Control Strategies to Increase the Photovoltaic Self-Consumption for Air-Source Heat Pump Systems

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Abstract

Decreasing the use of fossil fuels for heating and cooling applications in buildings is one of the main concerns in reaching the energy reduction targets defined by the European Union countries. For this purpose, high efficiency heating and cooling systems are required, together with appropriate control strategies. The use of heat pumps (HP) in residential buildings is spreading, and the combination of these systems with the on-site production of photovoltaic (PV) energy can lead to high levels of renewable energy self-consumption. However, a poor design and a lack of control in the system can lead to a large amount of PV energy surplus, which has to be sold to the grid, or wasted. For this purpose, the use of energy storage and demand-side management strategies are crucial. This paper describes a control strategy for an air-source HP system combined with a PV plant for a residential building. The control strategy aims to maximize the self-consumption of PV power, varying the system behavior depending on the instantaneous PV production. When an overproduction of PV energy occurs, the HP operates to store the surplus of solar energy by exploiting the storage capacity and the building thermal capacitance. In this study, the heat pump was controlled by acting on the compressor rotational speed (i.e. the frequency of the supplied power). The compressor was controlled in order to operate at the maximum capacity level compatible with the power supplied by PV. The effectiveness of the control strategy was assessed over a whole year, considering both the heating and cooling season and domestic hot water (DHW) preparation. The simulations were performed using the TRNSYS simulation software, considering a double-story residential building in northern Italy. The results obtained with the proposed demand side management (DSM) strategy show a reduction of around 33% of the energy taken from the grid with respect to a similar system with a standard control strategy.

1. Introduction

In Europe, about 40% of the final energy consumption is related to building use (European Parliament and Council, 2012), and in particular the residential sector is responsible for about 25% of the total consumption (Eurostat, 2019).
Moreover, in 2017 Eurostat reported a share of renewable energy for heating and cooling in the residential sector of about 19.5% and about 30% for electricity production (Eurostat, 2018).
Decreasing the use of fossil fuels for heating and cooling applications in buildings is one of the main concerns in reaching the energy reduction targets defined by the European Union countries. A more efficient use of energy and a larger share of renewable energy sources are required solutions to decrease the impact of building energy use over the final European energy consumption. For this purpose, one of the most promising technologies, the use of which spreading in European countries , is the heat pump system coupled with photovoltaic panels (Battaglia et al., 2017). In Europe, the most common solution is the use of air-source heat pumps, which are able to provide heating, cooling and DHW simultaneously (Hardorn, 2015). These systems are driven mainly by electricity and can operate efficiently in combination with PV systems. Indeed, the heat pump can be directly connected to the photovoltaic panels and lead to direct consumption of the solar energy generated on-site. One of the main issues to optimize the self-consumption of these systems is the time gap between the peaks of the building loads and the PV power availability (Luthander et al. 2015). There are different solutions to improve the self-consumption rate, among which are the use of energy storage technologies and the

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demand-side management (DSM) strategies for the building load shifting (Battaglia et al., 2017; Fischer and Madani, 2017). Different strategies for DSMs have already been de-fined, such as direct-load control, load limiters, de-mand bidding and smart metering and appliances (Strbac, 2008).
Several studies have analyzed different DSM controls and their impact on the overall energy consumption and performance of the system. In these studies, the use of modulating heat pumps is widespread to ensure a high level of PV self-consumption. Dentel and Betzold (2017) propose a control strategy which adapts the heat pump to the PV production, together with the use of thermal and electric storage, and reaches an increase of 21% in PV direct consumption. Bee et al. (2018) define a control strategy to store the energy within the thermal storage capacity of the system and the building thermal capacitance when the PV power is available. In this study, the self-consumption of the system increased from 7% to 65%.
The aim of this study is to define and analyze a DSM strategy to maximize the self-consumption rate for a modulating air-source heat pump system, considering a reference residential building in Bolzano, in the north of Italy.

2. Method

The study proposes and analyzes a control strategy for demand-side management, considering a modulating air-source heat pump for a residential building in northern Italy. The system provides space heating, space cooling and domestic hot water to the building over the whole year. The proposed DSM operates by varying the system's behavior according to the instantaneous PV power availability. The assessment of the system's performance and energy consumption was carried out by means of dynamic simulations with the TRNSYS software.

2.1 Test Case Building

The considered building proposed in the study is a small two-story building with 140 m^2 heated floor area and a heat dispersion surface vs a conditioned volume ratio S/V of 0.59. The building is divided into four thermal zones, one in the north and one in the south part of each floor of the building. The envelope of the building has a high-insulation level, as shown in Table 1.

Table 1 – U-values of the building elements

Element	U-Value
Wall	0.18 Wm^{-2}K^{-1}
Ground floor	0.18 Wm^{-2}K^{-1}
Roof	0.17 Wm^{-2}K^{-1}
Window	0.86 Wm^{-2}K^{-1}
Ceiling	0.20 Wm^{-2}K^{-1}

The heating and cooling loads of the building were calculated using the software TRNSYS and considering the test reference year for the climate of Bolzano. The building model was set up using the multi-zone building subroutine type 56 in TRNSYS. The DHW consumption was estimated around 186 l per day based on the Italian technical specification (UNI 2014) using the hourly demand profile determined by the European Standard (European Committee for Standardization-CEN 2016). The HVAC system includes a heat-recovery ventilation system and a dehumidification unit, which operates during the summer period to avoid the risk of condensation on the cooled floor. The air change rate is set to 0.5 vol/h during the heating season and 1.5 vol/h during the cooling season.

2.2 Building System

An air-source heat pump system was modelled in TRNSYS with a previously developed type (Bee et al., 2016). This type modelled a heat pump with a variable speed compressor, and evaluated the part load operation of the component by means of the performance map and the part-load performance function provided by the manufacturer. The heat pump provided the building with space heating (SH), space cooling (SC) and DHW production. The heat pump is connected to two tanks (type 60), one for DHW and the other one for SH and SC. The tank for SH and SC is connected to a radiant floor panel system, which has a pipe spacing of 0.12 m and diameter of 0.016 m. The radiant floor was modelled as an active layer within the floor in the building model. Four on-off thermostat controllers were connected to each thermal zone. The set-point for the ambient temperature is equal to 20 °C for the heating mode and 26 °C for the cooling mode. The thermostats control the inlet flow of the radiant panels for each zone by switching on and off four single-speed pumps (Type 114). The SH tank temperature set-point is reset depending on the outdoor temperature. In the heating mode, such set-point varies from 40 to 20 °C. while in the cooling mode it goes from 26 to 18 °C. The inlet water temperature of the radiant panels varies accordingly.

A PV plant was modelled considering polycrystalline modules (Type 94) with a nominal power of 270 kWp. The panels have an array slope of 45° and a total area of about 20 m².

2.3 Control Strategy

The HP model was controlled by setting the compressor rotational speed. The input parameter is the frequency of the supplied power, which is controlled according to the difference between the set-point temperatures for SH and SC and the actual temperature of the outflow of the HP. In the DHW production mode, the compressor always runs at its maximum speed. The priority is given to the DHW production. The model calculates the heat pump power according to the inverter frequency (f), as the percentage of the total electric input ($Y_{el,\%}$) for the actual operating conditions. The relation between frequency and electric input was assessed for different sink and source temperatures based on manufacturer data, obtaining the curve shown in Fig. 1.

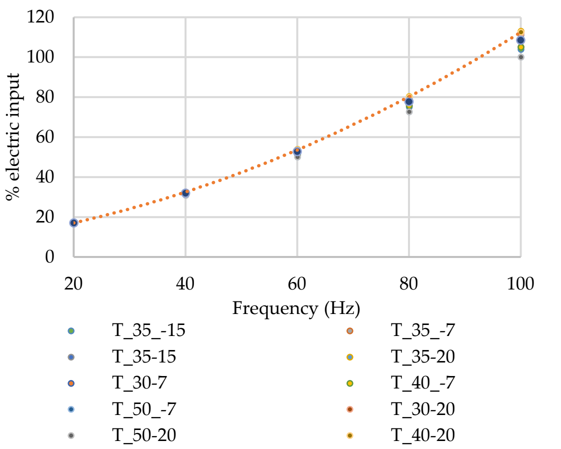

Fig. 1 – Inverter frequency and relative percentage of electric input for the heat pump at different operating conditions

Considering different operating temperatures, the results are similar at low frequency values, but they diverge (a little) at higher frequency levels. For the purpose of this study, the function used for the relation between frequency and electric power used by the heat pump is the one corresponding to the highest values of $Y_{el,\%}$. The trend can be fitted by the following quadratic function (Eq. 1):

$$Y_{el,\%} = 0.007 \cdot f^2 + 0.3522 \cdot f + 7.2073 \qquad (1)$$

During each time step of the simulation, the software computed the power generated by the PV panels. The PV power covers directly the electric loads for ventilation, dehumidification, heat pump operation and hydronic system circulation pumps. In the base case, any PV overproduction is sent to the grid. The DSM proposed in this study aims to exploit the PV overproduction to maximize the self-consumption of the system and decrease the purchase of energy from the national grid. When a PV overproduction occurs, the DSM controls the compressor speed depending on the actual PV production, adapting the heat pump thermal output to the available PV power. Considering the operating conditions of the heat pump at the time-step where the overproduction is detected, the electric input (Y_{el}) is computed using a polynomial equation obtained from the manufacturer data of the heat pump power working at different sink and source temperatures. The equation (Eq. 2) contains four coefficients (b_n), the condenser outlet temperature ($\varphi_{cond,out}$) and the evaporator inlet temperature ($\varphi_{ev,in}$).

$$Y_{el} = b_0 + b_1 \cdot \varphi_{cond,out}^2 + b_2 \cdot \varphi_{ev,in} + b_3 \cdot \varphi_{ev,in}^2 \qquad (2)$$

The available PV surplus power is then expressed as a percentage of the electric input Y_{el} and the frequency is calculated using Equation 1. This frequency is used as input to control the HP type. This frequency corresponds to the maximum capacity level of the HP compatible with the supplied PV power.

3. Simulations

The simulations were performed with the TRNSYS software, to assess the behavior of the building and the system during the whole year, using a time-step of 1 minute.

Five different cases were simulated to evaluate the efficiency of the proposed DSM.

In the first case, a standard HVAC control strategy was assessed without the integration of DSM. In this case, the PV power directly covered the electrical building loads, as defined in the previous chapter, and during the PV overproduction, the electricity was sent to the grid.

In the other cases, the DSM was applied with different strategies to store the excess thermal energy overproduced by the heat pump. The energy was stored by changing the set-point temperatures of the SH and SC tank to 65 °C for the heating mode and to 7 °C for the cooling mode. A diverting and mixing valve system controlled the return water from the radiant panels and mixed it with the hot water in the tank to maintain the inlet temperature of the water entering the panel at the set-point level. As described in the previous chapter, the set-point temperature varies depending on the outdoor air temperature. The overheating of the DHW tank brings the temperature up to 75 °C. Moreover, the possibility of exploiting the building thermal capacitance to store a larger amount of energy was evaluated. In this case, during the PV surplus periods, the set-point of the thermal zones of the building was modified by ±2 °C. The four DSM strategies are defined as follows:

- DSM 1: in the case of PV overproduction, the priority was given to the overheating and overcooling of the SH-SC tank. When the maximum set-point was reached, the energy was stored in the DHW tank.
- DSM 2: the heat pump worked as in DSM 1, plus the set-points of the thermal zones were modified by ±2°C.
- DSM 3: the priority was given to the overheating of the DHW tank.
- DSM 4: the same as DSM 3, together with the change of the thermal zones' set-point.

4. Results and Discussion

The four DSM solutions were evaluated and compared with a standard HVAC control strategy to assess the potential reduction of energy use. The results are expressed as the amount of purchased energy from the grid. The monthly results for the 5 cases are shown in the graph (Fig. 2).

The results show that the DSM strategy reduced appreciably the amount of energy taken from grid with respect to the standard HVAC control strategy. Moreover, prioritizing the DHW tank overheating appeared to be favorable throughout the whole year. The difference between DSM 1 and DSM 3 consumption was larger during the summer season.

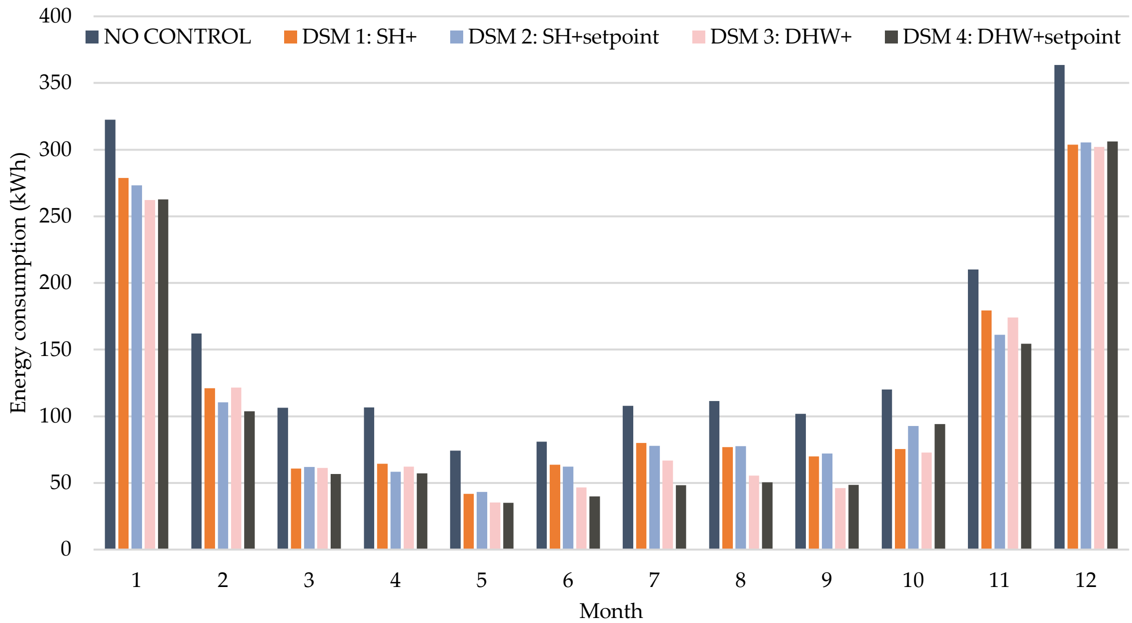

Fig. 1 – Grid consumption of the standard HVAC strategy and the different DSM solutions

The alteration of the thermal zones' set-point, evaluated in DSM 2 and DSM 4, was advantageous during most of the months. In the middle seasons, prioritizing the DHW or SH-SC led to similar results.
Considering the annual energy consumption taken from the grid (Fig. 3), the results for the standard HVAC control strategy was around 13.30 kWh $m^{-2}y^{-1}$. The annual grid consumption reduction achievable with the DSM strategies were 24%, 25%, 30% and 33% for the DSM 1, DSM 2, DSM 3 and DSM 4, respectively.

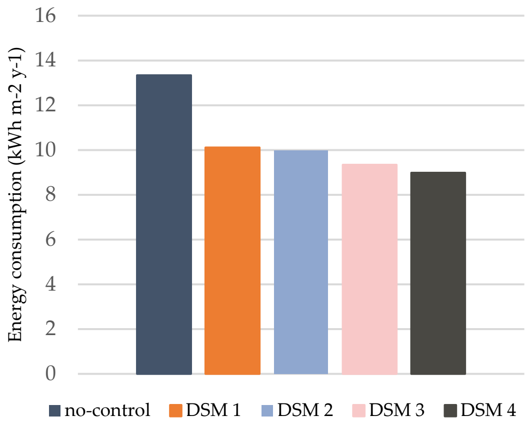

Fig. 3 – Total annual energy consumption from the grid for the standard HVAC strategy and the proposed DSM

Looking at the annual grid consumption, the DSM 4 seems to be the optimal solution.
A more detailed comparison has been carried out between the standard HVAC -control strategy and the DSM 4.
For these two cases, the total energy consumption is shown in the graphs in Fig.s 4 and 5, highlighting the different amounts of energy self-consumed by the system and purchased from the grid. For the DSM 4 case, the total amount of energy consumed by the system increased, but most of it was covered with the use of on-site solar energy production. In particular, the self-consumption rate reached values of around 85% during the summer period. For the no-control strategy, the maximum amount of self-consumption was around 55% during the summer.
In the same graphs, the COP and EER values show the average performance of the two systems for each month. Comparing the results for the two systems, the standard HVAC -control strategy presents higher levels of performance. The reason is due to the overheating and overcooling of the tank in the DSM strategy, which lead the heat pump to work with a higher temperature difference and consequently , with lower performance. The only increase in EER value for the DSM 4 case is due to the fact that the systems worked during May for the overcooling of the tank, when the external temperatures were lower and the heat pump worked with higher performance, while in the standard HVAC control case the cooling was not required in that period.

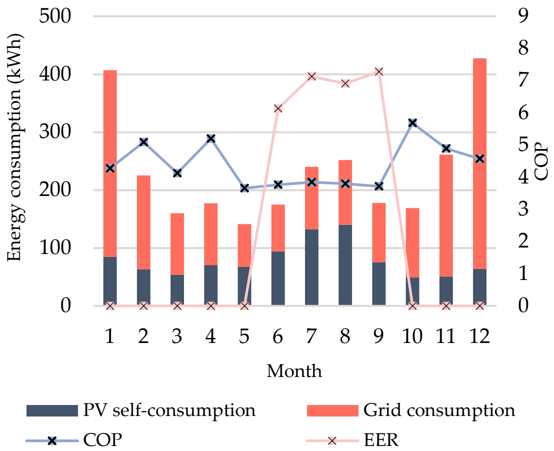

Fig. 4 – Total energy consumption of the system and performance indicators for the standard HVAC control

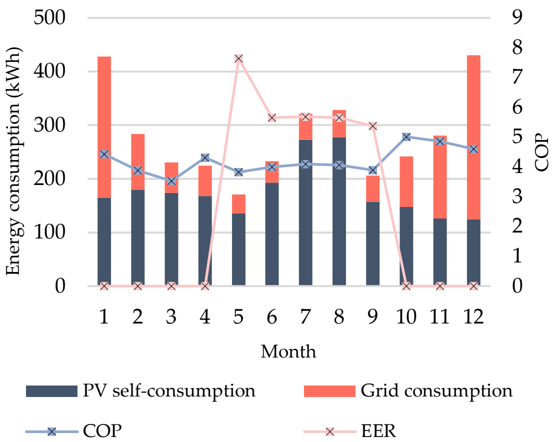

Fig. 5 – Total energy consumption of the system and performance indicators for the optimal solution DSM 4

In the following graphs, the PV power generation and the system's loads are shown for a few days of the heating season, the middle season and the cooling season for the two analyzed strategies. For the month of January (Fig.s 6 and 7), the PV production was almost half the production during the summer season, but the DSM shifted the system's load during the time when the PV was available, reducing

significantly the peaks due to the DHW production. During the middle season (Fig.s 8 and 9), the PV production was higher but the loads were lower, because no heating or cooling was required. In this case, the DSM shifted most of the load during the PV production period.
The same considerations are valid for the summer period (Fig.s 10 and 11), where a larger fraction of PV generated energy was self-consumed by the system because of the cooling loads.
Between the analyzed DSM strategies, the prioritization of the DHW tank overheating is the most effective solution. The self-consumption rate of the proposed DSM strategies is shown in Fig. 12.

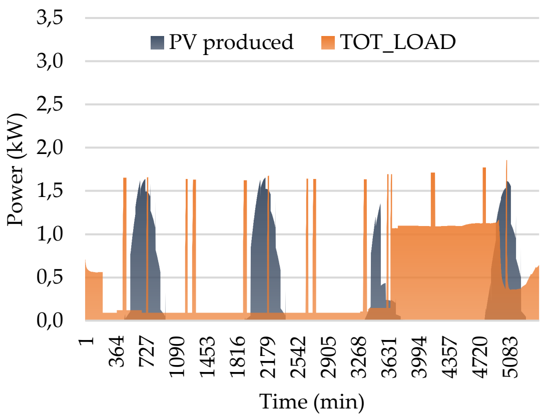

Fig. 6 – PV produced power and system's load for the standard HVAC strategy, from 15th to 19th of January

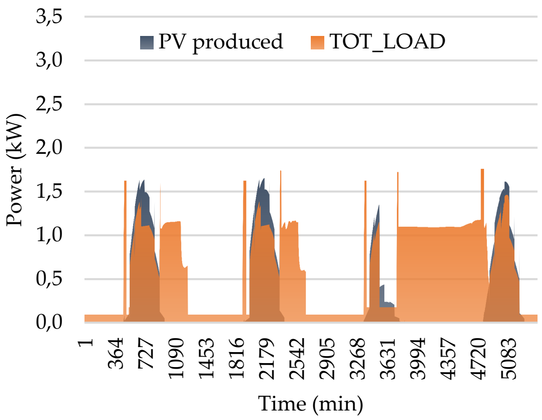

Fig. 7 – PV produced power and system's load for the DSM 4 strategy, from 15th to 19th of January

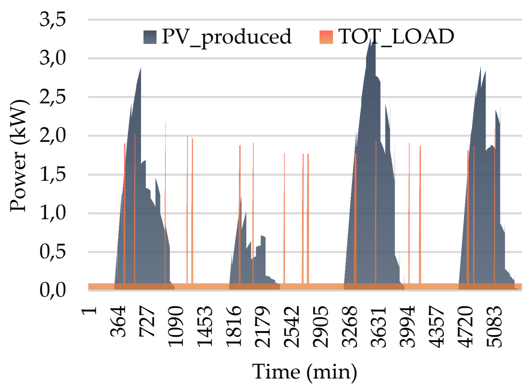

Fig. 8 – PV produced power and system's load for the standard HVAC strategy, from 15th to 19th of April

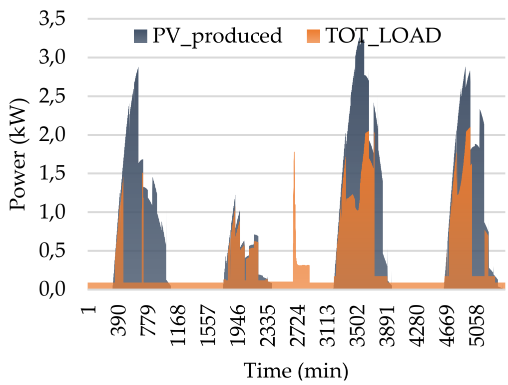

Fig. 9 – PV produced power and system's load for the DSM 4 strategy, from 15th to 19th of April

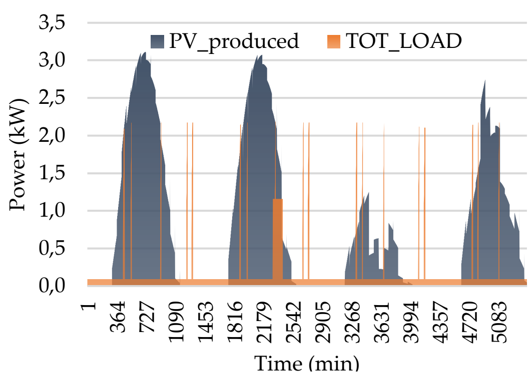

Fig. 10 – PV produced power and system's load for the standard HVAC strategy, from 15th to 19th of July

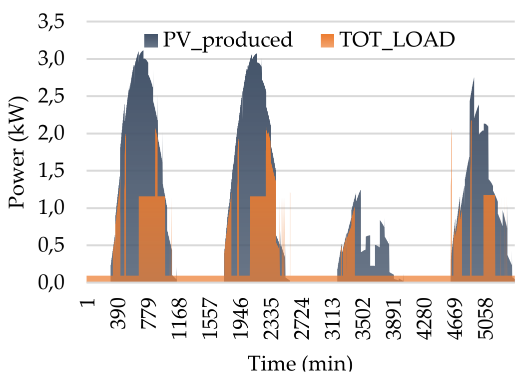

Fig. 11 – PV produced power and system's load for the DSM 4 strategy, from 15th to 19th of July

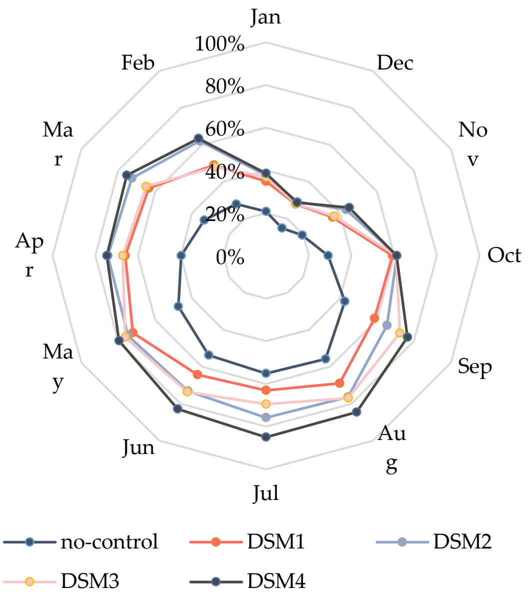

Fig. 12 – PV energy self-consumption during the whole year for the proposed DSM solutions

The figure shows the self-consumption for each month of the year, comparing the standard strategy with the proposed DSM. The comparison highlights how the amount of energy which is self-consumed by the system increases during the whole year for all the DSM strategies. In particular, the four DSM strategies have similar results during the winter period. The strategy where the thermal zone set-point is modified based on the PV overproduction, DSM 2 and DSM 4, shows the best performance during the middle seasons. Strategies DSM 3 and 4, where the DHW tank overheating is prioritized, increase their level of self-consumption during the summer season, in comparison to the other solutions. DSM 4 appears to be the best solution for most of the year, reaching levels of self-consumption of around 85%, and leading to the lowest energy withdrawal level from the grid. This result could likely be related to the high energy performance of the building envelope, which reduces the heating and cooling needs, leading to the DHW demand becoming more relevant. Different results are to be expected for less efficient buildings.

5. Conclusions

This paper has proposed different DSM strategies for an air-source heat pump coupled with a PV plant to increase the self-consumption rate of the system. Different solutions are evaluated by considering control strategies, which prioritize the space heating and cooling or the DHW production. Moreover, the exploitation of the thermal capacitance of the building to store energy is considered. The assessment of the DSM is carried out by means of dynamic simulations for the whole year, considering both the heating and cooling season.

The results of the study show that the DSM is effective in reducing the heating and cooling peak loads of the system and to reduce the grid energy consumption of the building. The maximum grid energy reduction achievable with the proposed DSM is 33%, compared to the energy consumption of a similar system with the standard HVAC control strategy. The increase in self-consumption is obtainable without the need for electric storage integration, therefore limiting the investment and the maintenance costs of the system.

Nomenclature

PV	Photovoltaic
DHW	Domestic Hot Water
DSM	Demand Side Management
SH	Space Heating
SC	Space Cooling
COP	Coefficient of Performance
EER	Energy Efficiency Ratio

Symbols

$Y_{el,\%}$	Percentage of electric input (-)
f	Frequency (Hz)
Y_{el}	Electric input (kW)

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