Optimization of a Solar Assisted Heat Pump System to Increase Thermal Efficiency Working on the Cold Source

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Abstract

This study introduces an innovative high-efficiency air conditioning system that utilizes solar-assisted heat pumps to enhance the coefficient of performance by elevating the thermal level of the lower temperature heat source. Solar energy stored in thermal storage is used to optimize operating conditions by increasing the cold source temperature. A demonstrator of such a system is investigated by referring to the residential building "Chiodo 2" located at the University of Calabria, where an existing plant equipped with heat pumps in master-slave configuration are already operational. The simulation model was developed within the TRNSYS environment. The development process of the virtual system model is presented in detail, encompassing solar collectors, thermal storage, heat pump and a photovoltaic system. Through an analysis of the winter operation of the system, the study identifies key requirements, including the optimal thermal storage volume and the optimal size of solar collectors, to maximize energy efficiency. Specific operating conditions are proposed, such as the synergistic use of solar collectors and heat pump in particular thermal scenarios, to enhance performance.

1. Introduction

On the road toward the reduction of greenhouse gas emissions and increasing sustainability, the building sector plays a pivotal role. The European Union's recent "Fit for 55%" package set ambitious targets and specifically, the Fit for 55% package underlines the pivotal role of HVAC systems in achieving these goals. For such a reason many countries' policies are pushing toward the mandatory adoption of a heat pump system for air-conditioning of buildings, dismissing traditional systems based on fossil fuels. The accurate design of such a generator requires a careful consideration of the real operating condition (Bruno et al., 2020). Heat pumps achieve maximum sustainability when combined with solar energy (solar-assisted heat pumps) (Baggio et al., 2018; Bee et al., 2019). In this regard, the most used configuration is the use of a photovoltaic system to supply electric energy to the heat pump (Nicoletti et al., 2022). However, in recent years researchers have focused on integrating heat pumps with solar collectors, photovoltaic panels, and hybrid systems. A study investigated the performance of a ground source heat pump system with free cooling and photovoltaic/thermal collectors at the service of a multi-family building in Stockholm (Pourier et al., 2024). The optimal design features of photovoltaic-thermal collectors for integration with ground source heat pump systems was investigated considering technical and economic factors (Beltrán et al., 2024). The impact of a control logic aimed at maximizing the utilization of excess renewable in a solar-assisted heat pump systems with electrical and thermal storage systems was assessed by Perrella et al. (2024). The thermal performance of a direct expansion solar assisted heat pump was analysed for several refrigerants using two collector configurations (Chata et al., 2005).

The use of appropriate storage system can play an important role in the integration and optimal utilization of renewable energy. In Pinamonti et al. (2021), the integration of a modulating water-to-water heat pump in a solar system with a seasonal storage was analysed. In terms of solar fraction, the

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results showed values reaching 85 %. A solar-assisted raw-water source heat pump (Han et al., 2024) was proposed to solve the performance degradation and improve heating performance thanks to solar collectors that can increase the entering water temperature. A multi-source energy system including photovoltaic thermal solar collectors, storage tanks for the heat source and domestic hot water and heat pumps was analysed in reference to a single-family dwelling located in Northeast Italy (Emmi et al., 2017). Results showed that the multi-energy source systems increased the energy efficiency by 16–25% compared to an ordinary air-to-water heat pump. A solar hybrid plant consisting of water-based PV-T collectors integrated with an air-to-water heat pump via thermal storage tanks was investigated considering a full-size pilot plant located in Spain and operating under real weather conditions (Herrando et al., 2023). Results showed that thanks to the simultaneous electricity and thermal generation of the PV-T collectors, overall the plant was self-sufficient to satisfy the building energy demand. A solar assisted heat pump solar supplied by thermal-photovoltaic hybrid panels was analysed numerically and experimentally (Del Amo et al., 2019). Results indicated that the system was not properly sized presenting a low solar radiation exploitation. A solar PVT assisted - heat pump system with a cold buffer storage tank on the source side of the heat pump and a hot storage tank for domestic hot water was measured over a nine-month period (Dannemand et al., 2019). The uninsulated PVT collector worked as an energy absorber and was able to extract heat form the ambient air and recharge the buffer storage tank to the ambient air temperature when no solar irradiance was available. In the less sunny and colder periods, the PVT added a significant amount of energy to the cold storage tank.

In this study, an assisted water-to-water heat pump that uses solar thermal collectors to increase the temperature of a water tank employed as cold source for the supply of heating and cooling loads in a university residential complex in Rende (Italy) was investigated. Simulations were performed in the TRNSYS environment to assess the effect of solar thermal collectors and thermal storage size on the fraction of heating demand saved by the integration of the solar source in the generation system

2. Methodology

2.1 Case Study Building

The building considered in the study is part of a student residential complex of the University of Calabria named “Chiodo2”. The building's energy demand has been calculated within the TRNSYS environment. The building's 3D model was created using Sketchup, incorporating the TRNSYS 3D plug-in to facilitate a comprehensive representation of its geometry. The geometrical representation of the analysed building is reported in Fig. 1.

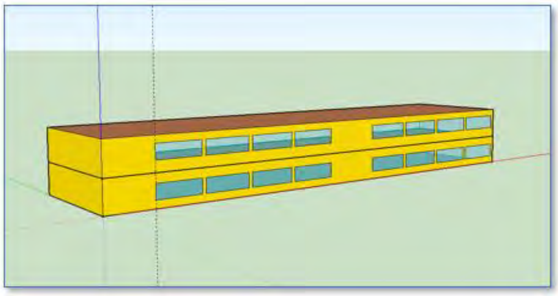

Fig. 1 – 3D representation of the building model

The thermal properties and stratigraphy of the main components of the building are reported in Table 1 and Table 2. Table 3 reports the U-values of the main building components.

Table 1 – Thermal properties of the external walls

	Thickness [cm]	Conductivity [W/mK]	Specific heat [J/kgK]	Density [kg/m³]
Plaster	2	0.9	800	1400
Brick masonry	30	0.157	1000	1250
Plaster	2	0.9	800	1400

Table 2 – Thermal properties of the external roof

	Thickness [cm]	Conductivity [W/mK]	Specific heat [J/kgK]	Density [kg/m³]
Tiles	2	0.9	800	2000
Screed	14	2	800	900
Insulation	2	0.035	800	55
Plaster	2	0.9	800	1400

Table 3 – U-value of the main building components

	U-value [W/m²K]
External wall	0.471
External roof/ground floor	0.236
External window	2.89

Internal gains account for an amount of 440 W of radiative and convective powers. Infiltration was set to 0.5 h^{-1}. The heating plant was considered with a set-point temperature of 20 °C.

2.2 The Air-conditioning Plant

The simulated air-conditioning plant of the building is composed of:

- a field of evacuated tube solar collectors designed to ensure maximum efficiency even under suboptimal solar radiation conditions,
- two thermal storage tanks, one supplied by the solar collector to be used as cold source (solar tank), and another supplied by the heat pump for the emitters provision,
- a water-to-water heat pump.

The heat pump was sized according to preliminary results of simulation, as reported in section 3.1. An available commercial model was chosen for simulation, and data of COP and thermal power delivered at the different source temperatures were taken from datasheet and provided to Type 927. In particular the selected model is a water-source reversible water condensed heat pump. The heat pump has a rated power of 12.6 kW and a nominal COP of 3.94.

A commercially available vacuum tube solar collector was chosen for simulations and pertinent parameters were provided to Type 71. The data of the solar thermal collector are reported in Table 4.

Table 4 – Parameters of the solar thermal collector

Parameter	Value
Optical efficiency [-]	0.785
First order coefficient [W/m²K]	1.847
Second order coefficient [W/m²K²]	0.005

The simulation scheme adopted within TRNSYS environment is reported in Fig. 2.

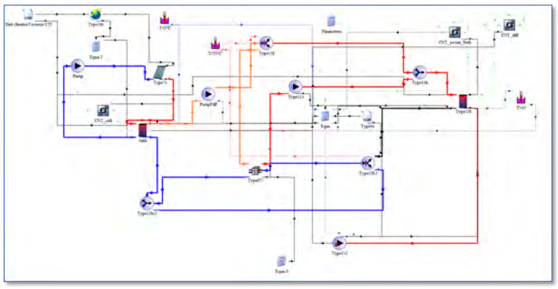

Fig. 2 – Simulation scheme adopted in TRNSYS

The solar collector directly supplies the solar storage tank, according to a control logic that checks the temperature difference between the panel outlet temperature and the tank temperature and decides whether to activate or not the circulation pump by setting a proper dead band. The solar tank supplies the heat pump acting as a cold source. A proper control strategy, monitoring the temperature of both tanks, determines if the solar tank directly supplies the user tank by-passing the heat pump or if it is used as cold source for the generator. In particular, in winter the system operates according to the following conditions:

- If the solar tank temperature is over 60 °C or if there is a temperature difference between the two tanks, space heating is directly satisfied by the solar collectors without the assistance of the heat pump.
- If the solar storage tank is lower than 5 °C, the heat pump does not operate to avoid freezing and heating is carried out by an alternative generation system (gas boiler).

Since this is a solar-assisted air-conditioning plant, the surface capturing solar radiation and the tank for energy store are of great importance. Therefore, a parametric study of the winter performance of the system was carried out varying the storage volume (V= 800 litres and 1600 litres) and the surface area of the collectors (10, 20, 25, 30, 40 m²).

3. Results and Discussion

3.1 Building Heating Load and Energy Consumption

A preliminary simulation was performed to determine the building heating load and the associated yearly energy consumption. Results of hourly simulation are reported in Fig. 3.

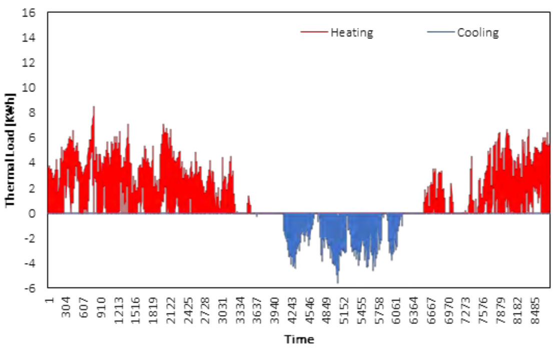

Fig. 3 – Hourly simulation of building thermal need

Accordingly, Fig. 4 reports the monthly energy demand of the building for winter heating. The months of December showed the highest request with a value of 2182 kWh, followed by January and February with an almost equal amount around 2000 kWh. The total amount of energy needs for winter heating amounts to 10771.7 kWh.

Furthermore, a frequency analysis was conducted to quantify the number of hours in which a specific load occurred. Results showed that a load of 12 kW occurred more frequently allowing to identify this value for the heat pump rated power. The set-point temperature of the water tank supplying emitters was set to 60 °C (fan-coils in every room).

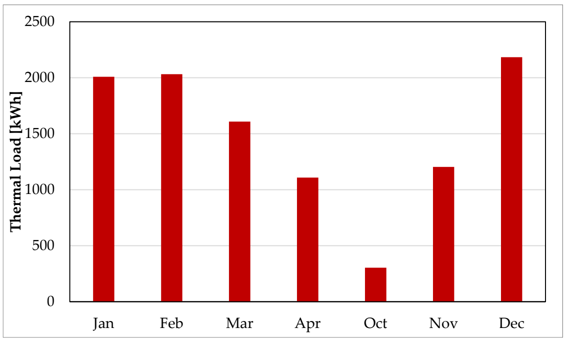

Fig. 4 – Monthly heating demand of the building for winter heating

3.2 System Thermal Performance

For each configuration of the parametric analysis, the percentage of the winter thermal energy demand met by the system has been quantified. Furthermore, concerning the addressed thermal demand, a further distinction has been made between the portion directly handled by the solar collectors and that managed through the heat pump. For instance, Fig. 5 depicts results obtained for the heating plant assuming the lowest size (10 m²) for collectors and water tank (800 l).

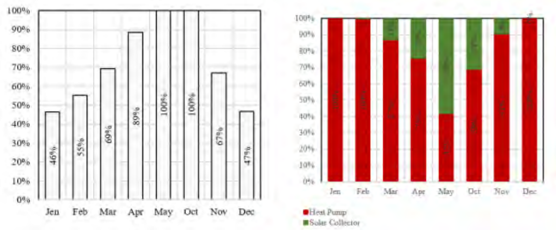

Fig. 5 – Monthly energy demand supplied by the system (left) and percentage of the thermal demand met by heat pump and directly by solar thermal collector (right) A=10 m²; V=0.8 m³

In particular, Fig. 5 (left) the monthly percentage of energy satisfied by the SAHP system appears, whereas in Fig. 5 (right) the separated share of energy directly supplied from solar collectors to the user and the share provided by the heat pump is shown. As expected, for low active surfaces of solar panels, the amount of energy provided by the system is not sufficient to completely satisfy the demand in the colder winter months, where the lowest percentage is found in January, at 46 %. In spring and autumn, the system is able to provide more than 50 % of the energy demand. Interestingly the solar thermal collector is able to directly provide an adequate amount of heating thermal energy in spring and autumn, reaching the highest value of 58 % in May and the lowest of 9 % in November.

When the solar tank is doubled in its capacity, it is possible to observe better performance in some months. In particular, the system capacity to provide thermal energy increases to 49 % in January and to 57 % in February while in April, May and October the percentages do not vary. As regards the percentage of load directly satisfied by the thermal collector, a substantial increase is observed in May, reaching 73 % while in April and October percentages of 27 % and 39 % are observed respectively.

When the solar collector surface is increased to 25 m² an overall upward trend shift in all percentages can be observed, as shown in Fig. 6.

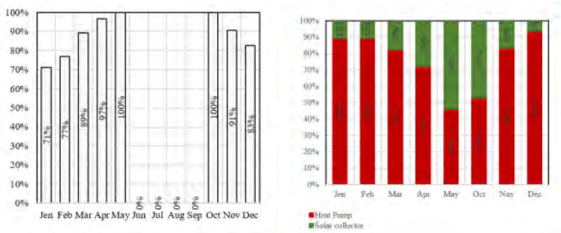

Fig. 6 – Monthly energy demand supplied by the system (left) and percentage of the thermal demand met by heat pump and directly by solar thermal collector (right) A=25 m²; V=0.8 m³

From May to November, the ability of the system to provide thermal energy is almost always higher than 90 %, and in the worst condition of January a value of 71 % is reached. The solar collector is in this case, able to directly provide heating to the building in all the months analyzed, with small percentages of 6 % in December and 10 % in January. The best performance is again observed in May where the percentage reaches 54 %. When a solar tank of 1.6 m³ is used in all the spring and autumn months, the system reaches complete sufficiency (100 %), whereas few increments are observed for the energy directly supplied by the solar collector in winter months, and many more increments are found in May (68 %) and October (57 %).

In Fig. 7 the same information is reported for a solar thermal collector surface of 40 m² and storage of 800 liters. Clearly the maximum exploitation of solar radiation is achievable in this configuration. In fact, from April to October the system can provide 100 % of energy to the building, and this period extends further to March and November if the solar tank volume is augmented to 1.6 m³. In the latter case, the minimum amount of 87 % is reached in January. When looking at the energy from solar collectors directly used for heating, the amount conspicuously augments in May and October, with percentages of 54 % and 52 % respectively, which further increase to 70 % and 65 % with a 1.6 m³ solar tank.

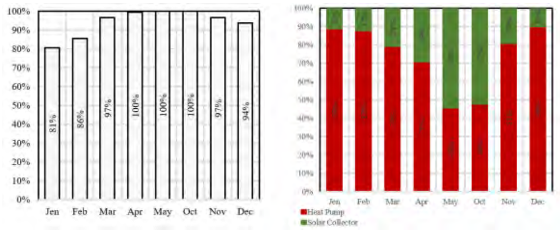

Fig. 7 – Monthly energy demand supplied by the system (left) and percentage of the thermal demand met by heat pump and directly by solar thermal collector (right) A=40 m²; V=0.8 m³

Finally, Fig. 8 reports the percentage of energy demand met by the SAHP system at different solar collector areas and for the two different sizes of solar tank volume.

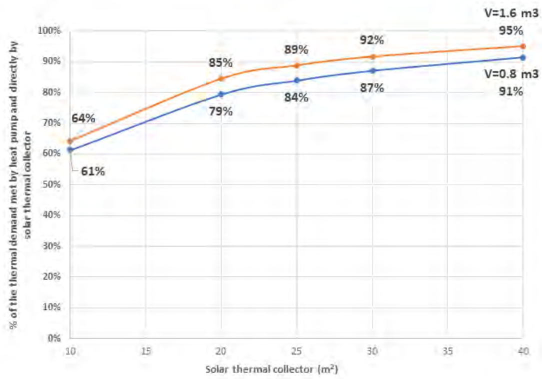

Fig. 8 – Annual energy demand met by heat pump for different solar collector surface areas and solar tank volumes

From Fig. 8 it is clearly evident that increasing the solar collector surface provides notable increments especially for lower capturing areas. In fact, in the case of the bigger solar tank, moving from 10 m² to 20 m² produces an increment of 32.8 %; moving from 20 m² to 30 m² produces instead a much more limited increment of 8.2 %.

From the results of simulation, it also emerges that the cost-optimal configuration necessitates a solar panel surface area ranging from 25 to 30 m², because greater areas would not be justified by the relatively small increase in thermal yield. Furthermore, it was observed that a thermal storage volume of 1.6 m³ can ensure the most efficient system performance. This configuration allows for the maximization of energy efficiency while avoiding unnecessary costs.

Finally, Table 5 reports the average monthly COP of the heat pump along with the yearly average value. The utilization of the solar collector to increase the temperature of the cold source evidently produces benefits in terms of performance of the heat pump.

Table 5 – Average monthly COP of the heat pump for the different collector surfaces considered

	S10	S20	S25	S30	S30
Jan	3.75	3.86	3.84	3.84	3.87
Feb	3.80	3.91	3.96	3.91	3.95
Mar	3.79	3.91	3.95	3.89	3.96
Apr	3.82	3.97	3.90	3.97	3.87
May	4.08	4.03	4.58	4.02	4.39
Oct	4.10	3.92	3.84	3.89	3.99
Nov	3.70	3.92	3.87	3.91	3.94
Dec	3.72	3.80	3.81	3.88	3.86
Ave	**3.85**	**3.92**	**3.97**	**3.91**	**3.98**

Interestingly, the average monthly COP surpasses the value of 4 in May for all the collector surfaces. In the other warmer months (October and April), the value is much closer to it. In colder months however, the COP maintains a relatively high value that in January reaches 3.86 for 20 m³ and in December 3.86 for 40 m². For the same months, the lowest values of 3.75 and 3.72 are observed for a surface of 10 m².

The highest value of 4.58 among all the cases is found in May for a surface of 25 m².

If the yearly average value of COP is considered it can be observed that a maximum value of 3.98 is found for a surface of 40 m². However, even in the worst case, the COP assumes a value of 3.85 (for 10 m²) that can be appreciated to be very close to the nominal value of the heat pump.

4. Conclusion

Heat pumps achieve maximum sustainability when integrated with solar energy (solar-assisted heat pumps). In this study solar thermal collectors are employed to increase the temperature of a water tank used as the cold source of a water-to-water heat pump for the provision of heating loads in a university residential complex in Rende (Italy). The air-conditioning plant of the building is composed of a field of evacuated tube solar collectors and two thermal storage tanks, one at the service of the solar collector, which represents the cold source of the water-to-water heat pump, the other for the emitters' supply.

Simulations were performed with the TRNSYS environment to assess the effect of solar thermal collectors and thermal storage size on the fraction of energy demand covered by the system.

When adopting 40 m² of solar collector surface and 1.6 m³ of volume for the solar tank, the system is able to provide 100 % of energy to the building from March to November. The energy from solar collectors directly used for heating amounted to 70 % and 65 % in May and October, respectively. Results of the simulations showed, however, that increasing the solar collector surface provided notable increments only for lower capturing areas, whereas moving to higher collector surfaces determined lower marginal increments. It emerged how the cost-optimal configuration requires a solar panel surface ranging from 25 to 30 m², and that a thermal storage volume of 1.6 m³ can ensure the most efficient system performance. Finally, results showed that the utilization of the solar collector to increase the temperature of the cold source of the heat pump produces evident benefits in terms of COP, which can reach a yearly average value of 3.98 and an average monthly value of 4.58 in May, considering that the rated COP is 3.94 assuming the favorable conditions of the cold source at 20 °C to supply hot water at 35°C.

Acknowledgement

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