units) and standard accumulation boilers for hot water preparation along with direct electric heaters installed. On the other side, the main HYS characteristic is that it is assembled using standard energy systems that can be found in majority of households. Hence, the idea was to prove that it is possible to modify existing used market available energy technologies and to form them into an energy solution that is renewable and economically reasonable. A significant advantage to the herein analyzed HYS concept is the avoided cost for installed electric power in accumulation boilers and heat pump systems (in the case of total PV autonomy), which is not an insignificant cost if several air-conditioning units and boilers are installed in a building facility (for example, the cost of electric power is around 250 Eur per kW in Croatia and in the case of small touristic hotels, the initial cost for installed electric power can reach up to a few thousand euros). The second HYS advantage is its suitability for implementation in rural or district regions with electricity supply issues. Finally, the third HYS advantage is its environmental acceptability, as it represents an entirely renewable energy solution.

The standard used (tested) air-conditioning device, i.e. heat pump system, was of 3.7 kW/3.5 kW heating/cooling capacity (maximal thermal output), the standard accumulation boiler was of 80 liter capacity, and the OFF grid PV system was of 1.8 kW installed electric power (monocrystalline PV technology, with four batteries, each of 330 Ah). The HYS was tested in summer and winter regimes where according to experimental measurements, the average coefficient performance (COP_{av}) ranged from 4.5 to 6.0, [42]. The average COP_{av} value was at around 5.0 for summer and winter seasonal working regimes, and that value will be used in further analysis as base for further calculations. The average absorbed electric power was at around 650 W for cooling regime and around 1,100 W for heating regime. The mean hot water temperature was around 48°C in summer regime and around 45°C in winter regime (the HYS was able to achieve a suitable hot water temperature level for domestic or other purposes). The maximum achieved coefficient performance value was in cooling regime, COP_{max}(EER)=6.7 as maximal water temperature was around 60°C in the same working regime.

From the previous elaboration, it can be concluded that the proposed HYS showed promising performance parameters; however, an overall energy efficiency and feasibility analysis (LCOE) should be provided to get a better HYS picture, i.e. to check its general suitability for market implementation. More specific details regarding performance analysis and its technical characteristics can be found in [39].

4. Energy analysis, thermodynamic approach

Basically, the herein analyzed HYS is assembled using two independent energy systems, i.e. a photovoltaic system and heat pump system with waste heat recovery. The previously mentioned single used energy technologies are now integrated into a unique energy system (HYS) that simultaneously provides heating/cooling capacity and hot water for domestic or other purposes in general. To provide a clearer upcoming energy analysis, a specific energy flow chart is provided and presented in Fig. 2.

Fig. 2 General HYS energy flow chart

From Fig 2, incoming solar energy $\dot{E}_{solar}$ is partially converted into useful electricity $\dot{E}_{el}$ but the majority of incoming solar energy is unfortunately transformed into heat loss, $\dot{Q}_{heat\_loss}$. Furthermore, depending on the working circumstances, one part of the produced electricity (or all) is used to drive a modified heat pump system, $\dot{E}_{el\_HP}$, and the rest is accumulated in the batteries, $\dot{E}_{bat}$ but both previously mentioned energy flows represent battery energy loss in practical terms. A heat pump system with an integrated boiler will consume the majority of energy for space heating/cooling, $\dot{Q}_{heating/cooling}$, and the rest will be spent on hot water preparation, $\dot{Q}_{water}$. There is a certain overall energy loss in the energy system as well, $\dot{E}_{loss}$, that is neglected as its influence will not be significant for the general purpose of this analysis (where we want to show and order the magnitude of overall HYS energy efficiency in general).The major impact of energy loss is due to energy losses in the copper spiral heat exchanger installed in the accumulation boiler (to provide more accurate analytical approach, this should also be taken into account in the analytical modelling). However, our approach will take average measured performance parameters that includes all energy losses in the HYS (by indirect way), which means that our calculated values for the overall energy efficiency of the HYS will be realistic one.

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

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

And then the converted energy into electricity equals,

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

According to [43] electrical efficiency η_{PV} of the crystalline silicon, PV panels can be given as the function of panel (cell) temperature as follows,

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

For the used PV modules in our experiment (Luxor, LM-195M), specific parameters in eq. (3) are, $\eta_0 = 15.29\,\%$ and $\beta = -0{,}0045\,°\mathrm{C}^{-1}$, [44]. 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,

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

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

The HYS was tested in a geographical location with a typical Mediterranean climate (city of Split, Croatia) and according to the provided measurements (i.e. experimental experience) the cell temperature ranged from 50°C up to 70°C in summer period and 30°C up to 50°C in winter period (on a clear day). Typical solar insolation for the specific geographical location is an approximate 430 W/m^2 average for summer period and at around 330 W/m^2in winter period (however, in recent years, the obtained readings of solar insolation are much higher where insolation peaks are over 1,000 W/m^2). General meteorological data for the geographical location where the HYS was tested can be found in [45].

The average cell temperature can be calculated according to nominal operating cell temperature (NOCT), [46], respectively,

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

where t_a is the surrounding (ambient) air temperature and the specific PV modules used equals NOCT= $47 \pm 2°\mathrm{C}$, [44] (regarding NOCT, it is important to emphasize that commonly used eq.(5) in fact overestimates cell temperature, [47], but for the general purpose of this study, i.e. to prove HYS feasibility, the mentioned influence would not be significant).

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, i.e. according to the energy balance equation it follows,

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

Rejected heat is energy potential that can be used for hot water preparation and in that sense there are lot of investigations where different hybrid PV/T concepts are proposed and analyzed in detail, [12],[32,33],[43],[48] to utilize that possibility. These hybrid PV/T systems are able to simultaneously produce electricity and hot water, and for these kinds of systems the overall energy efficiency reaches an average of 60% up to 80%, in accordance to the specific PV/T concept chosen. In our case, the calculated heat loss (dissipated heat in the PV system) equals an approximate 85 % average and a yearly trend is presented in Fig. 3 so as to present a specific potential.

Fig. 3 Dissipated heat versus available solar energy for HYS

Hence, around 15.000 kWh (1,470 kWh/m^2) per year is the potential for hot water preparation, if dissipated heat is utilized from the PV panel through the implementation of a specific cooling technique for PV panels or through implementation of a hybrid PV/T system. In real circumstances, the achieved hot water temperature level is crucial to determine effective usage of the above mentioned quantity in available heat waste; therefore the realistic value could be somewhat lower than the above mentioned.

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,

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

In relation to the previously elaborated approach, it was possible to simulate PV system performance for the specific geographical location where the HYS was tested, using the average solar irradiation data, [44] and with an inclination of the PV panels to 25°. So according to the available experimental data and above specified approach, PV system performance parameters are presented in Table 1. In Table 1, it is noticeable that an installed PV system in HYS can annually produce around 2.500 kWh of electricity with an average PV electrical efficiency of 14.5%. The values for the cell temperature in Table 1 are slightly corrected due to shadowing effects and other circumstances that are specific for the chosen geographical location where the HYS was tested. 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 and as it was previously specified, the engaged electric power ranged from 600 W to 1.100 W in correspondence with the working regime.

Table 1 PV system performance parameters in HYS

Nevertheless, specific energy demands for the HYS are in accordance with the average engaged daily working time, which can range in general from 4 h up to 12 h (in accordance with the type of building facility, general occupants' habits and working regime). We have provided a HYS simulation of yearly electric demands as the function of expected daily working hours (operating time) to check its autonomy and the results are presented in Fig. 4. The simulations were performed for a range of daily operating times, from 4 hours/day up to 12 hours/day. If we analyze HYS demands for electricity, and if we assume that the average HYS daily working time is around 8 hours per day, it can be noticed that the installed PV system can easily cover all HYS energy demands from April to October and the only critical period would be in winter period according to the simulated results (i.e. months of January and December). Based on the simulation results, in critical winter months, energy demands would not be covered at around 23% of the time, therefore, grid electricity should be used to ensure total system autonomy (in the herein analyzed case, a PV system was first designed for summer operation and we wanted to check its winter PV system autonomy additionally where we found that from 10% up to 30% of demands would not be covered in critical winter months, in accordance with the average daily working hours).

Fig. 4 HYS demands for electricity as the function of estimated daily working times

Another option is to install additional PV panels, i.e. to increase the installed electric power of the PV system. In our case, to obtain total autonomy, up to 8 hours/day of engaged installed electric power of the PV system should be increased up to 2.0 kW for the whole year, i.e. one additional panel should be added (for example, to achieve a 10 hour autonomy per day, two additional panels would be sufficient to cover all electrical demands for the HYS). Hence, for the herein analyzed and tested HYS, with an average working time of 8 hours/day, the sufficient installed electric power of the PV system would be 2.0 kW using 4 batteries, each with a capacity of 330 Ah. In the case of cloudy days, the HYS autonomy can significantly be disturbed and it can be a critical issue for HYS operation in cases where HYS is used in remote areas that do not have connections with grid electricity. In a present configuration system, i.e.

regarding the battery storage design, the system can provide autonomy from 10-12 hours in summer operation and from 6 to 7 hours in winter operation. As a result, battery storage needs to be carefully designed to provide an electricity buffer on cloudy days. The herein proposed HYS is assumed to be used in the majority of summer (or also spring/autumn), in geographical locations with mild climates where PV system autonomy would be around 10 hours/day.

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. In relation to the possible working regime, overall HYS energy efficiency can be calculated for summer period as follows,

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

And also for winter period,

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

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 COP_{av} value (for the whole year), with engaged compressor power and incoming solar radiation, respectively,

$$\bar{\eta}_{HYS} = \bar{P}_{comp} \cdot \frac{\mathrm{COP}_{av}}{\dot{E}_{solar}} = \frac{\bar{P}_{comp} \cdot \mathrm{COP}_{av}}{G_s \cdot A_{PV}}, \tag{10}$$

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

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

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, [45] and measured average engaged compressor power, it was possible to calculate overall HYS energy efficiency, i.e. its average value $\overline{\eta}_{HYS}$ for the expected COP range (according to experimental experience, [42] it ranges from 4.0 to 6.0). For previous circumstances, calculation results for $\overline{\eta}_{HYS}$ are presented in Fig. 5, i.e. average expected values for specific months and expected COP_{av} range value.

Fig. 5 Yearly overall HYS energy efficiency trend as the function of the COP_{av} value

For the expected COP_{av} range values depicted in Fig. 5, the overall HYS average energy efficiency ranges from 50% up to 86% per cent for summer period and from 100% to over 200% in winter period. It is therefore obvious that the heat pump system acts as a kind of efficiency booster in this specific hybrid energy concept. Furthermore, in Fig.5, it can also be noticed that the lowest values of overall energy efficiency are achieved in summer months, although engaged compressor power is almost twice as low compared to winter period. The reason for this is higher solar energy input into the HYS for summer period in comparison to winter period, hence a lower overall energy efficiency value in a summer working regime.

Therefore, wherever possible, regarding favorable (available) climate circumstances, it is preferable to integrate a heat pump system into the hybrid energy system as it was also the case in this analysis.

Finally, it can be concluded that the proposed HYS is certainly energy efficient, but the feasibility (economic) aspect of it should also be analyzed, which is done in the next section of the manuscript using LCOE analysis.

5. HYS produced energy feasibility aspect

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, i.e. ways how HYS can be assembled in commercially applicable conditions, in accordance with the situation of each potential user and relating to this aspect we have further covered the most probable 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.

A second option is to add a PV system, which calls for an overall investment of approximately 3,700€, namely for the PV system and the modification of the existing heat pump system. Finally, the third option is to buy a new HYS, i.e. a set heat pump with an integrated boiler for the hot water preparation and a proper PV system, which calls for an investment of approximately 4,300€.

Regarding the investment options, the HYS can be purchased by one's own capital or credit. If the HYS is bank credit purchased, the expected interest rate would range from 5% to 8% and the expected reimbursement would approximately last 6 years. One has to keep in mind that the overall real net investment is increased to approximately 4,400€ , due to bank fees that are usually applied. According to the experimental experience for a specific geographical location, the average HYS yearly COP_{av} can be taken as COP_{av}=5.0, where in these circumstances the overall expected average HYS yearly energy output will be around 12,500 kWh/year (which corresponds with average HYS daily operation in the amount of 10 hours/day). However, in the upcoming feasibility analysis we will take into account an annual PV system degradation in the amount of 0.5% per year and which will finally affect the slightly reduced HYS energy output (slight reduction is expected as we talking about a relatively small hybrid energy system). In the continuation of the feasibility analysis, we have predicted an investment for the novel HYS through an own capital or credit option, so that both possible options could be covered.

In order to estimate the cost of overall HYS produced energy, a LCOE framework was used, [49], where the LCOE overall HYS produced energy can be estimated as a total life cycle cost ratio, AC and average HYS annual output, $\mathrm{EO_{HYS}}$, respectively,

$$\mathrm{LCOE} = \frac{\mathrm{AC}}{\mathrm{EO_{HYS}}} \tag{14}$$

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

$$\mathrm{AC} = \mathrm{IC} \times \mathrm{CRF} + \mathrm{OM}, \tag{15}$$

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

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

In the previous eq. (16), n (years) represents amortization period and $p(\%\text{p.a.})$ represents interest rate.

To estimate the LCOE magnitude for the herein analyzed HYS, the following input parameters were adopted and are presented in table 2.

Table 2. Input parameters for LCOE calculation in HYS

According to the previously elaborated analytical approach and specified input parameters we have calculated LCOE for these circumstances which equal 0.060 € /kWh. Additionally, if HYS is purchased via cash, LCOE then equals 0.044 € /kWh. If HYS is assembled without a PV system, only including a modified split heat pump system with heat recovery, the LCOE will be around 0.016 € /kWh for credit scenario and only 0.012 € /kWh for cash investment.

The average retail price for electricity in EU households ranges from 0.15 € /kWh up to 0.30 € /kWh, [50] varying from country to country and depending on suppliers' fees, hence, it is clear that the HYS has proven its economic viability, with respect to the produced energy cost, particularly in the case of increased daily working hours. If we calculate LCOE only for the PV system, it is profitable to take electricity from the PV system as the LCOE equals 0.14 € /kWh (in that case, the LCOE economic input parameters are taken from table 2). However, as average HYS daily operation time significantly influences the magnitude of the LCOE, in the continuation of the paper, a sensitivity analysis was provided to determine the mentioned influence for cash and credit investment option.

Finally, it can be concluded that the herein analyzed hybrid energy concept presents an economically viable option, as the price of produced energy is certainly competitive with current energy prices on the market, especially for countries with mild climates (like the Mediterranean), where heat pump technology can be efficiently used throughout the year.

5.1. LCOE sensitivity analysis in relation to HYS average working hours

According to field experience and performed measurements, the primary energy source for the HYS is electricity. A PV system was optimized to ensure total HYS autonomy for the number of 6 to 12 working hours per day (depending from operation mode). Namely, a PV system design focus was aimed to cover the period from April to October, as it is assumed that a HYS would be the most attractive solution for touristic building facilities in geographical locations with a Mediterranean climate. The analysis is provided for scenarios where the HYS is driven by a PV plant, taking LCOE magnitude as the most unfavorable case. Hence, according to the previously elaborated LCOE calculation framework, we have calculated the LCOE magnitude as the function of the HYS expected average working hour range for a credit and cash option (the LCOE input parameters are the same as the ones specified in table 2).

The LCOE calculated result carries a noticeable impact, i.e. its range is presented in Fig. 6 as the function of average working hours for a credit and cash investment option. An empirical LCOE dependence in relation to average daily working hours for the HYS can be expressed as follows for a cash or credit option,

Fig. 6 LCOE as the function of HYS daily working hours

$$\mathrm{LCOE}_{\mathrm{cash}}(€/\mathrm{kWh}) = 0.4391 \cdot \tau_d^{-1.009} \qquad (17)$$

$$\mathrm{LCOE}_{\mathrm{credit}}(€/\mathrm{kWh}) = 0.5891 \cdot \tau_d^{-1.006} \qquad (18)$$

The above specified equations, eq. (17) and eq. (18) can be used to estimate LCOE magnitude for specified average working hours (for HYS technical characteristics elaborated in this paper). For the previous circumstances, the calculated produced energy price ranges from 0.035 €/kWh up to 0.11 €/kWh for a cash option and from 0.049 €/kWh up to 0.15 €/kWh for a credit option, as shown in Fig. 6. Regarding the presented LCOE range in Fig. 6, the overall produced energy cost is competitive in all cases with the current price of electricity on the market.

6. Conclusion

The focus of this paper was to analyze a specific hybrid energy system [39], where investigation was related to overall HYS energy efficiency calculation and its feasibility evaluation aspect, which affects its possible market implementation. Regarding the overall efficiency analysis, it can be concluded that for an average expected working time of 8 hours/day, the specific HYS will have an overall energy efficiency varying from 50% to 86% in summer period and from 100% up to 258% in winter period. In that sense, it is interesting to notice that the heat pump system acts as an efficiency booster for the HYS. On the other hand, the specific value for total HYS energy efficiency relates to the average COP value, which according to experimental experience, will range from 4.0 to 6.0 for locations with a Mediterranean climate. A HYS simulation was also performed for the needs of electricity and was used as function of estimated working hours. Therefore, it can be concluded that the herein analyzed HYS will have an autonomy of up to 8 hours/day with a 2.0 kW PV system. These 8 hours correspond to the system's expected average daily working time in real circumstances.

An HYS economic analysis was also discussed in detail; the results show that the cost of produced energy (heating/cooling capacity and hot water preparation) is competitive with current retail prices of electricity. Namely, the produced energy price will range from 0.035 € /kWh up to 0.15 € /kWh, in accordance with the average HYS daily work time and investment scenario, i.e. own capital or credit option. As the current retail price of electricity in the EU is definitely above 0.15 € //kWh, it is clear that the HYS is a financially appealing option and that investment in the novel HYS is a feasible one. In countries with government subsidies for implementation of renewable energy sources, HYS produced energy price would additionally be reduced, in comparison with the above specified values, and the expected produced energy cost would certainly be under 0.1 € //kWh.

Finally, we have proven that it is possible to assemble an efficient and economically viable renewable energy system using market available energy technologies. Therefore, in circumstances where we have appropriate building facilities and that are located in mild climates, the herein analysed hybrid energy solution should certainly be considered as an option. It is of great importance to emphasize that the majority of existing users already use single energy technologies that are mentioned in this paper and only need to be redone to form the proposed HYS. In that sense, it is also important to underline the role of providing the necessary expertise to the engineers and the general information to the stakeholders involved, so as to make the proposed solution better known and trusted; dissemination of targeted information has always been a critical part for the promotion of renewable. Finally, and besides the fact that the HYS represents a renewable energy system, it features a second major advantage, namely its independence from electric grid, if considered with a proper battery storage design. In that sense, it would be simple and effective to implement the HYS in isolated and rural areas with electricity supply issues.

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Nomenclature:

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

AC - Total life cycle cost, €

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

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

Tables:

Month	t_a (°C)	G_s (W/m²)	t_{cell} (°C)	η_{PV} (%)	E_{el}(kWh/month)	τ_d (h/d)
January	7.6	289	22	15.5	127	9
February	8.2	330	25	15.3	159	11
March	10.5	408	31	14.9	211	11
April	13.9	400	35	14.6	233	13
May	18.7	398	41	14.2	268	15
June	22.5	440	47	13.7	278	15
July	25.4	449	51	13.5	287	15
August	24.9	472	52	13.4	261	13
September	21.4	410	45	13.9	227	13
October	16.9	395	38	14.4	198	11
November	12.3	311	29	15.0	129	9
December	8.9	250	22	15.5	110	9

Table 1. PV system performance parameters in HYS

LCOE input parameters	
Interest rate (*p*)	7%
Amortization period (*n*)	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

Table 2. Input parameters for LCOE calculation in HYS

Figures:

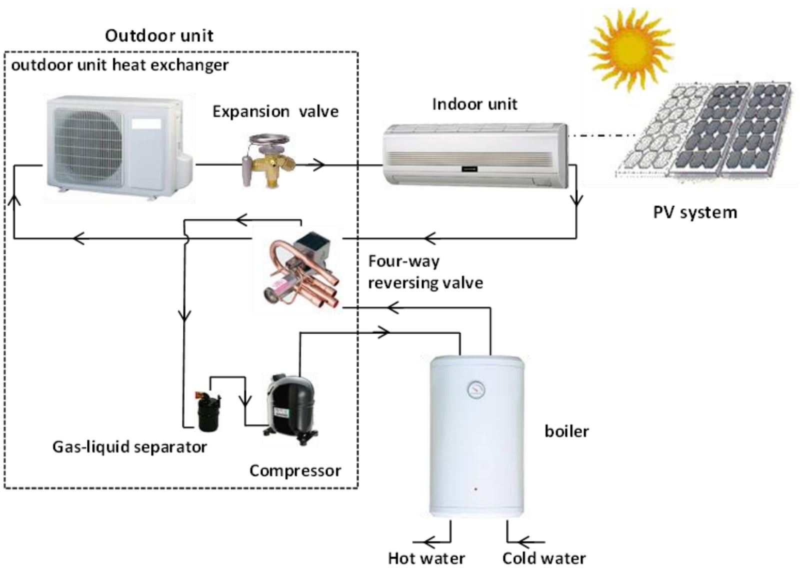

Fig. 1 The hybrid energy system (HYS) schematic proposed in [39]

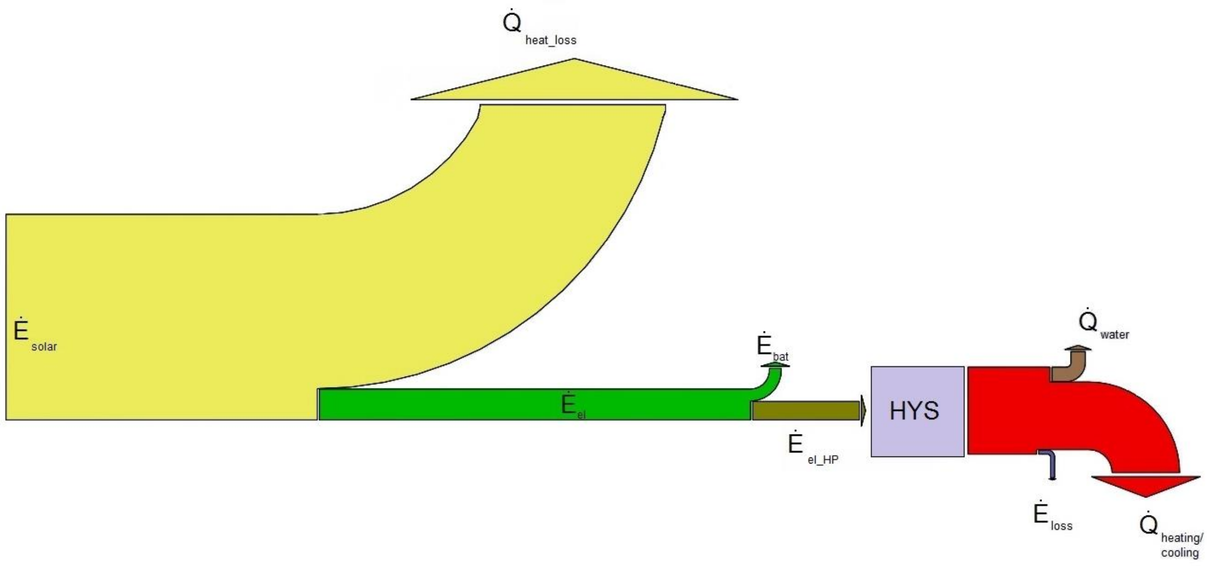

Fig. 2 General HYS energy flow chart

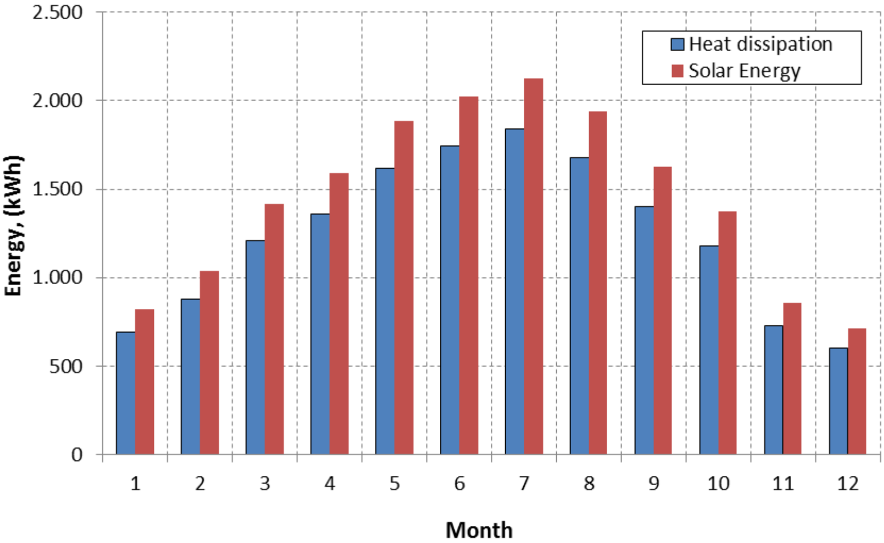

Fig. 3 Dissipated heat versus available solar energy for HYS

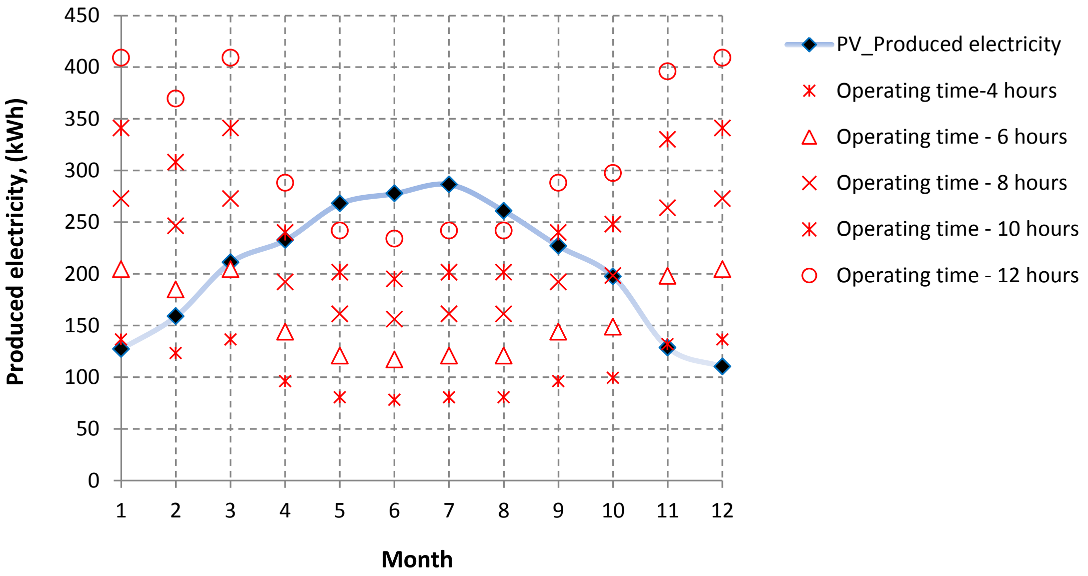

Fig. 4 HYS demands for electricity as the function of estimated daily working times

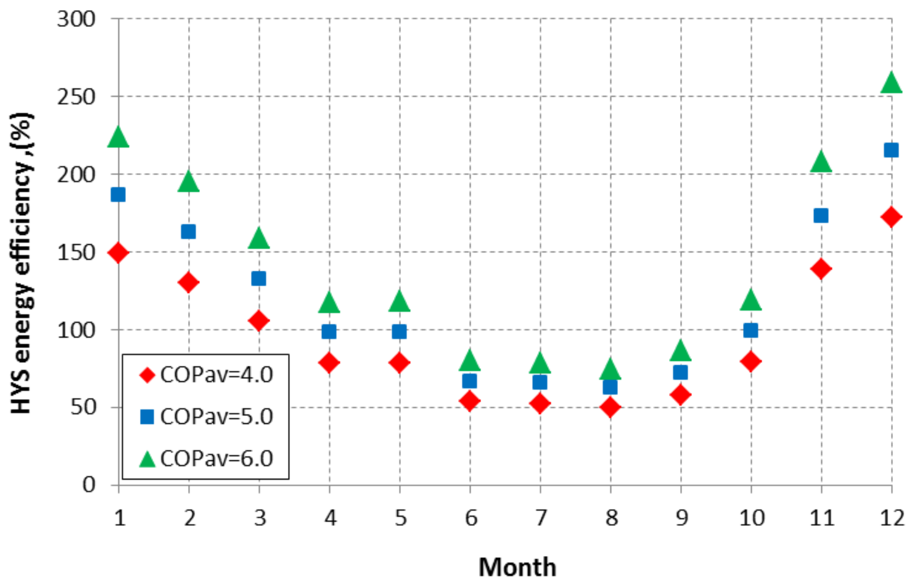

Fig. 5 Yearly overall HYS energy efficiency trend as the function of the COP_{av} value

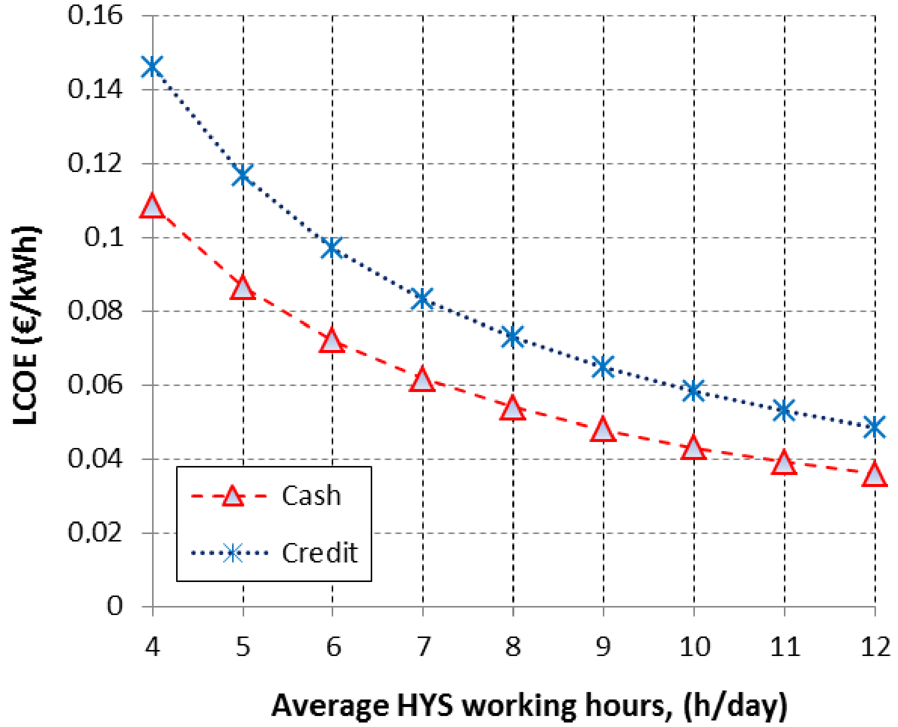

Fig. 6 LCOE as the function of HYS daily working hours