Utilisation of groundwater heat pumps for the decarbonisation of heating and cooling sector: the analysis of an Italian case study

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Abstract:

In this paper, the utilisation of groundwater heat pumps for residential heating and cooling purposes is presented. A case study located in Florence (Italy) is discussed. First, a building energy analysis has been performed to obtain the thermal loads. Then three heat pump systems (system 1: air-to-water, 2: groundwater-to-water, 3: surface water-to-water) have been designed and compared in terms of electric energy consumption, taking into account the dynamic changing of boundary conditions of the building. Finally, a Life Cycle Assessment analysis has been conducted to evaluate the environmental impacts of the systems. To ensure a yearly heating energy request of 2 780 kWh (peak load of 5 kW) and a yearly cooling energy request of 630 kWh (peak load of 4.4 kW) the systems present a yearly electricity consumption of 1 088 kW, 770 kW and 872 kW for system 1, 2 and 3 respectively. So the groundwater-to-water solution is the most efficient in terms of energy consumption. Based on LCA evaluation, system 2 is the environmentally less impacting system, with a Climate Change factor of 0.15 kg CO_2 eq/kWh against the 0.21 kg CO_2 eq/kWh of system 1. In terms of single score level, system 2 and system 3 are characterised by a reduction in impacts of about 24 % compared to system 1. The dynamic energy and LCA studies clearly show that the solution based on groundwater exploitation, in this context, is a very effective way to reduce electricity consumption and environmental impacts, confirming that the large-scale implementation of groundwater heat pump systems could be a promising option for the decarbonisation of residential heating and cooling sector.

Keywords:

Groundwater heat pump, Heating&Cooling, Energy-efficiency, Energy-saving, Decarbonisation, Dynamic energy analysis, LCA

1 Introduction

Energy requirements for refrigeration and air conditioning (AC) sectors are becoming wider and wider, with AC systems that account for 20-30 % of the electricity consumption of buildings [1–4]. To obtain large-scale decarbonisation, it is evident that it is necessary to reduce the energy needs of AC systems. The utilisation of efficient heat pumps, instead of the classic thermal power generation devices (e.g. boilers), has represented an important step forward [5]. Heat pumps consume electricity to operate, that in many cases is produced from fossil fuels. To reduce the consumption of this form of primary energy in heat pumps operation, it is possible to implement two main strategies: producing electricity starting from renewable sources (e.g. photovoltaic), and enhancing the efficiency of the system through the utilisation of favourable external thermal sources. This last point is crucial: if the external heat exchanger of a heat pump (evaporator in heating season, condenser in cooling season) works with a source at a temperature close to the one of the user, a consistent increase in the efficiency happens. In this sense, a very promising solution is coupling heat pump devices with ground (or geothermal) sources. This is the concept of a Ground Source Heat Pump (GSHP). At depths of a few meters, the ground temperature is stable during the year and it is in contrast with the trend of air temperatures, as in the hot months ground is cooler than the outdoor air, conversely, in cold months the ground is warmer than the outdoor air. The quasi-constant temperature, quite close to the setpoint temperature of indoor environments, leads to obtaining very high values of the Coefficient Of Performance (COP) of the systems, with consequent energy savings [6]. A GSHP system consists mainly of a ground heat exchanger, a heat pump, and a heating/cooling distribution network [7]. The type of geothermal source used for heat exchange, like ground, groundwater and surface water, defines the type of system: ground heat pump (GHP), groundwater heat pump (GWHP) and surface water heat pump (SWHP) [8]. The last two systems are the object of this study. In a GWHP system, the groundwater is extracted from a water source and it exchanges

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heat with the heat pump, then is discharged. A GWHP could be built in different configurations: *open loop with aquifer reinjection*, *standing column wells* and *open loop systems discharging to waste*. In an SWHP there is the presence of a reservoir in which the groundwater is pumped. In this case, there is the possibility to realise an *open loop* or a *closed loop* configuration.

In this paper, the utilisation of groundwater heat pumps for heating and cooling purposes in a residential building located in Florence (Italy) is analysed. The work aims to show, considering real and dynamic boundary conditions, how the exploitation of a natural, renewable and local source such as groundwater could improve the performance of heat pumps. An energy analysis of the building has been performed, in order to obtain the heating and cooling loads necessary to design the systems. Three systems have been studied and compared: a traditional air-to-water heat pump, a groundwater-to-water heat pump and a surface reservoir water-to-water heat pump. With specific dynamic calculations, the energy needings of the three systems have been evaluated. Then, a Life Cycle Assessment analysis has been conducted. The obtained results lead to consider the utilisation of groundwater-driven heat pumps as a very energy-efficient solution in this case study and in general a promising option for the decarbonisation of the residential heating and cooling sector.

2 Materials and methods

The studied building is located in Florence (Italy). The analysis has been conducted assuming a revamping of the existing building envelope, able to bring it to respect the prescriptions of Italian standards [9] in terms of thermal insulation. Three heating/cooling systems are proposed: an air-to-water heat pump (system 1, AHP), a groundwater-to-water heat pump (system 2, GWHP) and a surface reservoir water-to-water heat pump (system 3, SWHP). The system 3 solution has been considered because the building is located in the proximity of a reservoir used for irrigation. Alongside the heating/cooling systems, it is supposed the utilisation of a mechanical ventilation system to ensure high indoor air quality. Two software have been employed to conduct the energy analysis of the building: *Design Builder* and *EC700*. Once the heating and cooling loads have been calculated with these software, they have been used to design the different schemes. Moreover, an hourly dynamic energy analysis (with *Design Builder* and *Matlab*, specifically for the surface reservoir water heat pump) has been performed to obtain the input data necessary to simulate the behaviour of the devices during the heating and cooling season. To evaluate the consumption, a switch-on profile of the systems is defined. In this way, taking into account the presence of people during the day and consequently the real behaviour of a heating/cooling system of a residential building, it has been possible to estimate the yearly consumption of the different schemes. The environmental analysis has been carried out according to ISO 14040 and ISO 14044 standards [10,11], employing the software *OpenLCA* with the *Ecoinvent 3.7* database [12] and following these steps: Goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), Interpretation. The aim was to define which of the three proposed solutions is the least environmentally impactful. The system boundaries are the heating and cooling equipment, considering all necessary devices for the different systems (in particular, for GWHP and SWHP, the pipelines necessary for water withdrawal from the wells and the water reservoir). The functional unit is 1 kWh of the total energy exchanged in the building by the heating and cooling system. This case has been considered a multiproduct system because the product that is generated is both heating and cooling. For this reason, an energy allocation factor equal to 0.81 is assigned, and it represents the produced fraction of heat compared to cold. The LCI has been derived from literature [13] and adequately scaled to the size of the case study. The different piping lengths for GWHP and SWHP have been also appropriately related to this situation. LCIA has been carried out following the Environmental Footprint 3.0 methodology. The analysis focused on the CO_2 emissions produced during the entire life cycle of the three systems. Then to investigate the causes of this impact, a contribution analysis has been conducted. Finally, results have been normalised and weighted to perform a single score comparison.

2.1 Climate and groundwater conditions

The local climatic conditions, necessary for the calculation of thermal loads and simulations, are directly defined by the energy analysis software, based on the indications of ASHRAE and Italian standards. The outdoor air conditions for the heating and cooling design have been set as follows (Table 1).

Table 1. Climatic conditions for heating and cooling design.

Mode			
Heating	T_o	0.0	°C
Cooling	T_o	32.0	°C
	RH_o	45.0	%
	R	0.85	kW

For the cooling design, the climatic conditions are referred to the hour of highest thermal load (deriving from the energy balance of equation (5) presented in the following). Moreover, the temperature of groundwater is assumed constant throughout the year and equal to 15.0 °C.

2.2 Indoor setpoint conditions

The indoor setpoint conditions, ensured during the operativity of the systems, are set as follows (Table 2).

Table 2. Indoor setpoint condition.

Mode			
Heating	T_i	20.0	°C
Cooling	T_i	26.0	°C
	RH_i	50.0	%

For the heating mode, there is not a setpoint value for indoor relative humidity because the systems do not include devices able to control humidity during the heating season. For the cooling mode, it is possible to control also the humidity with the regulation of heat pumps and heat transfer devices (fan coils).

2.3 Characterisation of the building

2.3.1 Geometric and envelope characteristics

The geometric characteristics of the simulated building (Figure 1) are reported in the following Table 3.

Table 3. Geometric characteristics of the building.

Number of floors	2	
Total volume	845.0	m^3
Floor occupied area	210.0	m^2

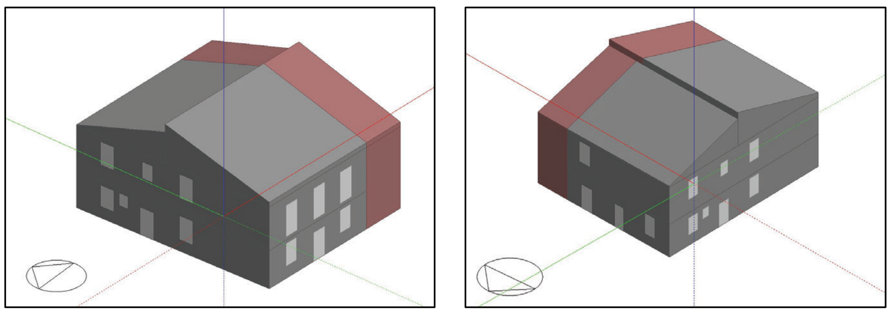

Figure 1. Models of the building (Design Builder).

The characteristics of opaque and transparent elements of the building are reported in the following Table 4.

Table 4. Thermophysical properties of opaque and transparent surfaces.

Element		
External wall		
Thermal transmittance	0.25	$W/m^2/K$
Infrared absorption-emission coefficient	0.9	
Solar radiation absorption coefficient	0.6	
Window (including frames)		
Thermal transmittance	1.0	$W/m^2/K$
Solar radiation transmission coefficient	0.4	

2.3.2 Internal generation, infiltration and ventilation loads

In the calculation of the thermal loads, it is necessary to consider the contributions of internal generation (only for cooling), accidental infiltration and ventilation. The input data are reported in the following Table 5.

Table 5. Heat generation contributions.

Contribution		
Household appliances, electronic devices, lightning		
PD	2.5	W/m^2
People		
OD (full occupancy)	0.03	$people/m^2$
$q_{s,p}$	50.0	W
$q_{l,p}$	50.0	W
Infiltration		
N_{inf}	0.1	vol/h
Ventilation		
$V_{v,p}$	11.0	L/s

The various contributions of thermal loads are calculated as follows:

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$$Q_{dev} = PD \cdot S \tag{1}$$

$$Q_p = OD \cdot S \cdot (q_{s,p} + q_{L,p}) \tag{2}$$

$$Q_{inf} = m_{inf} \cdot |j_o - j_i| \tag{3}$$

Concerning the repartition of the terms:

- The internal generation due to appliances and electronic equipment contributes to sensible load.
- People load is divided between sensible and latent.
- Infiltration load is divided between sensible and latent. The value of air changes per hour derived from the accidental infiltration is assumed low due to the refurbishment of the building.
- The ventilation load is evaluated taking into account the presence of people and the air change per person. The effective value of ventilation load depends on the functioning of the air-to-air recuperator, which is explained in the paragraph dedicated to the mechanical ventilation system. This load is divided between sensible and latent.

2.4 Heating and cooling loads and needs

2.4.1 Heating load calculation

The design heating load (calculated in the worst condition) is determined by thermal losses through opaque and transparent surfaces, accidental infiltration and ventilation:

$$Q_h = Q_{bs} + Q_{inf} + Q_v \tag{4}$$

2.4.2 Cooling load calculation

The design cooling load (calculated in the worst condition) is determined by thermal gains through opaque and transparent surfaces, solar radiation, appliances generation loads, people presence, infiltration and ventilation:

$$Q_c = Q_{bs} + Q_r + Q_{dev} + Q_p + Q_{inf} + Q_v \tag{5}$$

2.4.3 Heating and cooling needs throughout the year

Thanks to the dynamic simulation performed by the software, it is possible to calculate the yearly heating and cooling energy needs. For each hour of the simulation, the two software take into account the different contributions of the building energy balances: the heating and cooling energies are the sum of the hourly needings during the respective season.

2.5 Systems description

Three heating/cooling systems have been analysed and compared. Regardless of the thermal sources, they are reversible heat pumps equipped with scroll compressors. The choice of the scroll compressor is dictated by its noiselessness with respect to a reciprocating compressor, making it very suitable in a residential context. All of them have fan coils as distribution terminals: the heat pumps produce hot/cold water that circulates in the indoor water loop and exchanges heat with the indoor air at the fan coils. Moreover, a mechanical ventilation system serves the building, in order to ensure the necessary air changes with outdoor air. A global schematisation of these systems and a general representation of the heat pump schemes are proposed in Figure 2.

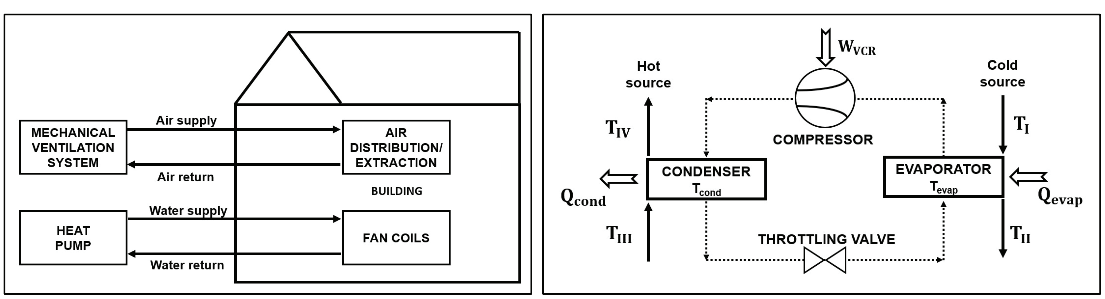

Figure 2. General representation of the systems serving the building (left) and heat pumps simulated in the systems (right).

The evaporator and condenser temperatures are defined by the following equations:

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$$T_{evap} = T_{II} - DT_{evap} \quad (6)$$

$$T_{cond} = T_{IV} + DT_{cond} \quad (7)$$

The consumption of the compressor in cooling mode is defined as:

$$W = Q_{evap} / COP_c \quad (8)$$

while in heating mode is:

$$W = Q_{cond} / COP_h \quad (9)$$

Q_{evap} and Q_{cond} correspond to the cooling and heating power exchanged between the heat pump and the internal water loop, so to the requested cooling and heating load. COP has been evaluated taking into account the change in boundary conditions: evaporator and condenser temperatures, evaporator or condenser power. So it is possible to write these general equations for the COP variation:

$$COP_c = F\,(T_{evap}\ ,\ T_{cond}\ ,\ Q_{evap}) \quad (10)$$

$$COP_h = F\,(T_{evap}\ ,\ T_{cond}\ ,\ Q_{cond}) \quad (11)$$

The mathematical formulation of COP_c and COP_h, which assumes the form of polynomials, depends on the commercially available models derived from [14].

2.5.1 Air-to-Water Heat Pump (system 1)

In this system:

- In heating mode, the outdoor coil acts as an evaporator taking heat from outdoor air and the indoor coil acts as a condenser releasing heat to the indoor water loop.
- In cooling mode, the outdoor coil act as a condenser releasing heat to outdoor air and the indoor coil acts as an evaporator extracting heat from the indoor water loop.

2.5.2 Groundwater-to-Water Heat Pump (system 2)

In this system:

- In heating mode, the outdoor coil acts as an evaporator taking heat from groundwater and the indoor coil acts as a condenser releasing heat to the indoor water loop.
- In cooling mode, the outdoor coil act as a condenser releasing heat to groundwater and the indoor coil acts as an evaporator extracting heat from the indoor water loop.

This system has 150 m of horizontal pipeline and 30 m of vertical pipeline.

2.5.3 Surface reservoir water-to-Water Heat Pump (system 3)

In this system:

- In heating mode, the outdoor coil acts as an evaporator taking heat from the surface water reservoir and the indoor coil acts as a condenser releasing heat to the indoor water loop.
- In cooling mode, the outdoor coil act as a condenser releasing heat to the water reservoir and the indoor coil acts as an evaporator extracting heat from the indoor water loop.

This system has 300 m of horizontal pipeline.

To perform the dynamic analysis of the heat pump, it is necessary to understand the variation of water reservoir temperature during the system activation. For this purpose, the energy balance of the reservoir is defined as follows [15]:

$$E_{res} = c_w * M_{res} * DT \quad (12)$$

where the reservoir energy content E_{res}, evaluated at each hour of systems activation, depends on the following terms of the thermal balance:

- Thermal power exchanged with the make-up water from the well, with turn-on time defined by the irrigation needs.
- Thermal power received by solar radiation.
- Thermal power exchanged by natural convection with the outdoor air.
- Thermal power exchanged by evaporation through the surface of the reservoir.
- Radiative thermal power in the infrared wavelength exchanged with the outdoor environment.

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- Thermal power exchanged by conduction with the walls of the reservoir.
- Thermal power exchanged with the outdoor coil of the heat pump.

The energy balance of the reservoir has been written for each hour of activation of the systems and has been solved with the software Matlab.

2.5.4 Mechanical Ventilation System

The system has been designed taking into account the prescription of Italian standards [16]. The airflow rate, in the case of full occupancy of the building, is defined as:

$$V_v = n_p * V_{v,p} \tag{13}$$

In order to reduce the ventilation load (both in heating and cooling mode), the system has been equipped with an air-to-air recuperator, at which the outdoor air, before entering the building, exchanges heat with the air extracted by indoor environments (Figure 3).

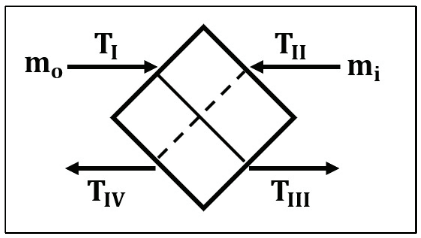

Figure 3. Representation of the air-to-air recuperator of the mechanical ventilation system.

The air-to-air heat exchanger operates on the sensible load, so it is possible to evaluate the temperature of outdoor air exiting the recuperator in heating mode as follows:

$$T_{III} = T_I + \varepsilon * (T_{II} - T_I) \tag{14}$$

and in cooling mode as:

$$T_{III} = T_I - \varepsilon * (T_I - T_{II}) \tag{15}$$

where ε is the efficiency of Kays and London, evaluated knowing that outdoor and indoor air flow rates are equal and with the same specific heat.

The thermal load (heating or cooling) generated by ventilation is equal to:

$$Q_v = m_v \cdot |j_{III} - j_i| \tag{16}$$

The ventilation load in heating mode is only in the sensible form, while it is sensible and latent in cooling mode. The energy consumption of fans for air moving has not been taken into account, due to the fact it is the same in all three systems.

2.5.5 Indoor water loop

The temperatures of the indoor water loop (as presented in the scheme of Figure 2), necessary to maintain the setpoint conditions in heating and cooling mode, are reported in the following Table 6.

Table 6. Temperatures of the indoor water loop.

Mode	Temperature		
Heating	Supply (T_{IV})	45.0	°C
	Return (T_{III})	40.0	°C
Cooling	Supply (T_{II})	7.0	°C
	Return (T_I)	12.0	°C

3 Results and discussion

In this chapter, the yearly performances of the three systems are presented. It is given attention to:

- Electric energy requirements to ensure heating and cooling needs.
- Environmental impacts (considering both the construction and operation of the schemes).

The results have been obtained considering a standard residential utilisation profile of the heating/cooling systems. For all the systems analysed, also the variation of COP (heating and cooling mode) alongside typical days as a function of sources temperatures is reported. The graphs presented for COP do not account for the switching-on profile, but show the behaviour of the systems during an entire day, in order to present the response of the systems to the variation of boundary conditions in a general utilisation of the devices.

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3.1 Heating and cooling design loads and energy requirements

For the design of systems, the following peak loads (Table 7) deriving from the resolution of equations (4) and (5), have been obtained:

Table 7. Thermal load contributions for the design of the systems.

Mode	Contribution		
Heating	Q_{bs}	4.2	kW
	Q_{inf}	0.5	kW
	Q_v	0.3	kW
	$\mathbf{Q_h}$	**5.0**	**kW**
Cooling	Q_{bs}	0.5	kW
	Q_r	1.7	kW
	Q_{dev}	0.5	kW
	Q_p	0.5	kW
	Q_{inf}	0.4	kW
	Q_v	0.8	kW
	$\mathbf{Q_c}$	**4.4**	**kW**

These values are perfectly similar between Design Builder and EC700. It is useful to note that, during the cooling season, a consistent part of the thermal load depends on solar radiation and ventilation, while the contribution of the surfaces is limited, as expected from a building with an energy-efficient envelope. In terms of necessary heating and cooling energy, the results of Table 8 have been obtained:

Table 8. Yearly thermal energy requirements.

Mode		
Heating	2 780.0	kWh
Cooling	630.0	kWh

The ratio between heating and the sum of heating and cooling requirements is 0.81, which justifies the utilisation of this value for the energy allocation factor in the LCA analysis.

3.2 Air-to-Water heat pump

The design conditions of the system are as follows (Table 9):

Table 9. Design condition for the air-to-water heat pump (system 1).

Mode			
Heating	$T_{II,d}$	-5.0	°C
	$T_{evap,d}$	-10.0	°C
	$T_{IV,d}$	45.0	°C
	$T_{cond,d}$	50.0	°C
	$COP_{h,d}$	2.6	
Cooling	$T_{II,d}$	7.0	°C
	$T_{evap,d}$	2.0	°C
	$T_{IV,d}$	37.0	°C
	$T_{cond,d}$	42.0	°C
	$COP_{c,d}$	3.0	

The changing of outdoor conditions (both in the heating and cooling season) leads to an appreciable variation of COP, as shown in the following Figure 4 referred to the heating and cooling design days.

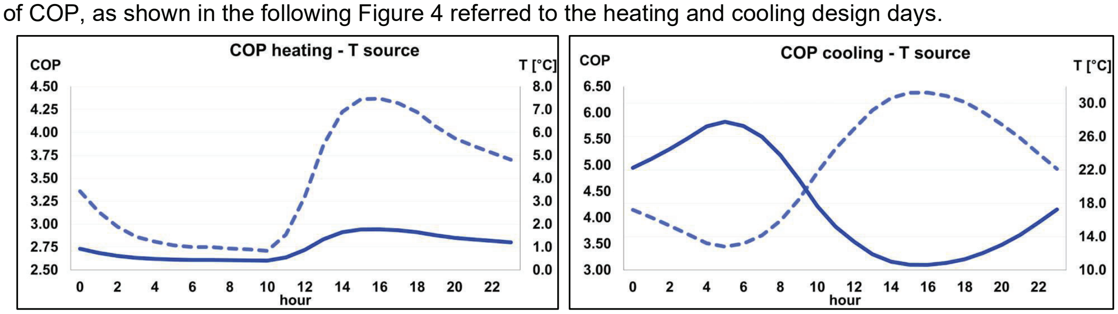

Figure 4. Heating (left) and Cooling (right) COP (left axis, continuous) against source temperature (right axis, dashed), system 1.

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It is easy to note that the air-to-air heat pump is particularly penalised in the hours of the cooling season in which the systems should be switched on to ensure the control of thermal loads, with a negative consequence on electricity consumption.

In terms of electric energy consumption, the system presents the following values (Table 10).

Table 10. Electric energy requirements for the air-to-water heat pump (system 1).

Mode	**Energy consumption**	
Heating	915.1	kWh
Cooling	173.0	kWh
TOTAL	1 088.1	kWh

3.3 Groundwater-to-Water heat pump

The design conditions of the system are as follows (Table 11):

Table 11. Design condition for the groundwater-to-water heat pump (system *2*).

Mode			
Heating	$T_{II,d}$	12.0	°C
	$T_{evap,d}$	7.0	°C
	$T_{IV,d}$	45.0	°C
	$T_{cond,d}$	50.0	°C
	$COP_{h,d}$	3.9	
Cooling	$T_{II,d}$	7.0	°C
	$T_{evap,d}$	2.0	°C
	$T_{IV,d}$	18.0	°C
	$T_{cond,d}$	23.0	°C
	$COP_{c,d}$	6.4	

The constant temperature of the groundwater throughout the year leads to obtaining a constant value of COP during the heating and cooling season (Figure 5).

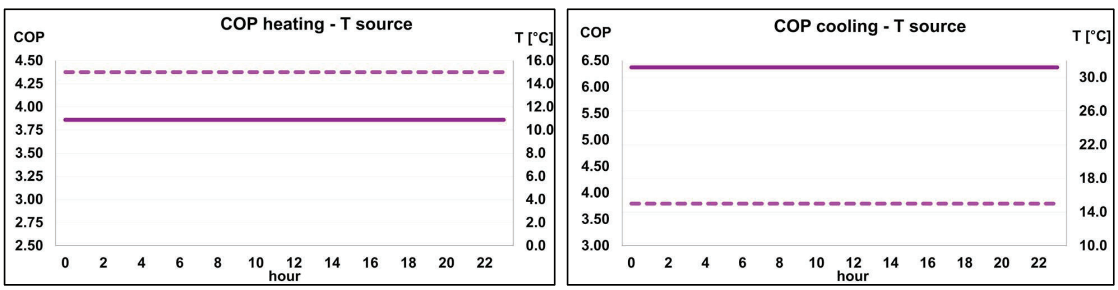

Figure 5. Heating (left) and Cooling (right) COP (left axis, continuous) against source temperature (right axis, dashed), system 2.

In the hours of the highest request for the system, the value of COP remains at the high design value without any influence of the outdoor air. This is the great advantage of a groundwater solution, i.e. the system can work with a very high COP also in the worst conditions of thermal loads. In terms of electric energy consumption, the system presents the following values (Table 12).

Table 12. Electric energy requirements for the groundwater-to-water heat pump (system 2).

Mode	**Energy consumption**	
Heating	679.8	kWh
Cooling	90.2	kWh
TOTAL	770.0	kWh

3.4 Reservoir water-to-Water heat pump

The design conditions of the system are as follows (Table 13):

Table 13. Design condition for the reservoir water-to-water heat pump (system 3).

Mode			
Heating	$T_{II,d}$	5.0	°C
	$T_{evap,d}$	0.0	°C
	$T_{IV,d}$	45.0	°C
	$T_{cond,d}$	50.0	°C
	$COP_{h,d}$	3.1	

Cooling	$T_{II,d}$	7.0	°C
	$T_{evap,d}$	2.0	°C
	$T_{IV,d}$	28.0	°C
	$T_{cond,d}$	33.0	°C
	$COP_{c,d}$	4.6	

The variation of reservoir water temperature is limited with respect to outdoor air, so the fluctuation in COP is quite limited in this case, even if COP is not constant as in the case of direct exploitation of groundwater (Figure 6). Nonetheless, the COP remains high also in the worst conditions for the system, making this technology an energy-efficient solution.

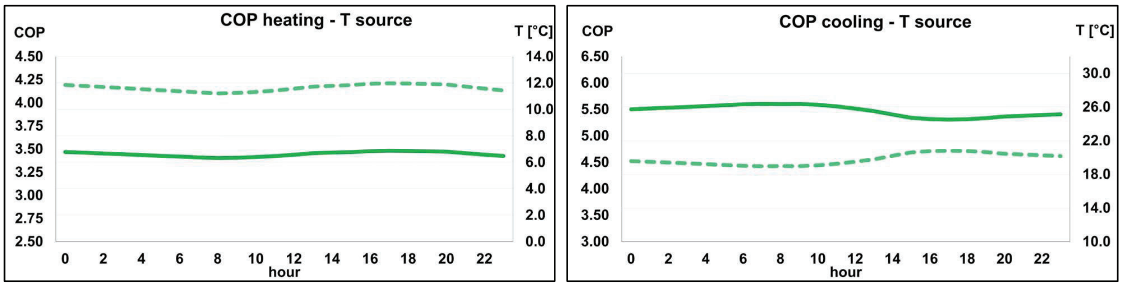

Figure 6. Heating (left) and Cooling (right) COP (left axis, continuous) against source temperature (right axis, dashed), system 3.

In terms of electric energy consumption, the system presents the following values (Table 14).

Table 14. Electric energy requirements for the reservoir water-to-water heat pump (system 3).

Mode	Energy consumption	
Heating	764.4	kWh
Cooling	107.2	kWh
TOTAL	871.6	kWh

3.5 Comparison of the energy requirements

Resuming the obtained results, it is possible to clearly show a comparison between the energy consumption of the systems (Figure 7).

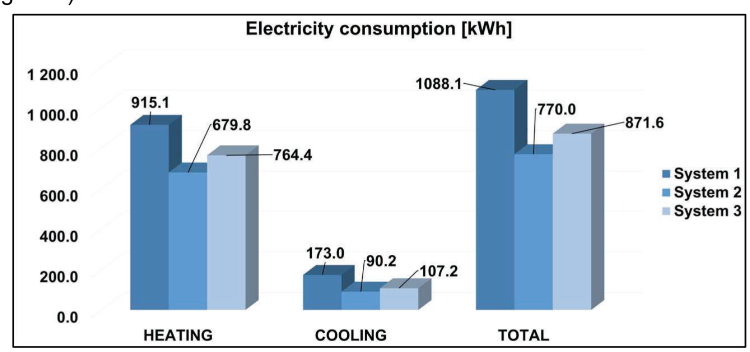

Figure 7. Comparison of electricity consumption for the different systems.

The GWHP (system 2) is the more energy-efficient system, with a yearly electric energy consumption of 770 kWh, which represents a saving of 30 % with respect to a traditional AHP (system 1). The SWHP (system 3), in turn, offers interesting savings (a reduction of 20 % in energy consumption compared to the traditional heat pump). Summing up, if the direct exploitation of groundwater is the most efficient solution in this context, the exploitation through the reservoir might be appropriate where the reservoir is already present, e.g. for irrigation purposes.

3.6 Life Cycle Assessment

The environmental analysis focuses on CO_2 emissions: the Climate Change category is shown in Figure 8. From the obtained results, it is evident that the largest CO_2 emission to the atmosphere is attributable to the AHP system equal to 0.21 kg CO_2 eq/kWh. The second largest system in terms of CO_2 eq emissions is SWHP, with 0.16 kg CO_2 eq/kWh, while GWHP emits slightly less, with 0.15 kg CO_2 eq/kWh.

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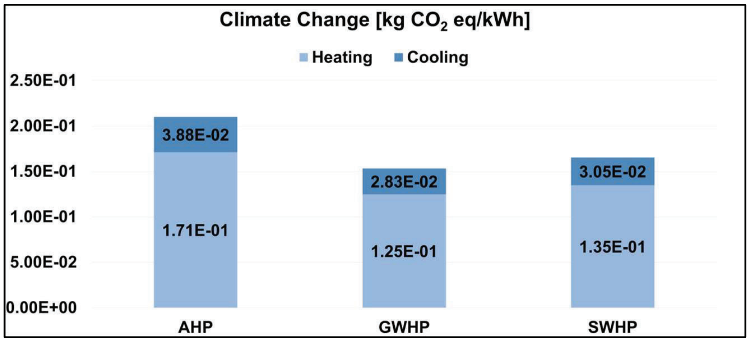

Figure 8. Comparison of the Climate Change LCA category for the different systems.

The contributions analysis (Figure 9) of the environmental impact categories shows that, for all three systems, the main impact comes from the operation phase, particularly in terms of electricity consumption. The construction and commissioning phase has much less impact, except for the categories of HTc, HTnc, and Rumm in which the use of metallic materials assume a great significance and covers about 44.4 %, 47.4 % and 72.2 % of the impacts, respectively. In the case of GWHP and SWHP, the presence of the piping required for water withdrawal assumes additional importance in the environmental impact. Particularly in the case of GWHP, where part of the piping is drilled into the ground to well realisation. Also, to be highlighted is the contribution that the working fluid assumes for the OD category of about 40 % for all three systems.

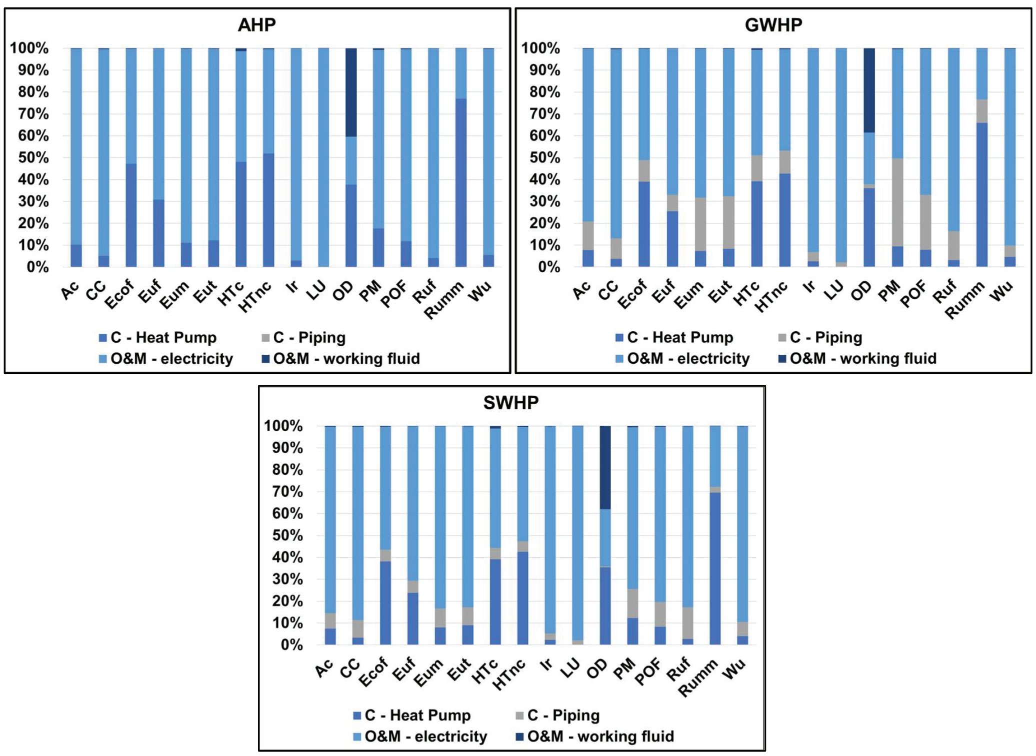

Figure 9 - Contribution analysis of all impact categories for the different systems.

Figure 10 shows the comparison of the three systems at the single score level. The single score shows the overall performance of the three systems. A similar trend to the Climate Change indicator is obtained. Indeed, AHP turns out to be the most impactful system, while GWHP and SWHP are less impacting. A reduction in impacts for both the ground source solutions is evident: about 24 % compared to AHP.

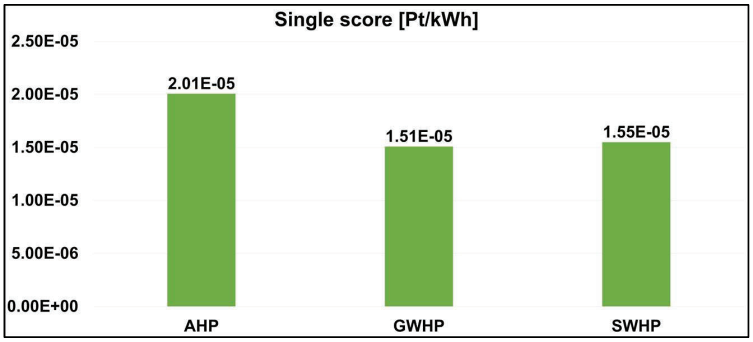

Figure 10 - Single score comparison for the different systems.

4 Conclusions

In this paper, the benefits of using groundwater as a thermal source for residential heat pumps have been discussed. In residential heating and cooling applications heat pumps are widely used, and for the reduction of energy consumption, groundwater represents a very favourable source for the external coils (evaporator in heating mode, condenser in cooling mode) of heat pumps. Three systems have been compared in the context of a specific case study located in Florence (Italy): air-to-water heat pump, groundwater-to-water heat pump and reservoir water-to-water heat pump. For the design of the systems, a detailed energy analysis of the building has been performed, in order to obtain the heating and cooling loads. Then the three systems, of which mathematical models have been presented, have been analysed considering the variation of boundary conditions (thermal loads, sources temperatures), that has been taken into account through a dynamic simulation of the building. Finally, an analysis with Life Cycle Assessment has been performed to show the environmental benefits of the proposed groundwater-based solutions with respect to a traditional heat pump. The analysis has demonstrated that the use of groundwater (direct or through the reservoir) greatly increases the COP (in particular the direct exploitation) of the devices, which results in consistent energy savings. In particular, the dynamic evaluation has shown that: with the groundwater solution it is possible to achieve a saving of 30 % with respect to the traditional air-to-water heat pump, while with the reservoir technology, the saving is 20 %. So the groundwater heat pump is the most energy efficient. Its utilisation is the best choice in terms of energy performance, but in the reality, due to its good results, also the reservoir option could be considered. In particular, a surface water heat pump can be used in all the situations in which the reservoir is already present and could be expensive to build the underground network, or the reservoir is necessary for irrigation needs. LCA analysis confirms, also under the environmental perspective, the advantages of using groundwater. As shown by the focus on the Climate Change category and the comparison to the Single Score, the most impactful system turns out to be AHP, while very little difference is made between the other two systems. GWHP and SWHP allow obtaining a global reduction of impacts of 24 %. The savings achieved with the groundwater solution also suggest a further management strategy for the system. Indeed, as this technology has a much lower electricity consumption than traditional air-to-water ones, it is much easier to integrate it with electricity production from renewable sources such as photovoltaics. In the heaviest situations of thermal or cooling demand of the building, since the groundwater heat pump works at higher COP and therefore lower energy demand, photovoltaic production would be advantaged. Moreover, the LCA analysis of the contributions shows the relevance owned by the electricity that is consumed for every environmental impact, encouraging the utilization of photovoltaic sources. It is therefore evident that, with the perspective of the realisation of *NZEB* buildings that may be integrated into energy communities, the adoption of groundwater technology, where exploitable, is an absolutely desirable strategy.

Nomenclature

Abbreviations		**Subscripts**	
AC	Air Conditioning	bs	building surfaces (opaque and transparent)
AHP	Air to Water Heat Pump	c	cooling
c	specific heat [kJ/kg/K]	cond	condenser
COP	Coefficient Of Performance	d	design condition
DT	Temperature difference [°C]	dev	internal appliances, devices,…
E	Energy [kJ]	evap	evaporator
F	General function of COP	h	heating
GHP	Ground Heat Pump	i	indoor
GSHP	Ground Source Heat Pump	I,II,III,IV	points of devices schematisation
GWHP	Ground Water Heat Pump	inf	infiltration
j	Specific entalphy [kJ/kg]	l	latent heat
LCA	Life Cycle Assessment	o	outdoor
M	Mass [kg]	p	person

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LCIA	Life Cycle Impact Assessment	r	solar radiation
LCI	Life Cycle Inventory	res	water reservoir
m	Mass flow rate [kg/s]	s	sensible heat
N	Number of air changes per hour [vol/h]	v	ventilation
n	number of people		
OD	Occupancy Density [W/m^2]		
PD	Power Density [W/m^2]		
Q	Thermal power [kW]		
q	Thermal load/person [kW]		
R	Direct normal solar radiation [kW]		
RH	Relative Humidity [%]		
S	Floor Area [m^2]		
SWHP	Surface Water Heat Pump		
T	Temperature [°C]		
V	Volumetric flow rate [m^3/s]		
W	Electric consumption of heat pump [kW]		
Abbreviations LCA			
Ac	Acidification	Ir	Ionising radiation
CC	Climate change	LU	Land use
Ecof	Ecotoxicity, freshwater	OD	Ozone depletion
Euf	Eutrophication, freshwater	PM	Particulate matter
Eum	Eutrophication, marine	POF	Photochemical ozone formation
Eut	Eutrophication, terrestrial	Ruf	Resource use, fossils
HTc	Human toxicity, cancer	Rumm	Resource use, minerals and metals
HTnc	Human toxicity, non-cancer	Wu	Water use

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