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Analysis of Ground Source Heat Pump Systems in Residential Buildings

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ABSTRACT

The aim of this paper is to analyze the energy, environmental, and economic benefits of the installation of ground source heat pump systems in residential buildings in Cyprus. Two typical reference buildings, a single-family and a multi-family one, have been designed for this purpose and the heating and cooling energy demands are calculated with the aid of EnergyPlus software for five representative locations on an hourly basis. The results are translated in primary energy consumption assuming two different conventional systems for heating, an LPG- and an oil-fired boiler, as well as an air-to-air split type heat pump for cooling. The same energy demands are assumed to be covered by a ground source heat pump system, which consists of a vertical ground heat exchanger and water-to-water heat pumps. The ground source heat pump system is dimensioned with the aid of EED 3.16 software and analyzed using an in house developed and validated code; as a result the primary energy consumption is calculated. Furthermore and based on the primary energy consumption, the CO_2 emissions of the alternative systems are calculated and compared. Finally the financial analysis of the alternative systems is performed using the net present value index. The results prove that significant energy and economic benefits can be achieved by the substitution of conventional heating and cooling systems with geothermal heat pumps on the residential sector of Cyprus. Conversely, the environmental benefit is eliminated as the ground source heat pump systems emit more CO_2 than the alternative common ones.

1. INTRODUCTION

The ground source heat pump (GSHP) systems are widely recognized for the high energy efficiency and environmental benefits, Blum et al, (2010), Sivasakthivel et al, (2014). Due to their extended potential, these systems, autonomous or hybrid, are expected to increase their penetration in the building sector in the forthcoming years. In winter, GSHP systems absorb heat from the ground and produce space heating and/or domestic hot water in commercial and residential buildings. Conversely, in summer the GSHP systems use the ground as a heat sink and reject heat in order to provide space cooling. Based on the fact that the ground has higher temperature than the air in winter and lower temperature in summer, GSHP systems achieve higher efficiency, expressed in terms of Seasonal Coefficient of Performance (SCOP) and Seasonal Energy Efficiency Ratio (SEER), than that of the alternative air source one. In latest years many studies focused on the analysis of the energy performance and environmental benefits of the GSHP systems. These studies can be categorized in two categories. The first category includes studies which present the results of the existing installations in different climate conditions, e.g. Yu et al. (2011), Vanhoudt et al. (2011), Michopoulos et al. (2013), Luo et al. (2015). In second category there are studies in areas or countries in which the installation of the GSHP is limited, resulting in lack of real operation data, and there are primarily based on the analysis of simulation results, e.g. Man et al. (2008), Jenkins et al. (2009), Lohani and Schmidt (2010). In both cases these studies provide useful information for the behaviour of these systems, not only for the research community but also for the local stakeholders, as well as for the designers that could be used in order to develop local energy action plans or to adapt and improve the design practice.

In Cyprus the design experience, as well as the installations of GSHP systems remain limited. It is estimated that in early 2014 160 systems were in operation. There were 151 closed loop vertical systems, accounting for 123.5 km of vertical ground heat exchangers (GHEx), 3 closed loop horizontal systems or 3.7 km horizontal GHEx, 2 open loop systems and 4 gross systems combining vertical and horizontal loops or vertical GHEx and open loop system. The majority of the installed systems are found in residential buildings, mainly in single-family houses, while there are 3 in hotels, 4 in office buildings, 2 in multi-space buildings, one in a private school and one in a clinic, which are also using the aforementioned technology for space heating and cooling. Moreover, the installed thermal capacity of the GSHP systems' is estimated to be about 9.5 MW_{th}. Although the oldest known installation is in operation from 2006, there is insufficient information concerning their energy efficiency, working conditions and overall behavior.

The aim of this study is to evaluate the energy performance, the environmental benefits, as well as the economic impact derived by the application of the GSHP systems in residential buildings of Cyprus. For this reason two reference freestanding and detached buildings, a single-family and a multi-family one that represent the existing construction practice and building typology of Cyprus are designed and simulated under the climate conditions of the island. It is assumed that these buildings fully cover their heating and cooling demand with a vertical GSHP system, as well as with the common conventional heating and cooling systems. Then the seasonal energy performance of the GSHP system as well as the primary energy consumption and the CO_2 emissions of both alternatives are calculated and compared in order to assess their behavior. Moreover, the net present value (NPV) for each alternative system has been also calculated and compared over its lifetime period. It is expected that the presented results should be interesting not only for Cyprus, but also for the neighboring regions and countries with similar climate conditions, in order to disseminate the benefits of the wider application of the GSHP technology.

2. ANALYSIS OF THE REFERENCE AREA

2.1 Climate conditions

Cyprus is the third largest island in the Mediterranean Sea, both in terms of area and population. It is located at the eastern part of the Mediterranean, extending between 34° and 36°N in latitude and between 32° and 35°E in longitude. The physical relief of the island is dominated by the Troodos Mountains, which cover most of the southern and western portions of the island.

In general the climate is regarded as intense Mediterranean, with hot dry summers and mild winters, separated by short intermediate periods. However, due to the changes in geographical relief, there are considerable differences on the local climatic conditions across the island. Within this context, 5 locations were selected as the most representative of the local climate conditions: the capital Nicosia, located at the center of the island with warm and dry summers and mild winters; the cities of Limassol, Larnaca and Pathos, located along the southern coastline, with hot summers and wet mild winters; the village Saittas, located on the mountainous area of Troodos, with cold winters and mild summers.

2.2 Description of the Cypriot building stock

The dwelling stock of Cyprus exceeds 420.000 units, 67.2% of which are located in urban areas, Cypriot Statistical Service (2013). Almost 80% of the recent constructions are single-family buildings, while the remaining are equally divided to semi-detached and multi-family buildings. In average, the single family buildings cover a surface between 150 m² and 260 m² and have an average number of 3 bedrooms. The vast majority of the apartments encompassed in multi-family buildings have 2 or more bedrooms and an average area of 130.8 m².

2.3 Reference buildings

For the purposes of this study, reference buildings were established on the basis of information retrieved from the Cypriot Statistical Service (2013). The buildings encompass the typical characteristics of recent constructions as regards the geometry (i.e. surface), the number of rooms, the number of floors, the type of heating and cooling systems, etc. Other typological characteristics, e.g. regarding the size of windows, the existence of balconies, the type of roofs, etc. were defined with the help of Cypriot engineers and developers.

The majority of buildings in Cyprus are made of reinforced concrete for the structural elements and hollow bricks for the external and internal masonries. It is assumed that both reference buildings comply with the Cypriot regulation on building energy performance. The vertical opaque building elements are thermally insulated with extruded polystyrene positioned on their external side. The roofs are flat, with the thermal insulation being positioned above the water protection layer. The floors above the external environment (i.e. ground, air) are also insulated with extruded polystyrene positioned below the concrete slab. The thermal transmittance of each building element was calculated in accordance with the Cypriot regulation on thermal protection and is presented in Table 1. Accordingly, the thermal transmittance of each transparent element was calculated, taking into account a PVC frame (U_f = 2.80 W/(m² K)) and double glazing (U_{gl} = 2.80 W/(m² K)).

2.3.1 Single-family building

The typical single family building is two-storey and covers a total area of about 205 m² (Figure 1). The ground floor, which is practically at the ground level, has an area of 104 m² and houses the dining- and the living room, the kitchen and a study. An internal staircase leads to the upper floor, which covers a reduced surface (97.8 m²) and accommodates three bedrooms and a sitting area. The windows account for approximately 15% of the total area of the building's façade; the majority (70%) is positioned on the southern façade and approximately 22% is orientated due north.

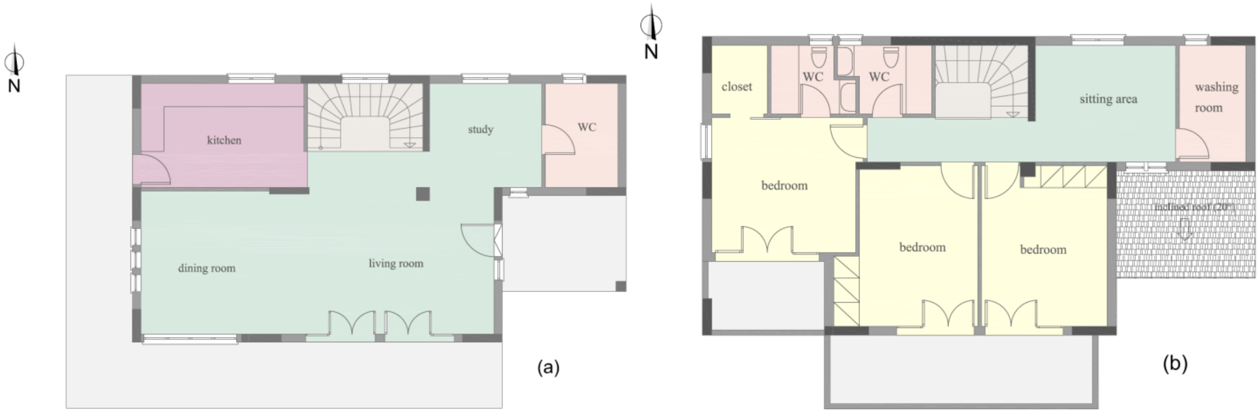

Figure 1: The architectural floor plan of the typical single-family house: (a) ground floor, (b) upper floor

2.3.2 Multi-family building

The reference multi-family building comprises of 4 storeys above the ground floor, which is basically used as an open parking space. Each floor, the plan of which is presented in Figure 2, covers an area of 247.9 m² and houses two apartments, 113.3 m² each, and the central staircase. The apartments consist of three bedrooms, an office, a living room and a kitchen. A balcony extends along the southern façade of each apartment, which hosts the highest share of transparent elements (60%). In average, the windows account for the 17% of the building facades.

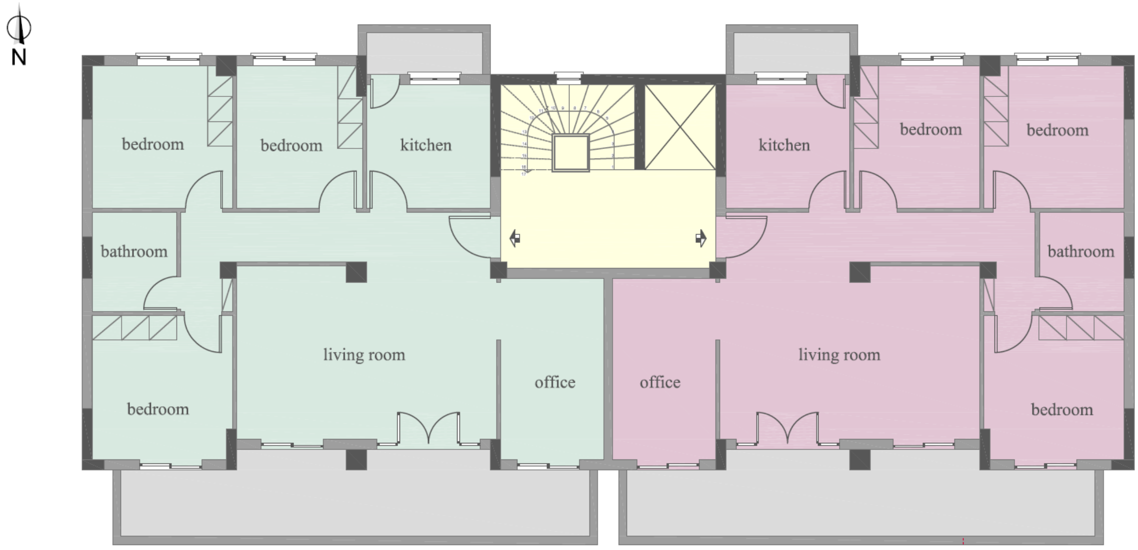

Figure 2: The architectural floor plan of the typical multi-family house

Table 1. The thermal transmittance of the building elements

Building Element	Thermal transmittance	Maximum thermal transmittance value
Masonry	0.691 W/(m^2·K)	0.72 W/(m^2·K)
Reinforced concrete	0.586 W/(m^2·K)	0.72 W/(m^2·K)
Flat roof	0.61 W/(m^2·K)	0.63 W/(m^2·K)
Floor above ground	0.766 W/(m^2·K)	2.0 W/(m^2·K)
Floor above pilotis	0.591 W/(m^2·K)	0.63 W/(m^2·K)

3. METHODOLOGIES FOR DESIGN, SIMULATION AND ANALYSIS

3.1 Buildings envelope

The energy analysis of the reference building envelopes' was performed with the aid of the EnergyPlus software, using the typical meteorological year (TMY-2) provided by Meteonorm database. In order to estimate the annual heating and cooling demand the single-family and the multi-family building has been divided into 11 and 64 independent thermal zones respectively, according to their usage and orientation. In addition the appropriate indoor conditions in each thermal zone have been applied in an hourly basis taking into account the usage of the zone as well as the ASHRAE's recommendations, ASHRAE (2013), and EN 15251:2007, EN 15251 (2007). In Table 2 the parameters used in energy analysis of the building envelopes' are presented.

Table 2. Energy analysis parameters

Parameter	Value
Operation period	24-h per day
Heating period	16/11-15/05
Winter indoor temperature	22°C [07:00-21:00] /20°C [22:00-06:00]
Cooling period	16/05-15/11
Summer indoor temperature	25°C [07:00-21:00]/27°C [22:00-06:00]
Air changes	0.8 ach [1:00-24:00]
Lighting power	6 W/m^2, 3.5 W/m^2 in WC
Number of occupants	0 to 2 depending on the zone's use
Equipment capacity	0 to 700 W depending on the zone's use

In Figure 3a and 3b the annual heating and cooling energy demand of the reference single-family and the multi-family building is presented for the five representative locations of Cyprus. Obviously, the annual cooling demand is higher than heating one in every building type, as this study is focused in one of the hottest areas of the Southern Europe. According to these findings the annual heating and cooling demand per square meter is higher for the single-family building than the multi-family one. This is due to the fact that the building energy demand is directly affected by the ratio of the external envelope's surface (A) to total building volume (V), which is higher for the single-family building (0.79) than the multi-family one (0.47). More specifically, the results for the reference single-family building show that the highest cooling energy demand is observed in the area of Nicosia (94.9 kWh/m^2/a), while the lowest one has been derived for Saittas (60.4 kWh/m^2/a), which are located in the central lowland and mountainous area's of the island respectively. Conversely, the highest and the lowest annual heating demand occur for the mountainous area of Saittas, 47.5 kWh/m^2/a, and for the southern coastal area of Limassol, 17.8 kWh/m^2/a, respectively. This trend is also observed in the case of the reference multi-family building. As it can be retrieved from figure 3b, the highest annual heating and cooling energy demand is resulted for the areas of Saittas and Nicosia with 25.7 kWh/m^2/a and 83 kWh/m^2/a respectively, while the lowest energy demand occurs in Limassol and Saittas. It is worth mentioning that the ratio between the heating and cooling energy demand for the typical buildings ranges from 1:1.3 to 1:5 and 1:2.2 to 1:8.5 respectively.

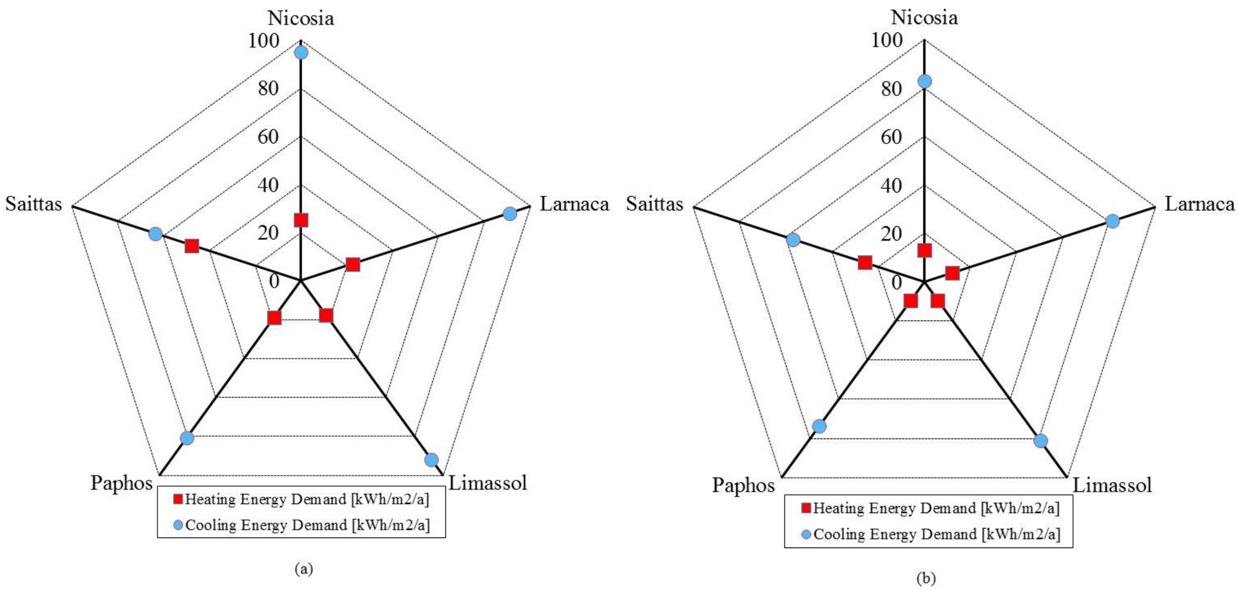

Figure 3: Annual energy demand of the reference buildings: (a) single-family (b) multi-family

Table 3. Specifications of the GSHP system

Component	Specification	
	Single-family house	Multi-family house
Heat pump	Manufacture: WaterFurnace International, Inc. Model: Envision NSKW 12 Heating capacity: 14.1 kW (10°C/40°C) Cooling capacity: 12.1 kW (40°C/10°C)	Manufacture: Rhoss Spa Model: THHEY 240 Heating capacity: 50.5 kW (10°C/40°C) Cooling capacity: 37.5 kW (40°C/10°C)
Water circulating pump	Manufacture: Wilo AG Model: Stratos 25/1-8 Power: 9 – 130 W	Manufacture: Wilo AG Model: Stratos 25/1-12 Power: 12 – 310 W
Borehole	Diameter: 150 mm Number of U-tubes: 2	Diameter: 150 mm Number of U-tubes: 2
Pipe	Material: HDPE – 16 bar Pipe diameter: Φ 32 mm Thickness: 2.9 mm Thermal conductivity: 0.42 W/(m·K)	Material: HDPE – 16 bar Pipe diameter: Φ 32 mm Thickness: 2.9 mm Thermal conductivity: 0.42 W/(m·K)
Grout	Manufacture: Fischer Type: GeoSolid 240 Thermal conductivity:2.4 W/(m·K) Heat capacity: 2.2 MJ/(m^3·K)	Manufacture: Fischer Type: GeoSolid 240 Conductivity:2.4 W/(m·K) Heat capacity: 2.2 MJ/(m^3·K)
Soil	Thermal conductivity:1.75 W/(m·K) Heat capacity: 2.1 MJ/(m^3·K)	Thermal conductivity:1.75 W/(m·K) Heat capacity: 2.1 MJ/(m^3·K)

3.2 GSHP system

The design of the GSHP system involves the selection and dimensioning of the GSHP, the circulation pump, as well as the dimensioning of the vertical GHEx. The selection of the GSHP was based on the design heating and cooling loads of the building envelope which have been calculated according to EN 12831:2004, EN 12831 (2004), and CLTD/CLF method, proposed by ASHRAE, ASHRAE (2013). The dimensioning of the vertical GHEx was performed for each reference building and representative location with the aid of EED 3.16 software. The calculation of the required GHEx length was performed using the monthly heating and cooling energy demand on each building and location, which has been obtained from the results of the energy analysis of the building envelope as it is described previously. Moreover it has been assumed that the maximum and minimum water temperature in the GHEx loop should be vary between 5°C and 38°C, and based on the specifications of the borehole, pipe, grout and soil presented in Table 3, the required GHEx length and bore-field configuration has been elected after a twenty years simulation and optimization with EED software. The specifications of the GHEx for the reference buildings are shown in Table 4.

Table 4. Specifications of the ground heat exchanger

Location	Specification	
	Single-family house	Multi-family house
Nicosia	Length: 260 m Configuration: L 2 x 2	Length: 1062 m Configuration: line 1 x 9
Larnaca	Length: 268 m Configuration: L 2 x 2	Length: 1125 m Configuration: line 1 x 10
Limassol	Length: 256 m Configuration: L 2 x 2	Length: 1080 m Configuration: line 1 x 9
Paphos	Length: 208 m Configuration: L 2 x 2	Length: 896 m Configuration: line 1 x 8
Saittas	Length: 150 m Configuration: line 1 x 3	Length: 590 m Configuration: line 1 x 5

The simulation of the GSHP system, aiming at the calculation of the electricity consumption of the GSHPs, was performed using an in-house developed and validated algorithm, Michopoulos and Kyriakis (2009). Moreover, the electricity consumption of the circulation pump in the bore-field loop has been calculated according to the methodology for decentralized pumping systems proposed by Sfeir et al. (2005), and finally the overall electricity consumption of the primary loop of GSHP system was calculated.

As illustrated in Figure 4 the annual electricity consumption per square meter is always higher in the case of the single-family building. More specifically, the electricity consumption varies between 65.7 $kWh_{el}/m^2/a$ and 78.3 $kWh_{el}/m^2/a$, and from 45.5 $kWh_{el}/m^2/a$ to 52.4 $kWh_{el}/m^2/a$, for the reference single-family and multi-family building, respectively.

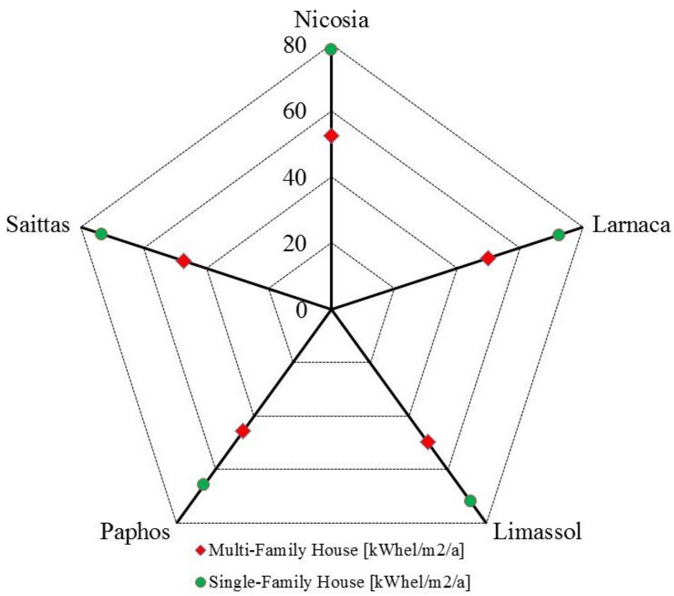

Figure 4: Annual electricity consumption of the ground source heat pump system

4. RESULTS AND DISCUSSION

4.1 Seasonal performance of GSHP system

The energy performance evaluation of a heat pump system is primarily based on the seasonal coefficient of performance (SCOP) and seasonal energy efficiency ratio (SEER) factors. These factors quantify the efficiency of the system in a long-term operation. As it is presented in Table 5 the SCOP of the studied reference buildings is in the range of 5.00 to 4.54 and 6.00 to 5.38 for the single-family and multi-family building, respectively. It should be noticed that these values have been calculated over a 20-year simulation period of the GSHP systems operation. At the same period the SEER is slightly decreased compared to the SCOP, and ranges between 4.75 to 4.61 and 5.64 to 5.33 respectively. It is worth mentioning that the differences between the results of the single-family building and the multi-family one are strongly affected by the efficiency performance level of the heat pump. Obviously and taking into account this interaction, these results should not be generalized as typical performances of the GSHP systems in the examined region, but illustrates the potential capacity of the examining technology utilization under the proposed building typologies and climate conditions. Similar results were also obtained from the real time monitoring of the existing GSHP system performance in the broader climatic area, e.g. Michopoulos et. al. (2013).

Table 5. The seasonal performance factors of the GSHP system

Location	Single-family house		Multi-family house	
	SCOP	SEER	SCOP	SEER
Nicosia	4.93	4.66	5.98	5.52
Larnaca	4.95	4.75	6.00	5.64
Limassol	5.00	4.63	6.09	5.51
Paphos	4.87	4.61	5.88	5.53
Saittas	4.54	4.72	5.38	5.33

4.2 Energy analysis

The energy saving potential of the GSHP system has been estimated by comparing its primary energy consumption with the corresponding consumption of the conventional system which is widely used in the residential buildings of Cyprus. Based on the up to date country's review, the common heating and cooling system in residential sector is an oil- or LPG-fired boiler and an air-to-air spilt type heat pump, e.g. Kitsios and Zachariadis, (2012). The primary energy consumption of the conventional boiler system has been calculated from the annual heating energy demand of the reference buildings in each location assuming the minimum efficiency of the oil- or LPG-fired boiler (0.92), according to the European directive 92/42/EC, European Union (1992), and the country-specific conversion factor into primary energy (1.1 for both fuels).

The primary energy consumption of the conventional cooling system was retrieved from the simulation of the air-to-air heat pump operation in an hourly basis. First of all, two and four high efficiency heat pumps, manufactured by Toshiba type RAS-10SAV2-E and RAS-13SAV2-E, were selected for the reference single-family and for each apartment of the reference multi-family building based on the design cooling load of each thermal zone. In addition the energy efficiency ratio (EER) for each heat pump system was calculated according to the performance data provided by the manufacturer and the corresponding hourly air temperature, which has been retrieved from the TMY-2 weather files in each location. Furthermore, the electricity consumption of the conventional cooling system was estimated in hourly base using the energy requirements of the building envelope obtained by EnergyPlus results and the corresponding EER factor. Finally the electricity consumption of the heat system was turned into primary energy consumption using the national reduction factor 2.7.

Figure 5 illustrates the comparison between the primary energy consumption of the GSHP system and the alternative conventional one in annual base. It is indicated that the GSHP system consumes less energy than the conventional in both buildings and in all locations. More specifically, it was found that there is a significant reduction in primary energy consumption which is up to 23.5% and 25.4% for the reference single-family and multi-family building, respectively. This reduction is higher in the mountainous area of Saittas while in southern locations the increase of cooling needs, maximize the electricity usage and minimizes limits the observed potential.

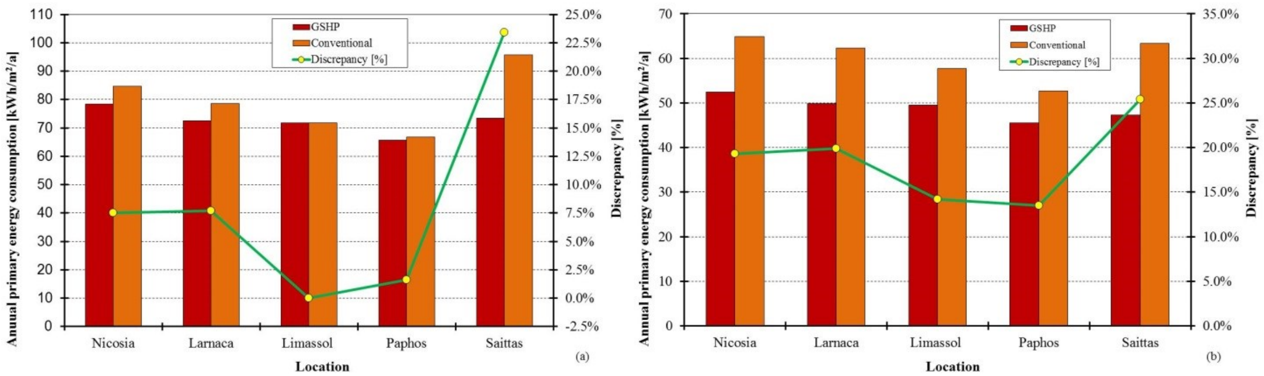

Figure 5: Annual primary energy consumption of the reference buildings: (a) single-family, (b) multi-family

4.3 Environmental analysis

The three alternative systems (GSHP and conventional ones) were compared as regards their environmental performance by calculating each system's carbon dioxide emissions on the basis of the country-specific emission factors. In general it turned out that the GSHP system has 19%-29% higher CO_2 emissions than its conventional counterparts, with emissions of the conventional oil-fired system being slightly higher than those of the LPG-fired system due to the higher carbon content of oil. The environmental disadvantage of the GSHP was more evident in the mountainous area of Saittas and less pronounced in Nicosia and Larnaca. It has to be stressed that this result should not be generalized because it is closely associated with the fuel mix of power generation in Cyprus – which is still dominated by fuel oil. The difference in carbon emissions between GSHP and conventional systems will largely be eliminated in the coming years due to the further penetration of renewable electricity in Cyprus and the introduction of natural gas in thermal power plants.

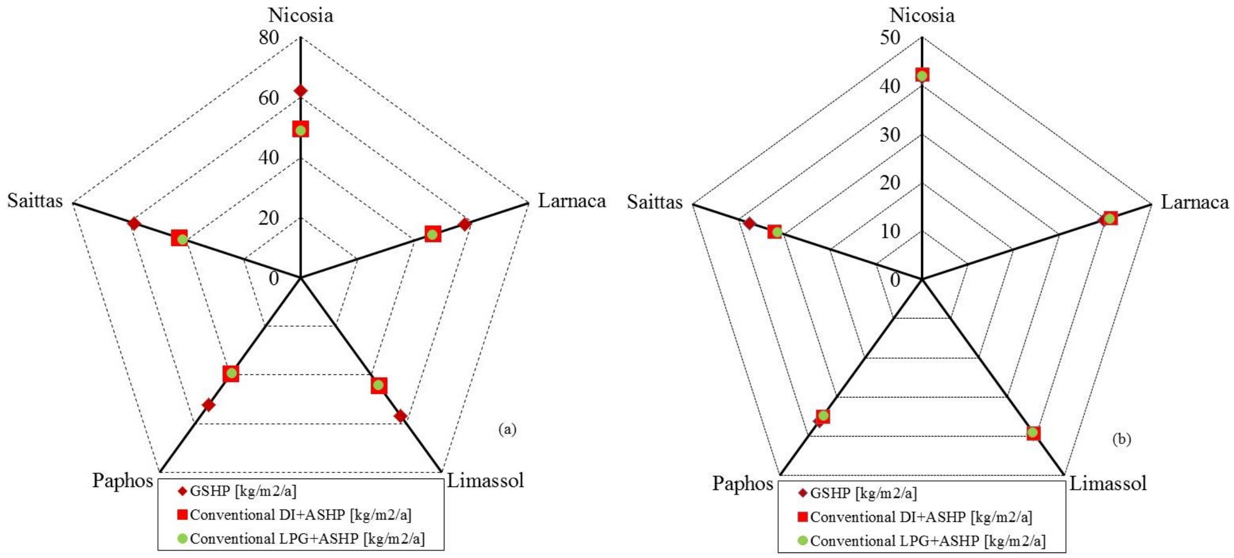

Figure 6: Annual carbon dioxide emissions of the alternative systems: (a) single-family, (b) multi-family building

4.4 Economical analysis

The economic comparison between the GSHP and the conventional systems was conducted by calculating the Net Present Value (NPV) of the different options, applying a 6% real discount rate. In line with EU Regulation 244/2012/EU, European Union (2012), an economic lifetime of 15 years was used, EN 15459 (2007). The construction cost of the conventional systems is shown in Table 6; it was calculated on the basis of actual market prices in early 2014. As both the GSHP system and the oil- or LPG-fired boiler were assumed to use the same distribution and emission systems, construction costs of these components could be removed from the analysis.

Table 6. The construction cost of the two alternative systems

Location	Single-family house		Multi-family house	
	GSHP system [€]	Conventional system [€]	GSHP system [€]	Conventional system [€]
Nicosia	12,700	8,500	35,500	15,700
Larnaca	13,000	8,500	37,000	15,700
Limassol	12,700	8,500	35,800	15,700
Paphos	11,500	8,500	31,800	15,700
Saittas	10,500	7,700	24,600	15,700

Annual fuel costs for each system and location were computed by using the calculated energy consumption by fuel (electricity, heating oil and LPG) and combining it with the corresponding fuel price forecasts made by Zachariadis and Michael (2014). Annual maintenance costs were assumed to lie at 2% and 4% of the initial investment cost for the boiler and heat pumps respectively.

As illustrated in Figure 7, the conventional LPG+ASHP system is the economically preferred option in southern and mainland areas of the island. The GSHP system's NPV is found to be ranged from 710 € to -4,750 € (or 0.9% to -6.0%) compared to conventional systems in these areas in case of single-family house or from -1,090 € to -3,000 €. (or -3.6% to 10.3%) for the multi-family one. Conversely, the GSHP system is economically attractive in cooler and mountainous regions, as its NPV is higher by 17.3% (12,000 €) or 10.8% (3,000 €) than the alternative systems.

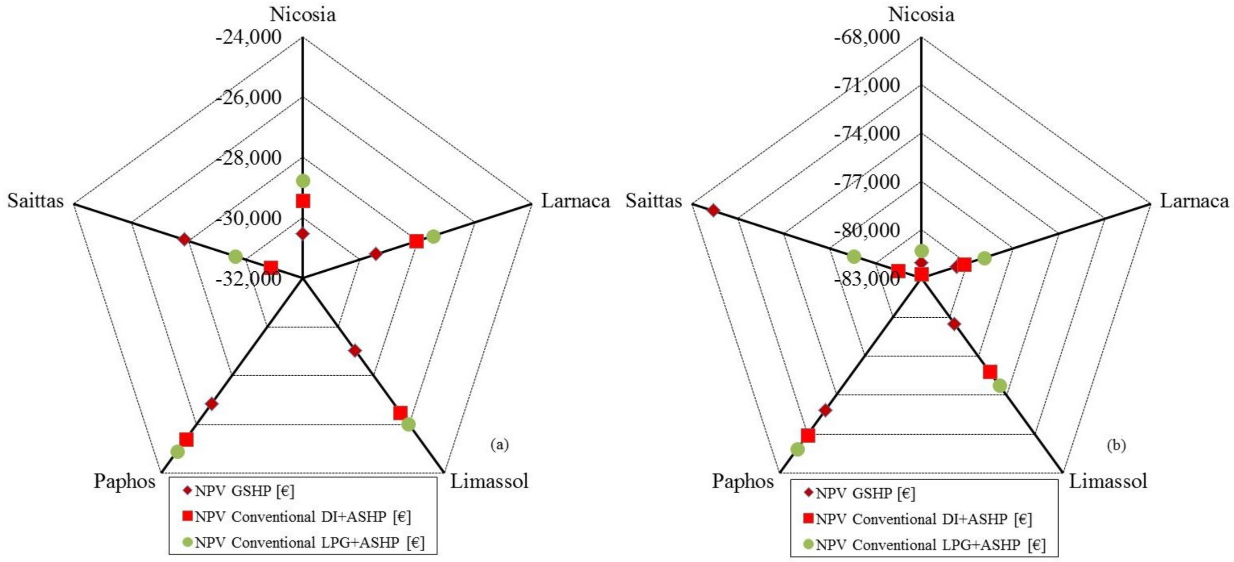

Figure 7: The Net Present Values (NPV) of the alternative systems: (a) single-family, (b) multi-family building

5. CONCLUSIONS

In this paper the energy performance as well as the environmental and economic impact of the installations of GSHP systems in residential buildings in Cyprus have been presented, analyzed and discussed. The main findings of this work can be summarized as:

- The Seasonal Coefficient of Performance was found to be in range of 4.5 to 6.0 based on the reference building types and climate conditions of the studied locations. In addition, the Seasonal Energy Efficiency Ratio fluctuates from 4.6 to 5.6, respectively.
- The introduction of the GSHP system of space heating and cooling in place of the common heating and cooling systems accounts for a significant primary energy saving which is up to 25.4%
- GHSP system emits up to 29% more CO_2 than the alternative conventional ones, which is directly influenced by the existing energy mix. It is expected that this discrepancy will be eliminated in the forthcoming years with the increase of the RES electricity share.
- GSHP system becomes economic beneficially in cold climate locations of the study, while in colder ones there is an increase in cost up to 3,000 € or 10.3%.

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REFERENCES

ASHRAE Handbook-Fundamentals: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc., Atlanta (2013).

Blum, P., Campillo, G., Münch, W., and Kölbel, T.: CO_2 savings of ground source heat pump systems - A regional analysis, *Renewable Energy,* **35**, (2010), 122-127.

Cypriot Statistical Service: Statistical service of Cyprus: construction and housing statistics 2011, report no. 34. (2013).

EN 12831:2004: Heating systems in buildings – Method for calculation of the design heat load, European Committee for Standarization (2004).

EN 15251:2007: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, European Committee for Standarization (2007).

EN 15429:2007: Energy performance of buildings - Economic evaluation procedure for energy systems in buildings, European Committee for Standarization (2007).

European Union: Council Directive 92/42/EEC of the 21 May 1992 on efficiency requirements for new hot-water boilers fired with liquid or gaseous fuels (1992).

European Union: Regulation No. 244/2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements (2010).

Jenkins, D.P., Tucker, R., and Rawlings, R.: Modelling the carbon-saving performance of domestic ground-source heat pumps, *Energy and Buildings,* **41**, (2009), 587-595.

Kitsios, K., and Zachariadis, T.: Energy Efficiency Policies and Measures in Cyprus. *Report* to the Odyssee-Mure 2010, (2012).

Lohani, S.P., and Schmidt, D.: Comparison of energy and exergy analysis of fossil plant, ground and air source heat pump building heating system, *Renewable Energy*, **35**, (2010), 1275-1282.

Luo, J., Rohn, J., Bayer, M., Priess, A., Wilkmann, L., and Xiang, W.: Heating and cooling performance analysis of a ground source heat pump system in Southern Germany, *Geothermics*, **53**, (2015), 57-66.

Man, Y., Yang, H., and Fang Z.: Study on hybrid ground-coupled heat pump systems, *Energy and Buildings*, **40**, (2008), 2028-2036.

Michopoulos, A., and Kyriakis, N.: A new energy analysis tool for ground source heat pump systems, *Energy and Buildings,* **41**, (2009), 937-941.

Michopoulos, A., Zachariadis, Th., and Kyriakis, N.: Operation characteristics and experience of a ground source heat pump system with a vertical ground heat exchanger, *Energy*, **51**, (2013), 349-357.

Sfeir, A., Bernier, M., Million, T., and Joly, A.: A methodology to evaluate pumping energy consumption in GCHP systems, *ASHRAE Transaction,* **111(1)**, (2005), 714-729.

Sivasakthivel, T., Murugesan, K., and Sahoo, P.K.: A study on energy and CO_2 saving potential of ground source heat pump system in India, *Renewable and Sustainable Energy Reviews,* **32**, (2014), 278-293.

Vanhoudt, D., Desmedt, J., Van Bael, J., Robeyn, N., and Hoes, H.: An aquifer thermal storage system in a Belgian hospital: Long-term experimental evaluation of energy and cost savings, *Energy and Buildings,* **43(12)**, (2011), 3657-3665.

Yu, X., Wang, R.Z., and Zhai, X.Q.: Year round experimental study on a constant temperature and humidity air-conditioning system driven by ground source heat pump, *Energy*, **36(2)**, (2011), 1309-1318.

Zachariadis, T., and Michael, M.: Update of national energy forecasts for the Republic of Cyprus, Report to the Ministry of Energy, Commerce, Industry and Tourism (2014).