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ScienceDirect

Energy Procedia 133 (2017) 183–194

Energy Procedia

www.elsevier.com/locate/procedia

Climamed 2017 – Mediterranean Conference of HVAC; Historical buildings retrofit in the Mediterranean area, 12-13 May 2017, Matera, Italy

Ground source heat pump systems in historical buildings: two Italian case studies

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Abstract

Reducing the energy demand of buildings has become one of the key points of the European Union. The issue related to the air conditioning of old and historical buildings is nowadays one of the most important field of operation for the primary energy saving and, at the same time, for the reduction of the CO_2 emission. The recent development of heat pump able to rise the supply of high temperature at the condenser side makes this technology suitable for the application also in historical buildings that are characterized by low thermal insulation and high thermal capacitance. In this context, the ground source heat pump systems can be used for both heating and cooling. The aim of this work is to analyze the thermal behavior of two historical buildings located in Italy, in Venice and Florence respectively. Detailed computer simulations of the buildings have been carried out by means of a transient calculation tool TRNSYS. Energy simulations of GSHP systems have been performed and a comparison with a common plant system using a gas boiler for heating and air-to-water chiller for cooling has been carried out.

Keywords: historical buildings, case study, geothermal heat pump, BHEs, renewable energies.

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10.1016/j.egypro.2017.09.383

Nomenclature

COP	Coefficient of performance of the heat pump
EER	Energy efficiency ratio of the heat pump
SCOP	Seasonal coefficient of performance of the heat pump
SEER	Seasonal energy efficiency ratio of the heat pump

1. Introduction

The use of ground source heat pump (GSHP) systems is one of the most interesting solutions for heating and cooling of the buildings [1]. In recent years, the heat pump technology is gaining new interest in the market due to the new laws and regulations which include this technology as one able to exploit renewable energy sources, in addition to the already acknowledged. In particular, the use of low enthalpy geothermal energy as heat source/sink for the heat pump looks very promising if compared to the more common air-to-water heat pump and it can give an opportunity to achieve significant energy and at the same time economic benefits if well applied [2].

In literature, many studies identify GSHP systems as the most important ones among the most efficient energy technologies for HVAC (Heating, Ventilation and Air Conditioning). GSHPs are divided into three main groups based on the use of ground water from wells, surface water or directly coupled with the ground by the use of ground heat exchangers [3].

The use of water usually involves low investment costs and no ground surface area is required for the installation. The result of ground water from wells is normally good in terms of energy performances because of a constant temperature level of the source/sink during the year, but often its wide application is not allowed because of the local regulation. Normally, systems with great heat pump capacity are coupled with open loop systems where water is pumped from the surface aquifers through a heat exchanger and reinjected at some distance from the intake point. When the use of subsoil or surface water is not possible, ground heat exchangers, called Borehole Heat Exchangers (BHEs), can be used. This type of thermal source/sink is however less efficiency then the use of water because an intermediate heat exchange between the ground and a secondary fluid (usually a mixture of water and antifreeze) is involved. The undisturbed ground temperature is about the mean yearly temperature of the location with a geothermal gradient of about 3 °C for each 100 m of depth. It can sometimes happen that the temperature of the subsoil is higher especially in areas with anomalous gradient of temperature [4, 5]. In such a case the geothermal system can be used only for heating and not for cooling. However, in some cases the BHEs can be connected directly with heating system bypassing the heat pump, especially when the building is heated with radiant systems.

Furthermore, when referring to Mediterranean cities, the relevant cooling needs must be taken into account. As a matter of fact, the heat rejected into the ground, especially in the case of highly insulated buildings, might imply, on the long term, temperature drifts of the soil, thus resulting in reduced cooling efficiencies. In this field, for example Urchueguía et al. [6], report an experimental assessment of GSHP performance in typical Mediterranean coastal climate. The analysis contains a comparison between GSHP systems and air-water heat pumps involving the presence of a specially optimized water–water heat pump using propane as a refrigerant fluid.

2. Method and case studies

This work has been divided into three main steps. The first one is the collection of the required building data for each case study in order to define the energy model of the buildings. The second part of the work is the development of the energy model of the buildings in the simulation tool. In this phase, several computer simulations have been carried out in order to evaluate the heating and cooling peak load and energy demand of the buildings using different hypotheses of managing of the air-conditioning systems. In the last part of the study, the design of the BHEs field, the definition of the properties of the heat pump and the electrical energy demand of the heat pump have been evaluated.

2.1. Description of the case studies

“Ca’ Lupelli Wolf Ferrari” (Venice)

The building is located in the historical city centre, fronting the “Canal Grande” in a complex of buildings where the main building is Ca’ Rezzonico which is the museum block. Ca’ Lupelli Wolf Ferrari is a smaller building which is occupied by the direction of-fices of the museum. The construction of the complex started in 1649, and it was closed in 1756. Afterwards it was decorated by some of the most famous painters of Venice, like Gianbattista Crosato, Pietro Visconti and Gianbattista Tiepolo, so the palace was perfectly finished in 1758.

Until 1810 the building was property of the Rezzonico family. It was then sold and went through many hands. Finally in 1935 it became property of Venice Municipality. It was immediately renovated and in 1936 it became a museum called “Museo del Settecento Veneziano” whose particularity was that all the works of art were disposed like they were part of the equipment’s of the buildings. In Figure 1 the overhead view of the city of Venice and of the “Ca’ Lupelli” building is represented, while in Figure 2 the overall dimension of the building reported in the section of the ground floor as example.

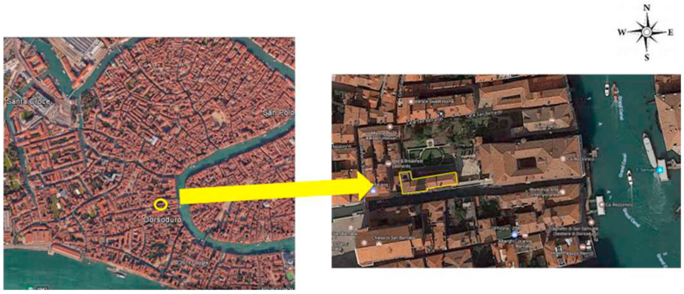

Fig. 1. Overhead view of the city of Venice and of the “Ca’ Lupelli” building

Fig. 2. Overall dimensions in meters of the “Ca’ Lupelli” building

“Opera Santa Croce” (Florence)

The building is a museum located in the historical city centre of Florence, on the south of “Santa Maria del Fiore” cathedral and on the east of “Ponte Vecchio”. The museum is part of the “Basilica di Santa Croce” complex, and it is located in correspondence to the ex-refectory and cenacle. It became a museum in 1900 under the direction of Guido Carocci, and it was enlarged in 1959. In 1969 both the building and the works of art were damaged, because of the flood of Florence. For that reason, it was under renovation for a long period. It was open again in 1975, but all the works of art were replaced only in 2009.

Today the museum is formed by 5 rooms. There is the ancient “Cappella Cerchi”, that contains frescos, sinopites, reliefes, sculptures and ligneus equipment’s, and the cenacle. The last one is a large rectangular room with a trussed ceiling, and it is used as expositive room for conferences, display of works of art or sometimes as a concert room.

Nowadays important works of famous artists are exposed, for example the “Crocifisso di Cimabue” and the Giorgio Vassari’s “Tavola dell’ultima cena”, that attract thousand visitors every year. In the past the site complex was studied aiming at improving the sustainability and installations efficiency.

In Figure 3 the overhead view of the city of Florence and of the building are represented, while in Figure 4 the overall dimension of the building reported in the section of the ground floor as example.

Fig. 3. Overhead view of the city of Florence and of the “Opera Santa Croce” building

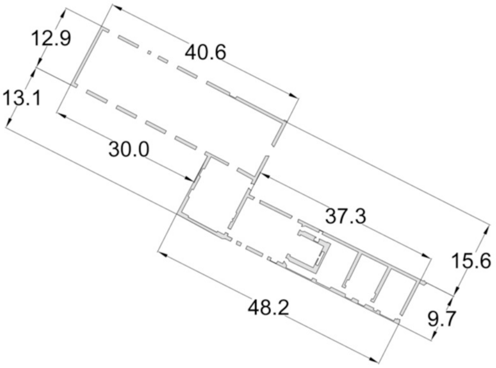

Fig. 4. Overall dimensions in meters of the “Opera Santa Croce” building

2.2. Thermal load analysis of the buildings

The thermal load profile of each case study has been calculated by means of TRNSYS simulation code. Several simulations have been carried out for different control strategies adopted for the air-conditioning system.

For each building, the data on the geometry (surface areas, volumes, etc.), the thermal properties of opaque and glazing elements, the internal loads due to lights, devices and occupants in the different rooms have been collected in the previous step and in some cases they have been estimated using the values suggested in the standard EN ISO 13790 [7].

The thermal peak load of the buildings (in heating and cooling mode) and the annual energy load profile, have been obtained from the simulations of one year of operation period using the TRY (Test Reference Year) of Venice and Florence, for Ca’ Lupelli and Opera Santa Croce building respectively. The climate data has been downloaded from the web page of EnergyPlus simulation tool [8]. The mean monthly temperatures of Venice and Florence are reported in Table 1.

Since different control strategies have been investigated, different results in terms of thermal peak loads and energy needs have been obtained from the simulations.

Five different control strategies have been defined and they are summarized in Table 2. The control of the emission system has been applied only during the heating period while in cooling the control is always the WD.

Table 1. Average monthly temperatures

Month	J	F	M	A	M	J	J	A	S	O	N	D
Venice												
Mean Temperature (°C)	2.3	4.5	7.4	12.5	17.8	21.4	24.4	23.0	18.7	14.0	7.9	4.4
Florence												
Mean Temperature (°C)	5.1	5.9	9.7	12.9	17.1	21.1	23.8	23.2	19.8	15.1	10.8	5.8

Table 2. Control strategies of the air-conditioning system considered in the simulations for the heating mode

Code	Description
WD	The air-conditioning system is switched on only during the working hours and from Monday to Friday. During the week-end the system is switched off for “Ca’ Lupelli” while is switched on for “Opera Santa Croce”.
H24NWE	The air-conditioning system is switched on h24/h24 with a set point temperature of 20°C. In the week-end the system is switched off. This control strategy has been considered only for “Ca Lupelli” because the “Opera Santa Croce” is open during the week-end.
H24NWE18	The air-conditioning system is switched on h24/h24 with a set point temperature of 20°C during the working hours and with a set point of 18°C in the rest of the day. In the week-end the system is switched off. This control strategy has been considered only for “Ca Lupelli” because the “Opera Santa Croce” is open during the week-end.
H24YWE	The air-conditioning system is switched on h24/h24 also during the week with a set point temperature of 20°C.
H24YWE18	The air-conditioning system is switched on h24/h24 for the entire week, with a set point temperature of 20°C during the working hours and with a set point of 18°C in the rest of the day.

The main results of the energy simulations of the buildings in terms of peak load and energy needs in heating and cooling are summarized in Table 3 and Table 4 respectively. The monthly energy results are shown in Figure 5 and Figure 6 for Ca’ Lupelli and Opera Santa Croce respectively.

Table 3. Thermal Peak Load in heating and cooling

	Heating/Cooling - Thermal Peak Load [kW_h \ kW_c]	
	Ca’ Lupelli (Venice)	Opera Santa Croce (Florence)
WD	111 \ 28	159 \ 54
H24NWE	91 \ 28	- \ - *
H24NWE18	78 \ 28	- \ - *
H24YWE	32 \ 28	97 \ 54
H24YWE18	45 \ 28	114 \ 54

*: this control strategy has not been considered because the museum is not open during the week end

Table 4. Annual heating and cooling energy needs

	Heating/Cooling – Energy need [kWh_h \ kWh_c]	
	Ca' Lupelli (Venice)	Opera Santa Croce (Florence)
WD	53112 \ 4803	152607 \ 5010
H24NWE	67595 \ 4806	- \ - *
H24NWE18	61356 \ 4803	- \ - *
H24YWE	76877 \ 4806	214547 \ 5020
H24YWE18	68230 \ 4803	185907 \ 4999

*: this control strategy has not been considered because the museum is not open during the week end

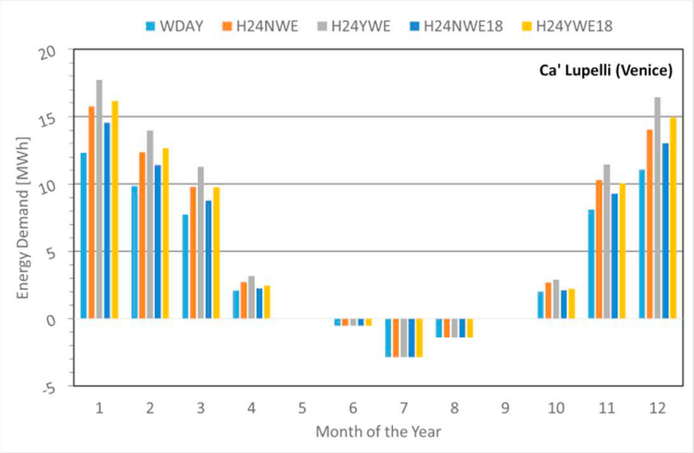

Fig. 5. Monthly energy demand for "Ca' Lupelli" Building

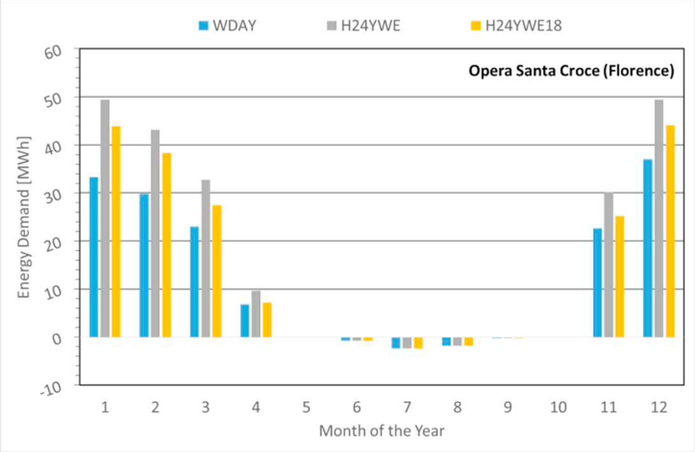

Fig. 6. Monthly energy demand for "Opera Santa Croce" Building

As it can be seen, the results of the simulations show a dominant heating thermal load profile and a sensible difference in terms of heating peak load in all cases. In particular, as expected, the dominant heating load profile is due to the uninsulated structures and the high thermal inertia of the building addicted to low energy demand in cooling mode for the two buildings otherwise the occupied spaces are used for offices or museum with significantly internal loads. The cooling load considers also the latent energy demand. For this purpose, the simulations of the GSHP system have been carried out over ten years in order to investigate the ground thermal drift effect in the long term.

2.3. Design of the GSHP systems

In order to study the thermal behaviour of the BHEs field coupled with the heat pump, the layout of the field has been designed. The analysis of the arrangement of the BHEs has been carried out by the use of the approach proposed by Kavanaugh and Rafferty [9]. In particular, the results of the simulations obtained in the previous step have been used to evaluate the depth and number of ground heat exchangers compatibly with the availability of ground surface for installation near the building. The thermal properties of the ground have been found in dedicated databases [10]. This data has been used to estimate the value of conductivity, density and heat capacity of the ground. The thermal properties for the ground used in the simulations are summarized in Table 5.

The main boundary conditions for the design of the BHEs used in the ASHRAE method are summarized in Table 6 and they were the same for the two case studies.

Table 5. Thermal properties of the ground in Venice and Florence city centre

Properties of the ground	Venice	Florence
Thermal Conductivity [W/(m K)]	2.0	2.2
Density[kg/m^3]	2700	2600
Specific Heat Capacity [J/(kg K)]	890	880
Undisturbed ground temperature [°C]	13.1	14.2

Table 6. Boundary conditions used for the ASHRAE method

Mean SCOP \ SEER [-]	4.2 \ 4.1
Design COP \ EER [-]	3.0 \ 3.3
Inlet temperature at HP in cooling [°C]	8
Inlet temperature at HP in heating [°C]	30
ΔT source side [°C]	3
ΔT load side [°C]	5

Since the control strategy used in the different simulations has been modified, the results in terms of energy demand and peak load are different. The design process of the BHEs field shows different layouts in terms of total length of ground heat exchangers installed in the GSHP system. The number of BHEs are the same for each case study, only the depth of the ground heat exchanger has been modified.

In this context, the possible issues related to the use of the drilling machines in historical city centre have not been taken into account. The reason of this choice was related to the main objective of this study, which is the possibility of using this type of technology for air-conditioning of historical buildings.

The main results of the BHEs field design are summarized in Table 7. Figure 7 and Figure 8 report the arrangement of the BHEs in the ground area near the building as a hypothesis of how the ground heat exchangers may be installed for the GSHP system application.

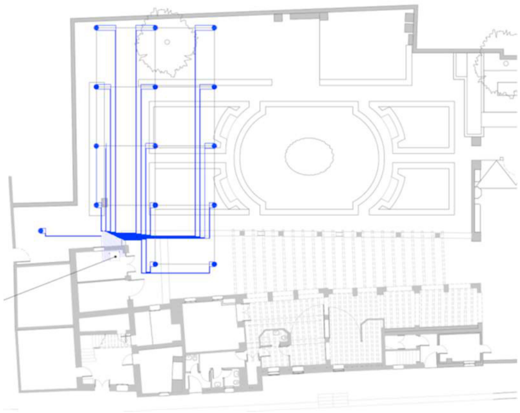

Fig. 7. Arrangement of the BHEs for the case study of “Ca’ Lupelli”

Fig. 8. Arrangement of the BHEs for the case study of “Opera Santa Croce”

Table 7. Properties of the BHEs fields

BHEs Field			Ca’ Lupelli Venice	Opera Santa Croce Florence
Type of BHEs			2U	
Int. \ Ext. Diameter		[mm \ mm]	26 \ 32	
Material			Pex-A	
Thermal conductivity of the pipe		[W/(m K)]	0.35	
Distance between pipes		[mm]	86.2	
Borehole diameter		[mm]	140	
Thermal conductivity of the grout		[W/(m K)]	1.83	
Density of the grout		[kg/m^3]	1655	
Specific heat of the grout		[J/(kg K)]	1460	
# BHEs/Depth	WD	[# / m]	15 \ 161	19 \ 143
	H24NWE		15 \ 161	- \ -
	H24NWE18		15 \ 143	- \ -
	H24YWE		15 \ 121	19 \ 130
	H24YWE18		15 \ 121	19 \ 130
Distance between BHEs		[m]	5	12

2.4. Modeling of the GSHP systems

For each case study, the simulations of the GSHP systems have been carried out by the use of the detailed simulation code CaRM (Capacity Resistance Model) [11]. This code has been tuned and verified in the last years using monitoring data and several papers have been published on this field by Zarrella et al. [12, 13, and 14]. These papers describe the potential of the tool to assess in detail the thermal behaviour of low enthalpy geothermal systems. At the same time the code considers the energy performance of the heat pump evaluating the COP and the EER in heating and cooling mode respectively. The energy performance of the heat pump has been evaluated as a function of the inlet and outlet temperature of the secondary fluids on the heat pump, on the source and load side respectively. Table 8 reports the main data about the energy performance of the heat pump.

The temperatures considered in the simulations on the load side are suitable with the use of fancoils (?)as emission units, which are considered in the case studies as type of air-conditioning systems. In particular, in design conditions the temperature of the secondary fluid is 40/45 °C and 7/12 °C for heating and cooling respectively. The return temperature of the secondary fluid on the load side has been evaluated considering the thermal load of the building for each time step.

Table 8. Energy performance of the heat pump in heating and cooling

Heating – COP					Cooling - EER				
	T load side [°C]					T source side [°C]			
T source side [°C]	25	30	35	40	T load side [°C]	20	23	27	31
8	5.54	4.78	4.17	3.67	10	5.56	5.05	4.47	3.97
10	5.80	5.02	4.39	3.88	11	5.70	5.18	4.59	4.08
12	6.06	5.26	4.55	4.08	12	5.83	5.31	4.71	4.20
14	6.41	5.49	4.82	4.28	14	6.10	5.57	4.95	4.42

3. Simulation results

The results of the simulations in terms of seasonal energy efficiency are summarized in Figure 9 and Figure 10, where the SCOP and he SEER are the ratio between the annual energy need for heating and cooling and the annual electrical energy demand for the two operation modes. The results in terms of electrical and primary energy demand are reported in Table 9 and Table 10. In these tables the results of other plant solutions are reported. In particular, two different systems have been investigated: an air-to-water heat pump and a condensing boiler coupled with an air-to-water chiller respectively.

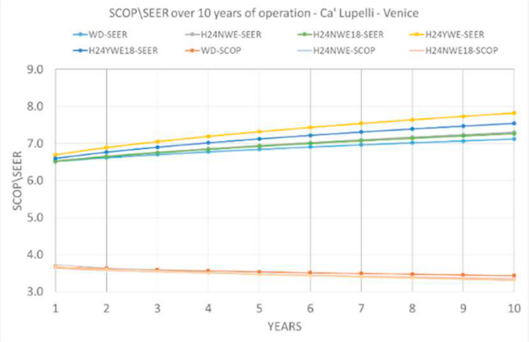

Fig. 9. SCOP\SEER over ten years of operation – Ca’ Lupelli – Venice

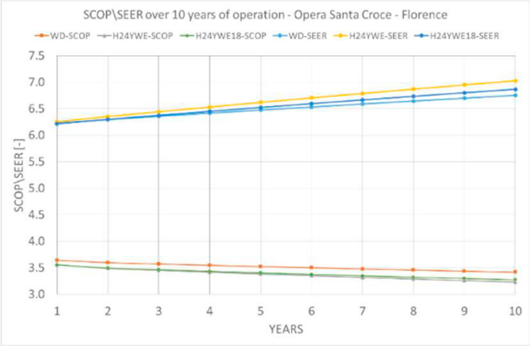

Fig. 10. SCOP\SEER over ten years of operation – Opera Santa Croce – Florence

Table 9. Results of the energy analysis for the case study in Venice

		Ca' Lupelli (Venice)				
	Building	WD	H24NWE	H24NWE18	H24YWE	H24YWE18
	Energy need for heating [MWh_H]	531	676	614	769	682
	Energy need for cooling [MWh_C]	48				
GSHP system	Mean SCOP 10 years	3.53	3.46	3.47	3.47	3.46
	Mean SEER 10 years	6.85	6.95	6.93	7.32	7.12
	Electrical energy demand for heating [MWh_{el}]	150.4	195.4	176.9	221.6	197.1
	Electrical energy demand for cooling [MWh_{el}]	7.0	6.9	6.9	6.6	6.7
	Primary energy demand for heating [MWh_p]	326.3	423.8	383.8	480.7	427.6
	Primary energy demand for cooling [MWh_p]	15.2	15.0	15.0	14.2	14.6
	Total Primary energy demand [MWh_p]	341.5	438.8	398.9	494.9	442.2
AW Heat Pump	Mean SCOP 10 years	2.56	2.5	2.52	2.58	2.55
	Mean SEER 10 years	3.11				
	Electrical energy demand for heating [MWh_{el}]	207.4	270.4	243.7	298.1	267.5
	Electrical energy demand for cooling [MWh_{el}]	15.4				
	Primary energy demand for heating [MWh_p]	449.9	586.6	528.5	646.6	580.2
	Primary energy demand for cooling [MWh_p]	33.5				
	Total Primary energy demand [MWh_p]	483.4	620.0	562.0	680.0	613.6
C. Boiler + AW chiller	Seasonal Efficiency of the boiler	0.95	0.95	0.95	0.95	0.95
	Mean SEER 10 years	3.11				
	Std m^3 of natural gas [Sm^3]*	51828	65980	59929	75057	66566
	Electrical energy demand for cooling [MWh_{el}]	15.4				
	Primary energy demand for heating [MWh_p]	586.9	747.2	678.6	849.9	753.8
	Primary energy demand for cooling [MWh_p]	33.5				
	Total Primary energy demand [MWh_p]	620.4	780.6	712.1	883.4	787.3

*: values evaluated with higher heating value of 10.78 kWh/Sm^3

For the primary energy calculation the conversion factors are 1.05 and 2.17 for the natural gas and the electricity respectively

Table 10. Results of the energy analysis for the case study in Florence

		Opera Santa Croce (Florence)		
	Building	WD	H24YWE	H24YWE18
	Energy need for heating [MWh$_H$]	1526	2145	1859
	Energy need for cooling [MWh$_C$]	50		
GSHP system	Mean SCOP 10 years	3.52	3.37	3.39
	Mean SEER 10 years	6.49	6.64	6.55
	Electrical energy demand for heating [MWh$_{el}$]	433.5	636.5	548.4
	Electrical energy demand for cooling [MWh$_{el}$]	7.7	7.5	7.6
	Primary energy demand for heating [MWh$_P$]	940.4	1380.7	1189.5
	Primary energy demand for cooling [MWh$_P$]	16.7	16.3	16.6
	Total Primary energy demand [MWh$_P$]	957.1	1397.0	1206.1
AW Heat Pump	Mean SCOP 10 years	2.54	2.57	2.55
	Mean SEER 10 years	2.91		
	Electrical energy demand for heating [MWh$_{el}$]	600.8	834.6	729.0
	Electrical energy demand for cooling [MWh$_{el}$]	17.2		
	Primary energy demand for heating [MWh$_P$]	1303.2	1810.5	1581.4
	Primary energy demand for cooling [MWh$_P$]	37.3		
	Total Primary energy demand [MWh$_P$]	1340.5	1847.7	1618.7
C. Boiler + AW chiller	Seasonal Efficiency of the boiler	0.95	0.95	0.95
	Mean SEER 10 years	2.91		
	Std m^3 of natural gas [Sm^3]*	148944	209360	181446
	Electrical energy demand for cooling [MWh$_{el}$]	17.2		
	Primary energy demand for heating [MWh$_P$]	1686.6	2370.8	2054.7
	Primary energy demand for cooling [MWh$_P$]	37.3		
	Total Primary energy demand [MWh$_P$]	1723.9	2408.1	2092.0

*: values evaluated with higher heating value of 10.78 kWh/Sm^3

For the primary energy calculation the conversion factors are 1.05 and 2.17 for the natural gas and the electricity respectively

4. Discussion

As it can be seen from the results of the simulation reported in the previous section, the design of the BHEs field, conducted by the use of the ASHRAE method, has provided good results in all the cases, even if the thermal load profiles of the buildings are basically only in heating. In fact, the thermal drift of the ground involved a reduction of the SCOP less than the 10% over the ten year of operation from the first to the last year. On the other hand, the SEER increased, but its magnitude on the final result is limited because of the cooling energy demand is negligible if compared to the heating one.

From the point of view of the control strategy for the air-conditioning system, as previously discussed in the paper, the results show differences on the energy demand, but at the same time there are differences in the peak loads. Looking at the results for “Ca’ Lupelli” building, an interesting solution may be the H24NWE18 (see Table 2) because it has an increase of the energy consumption of about 17% over ten years of operation, compared with a reduction of the size of the heat pump of about the 30%. From the cost of operation point of view, this solution presents an increase of the electrical energy demand of about 26500 kWh$_{el}$ over ten years if compared to the WD control (see Table 2). With a cost of electrical energy of about 0.23 €/kWh$_{el}$ the estimated increase of the cost is about 6100 €.

From the primary energy point of view the GSHP system is always the best solution in all the cases. In particular, the use of air-to-water heat pump involved an increase of about 30% with respect to the GSHP system. The primary energy demand of the com-mon solution (condensing boiler for heating and air to water chiller for cooling) was about 70% (30%) higher than that of the GSHP system (air-to-water heat pump).

5. Conclusions

The application of ground source heat pump system in historical buildings was investigated. In particular, two case-studies in Venice and Florence were considered. The analysis was performed by means of computer simulations, regarding both the buildings and the plant system made of borehole heat exchangers and heat pump, by means of models already published in literature. The building simulations outlined a heating dominant load profile in both cases. This involved a change of the ground temperature in the long-term operation period and, consequently, also of the energy efficiency of the heat pump. However, the results show that if the borehole filed was well designed, this issue could be controlled. The ground source heat pump system was also compared to the air source heat pump and to the common system consisting of a condensing gas boiler and air-to-water chiller. The results outlined that the ground source heat pump system is the best solution in terms of primary energy saving point of view.

Acknowledgements

This work has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 657982.

Authors express their gratitude to the direction and staff of "Fondazione Musei Civici di Venezia" and "Opera di S. Croce" for their support in furnishing the necessary data to perform the described analysis of the buildings.

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