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Air cooled heat pump coupled with Horizontal Air-Ground Heat Exchanger (HAGHE) for Zero Energy Buildings in the Mediterranean climate

Cristina Baglivo[a]*, Paolo Maria Congedo[a], Domenico Laforgia[a]

[a]*Department of Engineering for Innovation, University of Salento, 73100 Lecce (Lecce), Italy*

Abstract

This study demonstrates how it is possible to increase the performances of an air-cooled heat pump by the use of Horizontal Air-Ground Heat Exchanger (HAGHE); the analysis has been carried out varying the air flow rate and heat conductivity of the ground. For a warm climate, the air treatment using HAGHE involves an improvement of the Energy Efficiency Ratio (EER) of the heat pump for the entire summertime. About the wintertime, the coefficient of performance (COP) results improved from November to February, but it is possible to install a by-pass to permit to the heat pump to work at the best conditions.

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Keywords: HAGHE; Heat Pump; COP; EER; ZEB; Ground; Geothermal; Efficiency.

1. Introduction

The knowledge of the environmental issues has resulted in the development of action programs and international policies addressed to the reduction of primary energy use and carbon dioxide emissions, which cause the greenhouse

* Corresponding author. Tel.:+39 0832 297750; fax:+39 0832 297750.
E-mail address: cristian.baglivo@unisalento.it

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effect and the temperature rise [1]. In this direction, it has been noted that the reduction of the consumptions in transport and building sector show the biggest potential on energy efficiency in all countries [2].

In the European Union, the construction sector affects the total energy demand and greenhouse emissions for approximately 40% [3]. In particular, it is responsible for the consumption of around 40% of natural resources, 70% of electricity and 12% of potable water [4]. The European polices are focused on these environmental issues. The Energy Performance of Buildings Directive (EPDB) considers the energy performance of the buildings as the amount of energy needed to meet the energy request linked to the specific use of the building. The article 9 of the EPDB sets a specific target that by the end of 2020 all new buildings must have nearly zero or very low energy needs. In this scenario, the Zero Energy Buildings target of new or existing building has become an urgent priority for designers and researchers. For a correct design, it is fundamental a careful study of the building parameters in order to guarantee the internal comfort and a high satisfaction level of the mind in the thermal environment occupied. The result of correct choices for the design of sustainable buildings involves positive environmental effects, reducing the consumption of natural resources and costs and especially ensuring a high quality of service for the end users and the whole community, in accordance with the EPBD [5].

Several studies on the IEQ (Indoor Environmental Quality) have been carried out, to guarantee the internal comfort, to preserve the human health and to improve the productivity on the workplaces.

In literature, it has been estimated that the use of Ground Source Heat Pump (GSHP) involves the reduction of the CO_2 payback–time and it results a good investment especially for large size buildings [6].

The stable temperature of the heat source during the year makes the use of the Ground Source Heat Pump convenient compared to the traditional systems. Furthermore, it has been shown that the GSHP leads lower operating costs than the natural gas boiler systems [7]. The exchange with the ground can take place using vertical and horizontal exchangers, the first one is preferred when the surface is not sufficient to allow the heat transfer. The depth of installation makes the vertical systems less influenced by the external atmospheric conditions.

About the horizontal system, it has been noted that the pipes are spaced at least 1.5 m to a depth between 1.2 and 1.8 m, to avoid the thermal influence between each other. Furthermore, as above mentioned, the external conditions highly influence the performance of the horizontal systems.

The HAGHE systems for buildings located in a warm area involves important advantages in summer seasons for the cooling of ventilation air up to different temperature degrees also using short pipes. On the other hand, the benefits in winter are just for a few hours during the day. The study presented by [8] investigates, through CFD simulations, how the main parameters impact on the behavior of the horizontal ground heat exchangers.

The analysis has been carried out for several geometry configurations and for different working conditions. Furthermore, properties such as the installation depth, the ground thermal conductivity and the velocity of the heat fluid transfer have been investigated as measures applied on the horizontal ground heat exchangers.

This paper shows a system based on an air-cooled heat pump combined with a HAGHE. The results are exposed in terms of COP and EER and are continually compared with those obtained by the same heat pump which exchanges directly with the external air. Several measures have been applied on the combined system, to reach the optimized solution for the warm climate. As shown, the variants are the airflow rate for single pipe, the underground depth of the pipe and ground conductivity in unsteady conditions by using annual weather data.

The present study highlights the behavior of the combined system focusing on the warm climate, considering a location of Brindisi, a city of the South of Italy (climatic zone C, 1083 DD). The average temperature is of about 13 °C over the last ten years for the winter time and 30.3 °C for the high aridity summer. In this climatic area, to ensure suitable comfort conditions, the operative air temperature is 20 °C during the heating period ranging from November 15th to March 31st and 26 °C during the cooling period [9]. Graphs shows the COP and the EER trend, for winter and summer time, respectively.

Nomenclature

COP	Coefficient of Performance
EER	Energy Efficiency Ratio
HAGHE	Horizontal Air-Ground Heat Exchanger
ACHP	Air-Cooled Heat Pump

GSHP	Ground Source Heat Pump
GHE	Ground Heat Exchanger
Tair in	Temperature of the external air at a specific time of the year [K]
Tout_xx	air Temperature in the probe output, variable according to the flow [K]
HAGHE	Horizontal Air-Ground Heat Exchanger
Greek symbols	
λ	thermal conductivity of the ground [W/mK]
Δ	gap
Subscripts	
ext-air	exchange with the untreated outside air
haghe	exchange with the outside air treated by a geothermal probe

2. Methodology

The present study aims to demonstrate how the performances of the air-cooled heat pump result improved using a HAGHE.
The simulations have been carried out considering a heat pump dimensioned to produce sanitary hot water and meets the need of heating/cooling of small and medium-sized buildings for residential or commercial use. The COP and EER of the heat pump are described by polynomial trends, obtained at maximum frequency, in function of the external air temperature and the treated water temperature, as shown in Figure 1 and Figure 2.

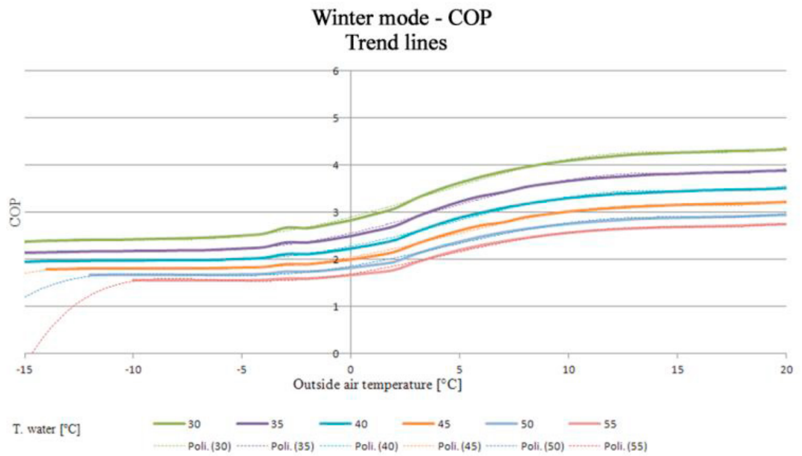

Fig.1. Hot mode: trend of the COP as a function of outside air temperature and water temperature produced at the maximum frequency.

Once defined the trend lines of the heat pump, the study focus on the investigation of the COP and EER of the heat pump combined with a HAGHE.
The dynamics simulations have been performed using TRNSYS 17 (Transient System Simulation) tool, which allows solving algebraic and differential equations and performing a modular approach through the division of a complex problem into a sum of simpler problems. TRNSYS is marked by internal codes which identify the thermal behavior of the single components. In addition, it permits to simulate the building-plant behavior or just one of them, as well as monitor every single system component. Each component is characterized by a Type; each Type requires the input data and provides the output values which can be used by subsequent Type or represent the final data. The envelope is implemented in detail through a special GUI program (TRNBuild), an add-on of TRNSYS.
The work is based on a simple model, the Types used are the Type 15 for the Weather Data, the Type 501 for the Ground Temperature profile and the Type 31 for the detailed buried pipe.

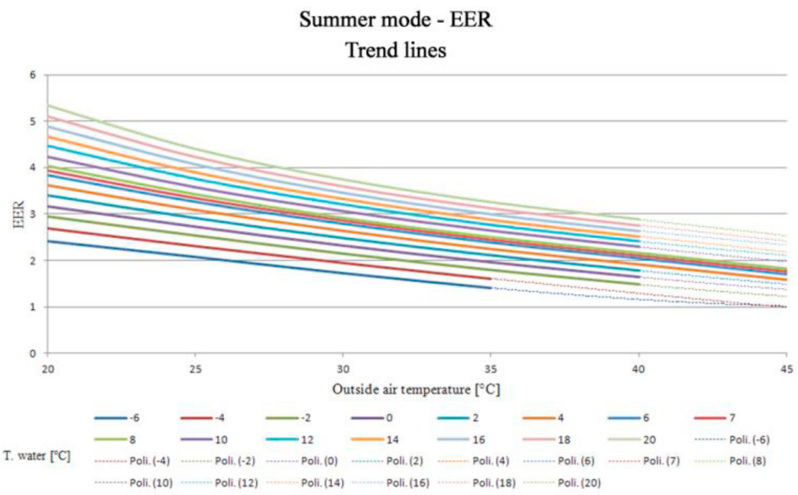

Fig.2. Cooling mode: trend of the EER as a function of outside air temperature and water temperature produced at the maximum frequency.

The geothermal system exploits the "free" heat from the ground. This study highlights the differences between the different burial depths considered. In particular, it has been noted that at one meter deep the temperature of the ground varies slightly in the transition from day to night, at 2.5 meters deep the annual temperature range is reduced by half and, at 7 meters of depth, the temperature is stable during the year.
The evaluations have been carried out for burial depth equal to 1, 2 and 3 meters and for low (1 W/mK) and average (2 W/mK) thermal conductivity of the ground.
About the HAGHE system, the airflow rate is related to the commercial fans (150 m^3/h, 250 m^3/h, 350 m^3/h and 450 m^3/h), the length of the pipe are 10 m, 20 m and 30 m, the diameter of the pipe fixed for each simulation is equal to 0.20 m.

3. Result analysis

To simplify and facilitate the analysis, the results have been divided for the summer and winter seasons and is described through the COP and EER trends.

Figure 3 shows the COP comparison, highlighting with red and blue colors the trend of the COP with and without HAGHE, respectively. The analysis focus on a thermal conductivity of the ground equal to 1 W/mK. The two columns of graphs point out the performances of the system considering the treated water temperature typical of radiant floors of 35°C and for fan coils of 55°C.

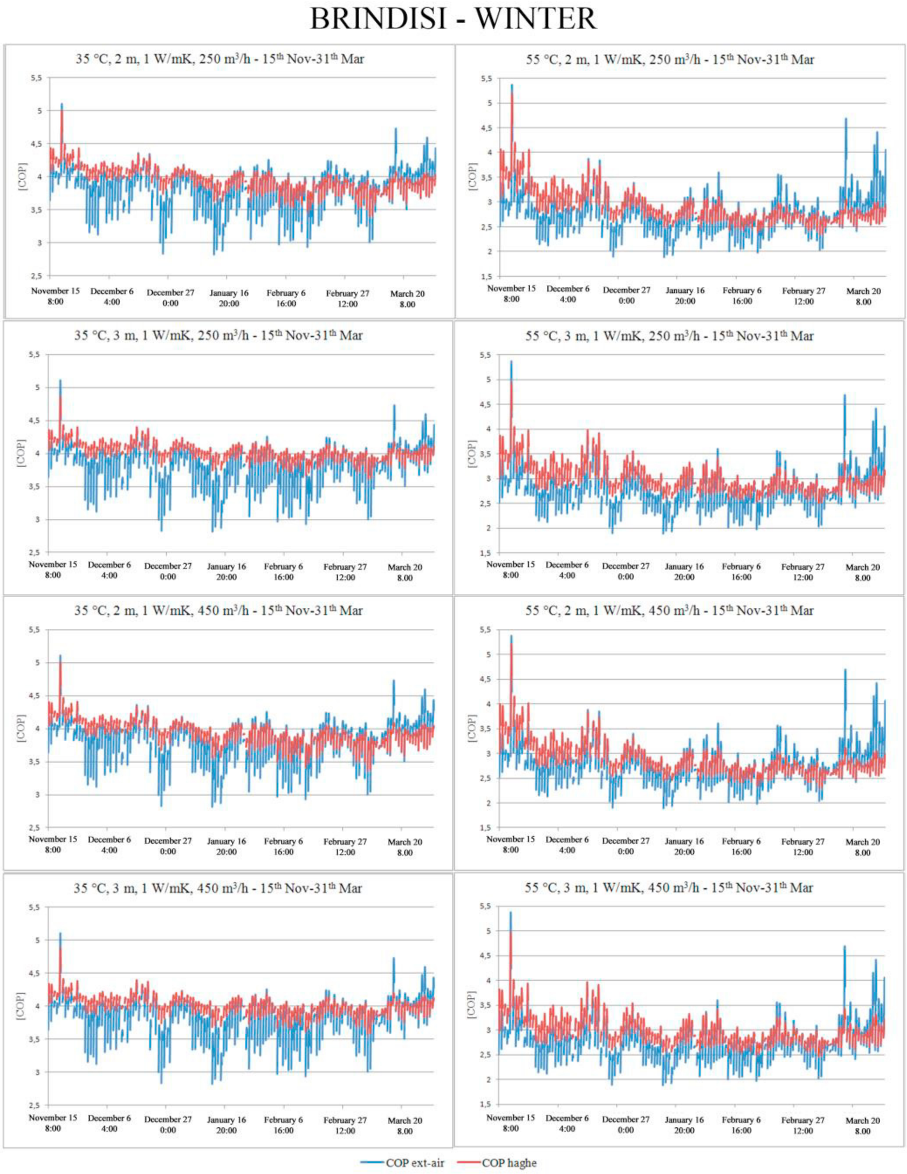

Fig.3. – Winter time, COP trends for a thermal conductivity of 1 W/mK.

Figure 4 shows the COP trends focusing on a thermal conductivity of the ground equal to 2 W/mK.

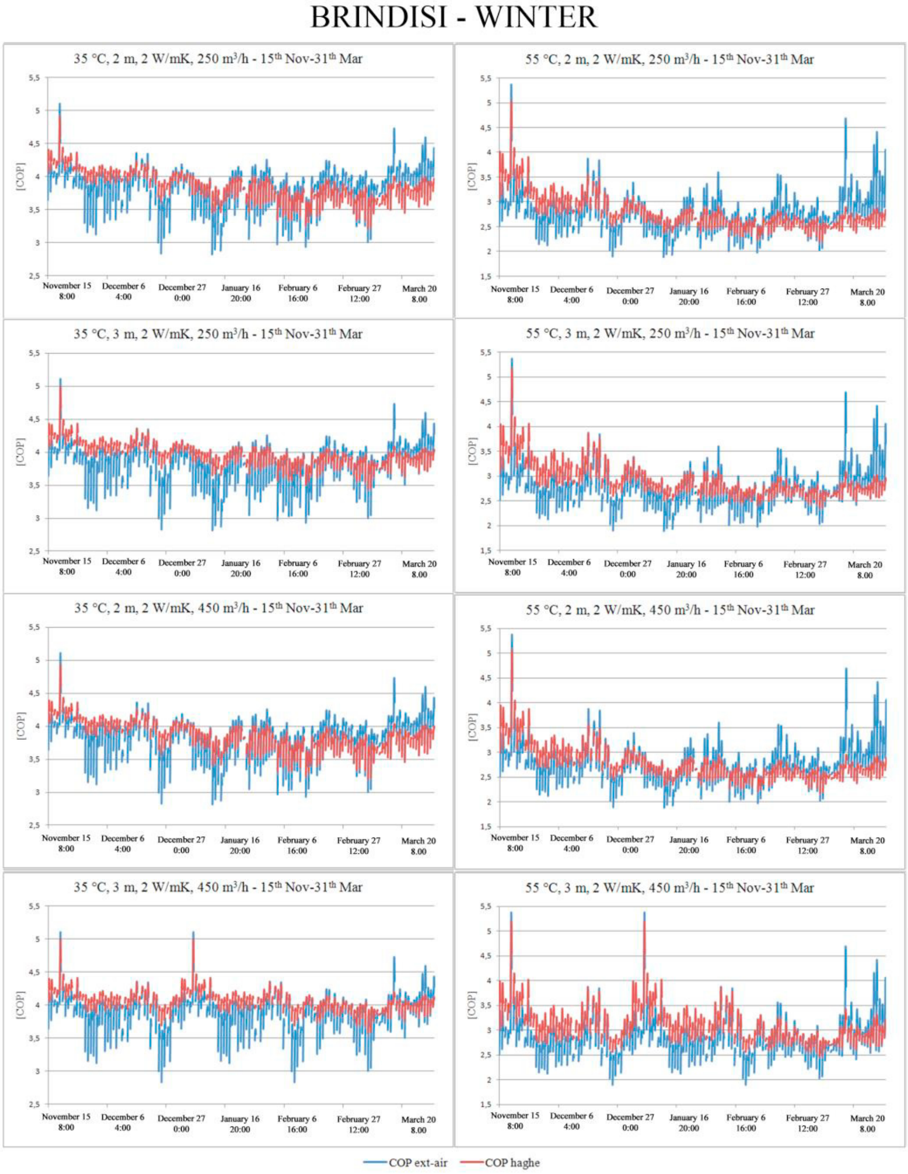

Figure 4 – Winter time, COP trends for a thermal conductivity of 2 W/mK

The combined system shows good results until February, then it loses the benefits and it is convenient to use the bypass in order to use the external air. Furthermore, providing water at 55 °C the improvement is even more evident compared to 35 °C, despite the COP is lower on average. The flow rate of air has little influence on the behavior of the system, therefore it is better to work with average high flow to reduce the number of probes. The thermal conductivity has a small influence on the behavior of the COP.
Figure 5 and Figure 6 show the summer performances of the ACHP-HAGHE system compared with a simple ACHP, which exchanges directly with the external air. The summer period ranges from 1 June to 31 August. In particular, the graphs underline that the combined system result always with higher EER values.
In the winter period, the data show the ability of HAGHE to preheat air. The best condition, in terms of temperature difference between the outside air and the air treated by the probe - in the winter period - is about 7 °C with a long

probe of 30 meters, the air inlet flow of 150 m^3/h and thermal conductivity equal to 1. Consequently, the COP of the pump has an increased peak of about 16% for water temperature of 55 ° C.

In the summer period, the simulations, relating to the probe operation, observed significant benefits. In this case the dependence on the thermal conductivity is more evident. For low conductivity values, the improvements are more evident, because the upper layer acts as insulation for the ground, protecting it from external conditions. For water temperature equal to 12 °C there is an improvement, compared to the system working for water temperature of 7 °C. In this case, the flow rate appears to have little impact compared to other parameters.

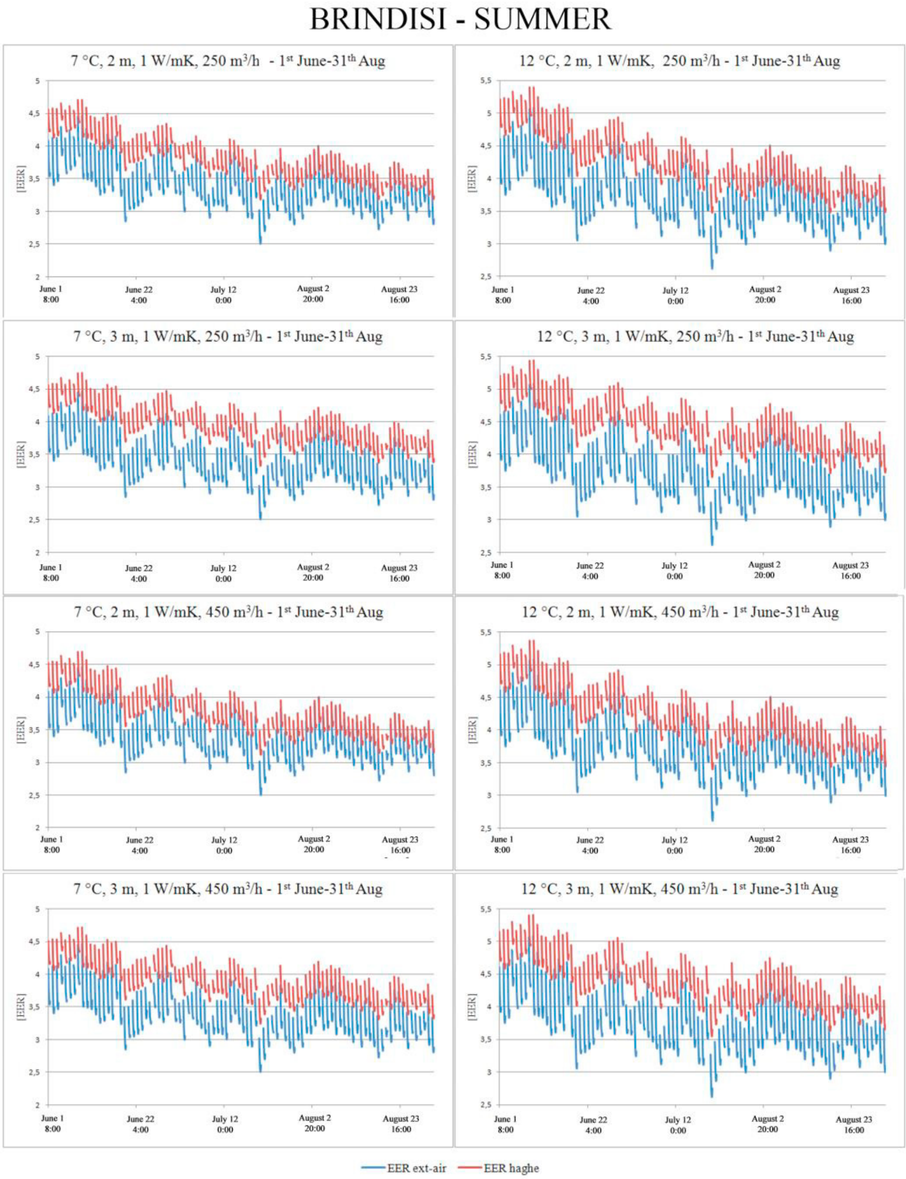

Fig.5.Summer time, EER trends for a thermal conductivity of 1 W/mK.

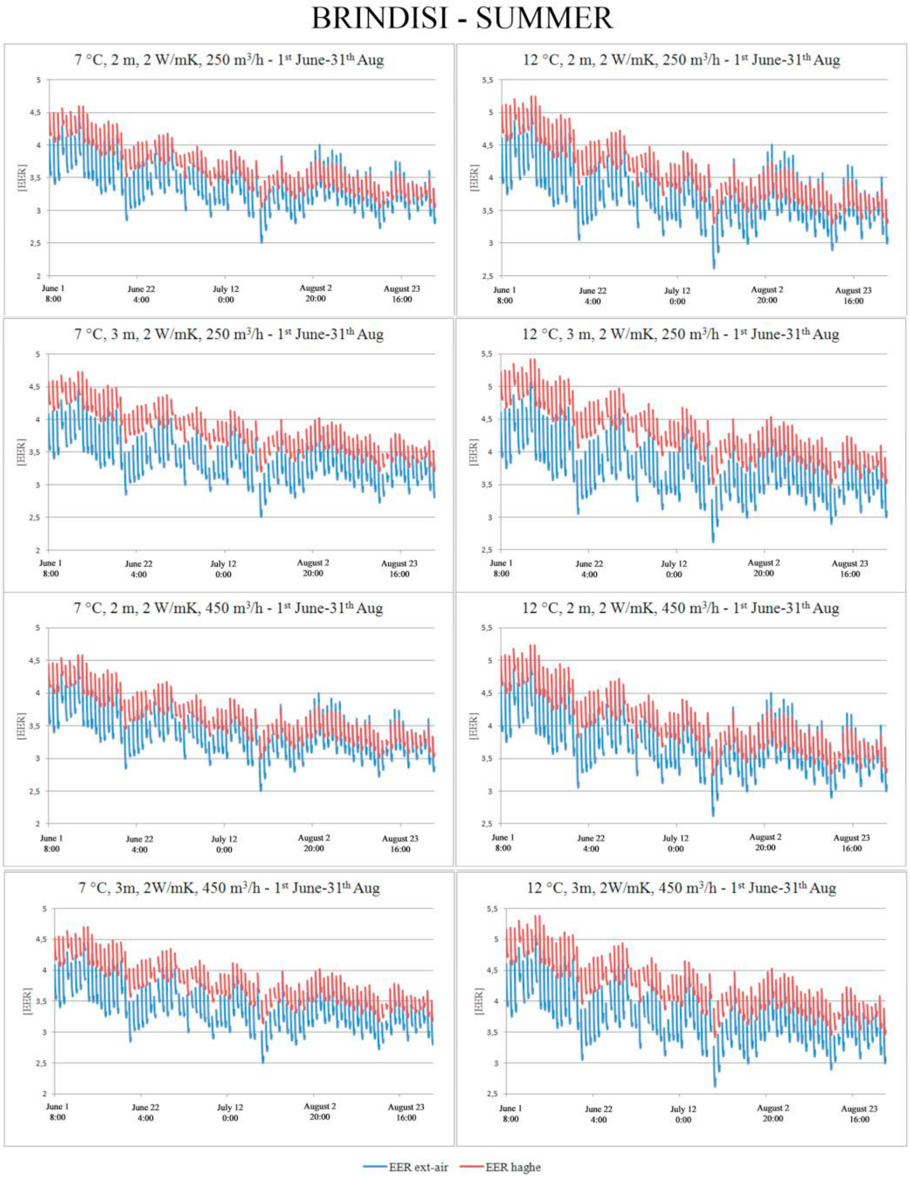

Fig.6. Summer time, EER trends for a thermal conductivity of 2 W/mK.

Table 1 and Table 2 summarize the average monthly values of the COP considering the ground thermal conductivity of 1 W/mK and 2 W/mK, respectively. The COP values for ground thermal conductivity of 1 W/mK are higher than those obtained for a ground thermal conductivity of 2 W/mK.

Table 1. COP values with ground thermal conductivity of 1 W/mK.

COP values for ground thermal conductivity of 1 W/mK								
Air flux Rate	250 m^3/h							
Burial depth	2m				3m			
Water temp.	35		55		35		55	
	EXT_AIR	ACHP - HAGHE	EXT_AIR	ACHP - HAGHE	EXT_AIR	ACHP - HAGHE	EXT_AIR	ACHP - HAGHE
Nov	4,022	4,254	3,037	3,567	4,022	4,222	3,037	3,484
Dec	3,861	4,082	2,794	3,113	3,861	4,110	2,794	3,183
Jan	3,773	3,943	2,685	2,831	3,773	4,020	2,685	2,967
Feb	3,807	3,851	2,707	2,705	3,807	3,968	2,707	2,857
Mar	3,964	3,854	2,950	2,710	3,964	3,973	2,950	2,867
Air flux Rate	450 m^3/h							
Nov	4,022	4,232	3,037	3,508	4,022	4,204	3,037	3,435
Dec	3,861	4,067	2,794	3,082	3,861	4,093	2,794	3,143
Jan	3,773	3,932	2,685	2,819	3,773	4,005	2,685	2,942
Feb	3,807	3,848	2,707	2,704	3,807	3,958	2,707	2,845
Mar	3,964	3,862	2,950	2,723	3,964	3,972	2,950	2,871

Table 2. COP values with ground thermal conductivity of 2 W/mK.

COP values for ground thermal conductivity of 2 W/mK								
Air flux rate	250 m^3/h							
Burial depth	2m				3m			
Water temp.	35		55		35		55	
	EXT_AIR	ACHP - HAGHE	EXT_AIR	ACHP - HAGHE	EXT_AIR	ACHP - HAGHE	EXT_AIR	ACHP - HAGHE
Nov	4,022	4,225	3,037	3,491	4,022	4,254	3,037	3,568
Dec	3,861	4,028	2,794	2,990	3,861	4,089	2,794	3,131
Jan	3,773	3,844	2,685	2,706	3,773	3,957	2,685	2,853
Feb	3,807	3,719	2,707	2,582	3,807	3,872	2,707	2,727
Mar	3,964	3,744	2,950	2,607	3,964	3,872	2,950	2,731
Air flux rate	450 m^3/h							
Nov	4,022	4,207	3,037	3,441	4,022	4,232	3,037	3,508
Dec	3,861	4,017	2,794	2,972	3,861	4,074	2,794	3,097
Jan	3,773	3,839	2,685	2,704	3,773	3,945	2,685	2,839
Feb	3,807	3,727	2,707	2,591	3,807	3,867	2,707	2,725
Mar	3,964	3,764	2,950	2,627	3,964	3,879	2,950	2,742

The ACHP-HAGHE system achieves high values of COP during the early months of the season. On the contrary, it is convenient to by-pass the HAGHE system when the external temperature begins to rise.
Table 3 and Table 4 show the trend of monthly average values of EER. As previously tested, with the pre-treatment through HAGHE, it is improved for low values of ground thermal conductivity and for high burial depth of the geothermal probe.

Table 3. EER values with ground thermal conductivity of 1 W/mK.

EER values for ground thermal conductivity of 1 W/mK								
Air flux rate	250 m^3/h							
Burial depth	2 m				3 m			
Water temp.	7		12		7		12	
	EXT_AIR	ACHP - HAGHE	EXT_AIR	ACHP - HAGHE	EXT_AIR	ACHP - HAGHE	EXT_AIR	ACHP - HAGHE
Jun	3,579	4,139	3,976	4,680	3,579	4,196	3,976	4,752
July	3,206	3,677	3,506	4,101	3,206	3,831	3,506	4,293
Aug	3,212	3,493	3,514	3,868	3,212	3,696	3,514	4,124
Air flux rate	450 m^3/h							
Jun	3,579	4,089	3,976	4,618	3,579	4,141	3,976	4,683
July	3,206	3,636	3,506	4,048	3,206	3,774	3,506	4,222
Aug	3,212	3,469	3,514	3,838	3,212	3,653	3,514	4,070

Table 4. EER values with ground thermal conductivity of 2 W/mK.

EER values for ground thermal conductivity of 2 W/mK								
Air flux rate	250 m^3/h							
Burial depth	2 m				3 m			
Water temp.	7		12		7		12	
	ext - air	ACHP - HAGHE	ext - air	ACHP - HAGHE	ext - air	ACHP - HAGHE	ext - air	ACHP - HAGHE
Jun	3,578657	4,019122	3,976197	4,529842	3,578657	4,154337	3,976197	4,69956
July	3,205506	3,514922	3,506256	3,89622	3,205506	3,704031	3,506256	4,134067
Aug	3,211918	3,325353	3,51442	3,657584	3,211918	3,523247	3,51442	3,906742
Air flux rate	450 m3/h							
Jun	3,579	3,981	3,976	4,482	3,579	4,103	3,976	4,635
July	3,206	3,488	3,506	3,863	3,206	3,660	3,506	4,078
Aug	3,212	3,316	3,514	3,646	3,212	3,496	3,514	3,873

4. Conclusions

Global Warming is one of the toughest challenges for the next future. The rising concern for this issue results in the need to reduce the greenhouse gases from energy consumption. On a global scale, the construction industry is amongst the most harmful. Nowadays, the design of Zero Energy Buildings (ZEBs) has become a challenge for designers, end-users and public authorities.

In Europe, EPBD (a guideline on buildings energy efficiency) encourages the reduction of energy consumption in the construction sector.

The present work outlines a series of measures and strategies for the definition of very high-energy performance buildings, focusing on a combined system of air-cooled heat pump (ACHP) coupled with a Horizontal Air-Ground Heat Exchanger (HAGHE). The proposed system seems to have lower emissions and energy consumption respect to a traditional air-cooled heat pump. The proposed innovation is to use HAGHE not for the ventilation air but for the air flux treatment before meeting the exchanger of an air-cooled heat pump; the heat pump works with colder and warmer air than outdoor air in summer and winter, respectively.

The analysis has been conducted on a case study located in a warm climate. The ACHP is for a medium/small building with residential or commercial uses. The study is a part of a large plan, which provides the application of the combined system for different climates.

Trnsys 17 has been used to evaluate several configurations, considering the conductivity of the ground, the flow rates and burial depth.

It has been noted that the treatment of cooling air using HAGHE leads an improvement of the heat pump efficiency for the entire summertime. During the winter-time, the COP rises by the higher output air values through the pipes compared with the external temperature of the air until December. From January to February there is a good performance during the cold hours of the day. In March, the use of HAGHE must be by-passed.

It is interesting to note that any defects in the assembly of the pipe can still allow its use functionality, in contrast to the pipes used for mechanical ventilation systems, which is crucial an adequate and precise positioning to avoid possible water stagnation. In particular, the presence of condensation leads improvement and benefits for the air-cooling.

This approach could be useful to support the development of Zero Energy Buildings and to reach the target of the national and international policies.

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