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ORIGINAL ARTICLE

Evaluation of ground source heat pump systems for residential buildings in warm Mediterranean regions: the example of Cyprus

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Abstract This paper presents a feasibility analysis for the installation of ground source heat pump systems in Cyprus. Two reference buildings, a single- and a multi-family one, are designed and analyzed using the EnergyPlus software, in order to calculate their energy needs for heating and cooling for the climate conditions of Cyprus, one of the warmest areas in Southern Europe. These energy needs are assumed to be covered by the conventional heating and cooling systems that are most widely used in Cyprus or alternatively by a ground source heat pump system, which consists of a vertical ground heat exchanger and water-to-water heat pumps and is analyzed using an in-house developed and validated code. Primary energy consumption and the resulting CO_2 emissions for both the conventional and the alternative systems are calculated and compared. Results show that the installation of the ground source heat pump system achieves in most cases substantial reductions in primary energy use for both types of buildings. As regards carbon emissions, the findings are less clear: Emissions of the geothermal system are higher than those of the conventional system for the single-family building but considerably lower for the multi-family one. From an economic perspective, the geothermal system compares favorably with the conventional systems in many cases, particularly for the multi-family building.

Keywords Ground source heat pump · Energy analysis · CO_2 emissions · Residential buildings · Economic analysis

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Introduction

The installation of ground source heat pump (GSHP) systems for space heating and cooling in residential and commercial buildings has become increasingly popular in the last decades due to their energy, environmental, and economic benefits. These systems have been categorized into three groups: (a) groundwater heat pump (GWHP) systems, (b) surface water heat pump (SWHP) systems, and (c) ground coupled heat pump (GCHP) systems (ASHRAE 2011). The GWHP and the SWHP systems exploit underground and surface water reservoirs, respectively, while the GCHP systems extract or reject heat into the ground via a ground heat exchanger (GHEx), a closed loop of high-density polyethylene pipe network, which is installed in vertical boreholes or in horizontal trenches (Yang et al. 2010; Sarbu and Sebarchievici 2014). The vertical GCHP systems are characterized by their higher efficiency and construction cost when compared with the horizontal ones (Congedo et al. 2012).

In the current study, vertical GCHP systems were analyzed. Previous studies on vertical closed systems focused mainly on (a) the comparison between these systems and other heat pump technologies such as air source heat pumps (e.g., Lohani and Schmit 2010; Urchueguía et al. 2008; Petit and Meyer 1998; Said et al. 2010; Liu and Hong 2010); (b) the energy, environmental, and techno-economic aspects of the conventional heating and cooling systems' substitution (e.g., Huchtemann and Müller 2012; Pardo and Thiel 2012; Boait et al. 2011; Shonder and Hughes 2006; Rodríguez et al. 2012); (c) the strategic design, controlling procedure, and the benefits of combined (e.g., Chen and Yang 2012; Xi et al. 2011; Wang et al. 2010; Pärisch et al. 2014; Rad et al. 2013) or hybrid systems (e.g., Pardo et al. 2010; Man et al. 2010; Yi et al. 2008; Yu et al. 2014; Alavy et al. 2013), systems which combine GCHP and other RES (e.g., solar panels, PV panels) or conventional (e.g., oil-fired boiler) technology; and (d) the overall design procedure of vertical GCHP systems in order to improve the efficiency and minimize the installation and operation costs taking into account the GHEx configuration, the geophysical properties of the materials and soil, as well as the climate conditions of the installing area (e.g., Robert and Gosselin 2014; Alalaimi et al. 2013; Chung and Choi 2012; Zanchini et al. 2010; Sanaye and Niroomand 2009; Luo et al. 2013). Urchueguía et al. (2008), for example, compared a vertical GCHP system and an air to water heat pump system for heating and cooling in typical conditions of the European Mediterranean coast. They concluded that during the heating season, the ground coupled heat pump system consumed in average 43 ± 17 % less primary energy than the alternative air source heat pump system. Moreover, it was found that the average primary energy savings in cooling season were in the range of 37 ± 18 % respectively. Yu et al. (2011) studied an air-conditioning system supported by a vertical GCHP system, 21 boreholes in the depth of 80 m, on an archive building in Shanghai. The archive building covered an 8000 m^2 air-conditioning area, and, based on the first year monitoring data, the GCHP system reduced the operating cost by 55.8 % compared with an air source heat pump (ASHP) system. They also reported that although the initial cost of GCHP system was 842.800 Yuan (~\$137.500) higher than that of the ASHP one, the payback time would be only 2 years.

Thygesen and Karlsson (2013) studied three solar-assisted GCHP systems, a combination of a PV system, and/or solar thermal system with GSHP, with regard to the economic feasibility and the energy (electricity) consumption. They reported that for the Swedish climate, the most profitable system is a ground source heat pump in conjunction with a PV system. Mokhtar et al. (2013) studied the application of an intelligent multi-agent control strategy on a combined GSHP and gas-fired boiler system. The intelligent strategy was provided by an artificial neural network agent, and the simulation results showed that there was a significant reduction on the energy used as well as an increase on GSHP usage, which resulted in a 23 % lower gas consumption and led to lower carbon emissions and greater energy cost savings.

Hackel and Pertzborn (2011) analyzed three hybrid GCHP systems, two cooling dominated and one heating dominated, for the climate conditions of Henderson NV, Las Vegas NV, and Madison WI. They found that the life cycle savings of the hybrid systems for a 20-year period ranged from \$22 to \$54/m^2 when compared to an autonomous GCHP system. Moreover, hybrid systems emitted 14–47 % less CO_2 than the conventional systems or 1 to 3 % more than the autonomous ones. However, the authors reported that for buildings with unbalanced energy needs between the heating and the cooling period, the hybrid systems were more cost effective than the autonomous or the conventional ones. Wang et al. (2012) studied a conjunction of a solar-assisted GSHP system and an autonomous GSHP one for space heating, cooling, and domestic hot water production on a university building in China. They reported that the performance of solar-assisted GSHP system was affected by the startup time (first time of operation), and based on the selected control strategy, the performance of the overall system could be increased between 0.3 and 0.5 % per year. Molinari et al. (2013) studied the influence of the roof's and external walls' insulation as well as the borehole spacing and length on the energy performance of GCHP systems in Stockholm and Madrid, respectively. They concluded that in both cases, the increase of the insulation decreased the electricity consumption of the GSHPs, but nevertheless in hot climates as Madrid's, it yielded an unbalanced energy need, which finally resulted in a lower performance factor for the heat pumps. They also reported that the effect of the borehole spacing on the electricity consumption was influenced by balanced or unbalanced energy need; in balanced energy need, the space between boreholes did not affect the electricity consumption, while in the unbalanced one, the more lengthy configurations were effective. The authors also found that the optimum borehole length was determined from trade-off between the electricity consumed by the circulation pump and the electricity consumed by the heat pumps. Madani et al. (2013) studied three control techniques called "constant hysteresis," "floating hysteresis," and "degree-minute" in order to control a GSHP system. They found that from the annual energy use point of view, the degree-minute and constant hysteresis methods had the lowest and highest annual energy use respectively, while floating hysteresis method leaded to an intermediate annual energy use.

The purpose of this study is to evaluate the energy, environmental, and economic benefits of the GSHP systems under the warm climate condition of Cyprus. The main objective is therefore to quantify the primary energy savings and the reduction of CO_2 emissions deriving from the substitution of the conventional heating and cooling systems with vertical GSHP systems in private households. Furthermore, the economic aspect of such a substitution was analyzed. Although the study is performed under the climate conditions and energy mixture characteristics of Cyprus, the results could be used in Mediterranean areas with similar characteristics, e.g., Malta and Crete. Within this context, emphasis is given on the performance and the benefits of the GSHP system in order to promote its wider application.

Description of the reference buildings

Within the context of the current study, it was considered necessary to establish reference buildings for the residential sector, which would represent the typical building geometry, structure, and operation, as well as the average standard of energy performance in the existing building block. Hence, two typical residential buildings of Cyprus were defined, a single-family and a multi-family one.

Single-family buildings have traditionally been popular in Cyprus, especially among high-income families. They are usually located in sub-urban areas and are surrounded by private grounds. The main building is developed in two levels, which are connected with an internal staircase. In the ground floor, Fig. 1, which is elevated from the ground, a spacious living room and a kitchen are located, while the upper floor, Fig. 2, accommodates the bedrooms and a lounge. In total, it covers an area of 210.6 and 116.7 m^2 for the ground floor and 93.9 m^2 for the upper floor, and taking into account that the floor to floor height is 3.0 m, the heated building volume results in 631.8 m^3. Windows are located on every façade of the building; the majority is positioned on the main façade, which is orientated due south. More specifically, southern windows account for the 40 % of the southern façade, whereas northern windows cover 16 % of the respective façade. Eastern and western transparent elements are substantially limited, occupying an area of 7 and 4 % of their facades.

The multi-family building comprises four storeys above the ground floor, which houses only the building entrance; the remaining space is used as an open circulating and parking space (pilotis). Each floor covers an area of 256 m^2, divided almost equally in three apartments (Fig. 3). The biggest apartment (80 m^2) is located at the rear of the building plan. The remaining two (74 m^2 each) have similar internal plan and are located along the main building façade, facing the street. The staircase (28 m^2) is located centrally on the building plan and is unheated. All apartments consist of two bedrooms, a living room with integrated kitchen and a bathroom. Each apartment has a balcony in front of the living room, projected 2.25 m from its external wall. With a storey height of 3.0 m, the total volume of the building is 3072 m^3 (256 $m^2 \times 3$ m $\times 4$), 2736 m^3 of which are heated. It is assumed that the examined building is free-standing; therefore, windows are placed on every façade. The main façade has a south orientation and almost 30 % of its area is covered with fenestration. The windows of the western and eastern façades are limited to 12.2 and 9.4 % of their respective area, while northern windows account for only 4.5 % of the façade's area.

In Cyprus, regardless of the building use and typology, the majority of new constructions is made of reinforced concrete with thermal insulation (usually XPS) positioned on the external side of the structure. The external masonry is made of hollow clay bricks with thermal insulation placed on the core of the wall. The building roofs are flat, thermally protected with expanded polystyrene, which lies above the water protection layer (bitumen layer) and is covered with gravels. The floor of the single-family is in contact with the ground, while the multi-family building is constructed above the open space of the pilotis. Both floors are insulated with expanded polystyrene below the concrete slab. The

Fig. 1 The ground floor plan of the typical single-family building in Cyprus

thermal insulation thickness and the resulting thermal transmittance of each building element were calculated in conformity with the recent building energy performance regulation of Cyprus (Table 1). Correspondingly, the U values of each window have been calculated analytically with regard to their geometry and configuration, assuming that the frame is made of PVC ($U_{fr}=2.80$ W/(m^2 K)) with an average width of 0.07 m and the glazing is double ($U_{gl}=2.80$ W/(m^2 K)). The linear thermal transmittance Ψ_g between the glazing and the frame is equal to 0.02 W/(m K). All windows comply with the current regulation for building energy performance, which sets a maximum value for thermal transmittance equal to 3.8 W/(m^2 K).

Besides the thermal transmittance of the opaque and the transparent building elements, the Cypriot regulation for building energy performance sets requirements for the average thermal transmittance of the vertical building elements (U_m). For the single- and the multi-family building, the average thermal transmittance of their

Fig. 2 The first floor plan of the typical single-family building in Cyprus

Fig. 3 The floor plan of the typical multi-family building in Cyprus

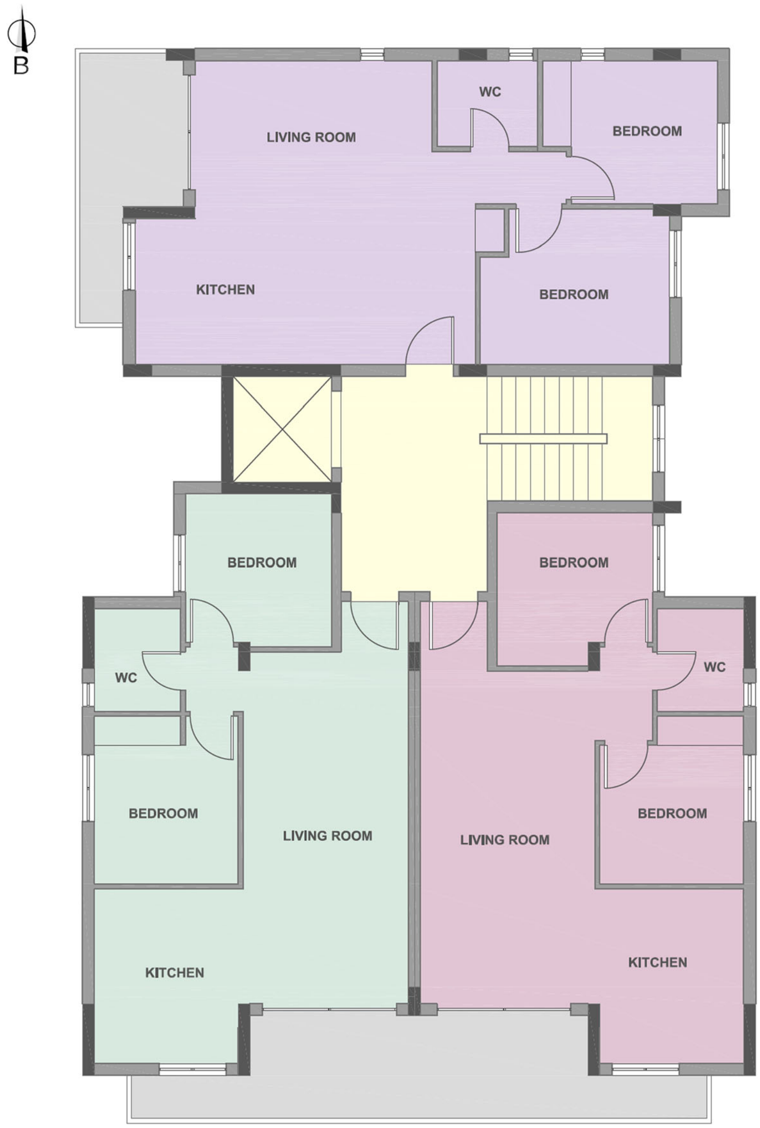

Table 1 The thermal transmittance of the building elements constituting the envelope of the reference buildings

Building element	Thermal transmittance *U* value W/(m^2 K)	Maximum thermal transmittance W/(m^2 K)
Vertical elements	Reinforced elements: 0.777, masonry: 0.689	0.85
Flat roof	0.610	0.75
Floor above ground	1.029	2.00
Floor above pilotis	0.667	0.75

façades was found equal to 1.0 and 0.937 W/(m^2 K), respectively; these values are lower than the maximum allowed level of 1.3 W/(m^2 K).

Definition of the design conditions and energy analysis parameters

Selection of the representative locations

Cyprus constitutes the southern part of Europe and covers an area of 9521 km^2. It lies between the latitudes 34.5° N to 35.8° N and between the longitudes 32.2° E to 34.6° E. The physical relief of the island is shaped by the mountain ranges of Troodos and Pentadaktylos, which occupy roughly 37 % of the island's area and reach the altitude of 1952 m. The main settlements of the island are located on the remaining lowland and coastline areas (Fé d'Ostiani 2004). The climate is characterized as Mediterranean, with mild wet winters, rainfall mainly between November and March, and very hot dry summers, separated by short autumn and spring seasons (Price et al. 1999).

In order to deliver results that reflect the local climatic conditions, five sites were selected to serve as representative locations of the reference buildings: the four main cities—Nicosia, Limassol, Larnaca, and Paphos—and the village of Saittas. Nicosia, the capital of the Cyprus Republic, is located at the center of the island and is characterized by warm and dry summers and mild winters. The cities of Limassol, Larnaca, and Paphos are located along the southern coastline and are characterized by a wet and hot climate. Saittas is a typical village of Troodos mountain and represents the mountainous climate of the island with cold winters and mild summers (Hadjinicolaou et al. 2011). These sites were regarded as representative of the local climate conditions, in the view of the fact that each one shared similar climate conditions with its broader region, covering thus the entire geographical area of the country. The availability of reliable weather datasets, containing typical meteorological year files and climatic design information, constituted an additional criterion for the selection of the representative locations, given that such information is critical for the assessment of building energy performance as well as for the design of the heating, cooling, ventilation, and air-conditioning (HVAC) equipment.

Design conditions and design heating and cooling loads of the reference buildings

The design heating and cooling loads for each building and representative location were calculated with the Elite Chvac® software (version 7.01.158). The input data included the geometrical characteristics and the thermophysical properties of the building components, as well as the required indoor conditions and the design climate conditions.

Information regarding the geometrical characteristics of the building components was derived from the architectural plans, whereas the thermophysical properties of the building elements are displayed in Table 1. The indoor design temperature was regarded equal to 22 °C for the heating period and 25 °C for the cooling one. The local climatic design conditions that were used in the calculations are presented in Table 2. For the cities of Larnaca (WHO# 176090) and Paphos (WHO# 176000), the required information was retrieved from the ASHRAE's climatic design information database (ASHRAE 2013). For the remaining three locations, the climatic design conditions were estimated on the basis of the available statistical records provided by the Cypriot Meteorological Service (CMS 2014), due to the absence of accurate design values both from national and international databases.

The heating and cooling loads calculated for the two reference buildings and on the five representative locations are presented in Table 3.

Energy analysis parameters

The energy needs for heating and cooling of the two reference buildings on the five representative locations were estimated using the EnergyPlus software. EnergyPlus is a dynamic simulation software which is widely used for the energy analysis of the building envelope and HVAC systems. It has been successfully tested under analytical tests conducted by ASHRAE, comparative tests, i.e., ANSI/ASHRAE standard 140-2011, IEA BESTEST, as well as released and executable tests. Moreover, its ability to introduce freely the simulation time step and the desirable indoor conditions justifies the characterization of EnergyPlus as one of the most appropriate software packages for building energy analysis.

The buildings were divided in thermal zones assuming that every space with a different usage constitutes a separate thermal zone. This assumption led to splitting

– The single-family building into 12 thermal zones and
– The multi-family building into 45 thermal zones (11 zones per floor and 1 unheated space).

For each thermal zone, the required values of the indoor comfort parameters, i.e., the air temperature during the winter and the summer months, the ventilation rates, the lighting level, the number of occupants, as well as the design power capacity of the electric equipment, were considered in line with ASHRAE

Table 2 The design climate conditions of the locations used in the analysis

	Larnaca	Limassol	Nicosia	Paphos	Saittas
Latitude/longitude	34° 52′/33° 37′	34° 41′/33° 03′	35° 09′/33° 24′	34° 43′/32° 28′	34° 52′/32° 55′
Elevation [m]	2	8	162	8	640
Indoor heating design temperature	22 °C				
Heating design dry bulb temperature	3.8 °C	5.8 °C	2.0 °C	4.8 °C	0.5 °C
Mean daily temperature in January	12.0 °C	13.2 °C	10.6 °C	12.5 °C	8.4 °C
Indoor cooling design conditions	25 °C/50 % RH				
Cooling design dry bulb (DB) and mean coincident wet bulb temperature (WB)	36.0 DB/23.2 WB	35.9 DB/23.3 WB	40 DB/26.3 WB	32.2 DB/26 WB	37.8 DB/19.9 WB
Mean daily temperature in summer	27.4 °C (August)	28.0 °C (August)	29.7 °C (July)	25.7 °C (August)	26.8 °C (July)

recommendations (ASHRAE 2013). The schedules of the aforementioned parameters on a daily, weekly, and monthly basis were also generated following ASHRAE suggestions. More specifically, the residential use of the typical buildings imposed their operation all around the year and for 24 h on a daily basis. However, it was assumed that the period between 23:00 and 6:00 is of reduced operation, during which the energy needs for heating, cooling, and lighting and equipment use are limited, whereas for the remaining period, the buildings are in normal operation. It is important to underline that these usage patterns are actually observed in the Cypriot buildings. The parameters that were used for the simulations in order to describe the profiles of the basic indoor parameters are presented in Table 4.

Besides the definition of the building envelope characteristics (geometry, construction materials, thermophysical properties) and the desirable indoor conditions, the climate and weather data prevailing on each location are required as input parameters for the energy simulation of the reference buildings. Within this context, the typical meteorological year (TMY-2) of the examined locations provided by the meteorological database of METEONORM (version 7.020) was used.

Table 3 The heating and cooling design loads

Single-family building		
Location	Heating design load [kW]	Cooling design load [kW]
Larnaca	9.5	8.7
Limassol	8.6	9.5
Nicosia	10.3	11.8
Paphos	9.0	9.5
Saittas	12.1	8.2
Multi-family building		
Larnaca	23.2	27.2
Limassol	20.7	31.0
Nicosia	25.5	35.8
Paphos	22.0	29.8
Saittas	27.3	23.8

Energy analysis of the reference buildings' envelope

The annual heating and cooling energy needs that have been calculated for the typical single-family building and the five representative locations of Cyprus are presented in Table 5. It is obvious that the cooling energy needs are substantially higher than the heating ones; the proportional difference ranges from 38 to 520 %, resulted for the city of Limassol and the mountainous region of Saittas, respectively. The highest cooling energy need is observed for the climate conditions of Nicosia (73.7 kWh/(m^2 a)), where an average continental climate prevails. The highest heating energy need has been derived for Saittas (32.9 kWh//(m^2 a)).

Similar trends are detected for the multi-family building (Table 5), though at different levels. The highest cooling energy needs have been calculated for the case of Nicosia (62.8 kWh/(m^2 a)) whereas the lowest for Saittas (42.8 kWh/(m^2 a)). The lowest heating needs have been derived when the building is located at Limassol (5.72 kWh/(m^2 a)), and the highest heating needs have been derived for Saittas (23.1 kWh/(m^2 a)).

It is worth mentioning that the significant differences among the energy needs calculated for the two reference buildings and the five examined locations are expected, and they are attributed to the variation of the climate characteristics prevailing in each location.

Table 4 The parameters of the usage schedules taken into account for the calculation of the energy needs for heating and cooling of the examined buildings

Operation period	24 h/day
Heating period	16 November–15 May
Desired temperature during normal/reduced operation for the heating period	22 °C/18 °C
Cooling period	16 May–15 November
Desired temperature during normal/reduced operation for the cooling period	25 °C/30 °C
Mean rate of air changes during normal/reduced operation	0.8 ach
Lighting levels	6 and 3.5 W/m^2 for WC only
Number of occupants	0 to 4 depending on the use of zone
Design power capacity	0 to 800 W depending on the use of zone

Design and simulation of the GSHP system

Design of the GSHP system

The design of the ground source heat pump system encompasses the dimensioning and selection of the heat pump, as well as the dimensioning of the vertical ground heat exchanger and the circulation pump for the ground heat exchanger loop.

The selection of the ground source heat pump was based on the heating and cooling loads presented in Table 3. It was assumed that the single- and multi-family buildings were equipped with high performance heat pumps with the characteristics presented in Table 5. The calculation of the required length of the vertical ground heat exchanger was performed for every reference building and each representative location using the EED software (version 3.16). The required length of the ground heat exchanger depends on the monthly heating and cooling energy use, the geometrical characteristics of the borehole, the number of U-tubes per borehole, as well as the thermophysical properties of the grouting material and the surrounding soil. For the present study, the monthly energy use of the typical buildings were calculated on the basis of the energy needs, retrieved from the EnergyPlus simulation, taking into account the efficiency of the emission and distribution system in accordance with the European Standards EN 15316-2-1 (EN 15316-2-1 2007) and EN 15316-2-3 (EN 15316-2-3 2007) (Table 5).

The vertical ground heat exchanger consists of a double U-tube high-density polyethylene pipes (HDPE—16 bar) per borehole. The borehole was assumed to be filled by a thermally enhanced grouting material, with a thermal conductivity of 2.4 W/(m K), in order to improve the thermal flux between the ground heat exchanger and the soil. The ground thermal properties of each location were reflected by the mean values of soil properties in line with the existing bibliography (Florides et al. 2011; Morgan 1973). The exact geometrical and thermophysical characteristics of the boreholes as well as the thermal properties of the ground are presented in Table 6.

Table 5 Annual energy needs for heating and cooling of the building envelope and electricity consumption of the GSHP system

Location	Annual energy needs of the building envelope [kWh/(m^2 a)]				Annual electricity consumption of the GSHP system [kWh/a]	
	Single-family		Multi-family		Single-family	Multi-family
	Heating	Cooling	Heating	Cooling		
Nicosia	12.2	73.7	9.8	62.7	4300	12,747
Larnaca	13.2	64.3	8.4	61.5	3795	12,065
Limassol	10.6	66.0	5.7	61.3	3795	11,584
Paphos	11.2	59.4	6.1	55.7	3492	10,573
Saittas	32.9	45.3	23.0	42.8	3787	11,348

Table 6 Description of the systems constituting the GSHP of the reference buildings

	Single-family building	Multi-family building
Heat pump	Design temperatures:	Design temperatures:
	0 °C/40–45 °C for winter—COP: 2.52 45 °C/7–12 °C for summer—EER: 2.16	0 °C/40–45 °C for winter—COP: 3.85 45 °C/7–12 °C for summer—EER: 3.6
Heat emitters	Fan coil Efficiency: 0.93	Fan coil Efficiency: 0.93
Distribution system	Dual pipe with adequate thermal protection Efficiency: 0.96	Dual pipe with adequate thermal protection Efficiency: 0.96

The total length of the ground heat exchanger as well as the borehole configuration for the typical buildings on five representative locations were selected after a 20-year analysis of the system operation, which was conducted by the EED 3.16 design software. For this purpose, the minimum and the maximum acceptable water temperatures in the outlet of the ground heat exchanger were set equal to 5 and 38 °C, respectively. The results for each reference building and location are presented in Table 7.

The selection of the circulation pump of the ground heat exchanger that is installed in every reference building and location (Table 8) was based on the pressure drop of the ground heat exchanger and the heat pump. More specifically, it was assumed that the boreholes are individually connected to a manifold and subsequently the thermal liquid (water) is distributed to the heat pump.

Simulation of the GSHP system

The simulation of the GSHP system aims at the calculation of the electricity that will be consumed by the system for covering the heating and cooling energy needs of the typical buildings in each examined location. During the operation of the ground source heat pump system, electricity is used by the heat pump and the circulation pump. The amount of electricity consumed by the heat pump was calculated using an in-house developed and validated code for the simulation of the vertical ground source heat pump systems (Michopoulos and Kyriakis 2009a, b). The electricity consumed by the circulation pump of each system was calculated with reference to the methodology for decentralized pumping systems proposed by Sfeir et al. (2005). The annual amount of electricity consumed by the ground source heat system of the typical single- and multi-family buildings at every examined location is presented in Table 5.

As regards the typical single-family building, the electricity consumption reaches its maximum when it is located at the city of Nicosia (4300 kWh annually) and its minimum in the case of Paphos (3492 kWh annually). For the remaining locations (Larnaca, Limassol, and Saittas), the electricity consumption ranges at similar levels.

In the case of the typical multi-family building, the maximum amount of electricity consumed by the GSHP system is observed for Nicosia (12,747 kWh annually), whereas the minimum derives for the region of Paphos (10,572 kWh annually).

Table 7 Main construction characteristics of the ground heat exchanger

Parameter	Value
Borehole diameter [mm]	150
Pipe diameter × thickness [mm]	Φ 32 × 2.9
Number of U-tubes per borehole [−]	2
Tube thermal conductivity [W/(m K)]	0.42
Grout conductivity [W/(m K)]	2.4
Grout heat capacity [MJ/(m^3 K)]	2.2
Ground conductivity [W/(m K)]	1.75
Ground heat capacity [MJ/(m^3 K)]	2.1

Table 8 The dimensions and characteristics of the ground heat exchanger estimated for the reference buildings and the representative locations

	Single-family house	Multi-family house
Location	Number of boreholes × length	
Nicosia	2 × 113 m	8 × 103 m
Larnaca	2 × 110 m	8 × 108 m
Limassol	2 × 108.5 m	8 × 110.5 m
Paphos	2 × 94 m	8 × 97 m
Saittas	3 × 78.5 m	7 × 91.5 m

Energy, environmental, and economic evaluation of the GSHP system

Energy evaluation

The energy performance of the GSHP system was evaluated by comparing the primary energy consumed by the system against the respective amount consumed in the case that conventional heating and cooling systems were installed. The conventional heating and cooling system corresponded to the ones that are most frequently employed in the Cypriot buildings: an oil- or LPG-fired boiler for space heating, as well as a split-type air-to-air heat pump for space cooling.

As regards the conventional heating system, it was assumed that the efficiency was equal to the minimum accepted one according to the European Directive 92/42/EC (EU 1992). More specifically, it was considered that the single-family house was equipped with a 10-kW boiler with an efficiency of 0.92 and the multi-family house was equipped with a 25-kW boiler with an efficiency of 0.925. Based on these efficiency rates and the calculated values of thermal energy use for each typical building and every representative location, the final energy consumption (delivered energy) was calculated. The primary energy consumption for the conventional heating system and for each case was determined from the final energy consumption, using the established national total primary energy factor (1.1 for both fuels (MCIT 2009)).

The split-type air-to-air heat pump, which was regarded as the conventional cooling system of the examined buildings, was selected according to the required cooling load of each thermal zone. More specifically, for the typical single- and multi-family buildings, two high-efficiency air-to-air heat pumps were selected (Table 6). The electricity consumption of the conventional cooling system was calculated on an hourly base using the cooling need of the reference buildings derived from EnergyPlus, the ambient air temperature retrieved from the Meteonorm files of the typical meteorological years, and the energy efficiency ratio (EER) of the heat pump resulted from the manufacturer's technical characteristics with reference to the ambient air temperature and the devices' loads (Toshiba 2010). Finally, the electricity consumption of the conventional cooling system, air-to-air heat pumps, was converted to primary energy consumption by using the established national total primary energy factor (2.7) for the Cypriot electricity production system (MCIT 2009).

By adding the primary energy consumption for covering the cooling and the heating needs, the overall primary energy consumption of the conventional system was calculated. The area-weighted values are presented in Fig. 4 for the typical single-family building and Fig. 5 for the typical multi-family building.

The primary energy that is consumed by the GSHP system was calculated on the basis of the electricity that is used by the system for every examined case and the total primary energy factor for the electricity that is adopted for the Cypriot energy system. The area-weighted values are also presented in Figs. 4 and 5 for the single- and the multi-family building, respectively.

From Fig. 4, it is depicted that for the single-family building, the primary energy consumption of the GSHP system is lower than the one derived for the conventional heating and cooling system for the locations of Nicosia, Larnaca, Paphos, and Saittas. The decrease of

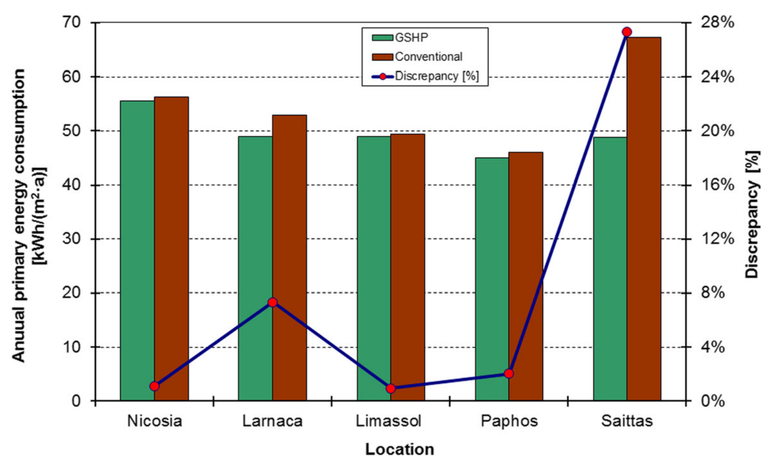

Fig. 4 The annual primary energy consumption of the GSHP and the conventional system for the single-family house

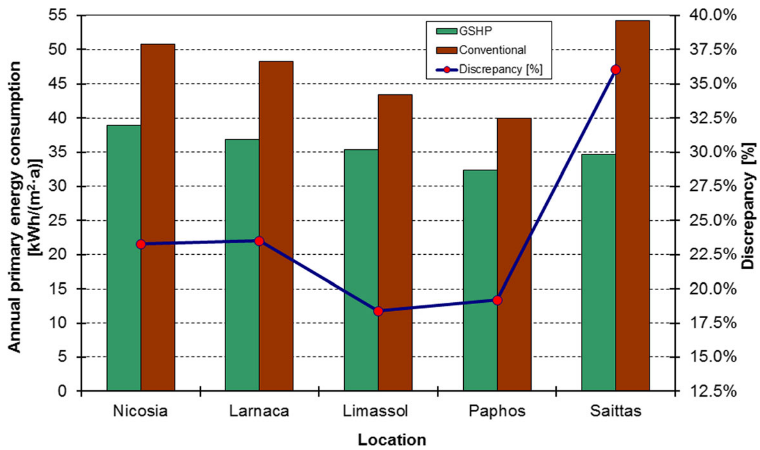

Fig. 5 The annual primary energy consumption of the GSHP and the conventional system for the multi-family house

primary energy consumption is higher for the northern and colder region, reaching 27.3 % in Saittas; conversely, in warmer regions, the improvement in primary energy use is marginal, around 1–2 %.

Figure 5 presents the annual primary energy consumption of the GSHP system and the conventional system calculated for the multi-family building and the examined locations. In all cases, the GSHP system appears to consume less primary energy, at a rate that ranges between 18.4% and 36.1 % for the regions of Limassol and Saittas, respectively.

Environmental evaluation

The environmental impact and the quantification of the benefits from the installation of GSHP systems in the residential buildings of a warm region, such as Cyprus, were assessed through the calculation of the CO_2 emissions produced by the GSHP system and the conventional ones. The CO_2 emissions were calculated on the basis of the primary energy consumption of the GSHP system, the conventional system using an oil-fired boiler and air-to-air heat pump (DI + ASHP), as well as the alternative conventional system using an LPG-fired boiler and air-to-air heat pump (LPG + ASHP) and the national carbon dioxide emission coefficients established for every fuel for the Cypriot energy system (Table 9). The results are presented in Figs. 6 and 7 for the single- and the multi-family building, respectively.

From Figs. 6 and 7, it is derived that the CO_2 emissions per heated/cooled area of the two alternative conventional systems (oil- or LPG-fired boiler for heating and a split-type air-to-air heat pump for cooling) are similar for both typical buildings (single- and multi-family buildings) and for all locations. On the contrary, there are significant differences between the CO_2 emissions per heated/cooled area that are produced by the GSHP system and the conventional ones. More specifically, in the single-family building, the CO_2 emissions of the GSHP system are always higher than the ones of the conventional system, at a rate that ranges between 16.0 and 24.1 %. This is different in the multi-family building; in this case, the CO_2 emissions of the GSHP system are considerably lower than the ones of the conventional systems, at a rate that ranges from 6.3 % for the Paphos region to 10.5 % for Larnaca. This pattern changes in the area of Saittas, since for the specific area, the GSHP system has up to 4.7 % lower CO_2 emissions when compared to the conventional ones.

Differences in emission reductions between the two building categories should be attributed to the different energy needs of each building. In general, the heating energy need of a building is strongly dependent of the ratio of the external envelope's surface (*A*) to total building volume (*V*), with the higher ratio accounting for the highest need (Al Anzi et al. 2009; Granadeiro et al. 2013; Enshen 2005). On the contrary, the cooling energy need of a building depends mainly on its cooling area and the façade characteristics (Depecker et al. 2001). For the present study, the façade characteristics of the single- and multi-family buildings are similar

Table 9 Carbon dioxide emission coefficients of Cypriot energy system (MCIT 2009)

Fuel	Electricity	Diesel oil	LPG
Emission coefficient [kgCO_2/kWh]	0.794	0.266	0.249

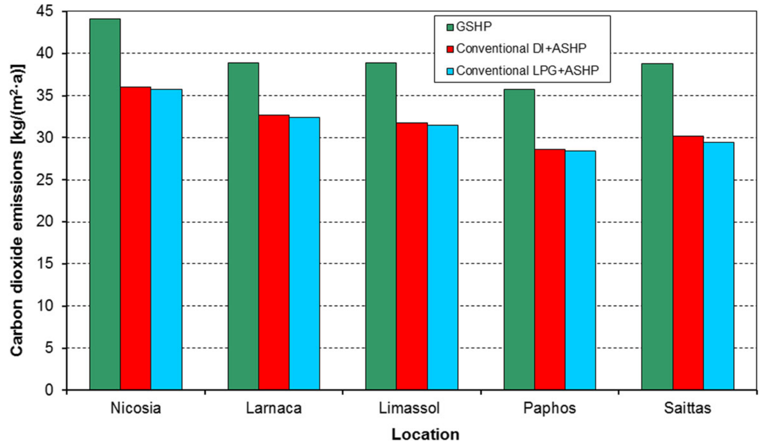

Fig. 6 The carbon dioxide emissions of the GSHP and the conventional system for the single-family house

(Table 1); as a result, the energy use per cooling area is similar for both buildings (Table 5), which leads to similar CO_2 emissions for the single- and multi-family building in cooling mode. Conversely as the reference single- and the multi-family buildings have an *A*/*V* ratio equal to 0.67 and 0.48 respectively, the energy use per heating area is significantly lower for the latter (Table 5), resulting in proportionally lower CO_2 emissions. Overall, this leads to a significant reduction of CO_2 emissions per heated/cooled area for the multi-family house when compared to the single-family one.

Coming to the difference in CO_2 emissions between GSHP and conventional systems illustrated in Figs. 6 and 7, these are partly due to the ratio of primary energy consumption of conventional systems to the primary energy consumption of GSHP: This ratio is 1:4.5 for the single-family building in all representative locations, while for the multi-family one, it is 1:7. In addition, it is also found that the ground source heat pump system introduces lower CO_2 emissions in cooling mode than the conventional air-to-air heat pump system, thanks to the higher seasonal energy efficiency ratio (1.1 to 1.4) which it achieves. These trends in combination with the CO_2 emission coefficients of heating oil, LPG, and electricity lead finally to a significantly different environmental behavior of the alternative systems in each case.

Economic evaluation

For the economic evaluation of residential GSHP systems in Cyprus, the net present value (NPV) of such investments was calculated in line with the methodology laid out in European Union's Regulation No. 244/2012/EU (EU 2012) and in the European Standard EN 15459 (EN 15459 2007) for an economic lifetime of 15 years. The initial construction cost of each system as well as the annual fuel and maintenance cost for each reference building and each site were determined on the basis of this methodology.

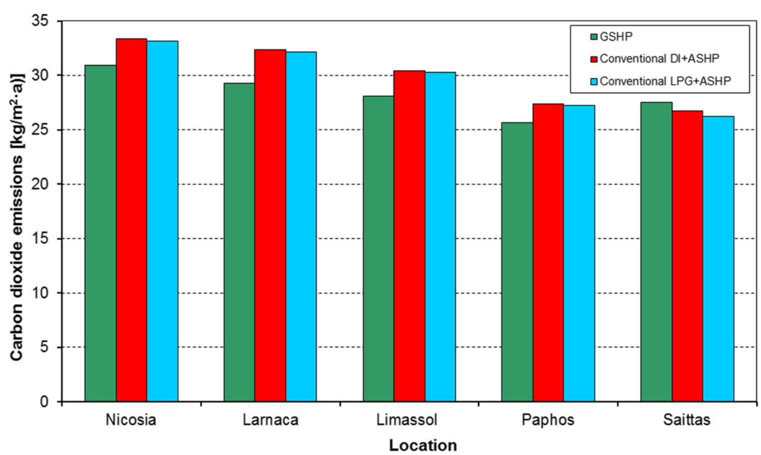

Fig. 7 The carbon dioxide emissions of the GSHP and the conventional system for the multi-family house

Table 10 Data used for the economic analysis

Single-family building		
Location	GSHP system [€]	Conventional system [€]
Nicosia	11,950	8500
Larnaca	11,300	7700
Limassol	11,700	7700
Paphos	11,000	7700
Saittas	10,000	7700
Multi-family building		
Location	GSHP system [€]	Conventional system [€]
Nicosia	30,000	14,700
Larnaca	31,000	14,700
Limassol	31,200	14,700
Paphos	28,900	14,700
Saittas	25,600	14,700
Annual preventive maintenance including operation, repair, and servicing costs in % of the initial investment (EN 15459 2007)		
Boiler	2 %	
Geothermal heat pump	4 %	
Air-to-air heat pump	4 %	
Fuel price		
Diesel [€/L]	1.0	
LPG [€/kg]	1.16	
Electricity [[€/kWh]	0.28	

As regards the building- and site-specific construction costs of the GSHP system and the conventional heating and cooling systems (with oil- or LPG-fired boiler and split-type air-to-air heat pump), cost data were obtained in spring 2013 through a market survey of firms specializing in the installation of such systems. For the estimation of annual fuel costs, the average annual fuel/electricity consumption obtained from the energy analysis of the buildings was combined with energy price forecasts that were recently carried out by one of the authors (Zachariadis and Michael 2013) with the aid of international energy price forecasts (IEA 2013). In line with standard EN 15459 (EN 15459 2007), annual maintenance costs were assumed to be equal to a fixed percentage of the initial installation cost of each system. Table 10 presents the data used for the economic analysis. The NPV of each alternative scenario was then calculated using 6 % as a real discount rate.

Figures 8 and 9 illustrate the NPV calculation results for the typical single-family and multi-family building, respectively. As Fig. 8 shows, GSHP systems are not the economically preferred investment in single-family buildings for the southern coastal cities of Limassol, Larnaca, and Paphos as their NPV is by 6.6–11.0 % (1645–2780 €) and 8.1–12.2 % (2020–3080 €) lower than that calculated for the conventional systems, DI + ASHP and LPG + ASHP, respectively. Conversely, the GSHP system turns out to be a particularly favorable solution in Saittas, with a NPV that is by 11.3 % (2720 €) and 7.5 % (1790 €) higher than the conventional alternatives. Finally, the conventional systems have lower NPV in the case of Nicosia (7.9 % or 2140 € and 9.2 % or 2490 €).

Results are slightly different in the case of the multi-family building. According to Fig. 9, GSHP systems are clearly preferred for Saittas as the NPV index is by 22.1 % (14,030 €) and 17.8 % (11,265 €) higher than the conventional DI + ASHP and LPG + ASHP systems, respectively. Furthermore, and in contrast to the single-family house, the GSHP systems are also financially favorable for the cities of Nicosia and Larnaca, where an economic benefit of 4.7 % (3350 €) and

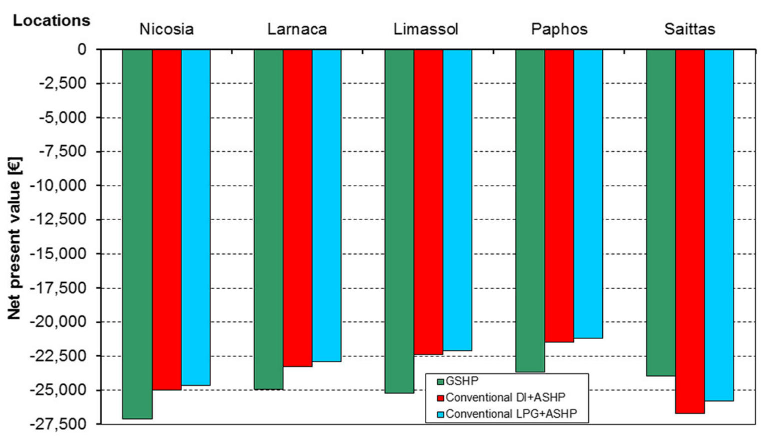

Fig. 8 Net present value of the GSHP and conventional system for the single-family house

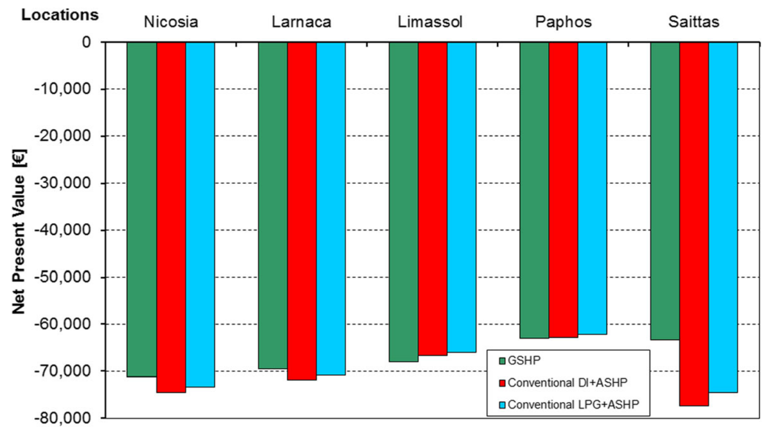

Fig. 9 Net present value of the GSHP and conventional system for the multi-family house

3.2 % (1220 €) can be achieved. Finally, the NPV indexes of the conventional systems are lower in Limassol and Paphos (0.3 % or 170 € to 3.1 % or 2130 €). Overall, the economic appraisal shows that GSHP systems are somewhat more favorable for a typical multi-family building in Cyprus than for a single-family one.

It is worth mentioning that these results are also influenced by the seasonal efficiency of the GSHP system which is expressed by the seasonal coefficient of performance (SCOP) and the seasonal energy efficiency ratio (SEER) for the heating and the cooling mode, respectively. It is found that the SCOP and SEER range between 4.0 and 4.5 and 5.0 and 5.5 for both buildings depending on the location of each installation. These efficiency values are common for GSHP installations and sufficiently high for the existing heat pump technology. Based on that, it can be deduced that the influence of the performance of the GSHP system on the economic analysis is limited.

Conclusions

This paper has presented a comparison between GSHP and conventional systems under the climate conditions of Cyprus using energy, environmental, and economic criteria. Two typical reference buildings, a single-family and a multi-family one, were simulated and analyzed for five representative locations in Cyprus. Results show that the GSHP can lead to substantial primary energy savings in residential buildings, which are more pronounced in multi-family buildings and relatively lower—or even marginal for some locations—for single-family buildings. Primary energy savings in hot and mild climates of Cyprus range between 1.0 and 7.3 % and 18.4 and 23.5 % for the single-family and the multi-family building, respectively. Even higher primary energy savings (up to 33.6 %) are attained in colder areas. For the specific buildings, climate conditions, and energy mix that were used in this study, the substitution of conventional heating and cooling systems with GSHP leads to a decrease of CO_2 emissions by 19.0 to 24.1 % in the single-family building and to mixed results in the multi-family building, ranging from an emission reduction of −4.7 % to an increase of 10.5 %. Highest CO_2 reductions are attained in the mild climate conditions of Nicosia, while the emissions' increase is calculated for the cold area of Saittas. Economic benefits are also dependent on the typology of each building. In the case of the multi-family building with the GSHP system, the 15-year NPV is higher than that of the conventional alternatives in the case of cold and mild climates as well as in a coastal city, indicating that the GSHP system becomes financially favorable, while in other coastal areas, conventional systems turn out to be preferable. For the single-family building, the GSHP system is financially favorable in cold areas only, while in all other climates, the conventional systems have lower overall costs.

The results obtained in this study illustrate that the residential building typology has a direct influence on the energy, environmental, and economic benefits of the ground source heat pump system. Buildings with a lower *A*/*V* ratio, e.g., the multi-family building, yield in general higher energy, environmental, and economic benefits than those with a higher *A*/*V* ratio such as the single-family building.

It should be emphasized that these findings are not easy to generalize for other countries or regions because they are associated with the specific characteristics of the energy system of Cyprus. However, since the two building typologies that have been studied in this paper are characteristic of the existing residential building stock of Cyprus and other Mediterranean regions, an interesting conclusion of this study is that the widespread installation of ground source heat pump systems may substantially reduce primary energy needs for space heating and cooling in Mediterranean climates. To enable such investments, modest financial support from public authorities is warranted, in order to compensate for the higher cost of GSHP compared to conventional systems.

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