A PVT Driven Direct Expansion Heat Pump Field Operation Results

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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 performance or cost-competitiveness. Solar-based technologies tend to be the most promising ones, but for high densely populated areas, the usual photovoltaic or thermal single approaches may not be efficient enough. The current work is focused on several day intraday performance analysis for the dual use of the solar resource by means of hybrid PVT collectors and their smart combination with direct expansion heat pumps through predictive control strategies. To that end, the solution was developed, two systems were installed in real-use single-family houses at Mediterranean and continental climates as a domestic hot water application, operated and monitored. The presented analysis is based on several key performance indicators calculated for the tested-period one representative day (considering meteorological boundaries and system operation) for both locations. The results (Mediterranean/continental) show 91/98% renewable energy share, 72/147% self-sufficiency ratio, 53/81% heat pump self-consumption and 26/99% of the solar fraction.

Keywords: PVT, heat pump, hybrid system, control, field results.

1. Introduction

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

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 base solutions always require back-up systems, which reduces their competitiveness. The electrical grid makes things easier, but thermal needs are still highly fossil fuel-dependent in a great part of Europe. However, heat pumps (HP) seem a promising technology for a reduction in building thermal comfort-related CO_2 emissions and enable the use of the electrical infrastructure to use them as a back-up (Gaur, 2021). Therefore, if solar and HP are individually suitable for electricity and heat generation, merging them in a unique hybrid system will enable to obtain higher benefits (Hadorn, 2015). Anyway, it is usually hard to compare technologies and quantify those real benefits to simply conclude which one shows overall greater performance. Thus, an experimental approach is proposed to shed some light on the real field performance of such systems.

The proposed solution is a solar hybrid PVT dually coupled HP. It is a fully integrated system comprising an unglazed hybrid solar collector, a direct expansion solar assisted HP (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 (Sanz, 2018) and experimental studies (Pei, 2008). The union of PV and solar thermodynamic technologies in one collector enables simultaneous electricity and heat generation and in a kind of symbiosis both technologies work optimally without mismatching the other’s performance (Ji, 2009), as occurs in conventional PVT where a trade-off between

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the thermal and electric performance is needed. Thus, the dually assisted HP significantly increases the total annual use of the solar resource while primary energy consumption is reduced.

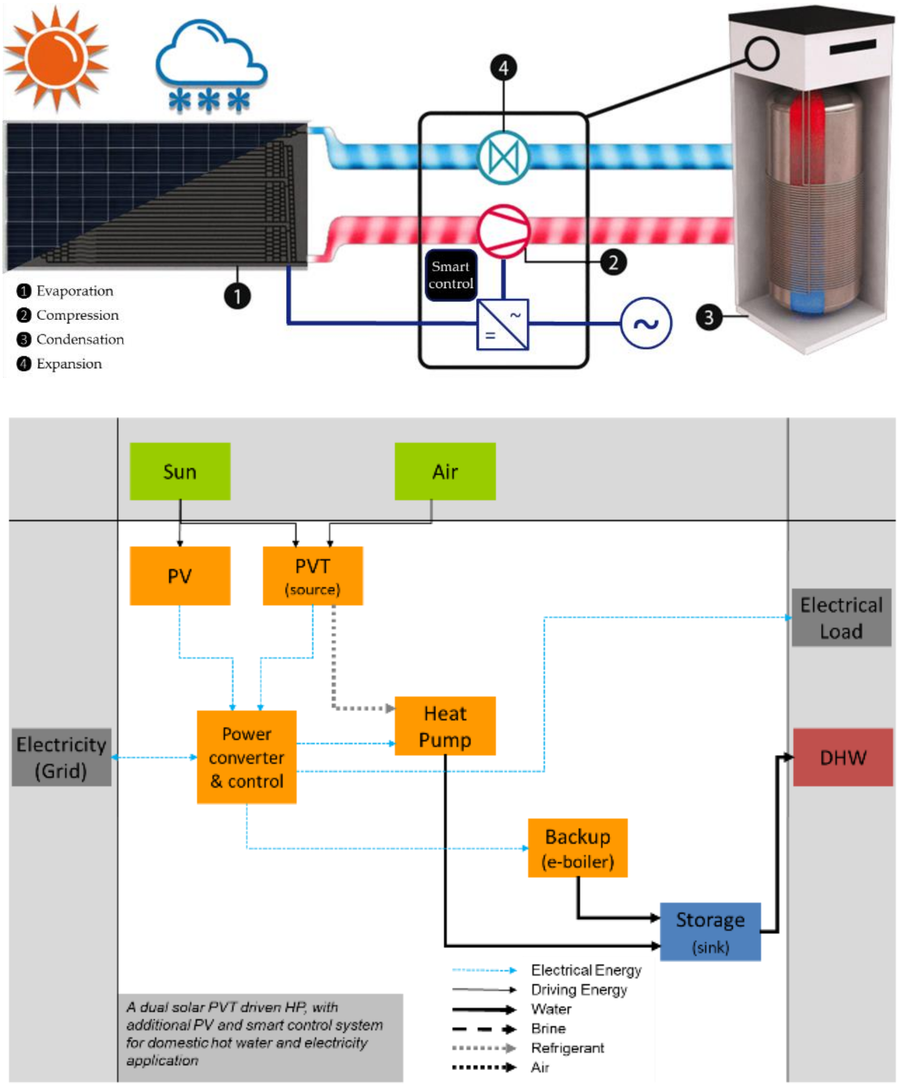

Fig. 1: A representation of the PVT dually coupled HP technology. Physical scheme of main system elements (up) and proposed representation of IEA square view (down).

2. Materials and Methods

In order to prove the previously exposed potential benefits, a couple of prototypes (Fig. 2) of the proposed solution were developed, installed and operated for one entire year in a real-use ap-plication. The objective of the test is double. First, to experimentally determine the technical performance of the whole solution by means of accurate monitoring. Second, to validate the robustness of the system under extreme working conditions.

2.1. Real-Use DHW Application

The demonstrator baseline is a single-family house. One of them is located at Jablonec nad Nisou (Czech Republic) and the other at San Martino di Lupari (Italy). The new solution has been installed to fully supply hot tap water for a 3 and 4 members family, respectively, replacing the previously existing gas boiler energy supply.

Fig. 2: The single-family house considered for the test previous (up) and post intervention (down), located at Jablonec nad Nisou (50.7N, 15.1W coordinates, left) and San Martino di Lupari (45°38'N, 11°51'W coordinates, right).

2.2. Components Sizing

The DHW application that has been chosen for validation purposes determines the strategy to be used for system sizing. Thus, according to the expected DHW day demand and its consumption profile, the thermodynamic bloc comprising the HP and the thermal energy store (TES) is selected. Traditionally, for DX-saHP, the key parameter to explore at this point is the time interval needed to ensure the entire tank water is heated at the set point. Usually, a maximum time is established. Then the HP and TES are selected to guarantee that in the worst-case scenario the elapsed time needed to reach the setpoint is below the defined one. For the current case study, at the coldest, lower solar resource and higher DHW demand months of January and December, with a 2.5 kW of heat output HP and a 200 l (Czech Republic) and 175 l (Italy) TES the elapsed period is below 2 h.

However, the new solution to be tested pretends to run mainly on solar resources. For this reason, an inverter HP has been selected. Even at its maximum regime, an output of 2.5 kW of heat would be reached, it will regularly work at lower operation points. Thus, a slightly higher TES volume has been selected. The final volume is increasing around 50% the TES capacity (till 300 l) and enabling us to heat it up during solar resource availability periods. Thus, the risk of reaching premature HP stops due to the maximum TES temperature being reduced.

Finally, for the selected thermodynamic block, the collection field is sized according to the required cold power for the HP in the previously commented winter period worst-case scenario. For the current case study, with a conventional DX-saHP system, a total of 2.72 m^2 (2 units of 1.36 m^2) of black painted roll bond solar thermodynamic collectors would be enough. However, the new solution is based on PVT collectors and the front layer might have a lower heat transfer capacity. Thus, the selected collection area is increased. For the Italian prototype the collection area has been increased by 17.6% up to 3.2 m^2 (2 units of 1.6 m^2). In the Czech Republic prototype up to 4.8 m^2 (3 units of 1.6 m^2). Even though 2 units might be enough to thermally run the HP, the additional collector is supposed to add a plus for the critical winter season. To avoid undesired excessive summer HP suction temperatures, independent blocking valves are added to each one of the collectors in both locations. An additional PV module is also added in order to enable a comparison of electrical yields for the Czech case study.

2.3 Instrumentation and Data Acquisition

The experimental activity requires accurate monitoring of energy fluxes and further relevant boundary variables to determine the technical performance of both system components and the complete solution. Thus, different kinds of sensors are displayed along the prototype. The most significant variables to measure meteorological conditions, energy collection (solar field), conversion (power electronics for PV and) HP and store (hot water tank) have been considered. A summary of them is listed below (Tab. 1).

Tab. 1: A selection of the most significant monitored variables, including the instrumentation features.

Instrument	Units	Description	Symbol	Range and Units	Accuracy
MET calibrated cell (Atersa)	2	Global plane of array irradiance	G_{PoA}	0 … 1400 W/m^2	±2.2%
	1	Ambient temperature	T_{amb}	−20 … 100 °C	±0.8 °C
	1	Wind speed	ws	2 … 140 km/h	±3% *1
	1	Crystalline silicon PV module reference temperature	T_{PVref}	−20 … 100 °C	±0.8 °C
RTF-100-S4B 5.0-C8 PT100 (Labfacility)	1 per collectors or module	Middle absorber/backsheet temperature	$T_{PVT,2}$ $T_{PVT,3}$ T_{PV}	−50 … 150 °C	±1%
VMU-E DC energy meter (Carlo Gavazzi)	4 one per collector	Voltage	$V_{PVT/PVm,X}$	0 … 400 V	±0.5% *2
		Current	$I_{PVT/PVm,X}$	0 … 20 A	±0.5% *3
		Power	$P_{PVT/PVm,X}$ *5	0 … 8 kW	±1%
		Energy	$E_{PVT/PVm,X}$ *5	*na* kWh	±1%
EM110 AC energy meter (Garlo Gavazzi)	3 Grid balance PV generation HP consumption	Energy	E_{Grid} E_{PVm} E_{HP}	*na* kWh	±1% *4
μPC HP controller (Carel)	1	Compressor voltage	V_{Comp}	*na* V	±1%
		Compressor current	I_{Comp}	*na* A	±1%
		Evaporation temperature	T_{Eva}	−50 … 100 °C	±1 °C
		Suction temperature	T_{Suc}	−50 … 100 °C	±1 °C
		Discharge temperature	T_{Dis}	−50 … 100 °C	±1 °C
		Condensation temperature	T_{Con}	−50 … 100 °C	±1 °C
		TES load temperature	$T_{TES,load}$	−50 … 100 °C	±1 °C
		TES middle temperature	$T_{TES,mid}$	−50 … 100 °C	±1 °C
		Condenser outlet temperature	T_{COut}	−50 … 100 °C	±1 °C

*1 The accuracy for wind speed is valid for 15 … 140 km/h range, but always greater than ± 1 km/h. *2 The accuracy for DC voltage is valid for 10 … 400 V range. *3 The accuracy for DC current is valid for 0.05 … 20 A range. *4 The accuracy for AC energy is 1.5% for a range of 0.25 … 0.5 A, according to EN50470-3. *5 The term E_{PV} is left for the total solar field electrical output.

2.3. Data Analysis, Cleaning, Processing and Key Performance Indicators

The gathered system performance is first analyzed in detail. The day-based files have an automatic checking algorithm. The procedure only enables us to filter entire day performance days with all dataset variables in range. Furthermore, all days are carefully manually analyzed using specific timeseries templates to filter any additional errors. Thus, days with partial operation, monitored variable outlyers or additional reported phenomena are removed at this stage. Any kind of gap filling is not considered. The analysis continues only with the valid-day dataset. For this selection, several intraday parameters and day-aggregated energy values are calculated. Additionally, day representative key performance indicators (KPI) are obtained. The determination of these KPIs is performed according to the common agreed procedure established within the International Energy Agency Solar Heating and Cooling programme (Zenhäusern, 2020).

3. Results and Discussion

The described systems have been operated for more than one entire year. Some of the obtained results are discussed below. The current work is focused on the intraday performance of the system. Thus, one hole year representative day is presented for each one of the locations, 3.1. Mediterranean prototype

The selected day for the analysis is the 25 May (Fig. 3). It is a fully sunny day without any cloud and a total of 2.9 kWh/m^2 of plane irradiation, 27.8 °C mean ambient temperature and no wind (0.13 m/s). The system presents a day operation starting previously than the smart controller expected (8h27), due to a sudden DHW consumption provoking a critical morning low TES average temperature (24.8 °C). Thus, the HP begins operation at a high booster mode to continue working at lowest speed due to the still poor morning PV production. The process is repeated at 10h15 with a new DHW consumption that moves the operation to a low booster operation mode for approximately half an hour. After this morning period the machine starts to run in regulation mode, following the PV production setpoint. For 1.55 h of operation the HP moves again to low regime. Finally, after 2.5 h of operation, the TES is completely heated, and in consequence the HP is stopped. During the evening, a first low DHW consumption event could be noticed around 19h30, but the second one at 20h00 significantly reduces the TES available heat. However, the TES average temperature does not go below 30 °C so the controller does not force the non-solar operation.

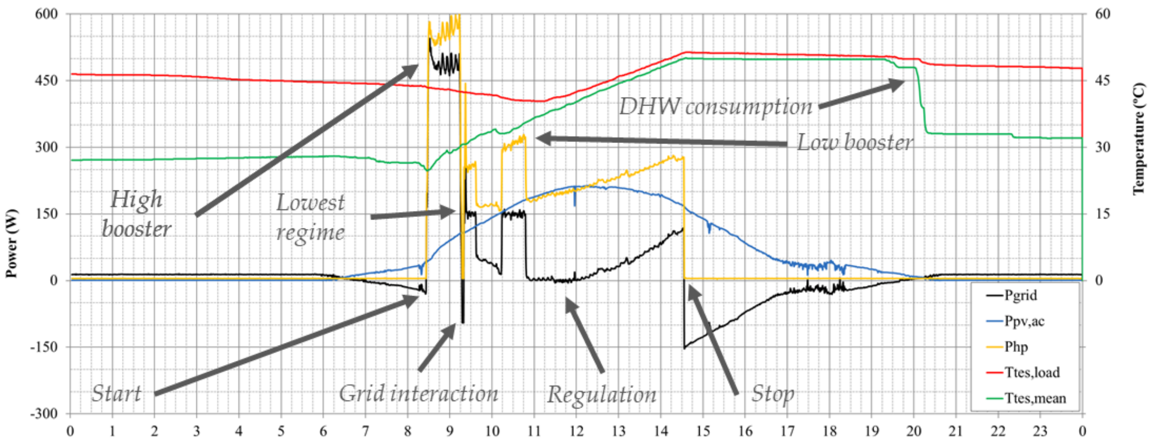

Fig. 3: Main system electric power and TES state of charge profiles for the 25 May.

The system-level KPIs show 91.4% value for renewable energy share (RES). The performance in term of self-sufficiency ratio (SSR) reaches 72.1%, below expected. This figure is aligned with the self-consumption ratio (SCR), an 80.7%. The main reason underling these KPIs is the still potentially optimizable control performance in other to avoid early morning booster activation and evening no HP operation. The narrow HP operation periods, due to high solar potential and lower thermal loads should limit the solar fraction (SF). Although SF is widely used for thermal systems, for DX-saHP solutions might not have sense, as the ambient air contribution is much greater than the solar gain. However, the day performance show also that operation during high ambient temperatures (>36 °C at 14h25) is possible, validating the system concept also for hot locations.

3.2. Continental climate

The considered day for the analysis is the 21 April (Fig. 4). This spring day has a 6.8 kWh/m^2 plane irradiation, a 17.0 °C mean ambient temperature and almost no wind (0.09 m/s). The smart controller of the solution starts up the operation at 8h41, with a relatively high TES average temperature of 37.9 °C. The HP starts operation in regulation mode, copying the PV production till 9h25, when it reaches the maximum regime. After this event the HP continues running at its maximum for more than 4 h, showing a non-constant consumption due to the dynamic PVT collector field contribution and TES status. At 13h45 the 50 °C setpoint is reached and the HP operation is stopped. In the operation period, the TES mean temperature is reduced to 35.7 °C at 10h35 due to a medium DHW consumption, although the load temperature does not go below 47.4 °C. During the almost 5-h operation the HP works almost at its full regime with almost no regulation. The evening period seems not to be needed for high irradiation and warm days, as the system is capable to heat up the entire TES without impacting the grid consumption or affecting user comfort.

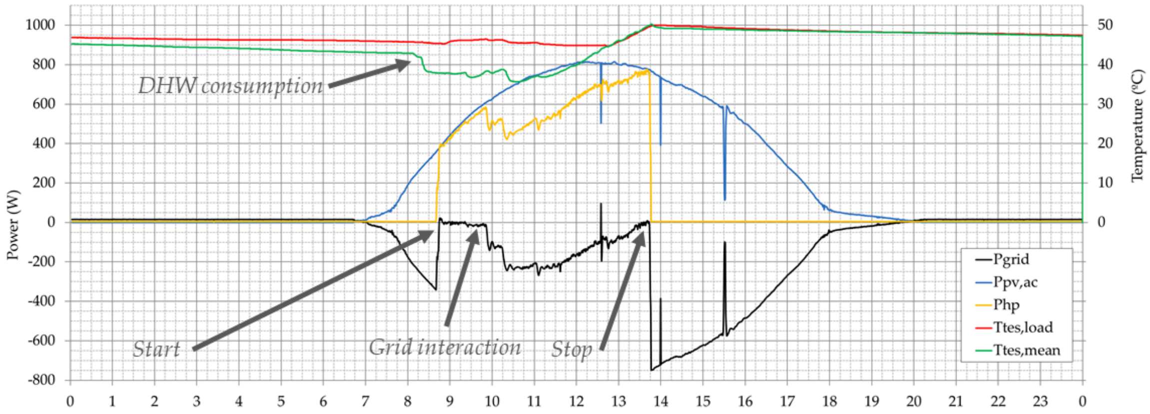

Fig. 4: Main system electric power and TES state of charge profiles for the 21 April.

The system-level KPIs evidence great figures for RES (97.8%) and SSR (147.2%), mainly driven by good solar resources. The non-evening operation reduces the SCR to 52.6%, but still shows a high capability to self-consume almost all the energy of the operating. The non-HP operation period and the low regime during operation are responsible for not gathering higher SF (25.9%). A half of SF is scored by electricity production, which shows that for such a day there is still much more potential heat to be produced.

4. Conclusions

The current work is focused on the analysis of the performance of the dual use of the solar resource by means of hybrid PVT collectors and their smart combination with direct expansion HPs through predictive control strategies. For that purpose, a solution with several innovations in the collector and in the overall control strategy was developed. A couple of real-use single-family houses have been selected for hosting the tests, at the Mediterranean climate location of San Martino di Lupari (Italy) and the continental climate representative location of Jablonec nad Nisou (Check Republic), both for a DHW application over one-year of operation. The sizing of the system has been carried out. The system comprising several PVT collectors and one PV module (only for Czech prototype), dually connected to an inverter DX-saHP with an oversized TES and a predictive control has been properly installed, commissioned and fully accurately monitored. The recorded dataset has been postprocessed according to specific internationally recognized procedures for PVT plus HP systems. The presented study is based on the intraday analysis of one representative day of the tested period for both location.

The experimental campaign feeds the calculation of the proposed system-level KPIs for two different days (one for each location). The presented figures show 91.4% for RES, 72.1% for SSR, 80.7% for SCR with an incoherent SF value for the Mediterranean prototype, while for continental climate the figures are 97.8% for RES, 147.2% for SSR, 52.6% for SCR and 25.9% for SF. The high RES is essentially based on HP performance and enhanced by solar field contribution. The obtained SCR shows good underlying control performance, although there is still big potential to better predict the optimum operation period and avoid early morning grid energy consumption (for booster or low regime HP operation) and the undesired unused evening solar resource. The obtained SSR and SF results are huge, but somehow artificially boosted due to the high solar resource and DX-saHP ambient heat collection. The short operation days caused by common high energy resource and limited TES buffering are an additional features to look at during system sizing. Further simulation and sensitivity analysis might be helpful in order to determine the required trade-off between objectives to achieve.

5. Acknowledgments

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