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Dual Source Solar Assisted Heat Pump Model Development, Validation and Comparison to Conventional Systems

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Abstract

This paper presents a new SAHP system integrated with hybrid photovoltaic/thermal panels (PVT). The main components of the system developed are a dual-source HP, PVT panels and two storage tanks. The use of two storage tanks allows to directly store the hot water for DHW if water temperature reaches the set-point or to send it to the cold storage. On the other side, the use of two heat exchangers on source side, allows the system to switch from air to the cold tank increasing system's performances.

In this work the developed system is compared with two conventional systems: an AWHP integrated with standard photovoltaic panels and an AWHP integrated with hybrid PVT panels for DHW production only. Those systems were investigated for a single family house, through one year simulation in the TRNSYS software. Control strategy, size of the tanks and number of panels were investigated with parametric studies. Thanks to the good results of the simulations, an experimental prototype has been designed and built. Data observed from first monitoring campaign highlighted better performances than expected. After a season of investigation and data analysis for the system, new findings will be illustrate.

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Keywords: SAHP; NZEB; PVT; Dual Source; Heat Pump

1. Introduction

It's been long time that increasing apprehensions regarding the reduction of fossil fuels, environmental pollution and global warming brought scientists to search sustainable systems responding to residential energy needs. In Italy

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in 2014 residential sector accounted for 36% of total energy consumption [1] with important growth rate in household sector [2]. For this reason Italian legislative decree n.28, specified that new constructions or relevant building renovations had to consider that a consistent part of building energy needs, 50% by January 1th 2017, has to be covered by renewable energy.

To reach this ambitious target, heat pumps and solar collectors are interesting solutions, in some cases indispensable. Even though these systems should have saved energy compared to most used conventional boilers, their performances decreased when load rose. An integrated system of solar collectors and heat pump, known as "Solar Assisted Heat Pump" (SAHP), is a promising solution because it solves some disadvantages of both components singularly considered, for the purpose of meeting space heating/cooling and domestic hot water (DHW) loads.

This project started investigating results from a case study placed in Terni [3], which studied performances of an air-to-water heat pump (AWHP) combined with 4 different kind of hybrid photovoltaic/thermal panels (PVT) used to generate electric energy but also to produce domestic hot water. It emerged that 3 PVT panels, with an aluminium roll-bond absorber, had generated sufficient heat to produce about 60% of yearly domestic hot water for a single family house with a daily withdrawal of 150 liters at 40°C. Moreover, water-glycol mixture that flows into panels, cooling silicon cells, increased their yearly electric energy production by 3%. During overall winter season, water heated by PVT panels didn't reach sufficient high temperature to be used for DHW. In this case system's performances were the same of a conventional AWHP.

Starting from this experimental results, this paper oriented improvements to develop and optimize configuration and control strategy of a SAHP system which:

- Should have minimized building yearly electric energy withdrawal from the grid;
- Should have been placed in the Mediterranean area (Most studies had been specifically conducted for very cold climates);
- Should have been technically sustainable and economically convenient.

2. Literature Analysis

2.1. SAHP Solution

The investigation on SAHP state of the art started from the IEA task 44 "Solar and Heat Pump Systems". In its Position Paper [4] were stated that in the near term, research activities should have been oriented on:

- Development and optimization of hybrid PVT panels;
- Investigation on best control strategies which might use low temperature heat coming from solar collectors directly in load storage tank or sending it to the HP evaporator;
- Optimizing control systems which might harmonize all components together for obtaining the best system performance.

The great amount of different configurations and solutions presented in literature, let the group of Ruschenburg and Herkel [5] had been noticed lack of a necessary classification and standardisation of systems and of the performance indices used to compare them. Lot of solutions had been investigated and optimized in specific locations, for definite buildings and loads. Those different conditions did not allow easy comparisons between them.

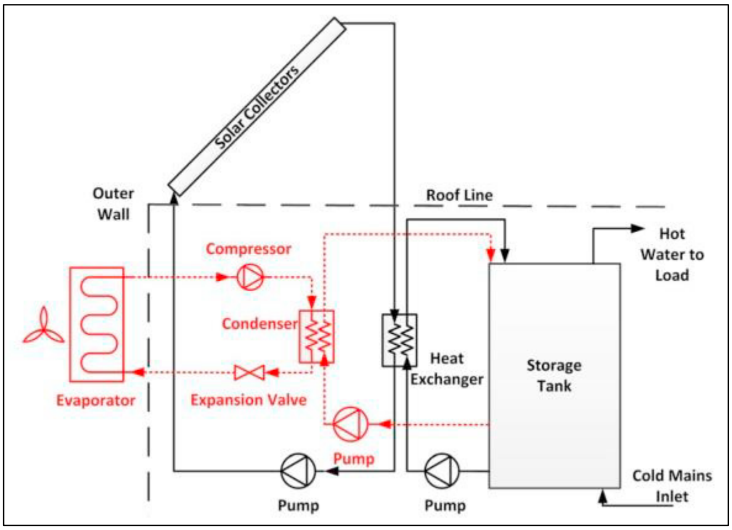
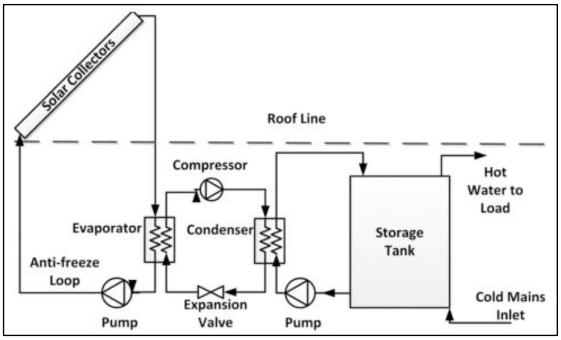


Figure 1-Schematic of parallel SAHP (from [6])

Main classifications of SAHP systems regards components integration, in particular the way solar heat is being used, as it is clearly described by J. Chu et al. [6]: in a *Parallel* configuration, Figure 1, heat pump and collectors supply useful thermal energy independently, through one or more tanks.



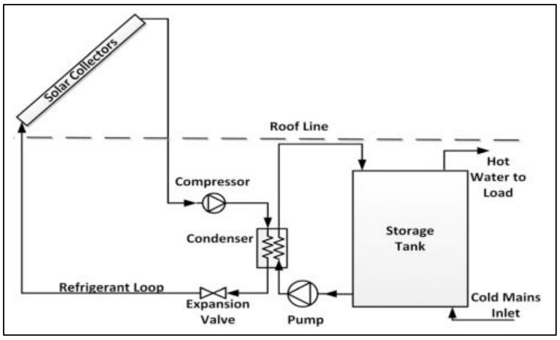


Figure 2- Schematic of indirect series SAHP (from [6]) Figure 3- Schematic of direct series SAHP (from [6])

In a Series system, solar panels work as sources of the heat pump, supplying heat indirectly via an halfway storage tank, as Figure 2 reported, or directly to its evaporator, Figure 2- Schematic of indirect series SAHP (from [6]) Figure 3. It is moreover defined dual source the configuration in which heat pump can switch from using, source side, thermal transfer with solar collectors, as it happens in indirect series systems, or external air. An example of dual source configuration has been illustrated in Figure 4.

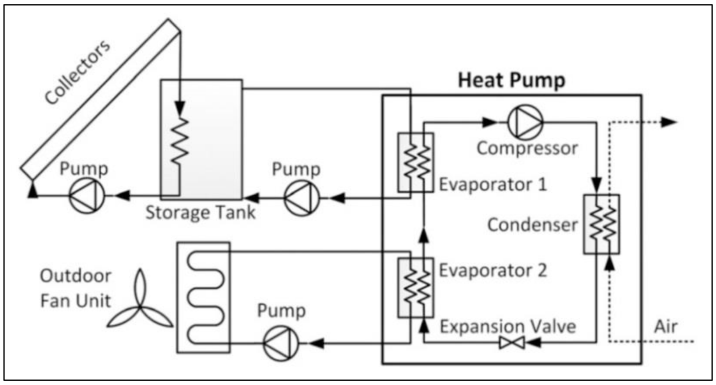


Figure 4 – Schematic of a dual source SAHP (from [6])

Already Freeman et al. [7], at the end of the 1970's, compared those different configurations. Completed the analysis they observed that:

- A Parallel asset reached the lowest thermal efficiency of solar collectors but proved to be the best choice regarding Free Energy Ratio;
- When possible, it would be convenient to directly use hot water from solar panels.

Chandrashekar et al. [8] in 1982 did disagree with Freeman founding dual source heat pump solutions the best in performances, thanks to high COP and efficiencies from solar collectors. Thanks to these outcomes it emerge that best performances should be obtained with the opportunity of switching between different sources optimizing their use. Already Karagiorgas et al. [9], identifying that with low irradiation level indirect asset results to be the best SAHP configuration, defined a mathematical relationship, applicable only on their system, for determining whether using solar energy on heat pump evaporator was more beneficial than using it to produce DHW directly. Developing Karagiorgas et al. [9] studies, Haller and Frank [10] presented a general equation, depending on COP variation and irradiation level, to choose direct or indirect solar heat use, as reported in Figure 5, for different systems in various conditions.

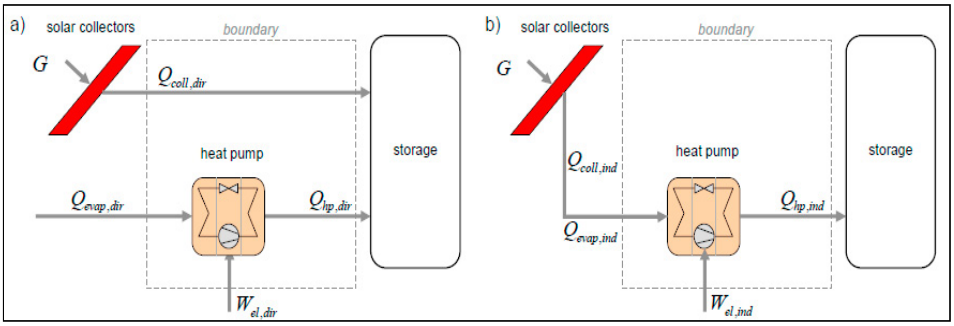


Figure 5 – Energy flow for a) a direct use of solar energy; b) an indirect configuration. (from [10])

Studies so far conducted, did not use an intermediate storage tank between solar collectors and heat pump evaporator. It should soften solar collectors temperature fluctuation and permits to absorb thermal power in a different time from heat pump evaporator needs. Banister and Collins [11] studied a dual tank system to collect thermal solar energy and reuse it, during unsufficient irradiation, with the heat pump. The complicated system resulted to be economically inappropriate for a single family house, it could be convenient for an apartment building.

Using TRNSYS, transient system simulation software, Lerch et al.[12] compared several SAHP configuration solutions. The one presented in Figure 6, representing a dual-source configuration, minimized electric energy withdrawal by the asset from the grid.

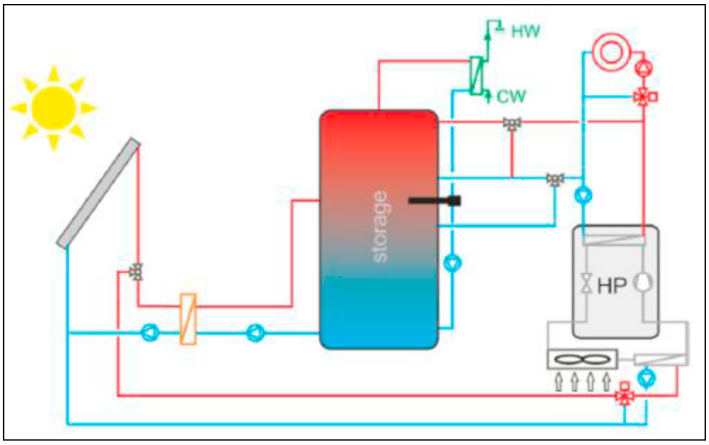


Figure 6 – Schematic of the dual - source configuration studied by [12]

2.2. The best source side solution: PVT

Choosing to investigate a dual – source heat pump configuration, a task of this study regards the definition of the best technology to use as solar source to optimize the system in a Mediterranean climate.

Dott and Afjei [13] studied how to optimize the use of 50 m^2 roof with different kind of solar panels and their integration with a SAHP to ensure space heat demand for buildings with various energy need.

The system with less electricity withdrawal from the grid, so the most efficient, resulted to be the one using PVT panels. With same surface, hybrid solution brought to highest energy generation, sum of thermal and electrical. However, again, this study were conducted for a freezing winter in Strasbourg. In the Mediterranean area so extended solar collectors surfaces, of any kind, bring to a disproportioned solar heat production, difficultly drainable in summer.

With an experimental study placed in Terni (IT), Croci and Viani [14] covered 60% of thermal energy need to produce yearly DHW for a single family house, 150 litres/day withdrawal at 40°C, with 6.4 m^2 roll-bond PVT panels. Croci and Quaglia [15], for Milan, studied the behaviour of an hybrid photovoltaic-thermal panel depending on direct or diffuse solar radiation.

In view of experimental data and literature studies, were conducted investigations on best PVT panels technologies which could be integrated with a SAHP, for the Mediterranean area.

A deepen bibliography analysis, regarding hybrid collectors state of the art, especially referring to [16-23], oriented research activities to choose:

- An indirect SAHP configuration: use of direct expansion through collectors had been brought to problems regarding:
    - Panels frosting possibility with performances reduction and potential breakdown;
    - Control strategy and system design complications.
- Roll bond PVT panels:
    - Economic, easy installation and maintenance;
    - Sufficient heat production in winter and not overstated in summer.

2.3. Description of the SAHP system developed

The SAHP system developed, was based on a standard air-source heat pump, with 7 kWth nominal power, to achieve DHW, space heating and cooling loads with one single system. Main new components were PVT panels, a plate heat exchanger to the heat pump source side and an intermediate storage tank, from now called “cold tank”, between collectors and the exchanger. A schematic of the system are presented in Figure 7.

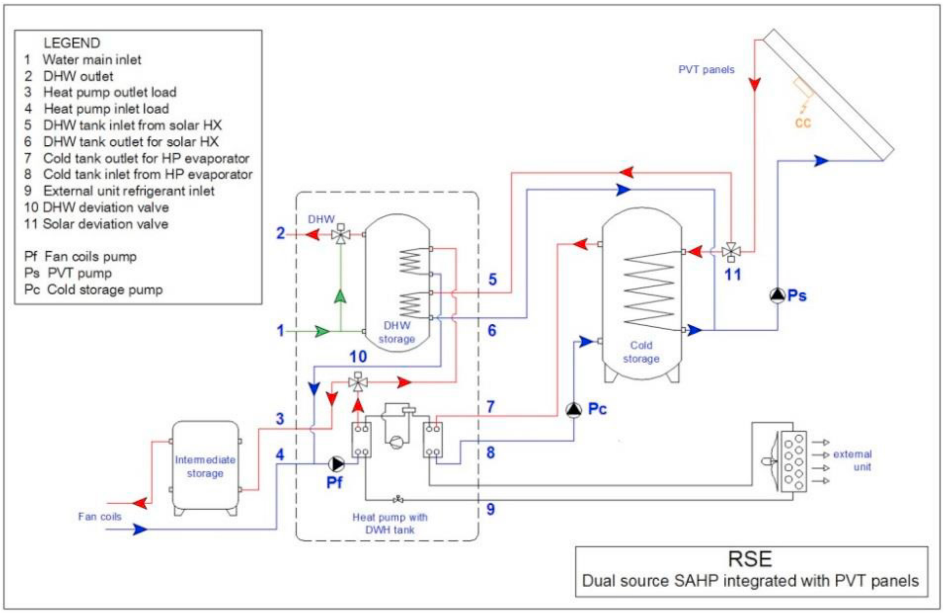


Figure 7 – Schematic of SAHP system developed

PVT panels absorbed solar energy, producing electricity and heating a glycol-water solution. Lower temperature reached by collectors, higher electrical and thermal efficiency resulted. If fluid temperature at the outlet of solar collectors reached sufficient high value, it would be delivered to a second tank, called DHW tank, to directly produce hot water. Otherwise heat would be accumulated in the cold tank, ready to be used by heat pump's new evaporator. Drawing hot water from solar panels via the intermediate cold tank, permitted to make less evaporator temperature fluctuation but, in particular, to direct stored, medium temperature heat, at any moment. In this way both external air and solar energy, with an appropriate control strategy, could be used minimizing system electricity withdrawal from the grid. During winter, with chilly and very moist weather, standard air to air heat pumps had worst performances exactly when higher loads were needed. In those cases, solar energy stored throughout the day, if hot water temperature from the cold tank resulted higher than external air, draw from the storage was used to increase heat pump COP. Energy flow of the system is represented in Figure 8.

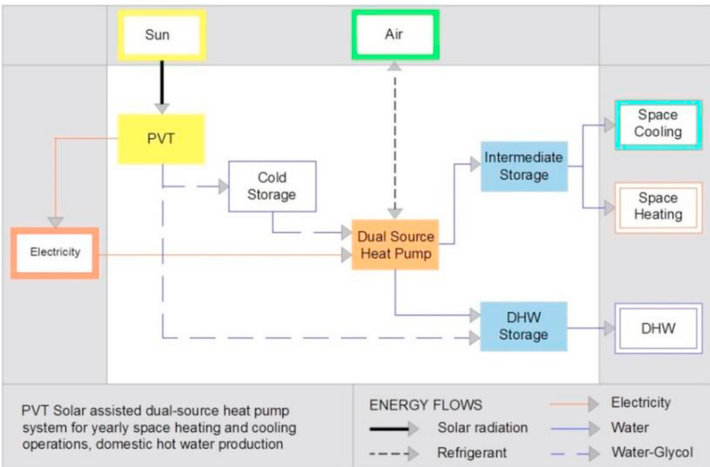


Figure 8 – Energy flow chart of the system

3. Models development and validation

A model of the system was created in TRNSYS 17. TRNSYS is a dynamic simulation tool used to investigate transient operation of energy systems by means of subroutines [25]. Every single element is reproduced with algorithms blocks, called "Types", collected in libraries, connected together as necessary.

3.1. Building and boundary condition

A multizone building was created using TRNBUILD, a TRNSYS plug-in. The model considered internal gains, infiltration, occupants schedule and construction characteristics. Main building parameters are reported in Table I.

Table I – Building Parameters

Parameter	Value	
Ground Floor Surface	80	m^2
Envelope UA value	205	W/K
Zone Thermal Capacitance	11000	kJ/K
Volume	240	m^3
Windows	10	m^2
Glazing and Frame Thermal Energy Loss Coefficient	1.4	W/m^2K

Building performances had been investigated using both weather data from a Typical Meteorological Year (TMY2) file for Milano, characterised by 2683 heating degrees-day, and Rome, 1833 degrees day. Located in these two places heating energy need for the building resulted to be of 149 $\frac{kWh}{m^2y}$ for Milan and 90 $\frac{kWh}{m^2y}$ in Rome.

3.2. Roll-bond PVT panel

A roll bond hybrid collector, Figure 9, was modelled with Type 560. This panel was chose, after two years of experimental comparison between roll-bond PVT solutions, because it reached higher thermal and electrical performances.

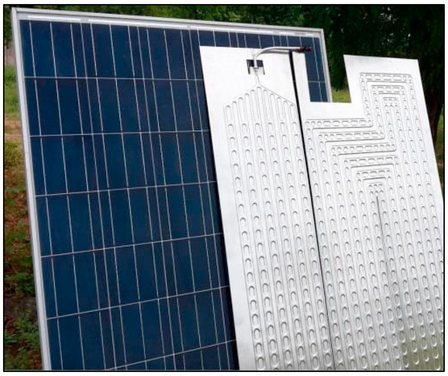


Figure 9 – Modelled Roll bond PVT panel

PVT panel had been tested for one year. Collected data included PVT thermal and electrical production, air temperature and relative humidity, direct solar irradiation, diffuse solar irradiation, wind velocity. Solar heat absorbed by the collector had been monitored and then send to a heat sink. Validation of the PVT panel model had been conducted using experimental data of a sunny and a cloudy day to verify its behaviour in relation with diffuse and direct conditions. Both thermal and electricity gap between simulated and measured results were limited to about 5%.

3.3. Dual source heat pump

To build the dual-source heat pump model, two different simulation were developed and combined: based on the same marketed product, one air to air and one water to air heat pump model were built and validated.
Receiving as input inlet source temperature, inlet load temperature and flow rate, they predicted efficiency, electrical absorption and thermal load production of the heat pump. In particular, compressor part load ratio and consequent performance variations was considered, thanks to data coming from a field trial monitoring campaign. Both test devices provides space heating and cooling, domestic hot water. Electrical power consumption and thermal load production comparisons between the monitored units and their models during space heating operations, are reported below in Figure 10 and Figure 11. Results for space cooling operation comparison was investigated for air source only and reported in Figure 12.

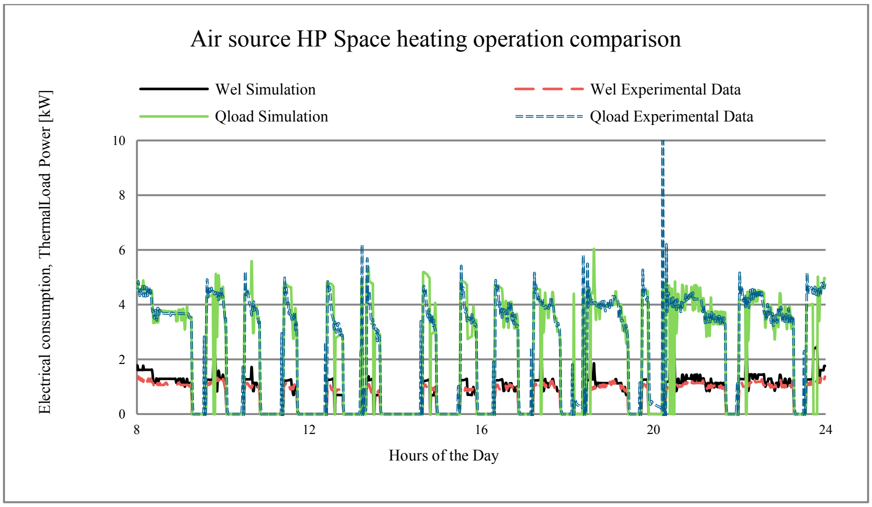


Figure 10 – Comparison of experimental air-source heat pump performances for space heating operation with simulation results

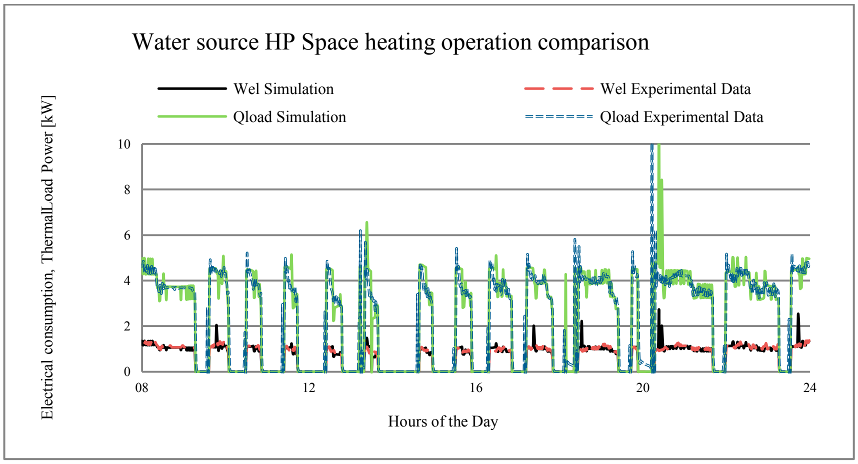


Figure 11 – Comparison of experimental water-source heat pump performances for space heating simulation results

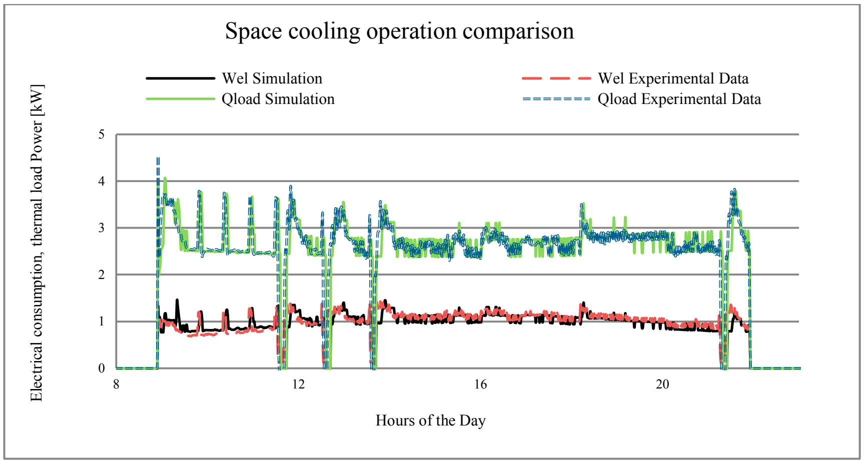


Figure 12 – Comparison of experimental air-source heat pump performances for space cooling operation with simulation results

All validation tests of heat pump models brought to a daily electrical energy consumption and heat production difference, between experimental data and simulations, of 5% at most. Combining air to air and water to air models, a dual source heat pump, with two heat exchangers on source side, was created.

4. SAHP system: integration of previous model

All examined models were linked together to build TRNSYS graphical interface of the system, represented in Figure 13. In Figure 8 the visualization scheme, proposed by Frank et al. [26] to easily present and compare SAHP systems.

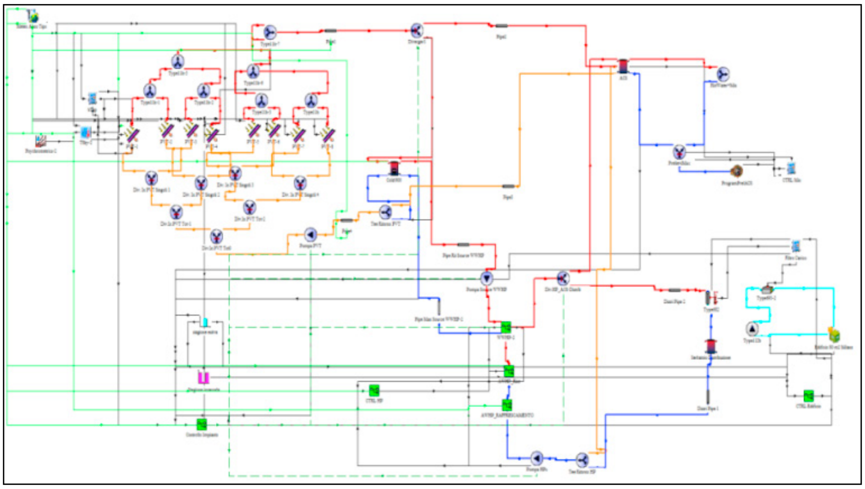


Figure 13 – Graphical interface of the TRNSYS model of the system

Were added a domestic hot water draw profile, to simulate a typical use for a 3 components family, of 120 litres day at 40°C. System control strategy, of which main operating states are shown in Table II, was studied and applied with the purpose of minimize system's consumption.

Table II - System control strategy

Action	State	Condition

Solar cycle: charging cold storage	$Pump_{PVT}$ On	$T_{InPVT} < T_{MeanPVT}$ AND $T_{MeanPVT} > T_{BotColdSTR}$
Solar cycle: charging directly DHW storage	$Pump_{PVT}$ On	$T_{OutPVT} > T_{TopDHW}$
Domestic hot water production	DHW loading On	$T_{TopDHW} < 42°C$
	DHW loading Off	$T_{TopDHW} \geq 48°C$
Winter: heat pump draws heat from cold storage	$Pump_{ColdSTR}$ On	(TTopColdSTR-TExtAir) > 5°C AND (TTopColdSTR > 10°C)
	$Pump_{ColdSTR}$ Off	(TTopColdSTR-TExtAir) ≤ -1 °C AND (TTopColdSTR ≤ 4 °C)
Winter: heat pump draws heat from external air	Fan external unit On	1-$Pump_{ColdSTR}$ On
Summer: heat pump drain heat to external air	Fan external unit On	Space cooling requested

Space heating and cooling were activated by a thermostat placed in the building type to control internal air temperature. In case of contemporary request for space heating or cooling and domestic hot water production, priority was given to DHW.

To minimize electrical withdrawal from the grid, a specific control model was prepared to established, in the winter season, the best hours of the day in which heat draw from cold storage was preferred. Air-source heat pump worked worst in minimal external air temperature periods. The algorithm calculates storage heat capacity based on tank volume and medium temperature reached. Combining this result with the determination of heat absorption by the heat pump for space heating operation, the model determine at which hour of the day stored hot water is preferable to be used, giving power to cold storage pump.

5. Results

5.1. Pametric study results and comparison to reference systems

The dual source SAHP system was optimize thanks to a parametric study, varying cold storage tank volume and number of PVT panels employed as reported in Table III, using market available components. Same control strategy, TRNSYS types, auxiliary, loads and DHW draw profiles were used to run simulations.

Table III – Parametrics study settings

System	Heat pump Configuration	Solar panels type and number	Cold storage volume [m^3]
C1	Dual-Source	8 PVT	0.5
C2	Dual-Source	12 PVT	0.5
C3	Dual-Source	12 PVT	0.9
C4	Dual-Source	16 PVT	0.9

Thanks to the developed TRNSYS model, configurations has been compared for Milan and Rome, with two reference assets:

- System A, composed of an air – source heat pump for space heating, cooling and DHW production, integrated with 12 standard photovoltaic panels;

- System B, composed of an air – source heat pump for space heating, cooling and DHW production, integrated with 12 hybrid PVT panels to produce both electric energy and DHW.

Simulated standard photovoltaic panels had same parameters of the electrical part of PVT panels. In this way variation of silicon cells efficiency with temperature, resulted to be the same for both PV and PVT panels. The best technology would be the one that worked at lower temperature for greater time.

System C3 resulted the best regarding electric energy consumption and PVT electric production. Simulation results for Milan and Rome of system C3 is shown in Figure 14 and Figure 15.

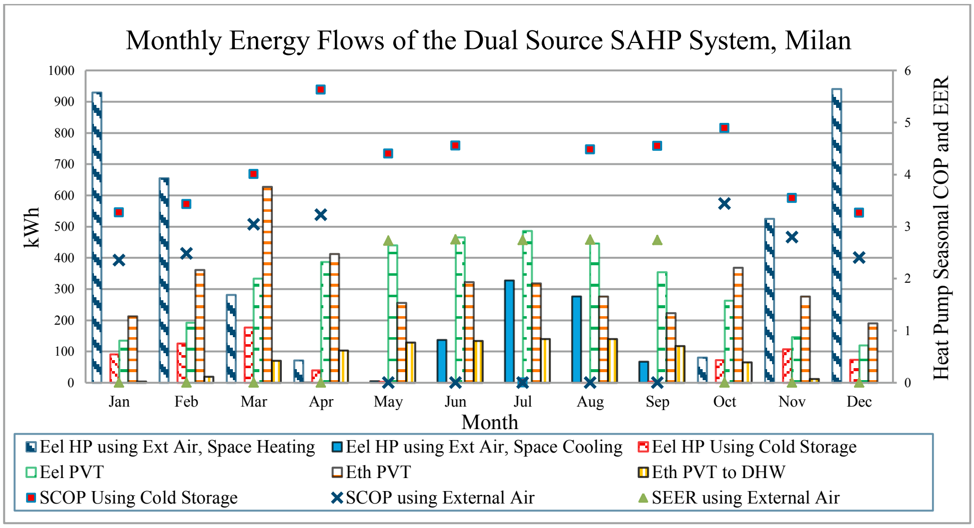


Figure 14 – Monthly energy flows and performance indexes of system C3 operations simulated in Milan

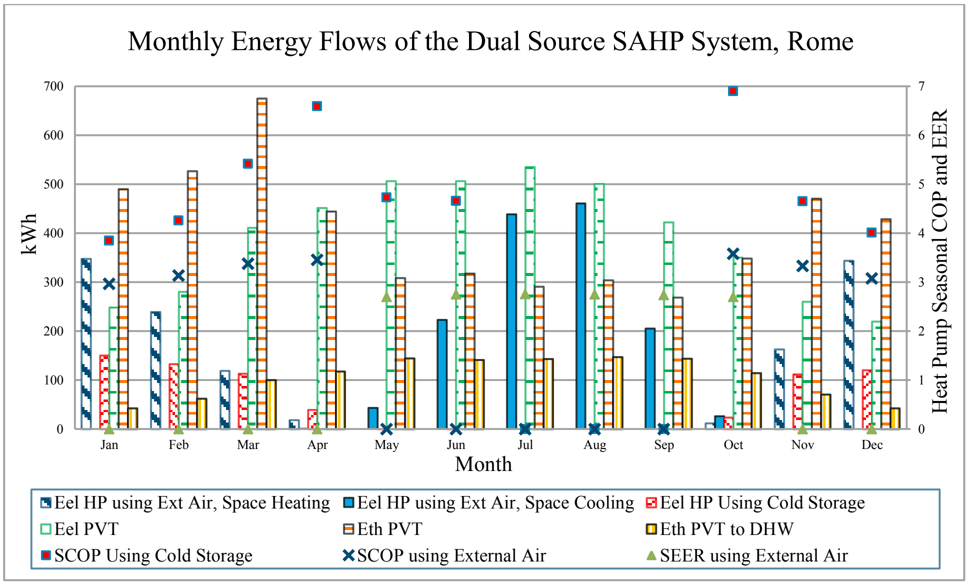


Figure 15 - Monthly energy flows and performance indexes of system C3 operations simulated in Rome

Graphs clearly shows an increased performances when stored solar energy were being used. In summer 12 PVT panels nearly fulfilled domestic hot water production in both places: residual heat needed was satisfy by the heat pump using stocked solar energy. Because a lot of heat absorbed in summer was unused, solar collectors tended to high operation temperature which had deteriorating electricity and thermal efficiency. Also with standard photovoltaic panels results were the same. Heat produced by heat pump using high temperature solar sources resulted to be 25% share for the system and the building placed in Milan and 46.89% for Rome. Dual source heat pump performances derived from inlet source temperature: in Figure 16 comparison between external air and stored solar energy in Rome is represented. The presented solution operated at higher source temperatures.

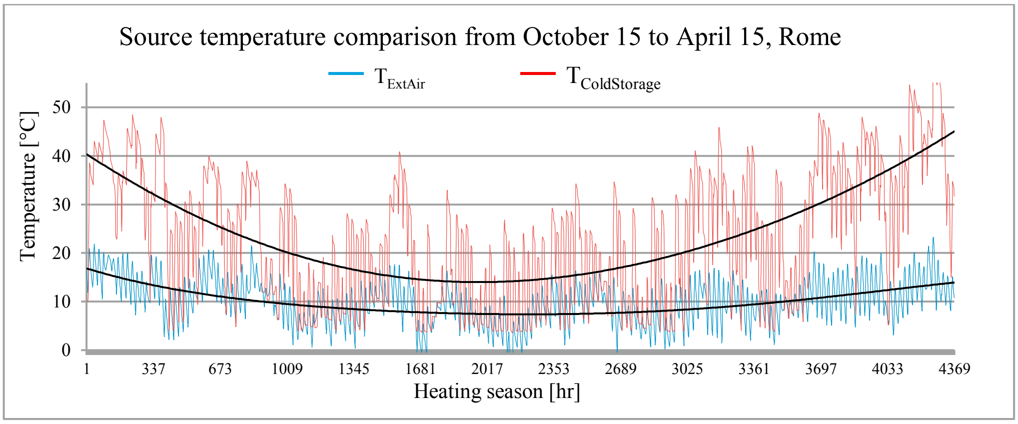


Figure 16 – Heat pump usable sources temperature comparison during heating season

6. System C3 comparison with reference systems

Comparison was based on electric energy production by solar panels and electric energy consumption by whole system, taking into account also auxiliaries. To consider both these results, was used as indicator the surplus of electric energy S, defined in equation (1).

$$S = E_{el\ Panels} - E_{el\ System} \quad (1)$$

Withdrawal from and injection to the grid of the investigated systems are reported in Figure 17.

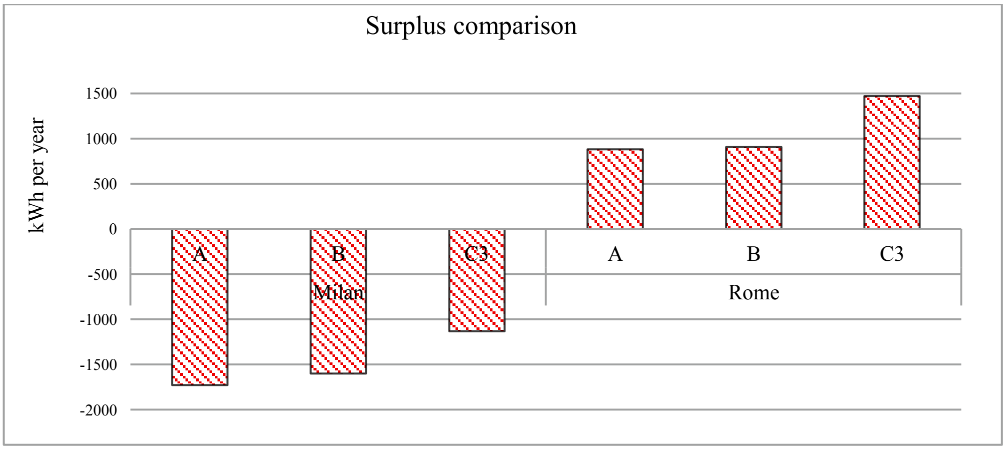


Figure 17 – Surplus comparison between related systems

The system composed by 12 PVT panels, a 0.9 m^3 of cold storage and the dual-source heat pump (C3), brought to a decreased yearly electrical energy consumption of 12% and withdrawal from the grid by 34% in Milan, compared to a conventional air-source heat pump combined with 12 standard photovoltaic panels (A). Relating the same systems with simulations in Rome, a decreased electric energy consumption of 18% was obtained together with an increased electric energy surplus of 76%. The studied system's performance was compared also to a conventional AWHP, with in addition 12 PVT panels for DHW production only (B). The results showed a decreased yearly electric energy consumption of 6% in Milan and of 12% in Rome, and a decreased grid consumption by, respectively, 29% and 71%. Energy flows for the compared systems are reported in Figure 18 examined by season and location.

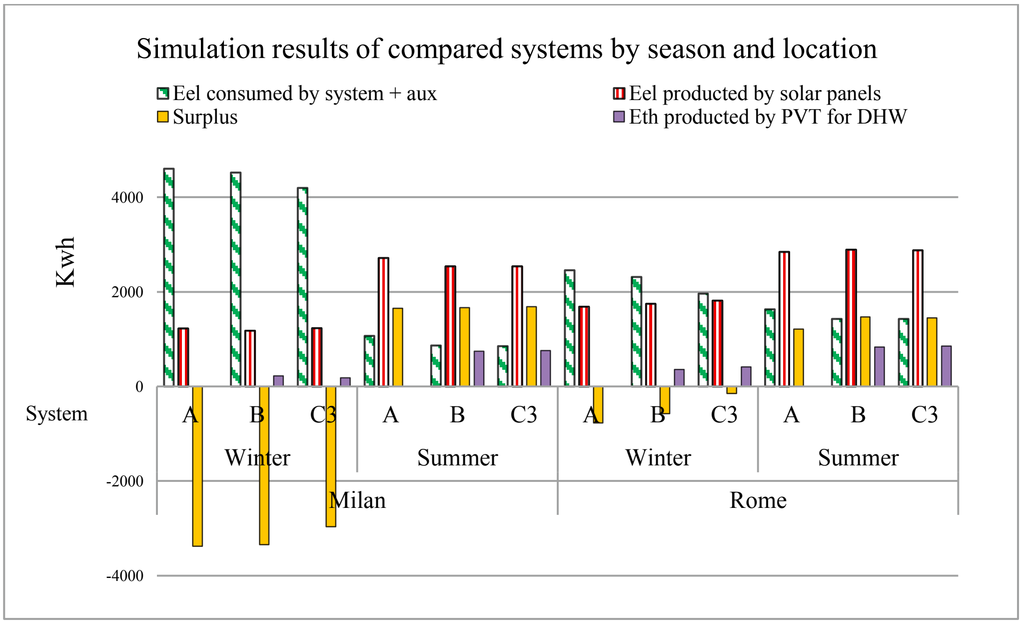


Figure 18 – Simulation results for the compared systems by season and location

In Milan electric energy consumption for system A, was reduced by the dual source heat pump of 10% in winter and 20% in summer. Regarding the comparison with system B those results became 8% from November to March and 6% from April to October. These results highlighted that during space heating operation the developed system brought to considerable performances improvement both for Milan and Rome. In summer when solar heat produced by panels was used only to produce domestic hot water in system B and C3, outcomes were similar. 12 standard photovoltaic or hybrid PVT panels installed, corresponding to 3 kW_p, from April to October produced more electric energy than necessary in place and could be injected in the grid and sold. In winter, instead, investigations in Milan greatly differed in Rome, where energy balance between consumption and production in place was almost reached.

7. Conclusions and future development

A solar assisted dual-source heat pump system, integrated with PVT panels, was designed, simulated by TRNSYS 17, optimized and finally built. The system was studied to optimize yearly performances, including space heating and space cooling operations, domestic hot water production. Solar heat could be directly delivered to produce domestic hot water or could be stored in an intermediate cold storage. Throughout winter period, heat-pump evaporator used solar heat stored in the Cold tank or external air, depending on performances optimization.

Parametric studies brought to choose a 12 PVT panels and 0.9 m^3 cold tank configuration, as best solution. Compared with standard systems, the developed one achieved significant energy savings for a single family building placed in Milan and Rome.

In terms of load scale, the dual-source SAHP system would be more suited to a multi-residential application. Otherwise it should be interesting to investigate behaviour of a less magnitude load scale heat pump for a single family house, considering that the system could not affect worst external conditions of minimal air temperature.

The system investigated in TRNSYS simulations was built in Milan on December 2016. Data resulted from first monitoring campaign highlighted better performances than expected. The developed system resulted to be really interesting to solve defrosting-cycle problems also. An example of monitoring interface for the system are presented in Figure 19. For future development Heat Rejection Technologies will be studied, to take advantage of cold tank for space cooling operations also.

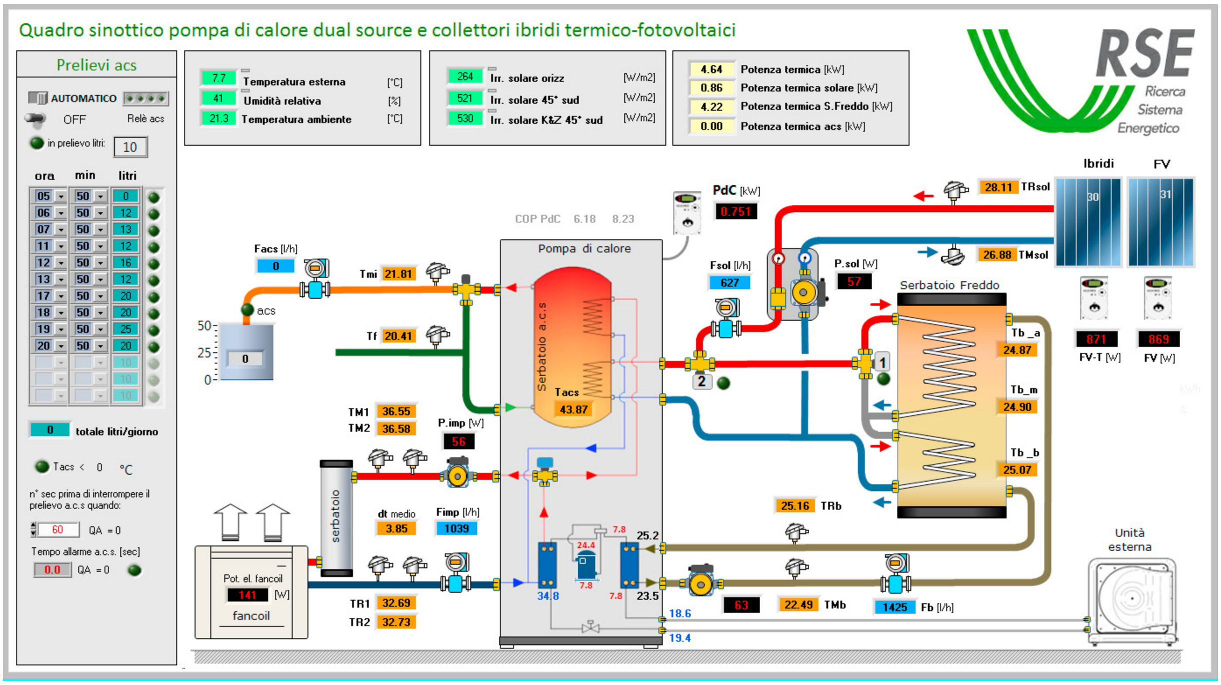


Figure 19 – Graphic interface of the monitoring system

Nomenclature

COP	Coefficient of Performance, ND
E_{el} PVT	Electric energy produced by PVT panels, kWh
EER	Energy Efficiency Ratio, ND
E_{th} HP	Electric energy consumption of the Heat Pump, kWh
SCOP	Seasonal coefficient of performance, ND
SEER	Seasonal coefficient of performance, ND
T_{ExtAir}	External air temperature, °C
Eel Panels	External air temperature, °C

Acknowledgements

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