Analysis of a double source heat pump system in a historical building

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Abstract

This work presents the case study of the retrofitting of a historical building of the University of Padua, equipped with a hybrid heat pump system, which uses as heat source/sink the ground and ambient air. The building is located in Padua (Italy) and it is a historical complex of the late 1800, previously used as a geriatric hospital, in which a retrofit process is occurring in order to build the new humanistic campus of the Padua University reaching the highest energy efficiency.

The refurbishment is in progress and regards both the building envelope and the plant-system. The building is equipped with two types of heat pumps: the first one is coupled to the ground with borehole heat exchangers and the second is a common air-to-water heat pump. The entire building plant system has been investigated through integrated computer simulations making use of EnergyPlus Software. A new control strategy in order to manage the two types of the heat pumps has been developed in order to increase the energy efficiency.

The results outline the potential of the computer simulations in order to control the hybrid heat pump system. In fact, a suitable switch temperature was found in order to move from ground to air source/sink for the heat pumps. In addition, this strategy allows the control of the thermal drift of the ground temperature throughout the years.

Introduction

The building sector represents a large part of the global energy consumption. As widely known and discussed in literature, the energy efficiency improvement, especially in building sector is one of the most important actions for the reduction of the greenhouse gases emissions in the atmosphere. The existing buildings are responsible of about the 40% of the primary energy demand in Europe (BP plc, 2018). The introduction of recent EU energy policies (European Parliament, 2009, 2010, 2012, 2018) allowed obtaining several important results in this field. The main results of reducing greenhouse gases emission can be obtained increasing the renewable energy exploitation and the overall energy efficiency of building envelope and systems. In Italy, the total amount of heritage monuments is about 4,000,000 of 5,367,000 present in the worldwide. Many buildings were built before the 1919 and today are used as residential buildings or for public services (Galatioto et al., 2017). From the UNESCO World Heritage List, Italy has 4.7% of the world architectural heritage that occupies 46% about of the entire country (UNESCO, 2018). In Italy according to the EPBD Directive (European Parliament, 2010, 2018), the recent standards and laws have focused mainly on the energy retrofit of existing buildings, but the energy retrofits are not mandatory for historical buildings due to their protected status. The energy retrofit of buildings usually starts from improving the energy performance of the envelope up to improving the efficiency of the air-conditioning systems. This assumption is right when the buildings do not present any restriction as instead happens in the case of historical buildings. These buildings have common characteristics of poor energy quality of the envelope and high primary energy demand (Ciulla et al., 2016). Furthermore, historical buildings present artistic and architectural constrains which make any activity on the envelope difficult and critical. These issues represent a limit and a difficult challenge for the refurbishment of historical building taking into account the matching among regulations, technical, energy and economic feasibilities (Galatioto et al., 2017). Some possible solutions for the improvement of the energy performance of the envelope are for example the use of plasters with improved insulation properties (for internal and external surfaces) or the use of internal coats and insulation panels and the substitution of the glazing elements (Johansson et al., 2014a, 2014b) (Bianco et al., 2015) (Pisello et al., 2016).

Nardi et al. (2017) studied a possible solution for the seismic and energy refurbishment of historical building in L'Aquila city centre. They used natural materials for the insulation of the internal surface of the walls and an "endothermic membrane" for the external side of the walls. The on field results showed an increase of the thermal performance, which was the purpose of the intervention. Doukas et al. (2017) investigated the energy performance of a school building in Edinburgh by the use of energy simulations. They made some hypotheses of energy improvements on the envelope. They also considered the use of renewable sources in the project. In particular, a ground source heat pump system coupled with a biomass boiler of rated capacity of 199 kW was considered in the study.

Since the limitation of possible actions that can be applied to the envelope side, it seems easier to move the attention on the possible solutions that can be used in the air-

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conditioning system. In literature, many works on historical buildings suggest the ground source heat pump or heat pump in general, as a possible solution that combines energy efficiency and exploitation of renewable energy source at the same time. Emmi et al. (2017) analysed two different case studies of historical building in Italy, in Venice and Florence. They carried out several energy simulations for three layout solutions for the plant system: ground source heat pump, air-to-water heat pump and boiler coupled with an air-to-water heat pump. The results outlined that the ground source heat pump system is the best solution in terms of primary energy saving point of view. Pacchiega and Fausti (2017) compared different system solutions in terms of economic impact and energy needs during the operation of the systems. The case study regards a rural single-family house in Ferrara, dating from the 15th century and subjected to various renovations over the years. They investigated the sustainability of ground source heat pump technology for heating and cooling. Righi et al. (2017) analysed a case study built before 1800 and located in Motta di Livenza, Italy. Their work provides a methodology of analysis for the identification of the best-facilitated interventions of energy efficiency which can be used also in historical buildings. The study suggests some non-invasive interventions. In historical buildings, in fact, the energy efficiency cannot be based on invasive interventions, as in other types of buildings.

Based on the previous studies reported in literature, the present work aims to investigate the possibility of using a double source heat pump system in a deep retrofit operation. The heat pump uses air and ground as heat source/sink for its operation. The use of two different heat sources/sinks can be exploited with a dedicated control strategy in order to optimize the energy efficiency of the entire system and control the thermal drift of the ground temperature due to the imbalance of the building load profile. At the same time, the installation costs for the borehole heat exchangers can be reduced making this solution economically attractive. The energy analysis was carried out by means of computer simulations with EnergyPlus software considering the building, heat pump and ground heat exchangers at the same time.

Case study

The complex (Figure 1) here analysed is located in Padua. It is a historical complex mainly of the late 1800, in which a retrofit process is occurring in order to build the new humanistic pole of the University of Padua reaching the energy efficiency rank of “A” (Class A according to the Italian Standards).

The building ensemble was formerly a Geriatric Hospital resulting, in turn, from successive transformations of the old “Beato Pellegrino” (Blessed Pilgrim) convent to a retirement home for the elderly. The first phase of enlargement dates from 1882, while two other phases took place: in the 30’s and 50’s of last century. Figure 2 shows the buildings retrofitted and those demolished or rebuilt.

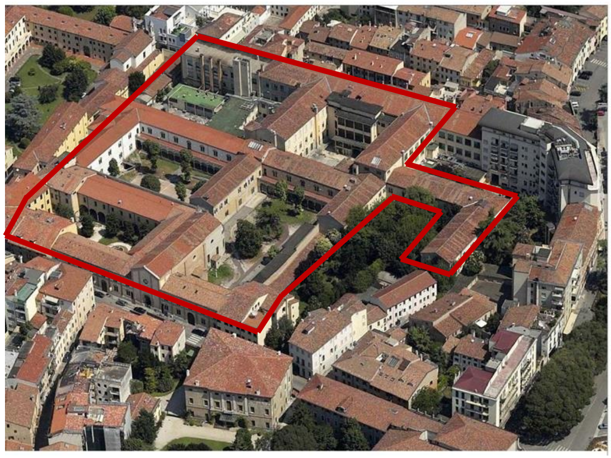


Figure 1: Aerial view of the building.

Figure 2: Comparison of the ensemble before (above) and after (below) the retrofit. The buildings circled in blue are the ex-novo constructions, the demolished buildings are circled in red.

The complex has an area of 16667 m^2 and a volume of 104672 m^3. The humanistic pole is composed of about 4300 m^2 of space for libraries, 2300 m^2 for new lecture rooms and 3800 m^2 for offices. There is a total of about 200 seats for libraries in the current configuration, 1500 for lecture rooms, and 400 workstations in offices.

The original facades of the complex have been preserved. An insulation layer has been added on the internal side of the walls of the existing buildings to reach the mandatory thermal transmittance level of 0.25 $W/(m^2K)$.

The ex-novo buildings have been built according to the actual legislation, reaching an average thermal transmittance level of vertical wall of 0.20 $W/(m^2 K)$.

The thermal transmittance of glazing surfaces is 1.4 $W/(m^2 K)$ with a solar factor of 0.36, except the windows of the building A1, having a thermal transmittance of 1.5 $W/(m^2 K)$ with a solar factor of 0.42. The glass roof of the new glazed corridor (building named P4) has a thermal transmittance of 0.5 $W/(m^2 K)$ with a solar factor of 0.18.

Model

The case-study was modelled in EnergyPlus software (US Department of Energy, 2018). The geometry of the building was firstly implemented in SketchUp (Figure 3) and, then, the characteristics of both the construction and plant-system were modelled in EnergyPlus environment. EnergyPlus software uses the *g-function* method to simulate the thermal behaviour of borehole heat exchangers (BHEs); however, the g-function has to be calculated by the user and then used as input to EnergyPlus: this is a disadvantage because common designers have not the possibility to carry out this calculation. The g-function of the BHE is convoluted with the incremental heat flux signal to obtain the mean fluid temperature in accordance with the equation below:

$$T_f(\tau) = T_g + q(\tau)\cdot R_b + \sum_{i=1}^{n}\left(\frac{q_i - q_{i-1}}{2\pi\cdot\lambda}\cdot g\left(\frac{\tau-\tau_{i-1}}{\tau_s}, \frac{r_b}{L_{bore}}\right)\right) \tag{1}$$

where $\tau_s = L_{bore}^2 / (9a_g)$ is the characteristic time.

In this work, the tool developed by Cimmino and Bernier (2013) was used to generate the g-function for the borehole field; the tool is very user-friendly and allows the consideration of the real layout of the borehole field.

The building model consists of 228 thermal zones. In fact, the building was modelled with high level of detail, using all the information reported hereafter:

- the composition of the walls considering the refurbishment;
- the characteristics of each plant device according to the design (e.g., fan-coils, radiant panels, primary air diffusers);
- the heat gains according to the design (schedules of lighting, occupancy, electrical appliances, etc.);
- the energy production equipment, using data supplied by the manufacturers.

This high level of detail has provided a deep understanding of the phenomena of energy use of the various devices and the production equipment.

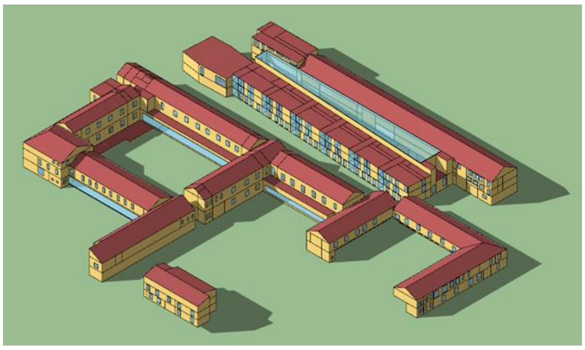


Figure 3: Rendering of the complex.

The various thermal zones in the building have been designed only with two configurations: fan-coils and air diffusers or radiant surfaces and air diffusers:

- *Fan-coils*: these devices are only used to control the air temperature and not the humidity ratio. Each fan-coil was modelled with its own technical data according to the manufacturer data sheet.
- *Radiant floor*: these terminals are used for both heating, with a design heating capacity equal to 60 W/m^2, and for cooling, with a design cooling capacity of 30 W/m^2. The radiant floor is used in the library area (B buildings and the library of the building C1 shown in Figure 2) and in some zones of the new buildings (ground floor of building P1 and P4 shown in Figure 2)). Where the radiant floor is present, there are not fan-coils.
- *Air diffusers*: these terminals move the air coming from the air-handling units (AHU) which operate to control the humidity ratio and to maintain the ratio of renewal air constant during the occupation time in order to improve the air quality inside each zone. These devices are present in the spaces with a constant occupation like libraries, classes, meeting rooms and in the wide corridors like in the building P4 (Figure 2).

The energy production consists of two identical air-to-water heat pumps, each one with thermal capacity of 447 kW and 318 kW in cooling and heating respectively, and other two identical water-to-water heat pumps each one with thermal capacity of 168 kW and 192 kW in cooling and heating respectively, coupled with the ground by means of vertical ground heat exchangers.

The borehole field consists of 60 double U-tube heat exchangers, made of PE-Xa crosslinked polyethylene pipes, with an external (internal) diameter of 32 mm (26 mm). The two U-loops of the same borehole heat exchanger are coupled in parallel as also all the borehole heat exchangers of the field. The g-function, which represents the thermal behaviour of the borehole field was obtained via the tool developed by Cimmino and Bernier (2013) considering the real layout of the boreholes that is reported in Figure 4.

The modelling of the borehole field is a key phase to define the energy performances of the ground coupled heat pumps. In a preliminary phase, the thermal response test (TRT) was also carried out in order to evaluate the equivalent thermal conductivity of the ground and the undisturbed ground temperature. These values were then used as input in the computer simulations. Hereafter the main data of the borehole field are reported:

- Borehole configuration: 2 U-shaped tube
- U-tube external diameter: 32 mm
- U-tube internal diameter: 26 mm
- Thermal conductivity of pipe: 0.4 W/(m K)
- Borehole diameter: 152 mm
- Borehole depth: 120 m
- Thermal conductivity of the grout: 2 W/(m K)
- Ground thermal conductivity: 1.62 W/(m K)
- Specific ground thermal capacity: 2.5 MJ/(m^{3}K)
- Undisturbed ground temperature: 17.5°C
- Number of borehole heat exchangers: 60

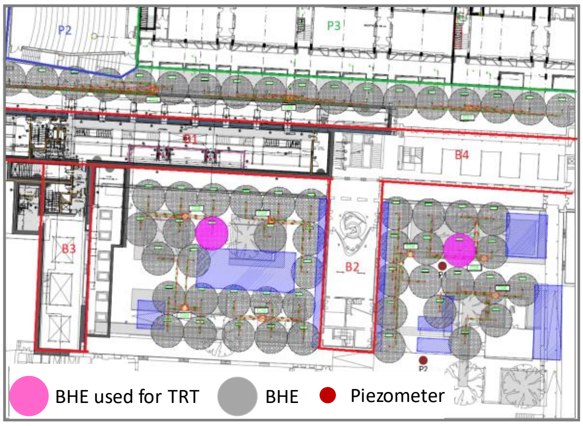


Figure 4: Layout of the borehole field.

Control strategy

As it was mentioned in the previous section, two types of heat pump with different heat source/sink were installed: two air-to-water heat pumps and two ground-coupled heat pumps. Therefore, a suitable control strategy to optimize the operation of the entire system is fundamental in order to maximize the energy efficiency. In addition, it was to consider that the building load profile is not balanced and this, as it is well known, involves a thermal drift of the ground temperature throughout the operating years. Two control strategies were investigated: a) the first one maximizes the operation of the ground coupled heat pump to exploit its higher nominal energy efficiency compared to that of the air-to-water heat pump; b) the second strategy controls the thermal drift of the ground temperature over the years.

The latter strategy is based on a switch temperature between the two types of heat pump (Figure 5): when the external air temperature is higher than the switch temperature, ground coupled heat pumps run; otherwise when the external air temperature is lower than the switch temperature the air-to-water heat pumps work. This kind of approach has already proved its efficiency of controlling the thermal drift of the soil in another study (Zarrella et al., 2018).

This approach was compared to a usual priority based on the machine start-up to satisfy the energy needs of the building: the ground-coupled heat pumps firstly operate, and, if this is not sufficient, the air-to-water heat pumps are switched on.

The control strategy implemented in this work combines the two strategies mentioned above. The operating mode is explained here:

- during the heating period, the control strategy leads to maximize the use of ground coupled heat pumps, extracting the maximum amount of seasonal heat from the ground.
- during the cooling period, the ground coupled heat pumps start operating only when the external temperature exceeds the value of switch temperature. When air temperature is higher than the switch temperature, the ground coupled heat pumps operate with a starting priority compared to air-to-water machines. When air temperature is lower than the switch temperature, only the air-to-water heat pumps run. In this operating mode, the switch temperature is calculated to ensure that the amount of heat injected into the ground in cooling mode is equal to the heat extracted from the ground in the heating operation.

This control strategy involves the following advantages: the prevention of the phenomenon of thermal drift of the ground temperature, the maximization of the use of the ground coupled heat pumps in the heating mode, and the use of air-to-water heat pumps during the most favourable times (in term of electric energy consumption) in summer period. On the other hand, the disadvantages are:

- the complexity of calculating the value of the switch temperature that requires dynamic simulations with a trial and error approach.
- the verification that the peak power of the air-to-water heat pump is sufficient to satisfy the peak of cooling demand of the complex at the switch temperature.

As it was mentioned, the switch temperature was found via a trial and error approach starting from an analysis of the building load profile: about 80% of the cooling load was concentrated when the external air temperature ranges from 15°C to 28°C. Using an iterative procedure, making use of computer simulations and the load profile of this building, the switch temperature resulted equal to 24°C: with this value, the heat extraction energy rate from the ground during the heating operation is equal to the energy injected into the ground during the cooling mode and, consequently, no thermal drift occurs.

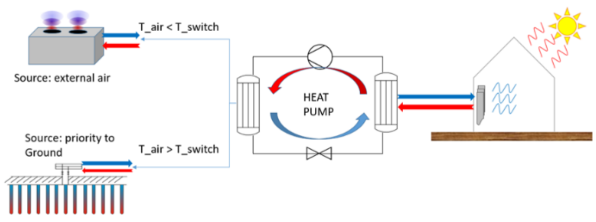


Figure 5: Control system approach.

Computer simulations

Computer simulations were carried out in order to analyse the effect of the control strategies adopted.

Boundary conditions

The simulations were based on the weather data of the Test Reference Year of Venice (Figure 6), which is available in the database of the EnergyPlus software (U.S. Department Of Energy, 2018).

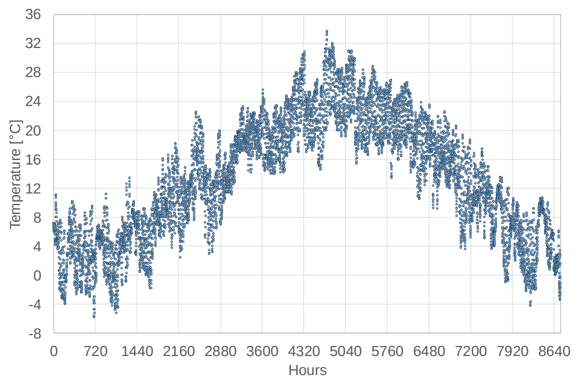


Figure 6: External air temperature of the Test Reference Year of Venice.

The internal design conditions set in the simulations are reported in Table 1. The entire plant system can provide only hot fluid in heating and cold fluid in cooling. Table 2 reports the characteristics of the heat pumps. The heat-carrier fluid in the borehole heat exchangers is pure water. The heat pump model implemented in EnergyPlus (US Department Of Energy, 2018) considers the change of the fluid temperature on both the heat source/sink and building side as well as the operation at partial loads by means of suitable equations with coefficients calculated using data provided from the manufacturer in order to fit the behaviour of the machine.

Table 1: Design conditions.

	Maximum comfort value	**Minimum comfort value**
Summer time	26°C	20°C
Winter time	24°C	20°C

Table 2: Characteristics of the heat pumps.

		Heating mode	**Cooling mode**
GCHP	Thermal capacity [kW]	192	168
	Energy efficiency [-]	4.6 (a)	4.2 (b)
Air to Water Heat Pump	Thermal capacity [kW]	318	447
	Energy efficiency [-]	2.2 (c)	3.0 (d)
a. Inlet-Outlet water temperature at the evaporator: 10-5°C Inlet-Outlet water temperature at the condenser: 40-45°C			
b. Inlet-Outlet water temperature at the evaporator: 14-8°C Inlet-Outlet water temperature at the condenser: 30-35°C			
c. External air temperature: -10°C Inlet-Outlet water temperature at the condenser: 40-45°C			
d. External air temperature: 35°C Inlet-Outlet water temperature at the evaporator: 12-7°C			

Results

The model of the building has been launched with varied assumptions in order to evaluate different aspects of the control and the building complex itself. The analysis of the electric consumption and thermal production of the heat pumps have allowed a comparison between a specific control strategy and the simple control based on the priority of the ground coupled heat pump.

Figures 7 and 8 outline the monthly specific energy and the hourly thermal load of the building (always satisfied by the production units), respectively. The ratio between the annual heating and cooling energy demands is about 0.68, confirming that the building's annual load profile is cooling dominant.

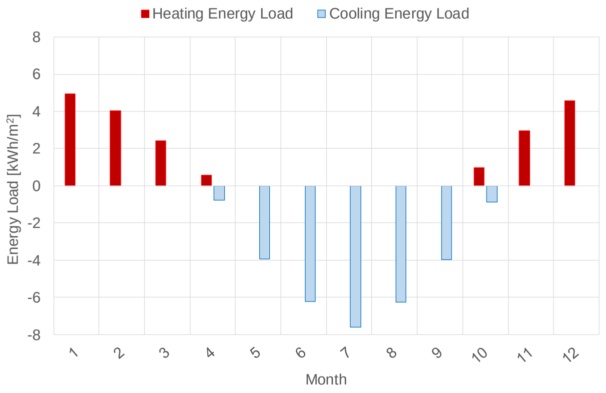


Figure 7: Monthly specific thermal energy requirement of the building.

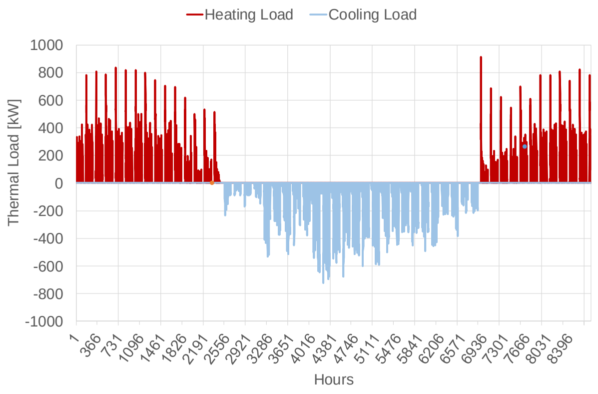


Figure 8: Hourly thermal load of the building.

Figure 9 shows the values of thermal energy for heating and cooling provided by the air-to-water and ground coupled heat pumps when the control strategy based on the switch temperature is adopted. As it can be seen, in the middle seasons (between May and June, and also in September) the air-to-water heat pumps are more frequently used in cooling operation as the external air temperature is lower than the switch temperature, which was set to 24°C. On the other hand, during the warmer summer months (i.e., July and August) the ground coupled heat pumps are used more frequently as the external air temperature is higher than the switch temperature value. This behaviour changes when the control strategy is only based on the priority of operation of the ground coupled heat pumps, which will lead to higher use of the ground coupled heat pump as shown in Figure 10. In this operating mode, no control on the thermal drift of the ground temperature is set.

In terms of total energy exchanged with the ground, the simulation results shown that:

- with the switch temperature control, the heat rejected to the ground is about 190 MWh in cooling mode whereas the extracted one is about 192 MWh.
- with the priority of the ground coupled heat pump control, the heat injected into the ground is 427 MWh in cooling mode and only the quantity equal to 193 MWh is extracted in heating operation.

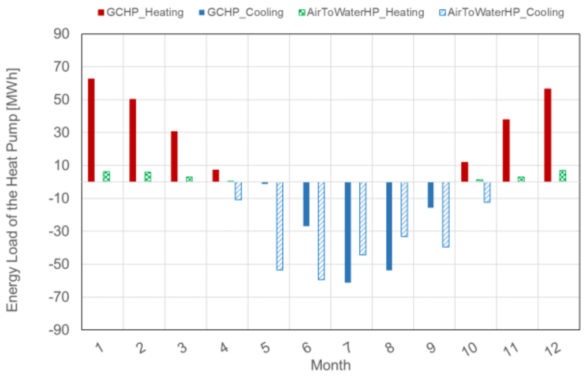


Figure 9: Results with the switch temperature control strategy.

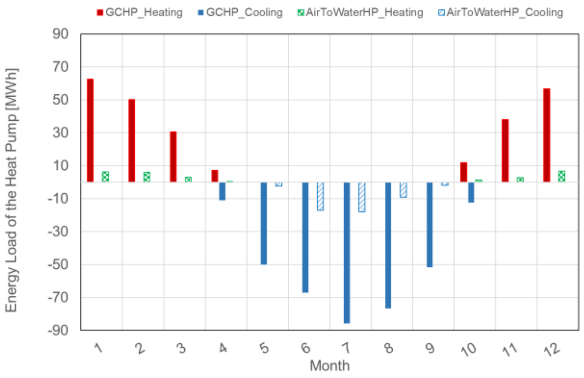
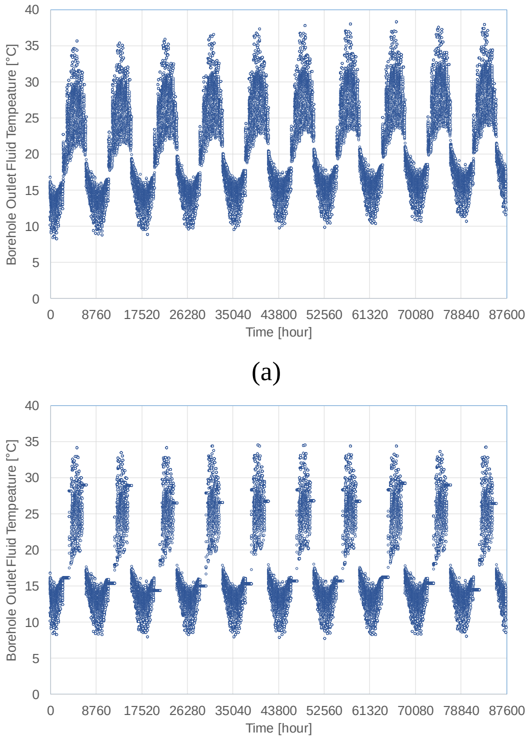


Figure 10: Results with only GCHP priority.

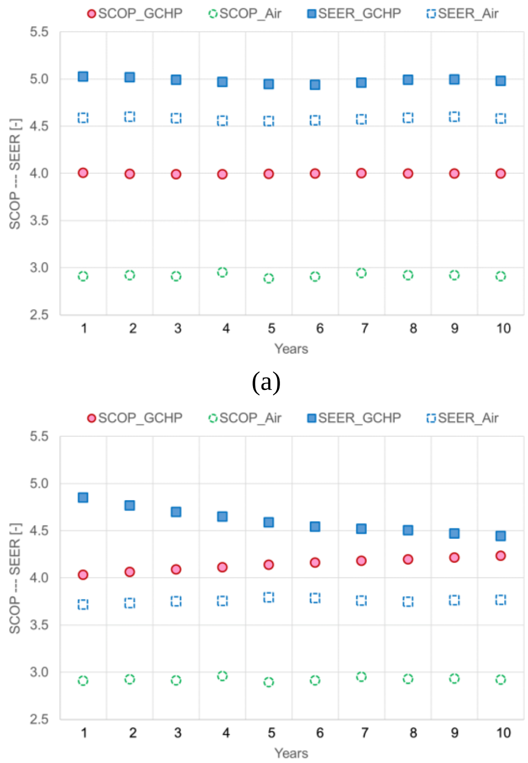
Figure 11 shows the temperature of the heat-carrier fluid entering the heat pump on the ground side when the two control strategies are adopted. As it can be seen, the control with priority of ground coupled heat pump leads to a thermal drift of the ground temperature of about 4°C over ten operating years (Figure 11.a). On the other hand, when the switch temperature control is set the annual energy extracted is equal to the energy injected, consequently the thermal drift of the ground temperature is controlled (Figure 11.b) and no appreciable changes of the energy efficiency of the heat pumps in long-term occur. This result is found in Figure 12 where the seasonal energy efficiency of the two types of heat pump in both heating (named *SCOP*) and cooling (named *SEER*) modes are shown. In particular, Figure 12.a outlines the seasonal energy efficiencies when the switch temperature control is set: as it can be seen, the values of the energy efficiency are constant during the ten operating years. On the contrary, Figure 12.b shows that without the switch temperature control the cooling energy efficiency (*SEER*) of the ground coupled heat pumps decreases over the years; the reduction is also lower than the increase of the heating energy efficiency (*SCOP*) on the same machine. This is clearly due to the effect of the thermal drift of the ground temperature involved by the unbalanced ground load profile. It is possible to see also that the cooling energy efficiency of the air-to-water heat pumps is lower than the corresponding values when the switch temperature control is set since, in this case, the air-to-water heat pumps are switched on when more favourable temperature of the sink occurs. In heating mode, no difference are found for air-to-water heat pumps as for this season the load is almost totally satisfied by the ground coupled heat pumps. In terms of annual electric energy consumption of the heat pumps, the difference between the two control strategies is low throughout ten operating years with the considered building load profile. However, it is evident how the control strategy set on the switch temperature is able to control the ground thermal drift which affects the energy efficiency of the ground coupled heat pumps over the long-term.



(a)

(b)

Figure 11: Entering heat pump fluid temperature over ten years: a) without and b) with the switch temperature control.



(a)

(b)

Figure 12: Seasonal energy efficiencies for ground coupled and air-to-water heat pumps: with (a) and without (b) switch temperature control.

At the end, Figure 13 shows the heating and cooling rates provided by each type of heat pump during the first operating year when the control strategy based on the switch temperature is set. As it can be seen, the contribution provided by the air-to-water heat pump for heating is about 10% of the contribution provided by the ground coupled heat pump in the same period. The ground coupled heat pumps cover about 38% of the total energy cooling demand whereas the air-to-water heat pumps provide the remaining rate.

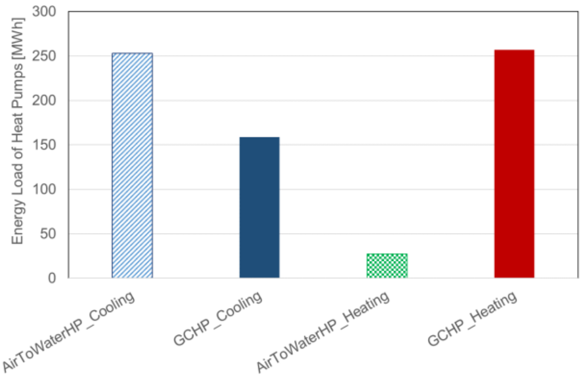


Figure 13: Energy provided to the building during the first operating year.

Conclusions

The work presented here investigated the application of ground coupled heat pumps in a deep retrofit of a historical building of University of Padua, Italy. In order to satisfy all the building load profile also air-to-water heat pumps were installed because of the limited ground surface for borehole field installation. This hybrid solution was also adopted to control the initial costs. The operating mode of the hybrid system needs to be optimized in order to increase the energy efficiency of the entire system and, at the same time, avoid the thermal drift of the ground temperature. This phenomenon can occur in ground coupled heat pumps when the building load profile is unbalanced. To this purpose, suitable control strategies have to be set. In this work, it is shown how the integrated computer simulations, considering both the building and the plant system, can help the designers to set the operating strategies of a hybrid system. This is a key process especially in hybrid system based on ground source heat pumps since the initial costs are very high compared to the standard systems, consequently the high energy efficiency has to be maintained over the years to have low operating costs.

In this work, a switch temperature was set in order to change the type of heat source or sink (ground and air). This value depends on the building load profiles, as a consequence it cannot be generalized; it can be found by means of computer simulations and then implemented in the building management system. It is evident also that the value of the switch temperature must be checked in real operating conditions because the building load profiles could be different from the design assumptions or change over the time. In fact, a suitable controller can update the switch temperature in real-time considering the actual heat rate exchanged with the ground. The results outlined that the switch temperature control limited the effect of the thermal drift of the ground temperature and, consequently, the energy efficiency was maintained high over the time.

Acknowledgement

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