Solar hybrid PVT coupled heat pump systems towards cost-competitive NZEB

Asier Sanz[1], Raquel Fuente[2] and Antonio J. Martín[3]

[1] TECNALIA Research & Innovation, Derio (Spain)

[2] University of the Basque Country UPV/EHU, Bilbao (Spain)

[3] Energy Panel, Lucena (Spain)

Abstract

The high energy consuming building sector needs to meet both electricity and heat demands. In a nearly zero energy building scenario most of the consumed energy would be generated locally by means of renewable solutions that nowadays seem not to provide an attractive cost-competitiveness. Solar based technologies tend to be the most promising ones, but for high densely populated and restricted areas the usual photovoltaic or thermal single approaches may not be efficient enough. The current work is focused on the analysis of dual use of solar resource by means of hybrid collectors and their smart combination with heat pumps through predictive control strategies towards entire-lifetime feasible solutions. A techno-economic analysis of the proposed system, market standard solutions and different solar coupled heat pumps has been carried out for multiple domestic hot water application case studies. The results show the cost-competitiveness of the solution in different European climates.

Keywords: PVT, heat pump, hybrid, NZEB

---

1. Introduction

According to the International Energy Outlook of 2017 the global energy consumption continues rising. The reference for 2015 was 575 quadrillion British thermal units with a 28 % estimated increase by 2040. The European Commission states that buildings are responsible for 40 % of the energy consumption and 36 % of CO_2 emissions, and pretends to reduce their impact through measures. The vast majority of those buildings need to meet both electricity and heat demands, for domestic hot water (DHW) and space heating/cooling (H&C). In the close nearly zero energy building (NZEB) scenario most of the consumed energy would be generated locally by means of renewable resources. Unfortunately, current renewable solutions could not provide an overall, simultaneous, integral and local solution to this need ensuring cost-competitiveness.

However, solar energy is available all over the surface of the earth. Thus, buildings should try to take more value form every beam of light reaching their envelopes. Photovoltaics (PV) are becoming today, and solar thermal (ST) applications in the past, widely used for built environment on-site generation. Nevertheless, for high densely populated and shadow-restricted areas this kind of single approaches are not enough to satisfy building energy needs. Detailed analysis of solar resource in built environments shows that not only roofs but also façades should be considered with higher efficiency solar conversion devices such as PVT (Sotehi et al, 2016).

Harnessing solar energy should be a must for new and refurbished buildings, but when the Sun is not shining and energy stores are empty solar based solutions always require back-up systems that reduce their competitiveness. The electrical grid makes things easier for some loads, but thermal needs are still highly fossil fuel dependent in great part of Europe. However, heat pumps (HP) seem to be a promising technology towards a reduction of CO_2 emission related to buildings thermal comfort and enable the use of the electrical infrastructure to use them as back-up source. Therefore, if solar and HP are individually suitable for electricity and heat generation, merging them in a unique hybrid system will enable obtaining even higher benefits. Anyway, it is usually hard to inter-compare technologies and quantify those real benefits to simply conclude which one shows overall greater performance. Thus, within the current work a dual techno-economic approach is proposed in order to shed some light among solar merged HP based solutions for different case studies.

doi:10.18086/eurosun2018.02.24 Available at http://proceedings.ises.org

2. Addressed technologies

The hybrid systems coupling solar collection and HPs could lead to multiple solutions. In the current work, seven different technological solutions have been analysed, focused just on their DHW application version. Every system has been selected according to its cost-competitiveness potential and/or current market share. These solutions could be classified into the following three different categories.

- Well-known non-renewable technologies.
- Commercially available HP based systems and their combination.
- One additional PVT smart coupled HP solution.

2.1. Non-renewable

Although this kind of solutions will gradually loose relevance and probably will not be part of the future energy ecosystem, still represent nowadays a huge market share in most of the countries (BSRIA, 2014). The most common non-renewable solutions for satisfying locally building heat demands are electric and gas boilers. Their simplicity, end-user acceptance and centralized energy grid infrastructures make these solutions hard to be beaten despite their high operation cost and service uncertainties. Thus, within the current analysis both boiler solutions have been considered.

2.2. Conventional HP base

The HP solutions market sector is experiencing a significant growth. The household appliance sales for all heating and cooling (H&C) market technologies increased by 20 % in 2015 and show a great potential for near future (EurObservER HPs barometer, 2016). The emerging trend over the last years is that: 1) air-source units are clearly gaining market share to the detriment of the ground-source market, 2) the use of air as the energy vector is taking advantage of record temperatures that has boosted the cooling market, 3) the energy independence and the growth of the self-consumption markets are driving another trend that can turn as a further advantage, 4) the units must reduce the greenhouse emissions with low global-warming potential (GWP) refrigerant selection, load reductions and efficiency improvements, and 5) a greater performance enhancement should come by combining with solar based systems. According to these trends, the air-water source HPs (awHP) and their combination with an additional uncoupled parallelly installed PV system has been included in the study in order to analyse also the performance of the a solar electrically driven solution.

Furthermore, solar thermally assisted HPs have also been considered. The approach of direct/indirect driven HP solution by means of solar thermal collectors makes scientific sense in order to improve efficiency and renewable share. Economically it may still be interesting for high power systems, but for single building scale application the solution seems to be far from being cost-competitively attractive in the near future if no disruptive innovation appears. Thus, the thermally driven HP has been studied trough the direct expansion solar assisted heat pump (DX-saHP) concept, first studied by Sporn and Ambrose (1955) and more recently widely worked out by Li et al (2007a, 2007b). In DX-saHP systems the conventional air or water evaporator exchangers are replaced by bare flat-plate collectors where the refrigerant evaporates after expansion. This kind of collectors absorb the heat transferred by convection with the ambient and solar radiation. In the same way as for the awHP concept, the solar assisted HP (saHP) solution has also been analysed with a non-merged and parallelly installed PV system to quantify the extra solar electrical potential.

2.3. The proposed solution

The proposed solar hybrid PVT coupled HP solution is a fully-integrated system comprising an unglazed hybrid solar collector, a DX-saHP and an overall system control (Fig 1). The base of the technology has been widely studied before by different research groups for comparative analysis (Pei et al, 2008) and experimental studies (Ji et al, 2008; Fu et al, 2012). The union of PV and solar thermodynamic technologies in one collector enables the simultaneous electricity and heat generation and in a kind of symbiosis both technologies work optimally without mismatching the performance of the other (Jie Ji et al, 2009) like occurs in conventional PVT where a trade-off between thermal and electric performance of the collector output is needed. Thus, the dually assisted HP increases significantly the total annual use of the solar resource while the primary energy consumption is reduced.

The proposed solution innovations are focused on two critical elements impacting the solution cost and performance, the solar hybrid collector and the overall system control. On the one hand, the proposed lightweight collector is almost a conventional PV module with a thermal recovery unit as backsheet, with no isolation or additional components. On the other hand, the day-ahead prediction service enables achieving higher solar fractions and self-consumption ratios, optimizing the overall system performance without affecting end-user comfort or grid impact.

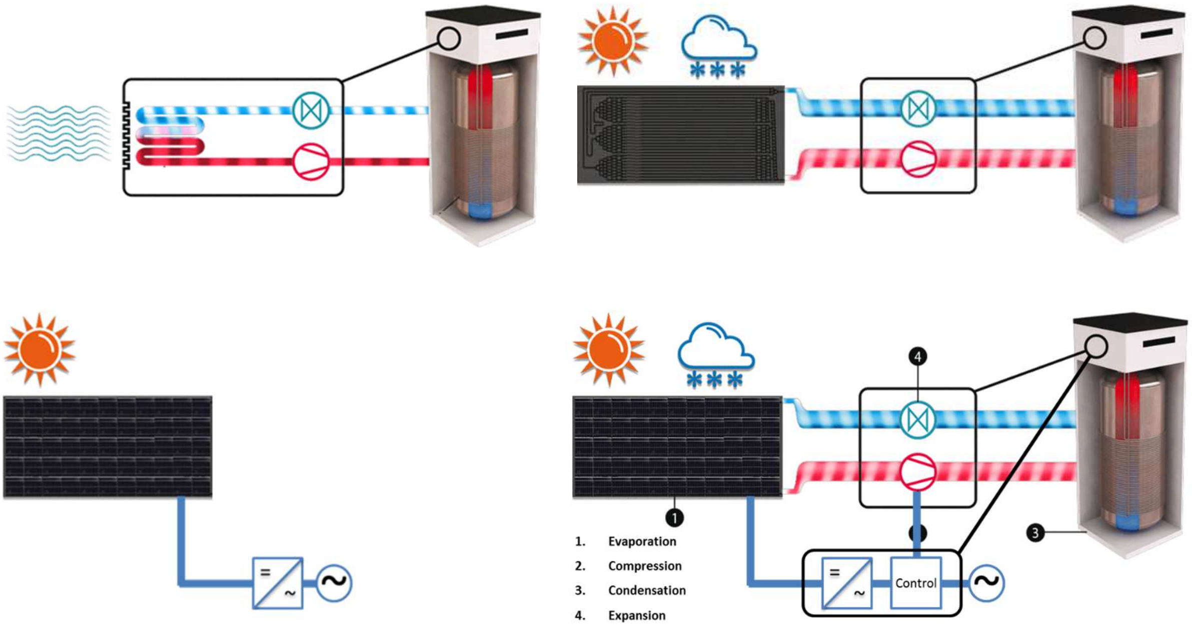

Fig. 1: Scheme of the different HP solutions analysed in the study, awHP (up left corner), saHP (up right), additional PV system (left low corner) to be added to saHP to generate the hybrid versions PV+saHP or PV+awHO, and finnaly the PVTaHP (low right)

3. Methodology

The assessment of new disruptive technologies or incremental innovations is commonly addressed just from cost or performance side, but real market success and massive deployment tends to come from a delicate balance of both. In the field of NZEB, the energy solutions will come from a technically feasible but economically market-competitive technology and/or systems combinations. Thus, as a previous step of the proposed PVT dually coupled saHP technology development, the potentially more-competitive different solutions comparative techno-economic analysis is needed.

The holistic techno-economic analysis carried out pretends to address the energy performance and economics as a whole, trying to clarify the traditional gap between the great efficiency results of new research results and real market standard solutions lower cost. In this sense, the implemented methodology is based on a simple quantitative multiple-approach of solutions entire lifetime costs and system performance, in order to conclude with the following key performance indicators (KPI).

- Financials: investment, operation & maintenance costs, return on investment and internal rate of return.
- Energy: building annual primary energy consumption, seasonal performance factor and self-sufficiency.
- Mixed: levelized cost of energy (LCOE).

3.1. Economics

The economic assessment of each addressed technology is based on traditional capital expenditures (CAPEX) and operating expenditures (OPEX). The CAPEX is essentially composed of system cost and turnkey installation. The OPEX is obtained as sum of system grid energy consumption, periodic maintenance labours and plausible lifetime component replacement. The market-dependent CAPEX and OPEX systems figures are usually high-sensitive, so retail prices, maintenance services and energy costs used in the analysis are a consequence of a deep market study. In the same way, in order to minimise the uncertainty of non-technology related phenomena, no financial costs are assumed but conservative energy costs updates are included.

3.2. Performance

The performance of the analysed solutions is based on annual operation simulation, for same load profiles and operating conditions (irradiation, ambient and tap water temperature). The tool determines the annual performance based on hourly-profiles of one representative day of each month in one year. The models used for each technology are listed by category below. One representative day of each of the

Non-renewable

The non-intermittent source for these grid dependent technologies makes easier their black-box basic performance modelling. Thus, the models implemented for electric (eq. 1) and gas (eq. 2) boilers are just characterized by constant conversion efficiencies (for each month and hour of day), where no start-stop energy losses or lifespan degradation is considered. The demand is satisfied by instant operation of units with no thermal store. According to conventional market available electric and natural gas boilers, the following efficiencies have been used $\eta_{Eboiler} = \eta_{NGboiler} = 0.9$.

$$E_{Load} = \eta_{Eboiler} \cdot E_{Egrid} \qquad \text{(eq. 1)}$$

$$E_{Load} = \eta_{NGboiler} \cdot E_{NGgrid} \qquad \text{(eq. 2)}$$

Conventional HP based

Four out of the seven analysed technologies of the study are based on market available conventional HP solutions. The cost and performance of these systems are often highly dependent. The scope of the study is focused on the assessment of different technological solution more than on specific products. Thus, in order to minimise the impact of comparing high performance (high cost) solutions versus cheaper (poorer performance) options, the core of all HP variations has been maintained the same. This approach enables the possibility of using the same compressor model and parameterization for both HP versions, the awHP and DX-saHP.

This way the model for the determination of the performance of the awHP is obtained through the following equations. The evaporation temperature is defined for 10 K below the ambient (eq. 3), but limited to a maximum of 15 ºC. Then, the awHP evaporator capacity could be obtained, with an error below 3 %, as function of the evaporation temperature (eq. 4) and the polynomic coefficients ($q_0 = 1182.6$; $q_1 = 49.25$; $q_2 = 0.6213$) for a cycle-representative condensation temperature of 40 ºC, as well as the compressor electric consumption (eq. 5) for the following parameterization ($p_0 = 396.14$; $p_1 = 2.7365$; $p_2 = -0.0734$; $p_3 = -0.0037$), fan electric consumption P_{fan} and annual equivalent day average defrost energy losses $P_{defrost}$. Then, the awHP coefficient of performance (COP) could be calculated (eq. 6) and the tank energy balance is obtained (eq. 7) for whole day state integration, where no thermal losses are considered. Finally, the electric grid consumption (eq. 8).

$$T_{eva} = T_a - \Delta T \qquad \text{(eq. 3)}$$

$$Q_{awHP} = q_0 + q_1 \cdot T_{eva} + q_2 \cdot {T_{eva}}^2 \qquad \text{(eq. 4)}$$

$$P_{awHP} = p_0 + p_1 \cdot T_{eva} + p_2 \cdot {T_{eva}}^2 + p_3 \cdot {T_{eva}}^3 + P_{fan} + P_{defrost} \qquad \text{(eq. 5)}$$

$$COP_{awHP} = {(Q_{awHP} + P_{awHP})}/{P_{awHP}} \qquad \text{(eq. 6)}$$

$$Q_{tank} = \sum_{h=0}^{23} (Q_{awHP} - E_{Load}) \qquad \text{(eq. 7)}$$

$$E_{Egrid} = {E_{Load}}/{COP_{awHP}} \qquad \text{(eq. 8)}$$

Using the same approach, the DX-saHP performance is described through the equations below (eq. 9-14). The modifications are applied just to two expressions. On one the hand, the evaporation temperature (eq. 9), where the solar gain needs to be considered. The collector-based evaporation was modelled and validated (Moreno-Rodriguez A. et al, 2012), where in absence of irradiation the evaporation temperature is decreased ($T_{G_0} = 8$ K) but for standard test conditions (STC) the evaporation temperature could be increased 15 K above the ambient ($k_G = 23.1$). On the other hand, for the DX-saHP electric consumption (eq. 11) the evaporator fan and defrosting consumptions are removed.

$$T_{eva} = T_a - \Delta T - T_{G_0} + k_G \frac{G}{G_{STC}} \qquad \text{(eq. 9)}$$

$$Q_{DX-saHP} = q_0 + q_1 \cdot T_{eva} + q_2 \cdot {T_{eva}}^2 \qquad \text{(eq. 10)}$$

$$P_{DX-saHP} = p_0 + p_1 \cdot T_{eva} + p_2 \cdot {T_{eva}}^2 + p_3 \cdot {T_{eva}}^3 \qquad \text{(eq. 11)}$$

$$COP_{DX-saHP} = {(Q_{DX-saHP} + P_{DX-saHP})}/{P_{DX-saHP}} \qquad \text{(eq. 12)}$$

$$Q_{tank} = \sum_{h=0}^{23}(Q_{DX-saHP} - E_{Load}) \qquad \text{(eq. 13)}$$

$$E_{Egrid} = {E_{Load}}/{COP_{DX-saHP}} \qquad \text{(eq. 14)}$$

For the additional parallelly installed PV systems, the electric performance is obtained from satellite-based data and PVGIS models. Then, for the PV plus awHP or DX-saHP solutions the grid net consumption equations (eq. 8 and 14, respectively) need to be rewritten (as eq. 15 and 16). The PV and HP systems are just electric grid connected, so depending on the operational mode (self-consumption, net balance, net billing or off-grid) the PV generation should be computed in a different way (totally, partially or not useful). .

$$E_{Egrid} = {E_{Load}}/{COP_{aw}} - E_{PV}(OM) \qquad \text{(eq. 15)}$$

$$E_{Egrid} = {E_{Load}}/{COP_{DX-saHP}} - E_{PV}(OM) \qquad \text{(eq. 16)}$$

The proposed solution

In the case of the PVT coupled saHP, the expressions used above are slightly modified to consider the singularities of both, the hybrid collection of sunlight and the full-integration of the electric performance. The first variation is made on the evaporation temperature equation, where the saHP version (eq. 9) is evolved (eq. 17) to include the PVT collector PV layer irradiation attenuation. This peculiarity is introduced as a function of the electrical STC conversion efficiency (η_{PV}), neglecting higher operation temperature conversion losses, and considering it is only applied to the PVT collector where active PV cells are placed, by means of the packing factor (*pf*). The second modification is a result of the fully merged operation of both systems, the PV side of the PVT field and the HP compressor. The active management of the PV generation for driving variable speed compressor enables instant self-consumption, minimising the HP grid electrical consumption and boosting the overall COP (eq. 19).

$$T_{eva} = T_a - \Delta T - T_{G_0} + k_G \frac{G \cdot (1 - \eta_{PV} \cdot pf)}{G_{STC}} \qquad \text{(eq. 17)}$$

$$Q_{PVTaHP} = q_0 + q_1 \cdot T_{eva} + q_2 \cdot {T_{eva}}^2 \qquad \text{(eq. 18)}$$

$$P_{PVTaHP} = p_0 + p_1 \cdot T_{eva} + p_2 \cdot {T_{eva}}^2 + p_3 \cdot {T_{eva}}^3 - E_{PV}(OM) \qquad \text{(eq. 19)}$$

$$Q_{tank} = \sum_{h=0}^{23}(Q_{PVTaHP} - E_{Load}) \qquad \text{(eq. 20)}$$

$$COP_{PVTaHP} = {(Q_{PVTaHP} + P_{PVTaHP})}/{P_{PVTaHP}} \qquad \text{(eq. 21)}$$

$$E_{Egrid} = {E_{Load}}/{COP_{PVTaHP}} \qquad \text{(eq. 22)}$$

4. Results

Multiple case studies have been carried out to determine the potential of the analysed technologies under different operating conditions. In order to provide a better comprehension of the results, the case studies shown in the current work have been focused just on a DHW application for a typical 4-member family. The consumption profiles used for thermal loads quantifications are the ones established in the Ecodesign Directive (European Union, 2013) for the XL profile, resulting on 6961 kWh/year heat demand.

1. Baseline

The following case study is the one that has been used as the baseline along the current work. The study is located at Barcelona and the additional parameters for full characterization of the analysis are described below.

The main economic parameters for each technological solution are listed on Tab. 1. The energy cost is hourly variable for electricity (9.91-13.52 c€/kWh) and constant for natural gas (0.095 c€/kWh). Average annual grid energy cost increments have been considered for electricity (3 %/year) and natural gas (2 %/year).

Tab. 1: Economic parameters for the baseline case study of Barcelona

CAPEX & OPEX (just maintenance)	**E boiler**	**NG boiler**	**saHP**	**PV + saHP**	**awHP**	**PV + awHP**	**PVTaHP**
Retail price + turnkey installation (€)	600	1100	2964	4314	3155	4505	4151
Annual (revision + repair) maintenance (€/year)	0	50	20	47	20	47	35

Furthermore, the following technical parameters have been used for performance modelling and simulation.

- For the operating conditions, PVGIS irradiance and ambient temperature have been used. Monthly variable tap water temperature (8-16 °C) has been considered.
- For HP based systems a 250 l volume tank has been used, with a hot water set point of 50 °C.
- For awHP solution outdoor evaporator operation has been assumed, with a 65 W fan power and an equivalent defrost cycle consumption of 0.266 kWh/day.
- For PV added solutions, PV+saHP and PV+awHP, a 540 Wp optimum tilt (37 °) south orientation grid tie installation has been considered. The operation mode of the PV installation is self-consumption, limited to a 70 % in order to avoid transient not entire balance situations. Additional energy losses have been considered, due to temperature and low irradiance (9.7 % using local ambient temperature), due to angular reflectance effects (2.5 %), other balance of system losses (14 %), resulting on combined PV system losses of 24.3 %.
- For PVTaHP collector characterization, a 19 % electrical conversion efficiency, 85 % packing factor, normal cell operation temperature (NOCT) of 47 °C and -0.4 %/K temperature coefficient has been used. The collector PV layer performance is identical to the PV system added to the PV+saHP and PV+awHP solutions, except the cooling effect. A total of 2 collector (540 Wp) are used in same parallel connexion.
- For PVTaHP system smart control characterization, the early morning thermal store initial charge state 60 % has been considered.

With these parameters the obtained KPI results are summarised in Tab. 2.

Tab. 2: Barcelona (baseline) case study summary KPIs by technology

Barcelona (Baseline) KPIs	**E boiler**	**NG boiler**	**saHP**	**PV + saHP**	**awHP**	**PV + awHP**	**PVTaHP**
CAPEX (€)	600	1100	2964	4314	3155	4505	**4151**
OPEX (€/year)	1184	906	270	153	290	173	**126**
ROI$_{Tech.Rel.}$ (years)	4.19	4.46	10.47	-	7.69	-	
IRR$_{10}$ (%)	12.4%	8.0%	-	-	-17.9%	-	
IRR$_{15}$ (%)	22.6%	19.2%	-6.0%	-	4.3%	-	
IRR$_{20}$ (%)	25.4%	22.4%	4.1%	-	10.9%	-	
LCOE$_{10}$ (c€/kWht)	16.6	14.0	7.9	8.3	8.4	8.8	**7.7**
LCOE$_{15}$ (c€/kWht)	17.6	14.1	6.7	6.3	7.2	6.8	**5.8**
LCOE$_{20}$ (c€/kWht)	18.9	14.5	6.3	5.5	6.8	5.9	**4.9**
Primary energy consumption (kWh)	7734	7734	1616	797	1742	923	**569**
SPF (pu)	0.90	0.90	4.31	8.73	4.00	7.54	**12.23**
Self-sufficiency (%)	-11%	-11%	77%	89%	75%	87%	**92%**

According to them, the following observations could be highlighted:

- A quick CAPEX analysis shows that the proposed solution is far from the current market standard solution (electric boilers are around 7 times cheaper), still more expensive than conventional HP versions (around +40 %) but could be cheaper than installing a combined solution of 2 different systems (around -4 % for PV+saHP and -8 % for PV+saHP).
- The OPEX analysis, performance driven operational costs plus maintenance labours, show that the proposed PVT dually assisted HP offers the lowest O&M numbers (126 €/year). The closest lower O&M costs are the ones of the PV+saHP solution, 22 % above (Fig. 2 right).
- The technology related additional investment shows that each monetary unit dedicated to the PVTaHP is always returned in less than 11 years, where the most critical ROI comparison is against the saHP solution. The lifespan of the solution is above 20 years, but for shorter horizons the extra investment on the PVTaHP might be critically returned.
- The IRR analysis evidence that the extra cost of the PVTsHP solution compared to saHP and awHP needs more time to be attractive, although even for the expected 20 years operation period, figures could still not be financially acceptable for some end-users/regions with no favourable PV regulation.
- The energy performance KPIs show great figures for HP based solutions, that could significantly be improved with PV generation. The PVTaHP primary energy reduction compared to non-renewable ones is important (only the 7.35 % of current market standard consumption).
- The SPF analysis evidences the huge electrical gain due to PV energy, boosting by 2 the initial figures for saHP (from 4.31 to 8.73) and 1.88 times for awHP (from 4 to 7.54). However, the PVTaHP figures are again the greatest, mainly due to the smart control (77 % of the gain compared to PV+saHP) and the PV extra generation (6.23 %) due to the PV cooling effect of the thermal recovery backsheet (23 %, the rest of the gain compared to PV+saHP).
- In the same way as for other energy KPIs, the self-sufficiency figures of PVTaHP are above all competitors and close to full autarky, enabled by the maximization of the self-consumption and higher PV yields while maintaining low HP gross grid consumption.
- For mix KPI as LCOE (Fig. 2 left), the good energy results are merged with tighter economic figures. Even in this field the proposed PVTaHP offers more attractive cost than the cheapest renewable solution for a 10-year period (-2.5 % below saHP) and conceptually closest PV assisted HPs at 15 and 20 years.

Graphically the results are shown below.

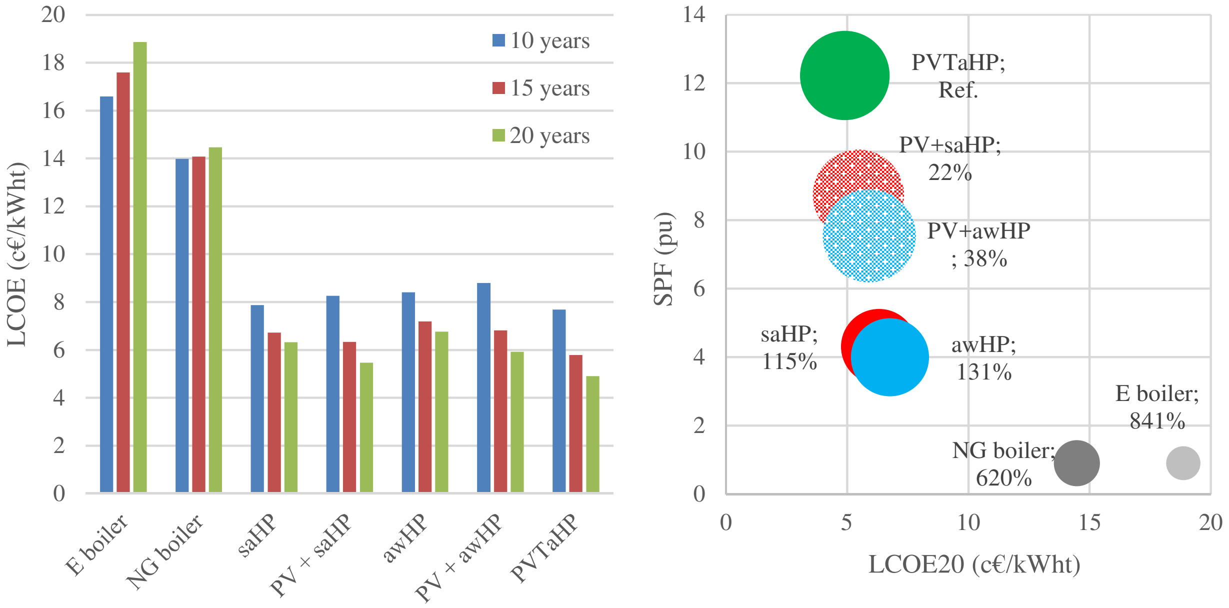

Fig. 2: LCOE for the analysed technologies and years of calculation (left) and SPF (right) versus system 20-year LCOE and CAPEX (bubble area), with PVTaHP relative OPEX comparison (labels).

The energy performance of each technological solution is a key factor for understanding the previously discussed underlaying results. Thus, the grid net energy consumption per month and technology is represented below (Fig. 3) and energy generation origin for the PVTaHP solution in Fig. 4.

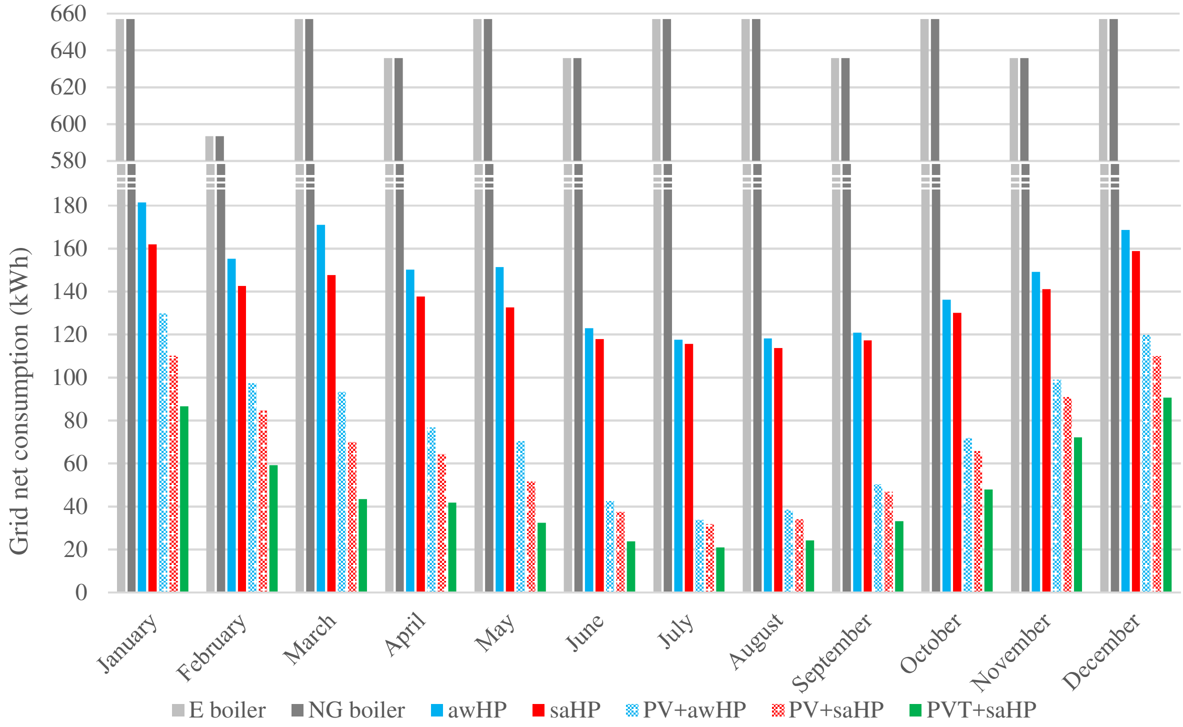

Fig. 3: Grid net energy consumption per month and technology

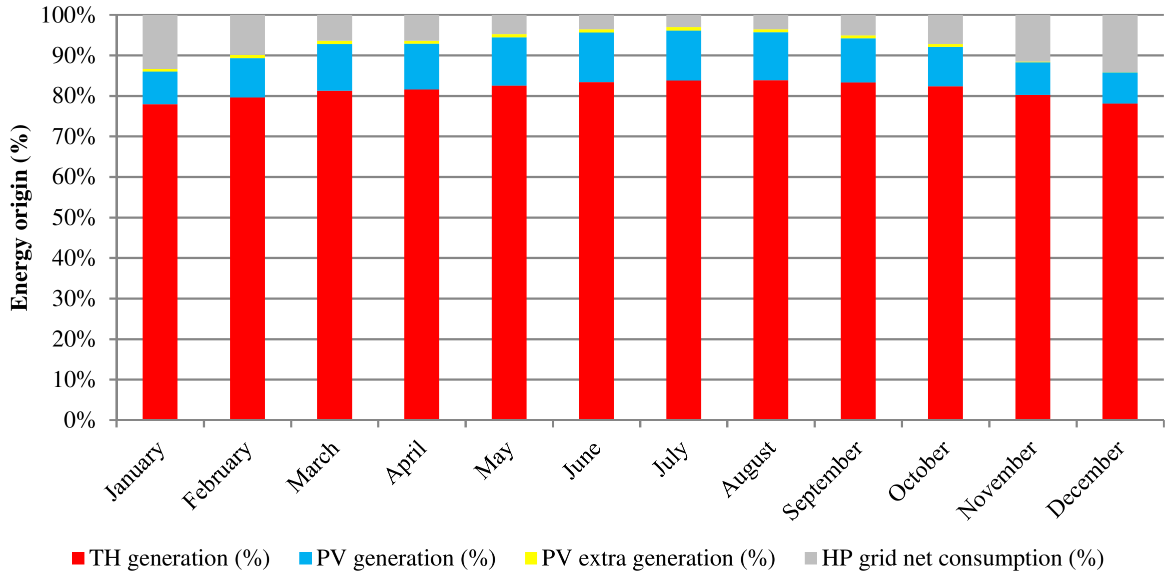

Fig. 4: Energy generation origin for the PVTaHP

2. Location

The location of the case study is usually one of the most sensitive parameters when comparative analysis conclusions are extrapolated. Thus, within the following Tab. 3 and 4 the same Barcelona baseline scenario has been obtained for London and Rome, respectively. The most important parameters on location modification are meteorological features (irradiance, ambient and tap water temperature) and energy costs (same CAPEX has been considered). For London the annual irradiation is 1300 kWh/m^2, average mean ambient and tap water temperatures are 10.9 and 5.1 ^{o}C, annual mean electricity and natural gas costs of 20.1 and 0.065 c€/kWh. For Rome the annual irradiation is 1930 kWh/m^2, average mean ambient and water temperatures are 16.61 and 8.46 ^{o}C, annual mean electricity and gas costs of 23.4 and 0.95 c€/kWh. While for Barcelona the annual irradiation is 2010 kWh/m^2, average mean ambient and water temperatures are 17.05 and 12.64 ^{o}C, annual mean electricity and natural gas costs of 11.5 and 0.96 c€/kWh. For all locations same CAPEX figures have been considered.

Tab. 3: London case study summary KPIs by technology

London KPIs	**E boiler**	**NG boiler**	**saHP**	**PV + saHP**	**awHP**	**PV + awHP**	**PVTaHP**
OPEX (€/year)	1927	630	516	381	539	404	**338**
ROI$_{Tech.Rel.}$ (years)	2.78	11.15	8.43	-	6.25	-	
IRR$_{10}$ (%)	31.4%	-	-	-	-6.1%	-	
IRR$_{15}$ (%)	37.3%	-14.8%	1.3%	-	10.4%	-	
IRR$_{20}$ (%)	38.6%	-1.4%	8.9%	-	15.5%	-	
LCOE$_{10}$ (c€/kWht)	26.5	10.2	11.1	11.3	11.7	11.9	**10.5**
LCOE$_{15}$ (c€/kWht)	28.3	10.1	10.3	9.6	10.8	10.1	**8.8**
LCOE$_{20}$ (c€/kWht)	30.4	10.3	10.1	9.0	10.6	9.5	**8.2**
Primary energy consumption (kWh)	7734	7734	1921	1379	2024	1483	**1181**
SPF (pu)	0.90	0.90	3.62	5.05	3.44	4.69	**5.90**
Self-sufficiency (%)	-11%	-11%	72%	80%	71%	79%	**83%**

The comparative analysis between Barcelona, London and Rome offers interesting results. The Mediterranean cities present similar climatology but different electricity costs, while London and Rome present closer electricity costs but different operating conditions. Regarding London, the results show that the UK cheap gas price make the boiler the hardest competitor with the lowest LCOE below 10 years and stable for longer periods, what enables a PVTaHP solution recovery. On the other hand, ROI figures show a fast return (< 3 years) of the additional investment against the electric boiler. However, the energy performance indicators show that great annual efficiency and self-sufficiency values could also be obtained in such low irradiance cold climate. In Rome the conclusion is clear for both non-renewable boilers, where double electricity cost compared to Barcelona show that the PV gain becomes even more interesting.

Tab. 4: Rome case study summary KPIs by technology

Rome KPIs	**E boiler**	**NG boiler**	**saHP**	**PV + saHP**	**awHP**	**PV + awHP**	**PVTaHP**
OPEX (€/year)	2244	897	556	329	581	354	**246**
ROI$_{\text{Tech.Rel.}}$ (years)	2.21	5.27	4.81	-	3.74	-	
IRR$_{10}$ (%)	43.4%	-0.1%	6.3%	-	17.7%	-	
IRR$_{15}$ (%)	47.4%	13.7%	18.3%	-	26.5%	-	
IRR$_{20}$ (%)	48.1%	17.9%	21.8%	-	28.8%	-	
LCOE$_{10}$ (c€/kWht)	30.7	13.9	11.7	10.6	12.3	11.2	**9.3**
LCOE$_{15}$ (c€/kWht)	32.8	13.9	10.8	8.9	11.4	9.4	**7.5**
LCOE$_{20}$ (c€/kWht)	35.4	14.3	10.8	8.2	11.3	8.7	**6.8**
Primary energy consumption (kWh)	7734	7734	1714	933	1811	1029	**660**
SPF (pu)	0.90	0.90	4.06	7.46	3.84	6.76	**10.55**
Self-sufficiency (%)	-11%	-11%	75%	87%	74%	85%	**91%**

3. Collector field

The solar gain offers greater performance figures but not always the extra investment is returned. In order to determine the impact of the solar collector field on the techno-economic figures the baseline scenario has been modified increasing by 50 % the collector area. For the PV+saHP combo just the PV field has been increased but for the PVTaHP one more collector has been considered (a total of 3 collectors).

Tab. 5: Barcelona (baseline +50 % collector field) case study summary KPIs by technology

Barcelona (+50% collector field) KPIs	**E boiler**	**NG boiler**	**saHP**	**PV + saHP**	**awHP**	**PV + awHP**	**PVTaHP**
CAPEX (€)	600	1100	2964	4989	3155	5180	**5636**
OPEX (€/year)	1184	906	282	106	301	126	**80**
ROI$_{\text{Tech.Rel.}}$ (years)	5.71	6.31	16.97	40.29	14.33	14.38	
IRR$_{10}$ (%)	-1.8%	-8.9%	-	-	-	-	
IRR$_{15}$ (%)	13.0%	8.5%	-	-	-	-15.8%	
IRR$_{20}$ (%)	17.5%	13.8%	-8.6%	-	-3.5%	-0.8%	
LCOE$_{10}$ (c€/kWht)	16.6	14.0	8.0	8.6	8.6	9.1	**9.2**
LCOE$_{15}$ (c€/kWht)	17.6	14.1	6.9	6.3	7.3	6.8	**6.6**
LCOE$_{20}$ (c€/kWht)	18.9	14.5	6.5	5.2	6.9	5.7	**5.2**
Primary energy consumption (kWh)	7734	7734	1616	387	1742	513	**131**
SPF (pu)	0.90	0.90	4.31	17.97	3.99	13.56	**53.17**
Self-sufficiency (%)	-11%	-11%	77%	94%	75%	93%	**98%**

As expected, the obtained results show that lower OPEX (63.5 %) and higher energy performance could be achieved. The SPF is exponentially increased with low grid consumption scenarios (by 4.34 the baseline) and the self-sufficiency is boosted (6 points more) till achieving almost full sufficiency. The LCOE figures for PVTaHP are still the most competitive ones compared to other technologies but slightly higher than the baseline scenario for a 20-year period (from 4.9 to 5.2 c€/kWh). The PV summer production covers completely the HP demand and for July around 19 % of the electric generation is injected into the grid for free. Modifying the operational mode to net-metering would reduce the LCOE figures even more (4.8 c€/kWh). However, from an economic point of view the extra cost of 50 % higher collection field is not traduced on a lower ROI.

4. Cost and performance sensitivity

Innovations cost and performance are rarely as initially expected. Incrementation on solution cost and reduction on performance features are common from lab prototypes to market products. Thus, a sensitivity analysis of both has been considered on the following case studies. The Tab. 6 shows the figures obtained for the baseline +20 % in the CAPEX (retail price + turnkey installation) and Tab. 7 a baseline +40 % in performance (non-maintenance) expenditures caused due to worst collector layers thermal behaviour and/or control algorithm failure.

Tab. 6: Barcelona (baseline +20 % CAPEX) case study summary KPIs by technology

Barcelona (+20 CAPEX) KPIs	**E boiler**	**NG boiler**	**saHP**	**PV + saHP**	**awHP**	**PV + awHP**	**PVTaHP**
CAPEX (€)	600	1100	2964	4314	3155	4505	**4981**
ROI$_{\text{Tech.Rel.}}$ (years)	5.17	5.67	17.79	34.88	14.09	13.49	
IRR$_{10}$ (%)	2.9%	-3.5%	-	-	-	-	
IRR$_{15}$ (%)	16.0%	11.6%	-	-	-	-15.2%	
IRR$_{20}$ (%)	19.9%	16.3%	-10.5%	-	-3.2%	-0.7%	
LCOE$_{10}$ (c€/kWht)	16.6	14.0	7.9	8.3	8.4	8.8	**8.9**
LCOE$_{15}$ (c€/kWht)	17.6	14.1	6.7	6.3	7.2	6.8	**6.6**
LCOE$_{20}$ (c€/kWht)	18.9	14.5	6.3	5.5	6.8	5.9	**5.5**

Tab. 7: Barcelona (baseline +40 % in performance) case study summary KPIs by technology

Barcelona (+40% in performance) KPIs	**E boiler**	**NG boiler**	**saHP**	**PV + saHP**	**awHP**	**PV + awHP**	**PVTaHP**
OPEX (€/year)	1184	906	270	153	290	173	**162**
ROI$_{\text{Tech.Rel.}}$ (years)	4.34	4.66	14.11	16.03	9.93	-	
IRR$_{10}$ (%)	10.9%	5.9%	-	-	-	-	
IRR$_{15}$ (%)	21.4%	17.7%	-20.1%	-	-4.0%	-	
IRR$_{20}$ (%)	24.5%	21.2%	-3.0%	-	5.4%	-	
LCOE$_{10}$ (c€/kWht)	16.6	14.0	7.9	8.3	8.4	8.8	**8.2**
LCOE$_{15}$ (c€/kWht)	17.6	14.1	6.7	6.3	7.2	6.8	**6.3**
LCOE$_{20}$ (c€/kWht)	18.9	14.5	6.3	5.5	6.8	5.9	**5.5**
Primary energy consumption (kWh)	7734	7734	1616	797	1742	923	**797**
SPF (pu)	0.90	0.90	4.31	8.73	4.00	7.54	**8.73**
Self-sufficiency (%)	-11%	-11%	77%	89%	75%	87%	**89%**

The last case studies versus baseline results comparative analysis show that such deviations make the solution less attractive in economic terms, as the ROI compared to the HP base solution is increased significantly, where the PV + saHP technology remains as the most critical competitor. However, even in the current over-cost scenario competitive LCOE figures are obtained. Furthermore, in a close LCOE competitive scenario, the better solar resource and available building surface harnessing of PVT technology could still be the key factor.

5. Conclusions

The techno-economic analysis carried out shows that the proposed solution of merging PVT dual collection with a saHP based unit by means of smart control strategies in one unique system is a current cost-competitive solution for highly populated and restricted NZEB areas.

More in detail, the initial investment is very far from the market standard non-renewable solution, slightly above conventional awHP or saHP equipment, but below combo systems where a PV installation is added to a HP based solution. From an OPEX perspective the proposed PVTaHP clearly offers lower costs among the rest of competitors, where the closest in terms of annual O&M expenses is the PV+saHP, even it requires double collection field surface.

The financial figures show that the PVT based solution extra investment is easily returned during its lifetime, although short payback-time demanding end-users and/or applications should take into consideration more than just economics, instead may not find them attractive enough. NZEB will imply to go one step further than the current non-sustainable lifestyle and economics, so future assessments will need to take it into consideration.

The performance of the proposed solution for the different case studies (location, collector field size, cost and performance sensitivity analysis) is great in comparison with the rest of the analysed technologies in terms of primary energy reduction, overall efficiency and self-sufficiency. When merging performance with economics under LCOE perspective, the PVTaHP shows the most competitive costs for 10, 15 and 20 years periods.

Acknowledgments

The work carried out is comprised under the HANDLE innovation project between Tecnalia Research & Innovation, Energy Panel S.L, Termoidraulica Brotto, Termosol and InnoEnergy, with the collaboration of the University of the Basque Country.

References

EurObservER HPs barometer, 2016. https://www.eurobserv-er.org/heat-pumps-barometer-2016/

European Commission building needs, 2018. https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

EU law, 2009. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32009L0125&from=ES

Fu et al, 2012. Experimental study of a photovoltaic solar-assisted heat-pump/heat-pipe system, DOI: 10.1016/j.applthermaleng.2012.02.036

G. Pei, J. Ji, T.T. Chow, H. He, K. Liu, 2008. Performance of the photovoltaic solar-assisted heat pump system with and without glass cover in winter: a comparative analysis, DOI: 10.1243/09576509JPE431

International Energy Outlook of 2017, 2018. https://www.eia.gov/outlooks/ieo/

J. Ji, G. Pei, T.T. Chow, K.L. Liu, H.F. He, J.P. Lu, C.W. Han, 2008. Experimental study of photovoltaic solar assisted heat pump system. Sol. Energy, 82, DOI: 10.1016/j.solener.2007.04.006

Jie Ji et al, 2009. Distributed dynamic modeling & experimental study of PV evaporator in a PV/T SAHP, DOI: 10.1016/j.ijheatmasstransfer.2008.08.017

Latest trends in the World Traditional & Renewable Heating Markets, BSRIA, 2014. https://www.iea.org/media/workshops/buildingwebinars/webinar4/4BSRIAKrystynaPresentationforIEA.pdf

Moreno-Rodriguez A. et al, 2012. Theoretical model and experimental validation of a direct-expansion solar assisted heat pump for domestic hot water applications, DOI: 10.1016/j.energy.2012.07.021

Sotehi, 2016. PV/T Hybrid Solar Water Collector for nZEB in Algeria, DOI: 10.1016/j.desal.2016.01.034

Sporn P, Ambrose ER, 1955. The heat pump and solar energy. Proceedings of the world symposium on applied solar energy, Phoenix, Arizona, DOI: 10.1063/1.3060075

Y.W. Li, R.Z. Wang, J.Y. Wu, Y.X. Xu, 2007. Experimental performance analysis and optimization of a direct expansion solar-assisted heat pump water heater. Energy, DOI: 10.1016/j.desal.2016.01.034

Y.W. Li, R.Z. Wang, J.Y. Wu, Y.X. Xu, 2007. Experimental performance analysis on a direct expansion solar-assisted heat pump water heater. Applied Thermal Engineering, DOI: 10.1002/er.893