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ABSTRACT

The use of vapor-compression heat pumps for space heating and domestic hot water preparation can help to improve the flexibility of the electric power generation from solar source and to reduce its impact on the grid, by increasing self-consumption from PV systems and the autonomy of the household. However, achieving this goal requires improving demand management strategies, for example by means of electrical or thermal energy storage. Simple control strategies based on the actual PV generation and the outdoor temperature can help in shifting the demand, by taking advantage of the total storage capacity of the system. In this study, the operation of a single-family house, equipped with a radiant floor and an air-source inverter-driven heat pump for space heating and domestic hot water preparation, is simulated with the TRNSYS simulation suite. The targets are to reduce the peak power taken from the grid and to increase the self-consumption of solar energy.

1. INTRODUCTION

The local generation of photovoltaic energy for residential use is nowadays often more convenient than purchasing electricity from the grid, due to the recent drop of the cost of PV systems. Electric driven heat pumps, if properly controlled, can help the transition to a decentralized energy system (Fischer and Madani, 2017), in particular variable-speed heat pumps allow flexibility in power consumption, by the modulation of the compressor speed. The increasing number of heat pumps installations in the heating sector across Europe is confirmed by market data (Nowak and Westring, 2016).

Typically, the self-consumption is one of the main objective in systems that combine PV systems and heat pump units for space heating or domestic hot water preparation. Other authors studied the demand side management (DSM) in similar systems. Different strategies to increase PV self-consumption can be applied (Luthander et al., 2015) and energy storage plays a crucial role, by offering the possibility to decouple heat generation from demand. Thygesen and Karlsson (2016) proposed a controller based on the radiation forecast and the PV electricity that changes the DHW tank set-point. Their system was based on a ground source heat pump and the Swedish climate. In the control proposed by Psimopoulos et al. (2017), weather forecast has been used in order to take rule-based decisions on the system operation (which involves an exhaust air heat pump).

Electric storage with batteries and thermal storage with water tanks are the most widespread storage techniques in the residential sector. The high cost of batteries is still an obstacle to their large-scale deployment, whereas water storage tanks are typically more convenient. While batteries are inherently programmed to be charged/discharged in order to increase the self-consumption, thermal storage is often managed without any control logic that takes in account the availability of solar energy. A simple rule-based (i.e. if/then) control logic can help to exploit the thermal storage, making its use more similar to the electrical storage.

Another advantage coming from the local use of PV generated power is the reduction of the peak injection into the grid (Binder et al., 2012). This is particularly important in a scenario where peak electric demand is growing and/or where the non-dispatchable generation share (typically from renewable energy sources) is increasing (Arteconi et al., 2012).

2. METHODS

In this study, control algorithms based on the instantaneous PV power production are tested by means of a dynamic simulation code. Coupled dynamic simulations of a single-family house and its heating system was set up in the TRNSYS® simulation suite, using standard and TESS libraries to model the building and the HVAC components.
As boundary conditions for the simulations, the weather data (test reference year) for Milan – a city having a 4A climate according to ASHRAE 90.1 classification – and the Italian electricity tariffs for the year 2017 were used. Simulations were run with a time-step of 1 minute and covering the heating season (from October 1st to April 30th). The analyzed control strategies were compared to each other and to the reference case.

2.1 Building model

A coupled simulation of a building and its heating system was set up in the TRNSYS simulation suite. The building is a two-floor single-family house, having a volume of 275 m^3, façades oriented towards the main cardinal directions and window exposure toward south, east and west. The choice of this building is due to a previous modelling work of a real experimental building, whose thermal variables have been monitored for several years. However, in this study, the envelope characteristics were set in order to consider a new high performance building having walls and roof with a thermal trasmittance equal to 0.25 Wm^{-2}K^{-1}, windows with a thermal trasmittance equal to 0.9 Wm^{-2}K^{-1} and a ventilation rate of 0.5 ACH with heat recovery. As regards to the geometry and the floor area (about 80 m^2), the building is considered representative of a single-family house. People presence is scheduled with a weekly pattern which takes in account the total internal gain due to people and appliances, with two different profiles for the living room/ kitchen and for the bedroom. The profiles are provided by the Italian standard UNI TS 11300-1. In the ground floor a small room is used as a mechanical room and has not heating/cooling terminals, however it has the internal gain due to the tank losses.

2.2 HVAC system and DHW model

The heating system is based on an air-source heat pump (ASHP), with variable speed compressor, coupled with radiant floor panels. The model used for the ASHP is based on the performance map and on the part-load performance function, which can be both provided by the user. Specifically, a high performance unit is modeled, with a COP value of 4.5 at 7-35°C, and a nominal heating capacity of 5 kW. The part load operation is modeled by a function that improves the performance of the unit when the it is operating around 50% part load and the maximum COP is up to 30% higher than the COP at the nominal capacity. The compressor rotational speed depends on the control strategy, which is managed externally to the ASHP type and takes different variables as input, including the outdoor temperature. The controller is proportional-integrative with an hysteresis for the on/off switch.
The radiant floor design is based on a typical commercial configuration with cross-linked polyethylene (PEX) pipes having a diameter of 0.016 m, a thermal conductivity of 0.44 W m^{-1} K^{-1} and a pipe spacing of 0.12 m. The ambient temperature is controlled by means of thermostats in each room with a dead band of +/-0.5°C around the set-point. The thermostat signal activates the flow in the radiant floor pipes for the corresponding room. There are two separate water storage tanks one for space heating (SH) and one for domestic hot water (DHW), with capacity volumes of 100 liters and 300 liters respectively. Both of them are stratified vertical cylindrical tanks. DHW tapping is modeled according to the EN 16147 (tapping profile M). DHW production has priority over the SH and its signal has an hysteresis with dead-band of +3°C on the set-point. A mechanical ventilation system with heat recovery guarantees a ventilation rate of 0.5 ACH in each room. The recovery efficiency is 75%. A photovoltaic array with a total area of 20 m^2 is also modeled. The electric power production, when available, is directly used by the heat pump, in addition with electric power from the grid, if necessary. The model assumes a conversion efficiency (DC/AC inverter) of 90%.

2.3 Control system strategy

The proposed control strategy, based on the actual PV generation and the outdoor temperature, have the main goal to increase self-consumption and to reduce the peak power fed to the grid, by changing the set-point temperatures of the system. At every time-step of the simulation, a simple function (PV function) checks if there is energy available from PV by comparing the actual PV power production with a fixed threshold of 300 W. Another function determines whether the outdoor temperature is high or low (OT function), with respect to the daily temperature oscillations by comparing it with the average temperature in the last 48 hours. On the base of these two functions, independently or combined together (see Table 1), the set-points of the DHW tank, the SH tank and ambient

thermostats are increased or reduced. Table 1 summarizes the four configurations that were simulated, reporting the control functions that are activated and how the set-points have been changed.
The variations have been established with the aim of not causing appreciable changes to the comfort of the occupants. Hence, the ambient set-point has a maximum of 22°C and a minimum of 19°C (the default one is 20°C). The DHW temperature is set to 48°C in the base case while it is incremented up to 55°C and reduced to 45°C by the control function (below 45°C it is considered to create discomfort). The SH tank temperature does not directly affect the comfort because the system controls the mass flow to the underfloor pipes. Since the supply temperature follows a heating curve with a maximum supply temperature of 35°C, a small increment (+2°C) can be accepted without risk of overheating the floor.

Table 1: Set-points configuration for the different control strategies

Description	**Control function**	**Set-points variations**		
		DHW tank	**SH tank (heating curve)**	**Ambient**
Reference case	-	0	0	0
Test 1	PV	+7/-3	+2/-2	+2/-1
Test 2	OT	+7/-3	+2/-2	+2/-1
Test 3	PV and OT	+7/-3	+2/-2	+2/-1
Test 4	PV and OT	0	+2/-2	+2/-1
Test 5	PV and OT	+7/-3	0	0
Test 6	PV or OT	+7/-3	+2/-2	+2/-1

3. RESULTS

Results of this study are presented mainly in terms of energy use, self-consumption (energy directly used from that generated by PV panels) and energy drawn from the grid, on a monthly basis.

3.1 Reference case

In the reference case the total electrical energy use shows a maximum in coldest months because of its direct correlation with the building losses (i.e. with the outdoor temperature) but also because of the poorer performance of the ASHP with lower source temperature. The average self-consumption percentage over the heating season is 14% and the remaining share of the load is covered with energy drawn from the grid. The month of April shows the lowest self-consumption percentage (7% of the energy need) because the heating system is active only during the night when there is no PV power generation.

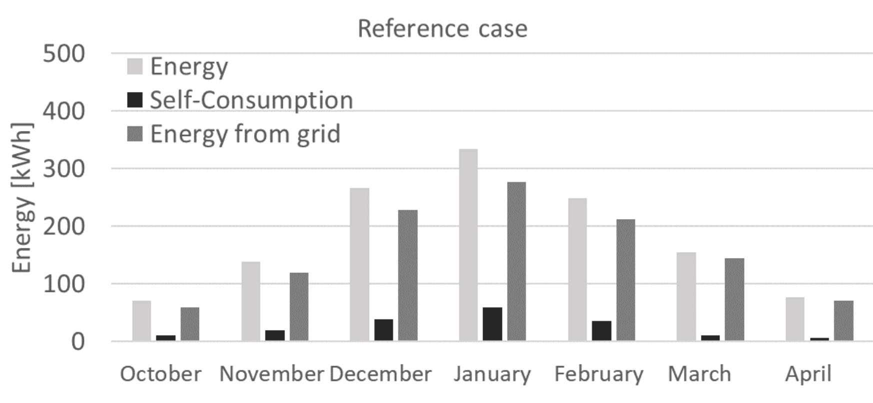

Figure 1: Electrical consumption for DHW and SH in the reference case

3.2 Control function

When the rule-based functions are applied, the self-consumption increases and the energy drawn from the grid decreases. The higher increment of self-consumption (with respect to the reference case) occurs in the simulation Test 1 where it reaches the 61% of the consumption (from 14% in the reference case). The best case as regarding the reduction energy bought from the grid is Test 3 (33% from 86% of the reference case). The solution that minimizes the grid energy is not necessarily the same that maximize the self-consumption, because the total energy use varies significantly. In both Test 1 and Test 3, all the set-points are modified and the PV function is applied. The other simulations do not shows such good results. It must be noted that a two sided effect is observed about the total energy use (sum of the PV production and energy drawn from the rid): the total consumption is reduced in cold months like January while it is incremented in months with a low heating need like October. This can be explained considering the low heating demand in October and April, which is increased by raising the set-points but then the energy stored is not used and it is consequently lost. While in January, shifting the demand to hours with higher outdoor temperatures makes the heat pump to operate with a better performance.

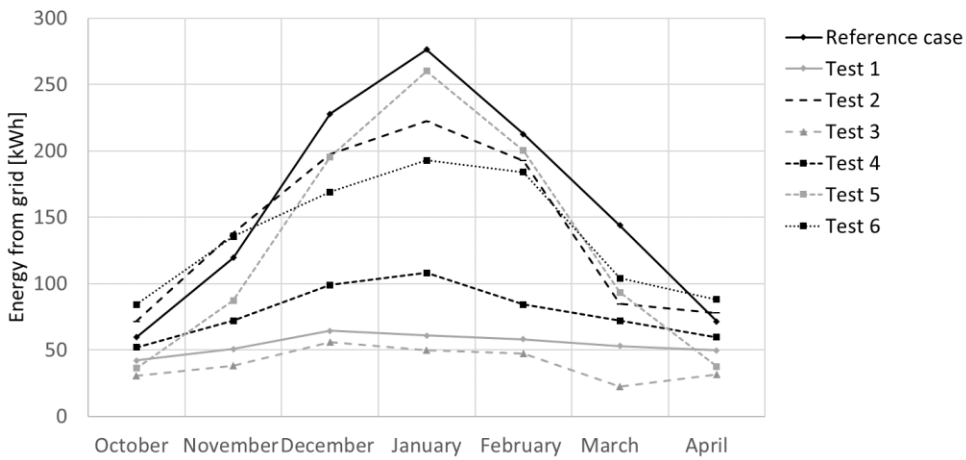

Figure 2: Energy taken from the grid for all the simulated control functions and for every month.

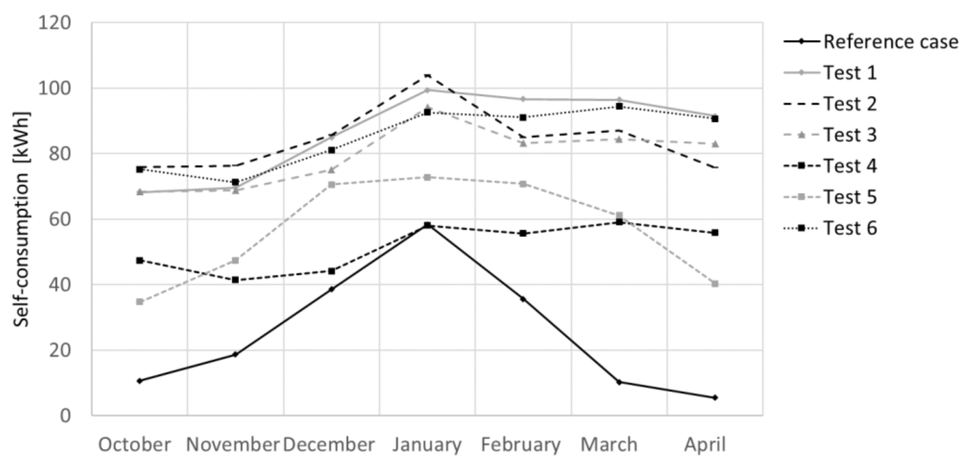

Figure 3: Self-consumption for all the simulated control functions and for every month.

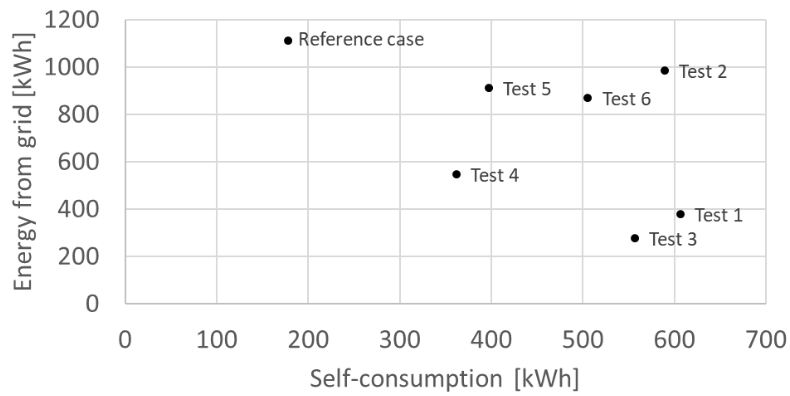

Figure 4: Combination of the seasonal self-consumption and the drawn energy for all the simulations.

3.3 Power peak reduction

For Test 1 and Test 3 the peak of power sent to the grid has been evaluated, obtaining a significant reduction with respect to the base case. Test 3 has the biggest reduction, which is -70%.

4. CONCLUSIONS

This study presents a simple control logic with the objective to shift the demand of electricity to hours with PV production greater than 300W and/or to hours with outdoor temperature greater than the daily average temperature. The first option is aimed at increasing self-consumption while the second is meant to operate the heat pump with a higher average performance (COP). As expected, both of the functions tends to shift the load during the daytime, whenever it is possible.

Despite the simplicity of the proposed rule-based functions, the purpose of their application has been achieved (in the North Italy climate), in particular when the logic is based on the PV production. Self-consumption reaches 61% of the energy use, from 14% in the reference case and commercial electric energy taken from the grid is reduced from 86% of the total energy use to 33%. The reduction of energy taken from the grid is partly due to the increased operation efficiency of HP, and not only to the increase in self-consumption.

This work may be further developed by optimizing the control strategy. All the set-points variations, with their constrains and the PV power threshold of 300W can be set as parametric values.

The model does not involve the consumption for electric appliances and consequently the energy consumption should be evaluated with a comparative approach, rather than absolute. Besides, despite the novel model (TRNSYS type) of variable-speed heat pump, which operation is based on a recently developed and commercialized product, the effects of the on-off cycles inefficiency are not taken into account.

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