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EFFECT OF CLIMATIC CONDITIONS ON THE DESIGN OPTIMIZATION OF HEAT PUMP SYSTEMS FOR SPACE HEATING AND COOLING

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Abstract—Domestic heating and cooling is responsible for a fair percentage of world energy consumption. Heat pumps offer the most energy efficient way to provide heating and cooling in many applications, as they can use renewable heat sources of the building's surroundings. A number of related heat pump technology versions exist that have led to significantly lower heating and cooling energy consumption in certain climatic conditions. In this paper, a comparative discussion is given of the effect of climatic conditions on applying ground source heat pump technologies. Specific examples are given for northern and southern parts of Europe. It is shown that the attainable building energy consumption reduction with ground source heat pump systems may be significantly higher in the warmer Mediterranean climatic conditions. To this end, advanced technology residential heat pump systems should be employed and their operation matched to the specific climatic conditions. It is concluded that climatic conditions significantly affect the performance of heat pump systems, which should lead to markedly different strategies for domestic heating and cooling, if an optimization is sought on sustainability grounds. © 1998 Elsevier Science Ltd.

Heat pumps Coefficient of performance Climatic conditions Ground source heat pumps Solar energy systems and controls

1. INTRODUCTION

Heating of buildings consumes about 25% of the primary energy used in the EU. The most widely used technology in this respect is oil or gas fired furnaces and boilers. Increased use of heat pumps could contribute to significant energy savings in this sector. About half of this primary energy in the EU is consumed in the form of oil, which is imported for the major part in Europe [1].

Compressor heat pumps could contribute to substitution of oil, as they provide heat by using electricity which can be produced from nuclear energy, coal or renewable energy. In addition, heat pumps could make a large contribution to pollution abatement, in particular in densely populated areas, depending on their efficiency superiority potential against conventional boilers. If the fuel used by conventional boilers were redirected to supply power of electric heat pumps, around 35% less fuel would be needed. The additional electric power requirement would result in somewhat increased pollution at the electricity plant, but this pollution could be more easily abated. Alternatively, the fuel savings could be raised to more than 50% with no additional electric power requirements, if electric heat pumps were driven by combined heat and power (cogeneration) systems.

To exploit fully this potential, the electricity requirements of heat pump-based building HVAC systems should be minimized by exploitation of solar and ground heat where possible and controlled by means of advanced building energy management systems. Assessing the part of this potential related to the climatic conditions of the building's location is the aim of this paper.

Steady-state performance of an electric compression heat pump at a given set of temperature conditions is indicated by the Coefficient Of Performance (COP). It is defined as the ratio of the

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heat delivered by the heat pump and the electrical energy supplied to the compressor. The COP of a heat pump is closely related to the temperature lift, i.e. the difference between the temperature of the heat source and the output temperature of the heat pump [2]. The COP of an ideal heat pump is determined solely by the condensation temperature and the temperature lift (condensation–evaporation temperature difference) [3].

Figure 1 shows the COP for an ideal heat pump as a function of temperature lift, where the temperature of the heat source is 0°C. Also shown is the range of actual COPs for various types and sizes of real heat pumps at different temperature lifts. The ratio of the actual COP of a heat pump and the ideal COP is defined as the Carnot Efficiency. The Carnot Efficiency varies from 0.30 to 0.50 for small electric heat pumps and 0.50 to 0.70 for large, high efficiency electric heat pumps.

The performance of heat pumps is affected by a great number of factors. For heat pumps in buildings, these include:

- The climate—annual heating and cooling demand and maximum peak loads.
- The temperatures of the heat source and heat distribution systems.
- The auxiliary energy consumption (pumps, fans, supplementary heat for bivalent system, etc).
- The technical standard of the heat pump.
- The sizing of the heat pump in relation to the heat demand and the operating characteristics of the heat pump.
- The heat pump control system.

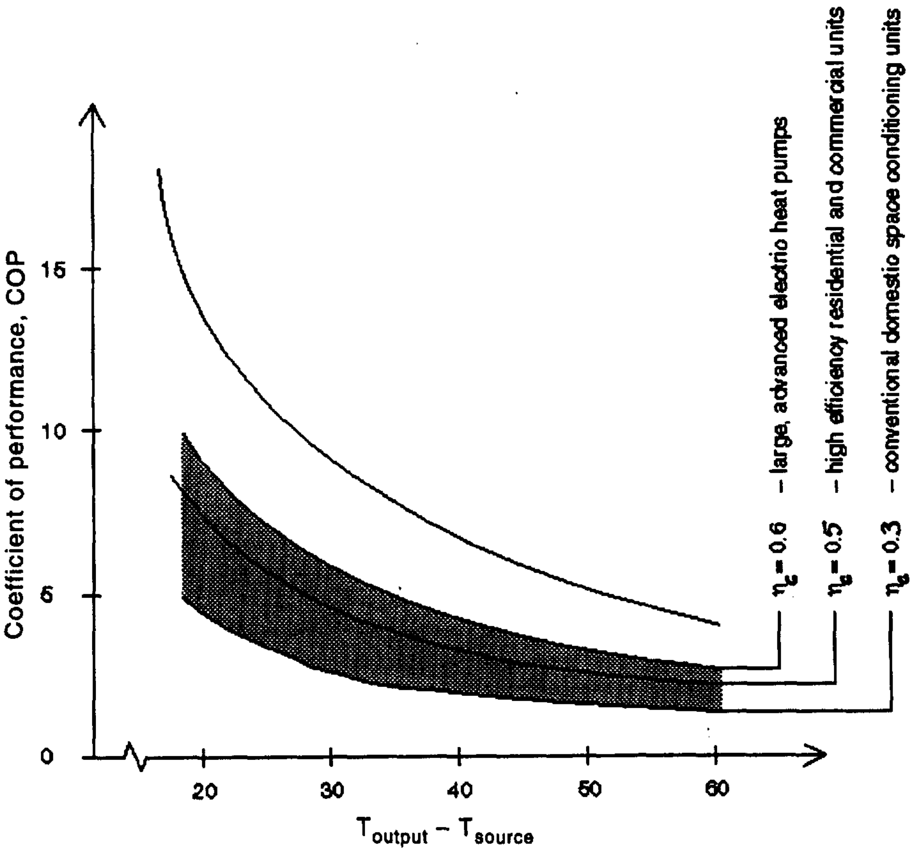

Fig. 1. Coefficient of performance (COP) for an ideal heat pump as a function of temperature lift (top line). Also shown are performance curves for conventional heat pumps (lowest curve, $\eta_c = 0.30$), high performance residential heat pumps (next lower curve, $\eta_c = 0.50$) and advanced heat pumps ($\eta_c = 0.6$).

Table 1. Commonly used heat sources for heat pumps

Source	Temperature range (in heating season)	Temperature range (in cooling season)
Ambient air	−10–15°C	26–45°C
Exhaust air	17-23°C	26–34°C
Ground water	4–15°C	6–18°C
Lake water	0–15°C	10–20°C
River water	0–15°C	8–18°C
Sea water	4–15°C	10–25°C
Rock	0–15°C	10–20°C
Ground	0–15°C	10–20°C

The practical, seasonally averaged COP values for regular applications of compressor heat pumps (Fig. 1) are a factor of three lower than theoretically indicated. Further development and systems' integration should, therefore, be able to increase performance levels by 50% [4]. In view of exploiting this potential, modern generation heat pumps include units with capacity control using continuously variable compressor and fan speed modulation, full condensing water heating capability and zonal heating capability [5, 6].

However, even with standard production heat pumps, it is possible to attain significant gains in seasonally averaged COP by application of ground source heat pumps and additional use of solar heat [7–9]. The effectiveness of such measures is significantly affected by the operation characteristics of the heat pump in relation to the climatic conditions prevailing in each specific place, as demonstrated in this paper.

1.1. Heat pumps in space heating and cooling

Heat pumps for heating and cooling buildings can be divided into four main categories, depending on their operational function [10]:

- Heating-only heat pumps, providing space heating and/or water heating.
- Heating and cooling heat pumps, providing both space heating and cooling. The most common type is the reversible air-to-air heat pump, which either operates in heating or cooling mode. Large heat pumps in commercial/institutional buildings use water loops (Hydronic) for heat and cold distribution, and they provide heating and cooling simultaneously.
- Integrated heat pump systems, providing space heating, cooling, water heating and sometimes exhaust heat recovery. Water heating can be by de-superheating only, or by de-superheating and condenser heating. The latter permits water heating when no space heating or cooling is required.
- Heat pump water heaters, fully dedicated to water heating [11]. They often use air from the immediate surroundings as heat source, but can also be exhaust air heat pumps, or de-superheaters on air-to-air and water-to-air heat pumps.

1.2. Heat sources

The technical and economic performance of a heat pump is closely related to the characteristics of the heat source [6]. An ideal heat source has a high and stable temperature during the heating season, is abundantly available, is not corrosive or polluted, has favourable thermophysical properties and its utilization requires low investment and operational costs. In most cases, however, the availability of the heat source is the key factor determining its use.

Table 1 presents some commonly used high- and low-temperature heat sources. Ambient and exhaust air, soil and ground water are practical heat sources for small heat pump systems, while sea-, lake- or river-water, rock (geothermal) and waste water are used for large heat pump systems [1].

2. EFFECT OF THE TYPE OF OUTSIDE HEAT SOURCE ON COP

Ambient air is free and widely available, and it is the most common heat source for heat pumps. Air-source heat pumps, however, achieve, on average, 10–30% lower SPF than water-source heat pumps. This is mainly due to the rapid fall in capacity and performance with decreasing outdoor temperature, the relatively high temperature difference in the evaporator and the energy needed for de-frosting and to operate the fans. In mild and humid climates, frost will accumulate on the evaporator surface in the temperature range 0–6°C, leading to reduced capacity and performance of the heat pump system. Coil defrosting is achieved by reversing the heat pump cycle or by other, less energy efficient means. Energy consumption will increase and the overall COP of the heat pump drops with increasing defrost. Using demand frost control rather than time control can significantly improve overall efficiencies.

Exhaust (ventilation) air is a common heat source for heat pumps in residential and commercial buildings. The heat pump recovers heat from the ventilation air and provides water and/or space heating. Continuous operation of the ventilation system is required during the heating season or throughout the year. Some units are also designed to utilize both exhaust air and ambient air. For large buildings, exhaust air heat pumps are often used in combination with air-to-air heat recovery units.

Ground water is available with stable temperatures (4–15°C) in many regions. Open or closed systems are used to tap into this heat source. In open systems, the ground water is pumped to the unit, cooled and then re-injected in a separate well or returned to surface water. Open systems should be carefully designed to avoid problems such as freezing, corrosion and fouling. Closed systems can either be direct expansion systems, with the working fluid evaporating in underground heat exchanger pipes, or brine loop systems. Because of the extra heat exchanger involved, heat pump brine systems have, in general, lower performance, but are easier to maintain. A major disadvantage of ground water heat pumps is the costs of installing the heat source.

Ground source systems are used for residential and commercial applications and have similar advantages to ground water source systems, i.e. they have relatively high annual temperatures. Heat is extracted from pipes laid horizontally or vertically in the ground (horizontal/vertical ground coils), and both direct expansion and brine systems can be employed. The thermal capacity of the soil varies with the moisture content and the climatic conditions. Because of the extraction of heat from the soil, the soil temperature will drop during the heating season. However, in summer, the sun will raise the ground temperature and complete temperature recovery may be possible. The first cost of such systems is currently high because of high costs of installing the ground heat exchanger. Vertical loop systems are known to operate better, especially in the cooling mode. This is because heat transfer to/from the ground is highly dependent on the amount of soil moisture and horizontal loops drive soil moisture away from the piping more readily than do vertical loop systems during cooling operation.

In general, ground water source and closed loop ground coupled heat pumps can operate at significantly reduced peak electrical demand compared to conventional air-to-air heat pumps. Tests on vertical closed-loop ground coupled heat pumps showed that the yearly heating and cooling electrical energy consumption of the ground-coupled system was from 30 to 50% less than that for an air-to-air system. Similarly, peak electrical power demand for the ground-coupled system was around 70% less than for the air-to-air heat pumps (due to complete elimination of backup heating) [6, 10, 12–14].

For the purposes of the present paper, we are going to consider a variation of heat pump COP according to the two limiting performance curves of Fig. 1 for real heat pumps ($\eta_C = 0.3, 0.5$).

3. CALCULATION OF ENERGY SAVINGS OF GROUND SOURCE HEAT PUMPS

As explained above, on efficiency grounds, there is a rationale towards shifting from air-source to ground water or ground source heat pump systems. However, the advantages to be gained should counterbalance the increased initial costs and complexities of installing ground source systems.

An estimation of the energy savings induced by the use of ground source heat pumps is absolutely necessary in any feasibility study of this type [15]. In this paper, we will formulate and use a simplified calculation methodology that is described in this section.

The influence of climatic conditions on heat pump heating and cooling requirements is discussed for the example of a standard building type (single-family house) defined by the NBS for the IEA study group [16]. Data for this house are presented in Table 2.

Table 2. Insulation and other data of the house considered in this study

Surface	Length (m)	Width (m)	Total heat transmission coefficient (W/m^2 K)	Surface area (m^2)	Wall absorptance (α)	U-value glass (W/m^2 K)	Window area (m^2)	Transmittance glass (τ)	Door heat transmission coefficient (W/m^2 K)	Door area (m^2)	Door absorptance (α)
South	12.53	4.27	0.374	51.8	0.8	2.62	1.67	0.8			
West	5.87	4.27	0.374	16.9	0.8	2.62	8.18	0.8			
North	12.53	4.27	0.374	51.1	0.8	2.62	2.42	0.8			
East	5.87	4.27	0.374	19	0.8	2.62	4.95	0.8	1.99	1.12	0.8
Roof	12.53	5.87	0.258	73.6	0.87						
Floor	12.53	5.87	0.158	73.6							

Note: Temperature setting heating: 21.1°C, temperature setting cooling: 23.9°C, maximum lighting load: 6 W/m^2 maximum equipment load: 18.9 W/m^2, maximum number of occupants: 5.5 persons, total internal load: 24.8 kWh/day (exclusive of solar gain).

To demonstrate the capacity of reduction of the total yearly heating and cooling expenditures of this house by application of ground source heat pumps, a specific heating and cooling energy consumption calculation methodology must be first formulated.

The calculation is laid out according to the following six steps:

(i) Heating losses are computed based on the geometry, insulation and indoor condition data of the house as a function of outdoor temperature.
(ii) Based on the previous expressions, heating losses are computed for each month. (This computation should be ideally done on a day-to-day basis. However, as shown in the spreadsheet of Table 3, the results indicate that a monthly degree-day calculation is sufficiently accurate for the purposes of this paper).
(iii) Based on the monthly average temperature, a mean COP is computed for the case of an air-source heat pump. This is supported by the performance data presented in Fig. 1.
(iv) Based on the ground source temperature, a mean COP is computed for the case of a ground source heat pump.
(v) Electricity consumption of the air source and the ground source heat pump for each month is computed based on the respective COPs.
(vi) The results are summed over the year and compared for the two alternatives.

The above-mentioned methodology is applied in the sequel to estimate the attainable ground source heat pump efficiency gains in the following geographic sites of Europe:

- Hamburg, Germany
- Thessaloniki, Greece

This simplified energy requirement calculation methodology may also be employed in the determination of heat pump performance in the cooling mode, based on monthly cooling degree-day data.

In order to be able to calculate the variation of heat pump COP with ambient air temperature during the months in which both heating and cooling of the house is necessary, we need to have a mean monthly ambient temperature for the heating hours and a mean ambient temperature for the cooling hours, which may be computed by means of weighted averages based on the respective monthly heating and cooling degree-day data [17].

A year round HVAC system is considered for this house, based on a central heat pump unit and hydronic circuit to fan coil units intalled in each room (Fig. 2a and b).

The heat pump is considered to deliver the necessary capacity levels with a nominal evaporation temperature of 0°C and a nominal condensation temperature at 50°C.

Two versions of the heat pump will be considered in this study (Fig. 2a and b):

- an air-to-water heat pump
- a ground source, water-to-water heat pump.

It must be mentioned here that the ground source heat pump version examined here could be even more beneficial if distributed water-to-air heat pump units were employed (Fig. 2c). This last version could achieve further energy improvements over closed loop heat pump systems. This results because the fluid temperatures tend to be more favorable for geothermal systems. Thus, the equipment operates at lower discharge pressures and may attain energy efficiencies as high as 20 EER. The other advantage of this version is the elimination of the heat adder and the heat rejector. As with variable pumping systems, the heat rejector and heat adder represent approximately 30% of the total operating cost of the system. Therefore, we could inherently achieve a 30% improvement in the operating cost of the system before even considering the improvements in heat pump COP considered in this comparison.

In order to be consistent in the comparison, in each different climatic site, the ground source temperature is assumed constant and equal to the yearly mean air temperature value. Table 4 presents a spreadsheet with the calculations of heating energy requirements of the house under consideration with the two heat pump versions in Hamburg, Germany and Thessaloniki, Greece.

Table 3. Comparative calculation of heating energy demand (daily versus monthly degree-day calculation). Climatic data from Warsaw, Poland (continental cold climate type) are employed here in a comparison between daily and monthly degree-day computations

Heating requirements			Daily average temperature °C			COP air source			Heating requirements air source			COP ground source	Heating requirements ground source		
Jan.	Feb.	Mar.	Jan.	Feb.	Mar.	Jan.	Feb.	Mar.	Jan.	Feb.	Mar.		Jan.	Feb.	Mar.
76	70	74	0.00	2.50	0.50	1.69	1.77	1.70	45	40	43	1.93	40	36	38
69	67	76	1.50	3.00	0.00	1.74	1.79	1.69	39	38	45	1.93	36	35	40
66	87	69	2.00	−0.50	1.50	1.75	1.67	1.74	38	52	39	1.93	34	45	36
56	93	66	4.00	−1.50	2.00	1.82	1.64	1.75	31	57	38	1.93	29	48	34
53	99	56	4.50	−2.50	4.00	1.84	1.61	1.82	29	61	31	1.93	28	51	29
45	102	56	6.00	−3.00	4.00	1.88	1.59	1.82	24	64	31	1.93	24	53	29
45	102	58	6.00	−3.00	3.50	1.88	1.59	1.80	24	64	32	1.93	24	53	30
58	99	61	3.50	−2.50	3.00	1.80	1.61	1.79	32	61	34	1.93	30	51	32
61	96	56	3.00	−2.00	4.00	1.79	1.62	1.82	34	59	31	1.93	32	50	29
53	82	51	4.50	0.50	5.00	1.84	1.70	1.85	29	48	27	1.93	28	42	26
48	82	45	5.50	0.50	6.00	1.87	1.70	1.88	26	48	24	1.93	25	42	24
43	87	61	6.50	−0.50	3.00	1.90	1.67	1.79	23	52	34	1.93	22	45	32
43	107	61	6.50	−4.00	3.00	1.90	1.56	1.79	23	69	34	1.93	22	56	32
61	121	74	3.00	−6.50	0.50	1.79	1.47	1.70	34	82	43	1.93	32	63	38
74	141	74	0.50	−10.00	0.50	1.70	1.36	1.70	43	104	43	1.93	38	73	38
74	147	69	0.50	−11.00	1.50	1.70	1.33	1.74	43	111	39	1.93	38	76	36
69	119	51	1.50	−6.00	5.00	1.74	1.49	1.85	39	80	27	1.93	36	61	26
51	87	76	5.00	−0.50	0.00	1.85	1.67	1.69	27	52	45	1.93	26	45	40
87	87	87	−2.00	−0.50	−2.00	1.62	1.67	1.62	53	52	53	1.93	45	45	45
87	102	74	−2.00	−3.00	0.50	1.62	1.59	1.70	53	64	43	1.93	45	53	38
74	138	45	0.50	−9.50	6.00	1.70	1.38	1.88	43	101	24	1.93	38	72	24
45	138	51	6.00	−9.50	5.00	1.88	1.38	1.85	24	101	27	1.93	24	72	26
51	99	61	5.00	−2.50	3.00	1.85	1.61	1.79	27	61	34	1.93	26	51	32
61	104	61	3.00	−3.50	3.00	1.79	1.57	1.79	34	66	34	1.93	32	54	32
58	102	58	3.50	−3.00	3.50	1.80	1.59	1.80	32	64	32	1.93	30	53	30
33	82	33	8.50	0.50	8.50	1.97	1.70	1.97	17	48	17	1.93	17	42	17
33	79	45	8.50	1.00	6.00	1.97	1.72	1.88	17	46	24	1.93	17	41	24
43	84	48	6.50	0.00	5.50	1.90	1.69	1.87	23	50	26	1.93	22	44	25
56		66	4.00		2.00	1.82		1.75	31		38	1.93	29	0	34
56		76	4.00		0.00	1.82		1.69	31		45	1.93	29	0	40
1727	2803	1837							969	1795	1040		895	1452	952

Table 4. Spreadsheet with the calculations of heating energy requirements of the house under consideration with the conventional heat pump version in Hamburg, Germany and Thessaloniki, Greece

	Hamburg						Thessaloniki					
Month	Heating requirements	Monthly average temperature °C	COP air source	Heating requirements air source	COP ground source	Heating requirements ground source	Heating requirements	Monthly average temperature °C	COP air source	Heating requirements air source	COP ground source	Heating requirements ground source
		50°C Condensation							*50°C Condensation*			
Jan.	2230	1.5	1.74	1284	1.97	132	1490	5.50	1.87	798	2.21	674
Feb.	1990	2.0	1.75	1135	1.97	1010	1251	7.00	1.92	653	2.21	566
Mar.	1345	5.5	1.87	720	1.97	683	790	9.90	2.01	393	2.21	357
Apr.	1145	5.5	1.87	613	1.97	581	42	14.60	2.17	19	2.21	19
May	400	12.0	2.08	192	1.97	203						
Jun.		16.0	2.21	0	1.97	0						
Jul.		17.5	2.26	0	1.97	0						
Aug.		16.5	2.23	0	1.97	0						
Sep.	385	14.0	2.15	179	1.97	195						
Oct.	1000	7.5	1.93	517	1.97	508						
Nov.	1670	5.0	1.85	902	1.97	848	472	11.9	2.08	227	2.21	213
Dec.	2370	2.0	1.75	1352	1.97	1203	1188	7.4	1.93	615	2.21	537
	12,535			6895		6363	5233			2705		2368

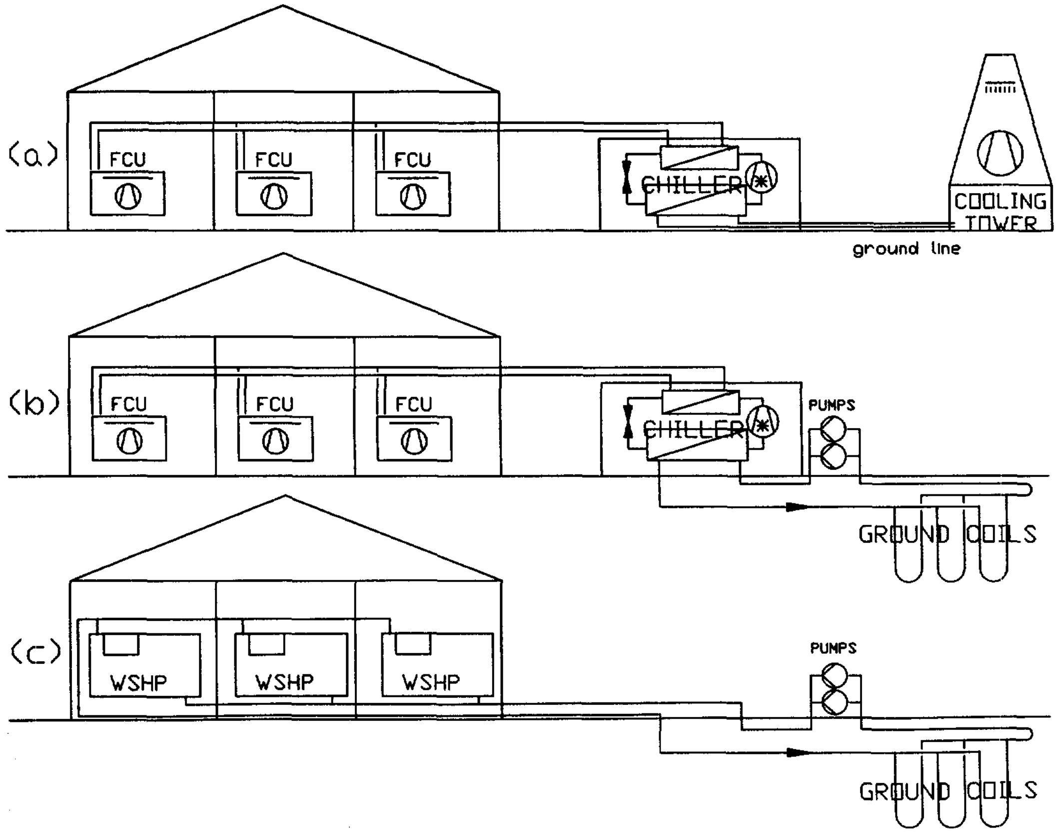

Fig. 2. Schematic of the two heat pump versions that are compared in this study based on different climatic conditions of the house (a,b). Also shown is a third, more energy conserving version based on distributed water-to-air heat pumps (c).

Table 5 presents a spreadsheet with the calculations of heating energy requirements of the house under consideration with the two heat pump versions in Hamburg, Germany and Thessaloniki, Greece.

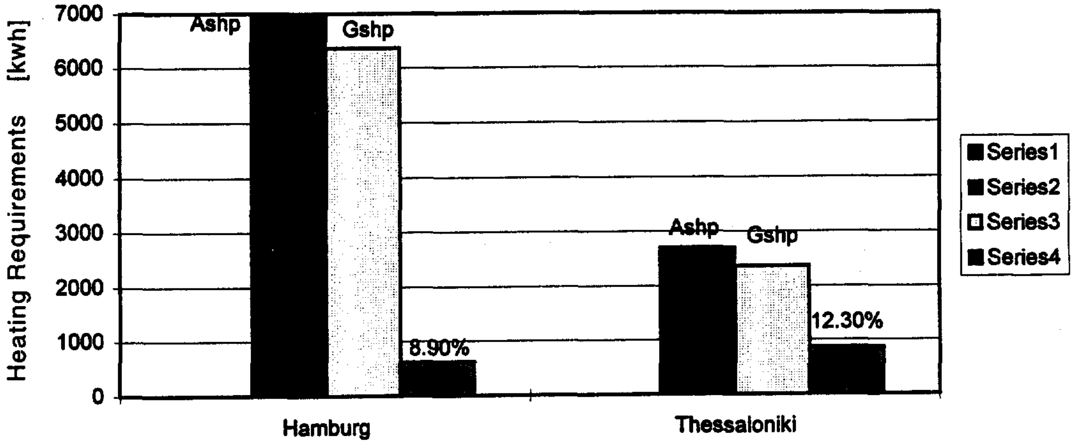

Fig. 3. Comparison of the heating mode performance of a conventional, domestic space conditioning unit for the reference house (air source vs ground source), in Hamburg and Thessaloniki.

Table 5. Spreadsheet with the calculations of heating energy requirements of the house under consideration with the conventional heat pump version in Hamburg, Germany and Thessaloniki, Greece. Two alternative operation points: 50 and 40°C condensation temperature, respectively

	Hamburg						Thessaloniki					
Month	Heating requirements	Monthly average temperature °C	COP air source	Heating requirements air source	COP ground source	Heating requirements ground source	Heating requirements	Monthly average temperature °C	COP air source	Heating requirements air source	COP ground source	Heating requirements ground source
		50°C *Condensation*							50°C *Condensation*			
Jan.	2230	1.5	2.7	820	3.20	697	1490	5.50	3.0	499	4.00	372
Feb.	1990	2.0	2.8	723	3.20	622	1251	7.00	3.1	404	4.00	313
Mar.	1345	5.5	3.0	450	3.20	420	790	9.90	3.3	236	4.00	197
Apr.	1145	5.5	3.0	383	3.20	358	42	14.60	3.8	11	4.00	11
May	400	12.0	3.5	113	3.20	125						
Jun.												
Jul.												
Aug.												
Sep.	385	14.0	3.8	102	3.20	120						
Oct.	1000	7.5	3.1	319	3.20	313						
Nov.	1670	5.0	3.0	566	3.20	522	472	11.9	3.5	133	4.00	118
Dec.	2370	2.0	2.8	861	3.20	741	1188	7.4	3.1	379	4.00	297
	12,535			4338		3917	5233			1663		1308
		40°C *Condensation*							40°C *Condensation*			
Jan.	2230	1.5	3.5	638	4.40	507	1490	5.50	3.9	379	5.80	257
Feb.	1990	2.0	3.5	562	4.40	452	1251	7.00	4.1	303	5.80	216
Mar.	1345	5.5	3.9	342	4.40	306	790	9.90	4.6	173	5.80	136
Apr.	1145	5.5	3.9	291	4.40	260	42	14.60	5.5	8	5.80	7
May	400	12.0	4.9	81	4.40	91						
Jun.												
Jul.												
Aug.												
Sep.	385	14.0	5.3	72	4.40	88						
Oct.	1000	7.5	4.2	238	4.40	227						
Nov.	1670	5.0	3.9	431	4.40	380	472	11.9	4.9	96	5.80	81
Dec.	2370	2.0	3.5	669	4.40	539	1188	7.4	4.2	284	5.80	205
	12,535			3324		2849	5233			1243		902

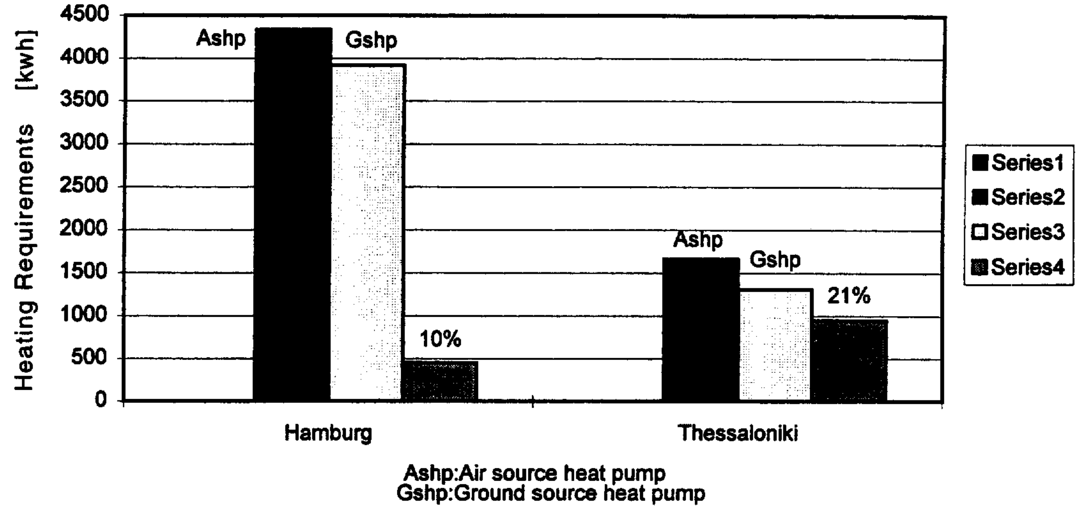

Fig. 4. Comparison of the heating mode performance of a high efficiency residential space conditioning unit for the reference house (air source vs ground source), in Hamburg and Thessaloniki.

4. COMPUTED EFFECT OF CLIMATE ON ENERGY SAVINGS BY GROUND SOURCE HEAT PUMPS

Figure 3 compares the efficiency gains by the use of ground source heat pumps in the two different European climatic types: Hamburg and Thessaloniki. Apparently, the gains are higher in the mild Mediterranean climatic type.

The observed higher percentage reduction in the milder Mediterranean climate may be explained by a careful examination of the slope of the respective COP curves in Fig. 1. The curve is nearly flat for temperature lifts higher than 40°C.

Hamburg has a mean annual air temperature of 8.75°C, while a 50°C condensation temperature is considered for the heat pump. Thus, the mean temperature lifts lie in the flat low COP region

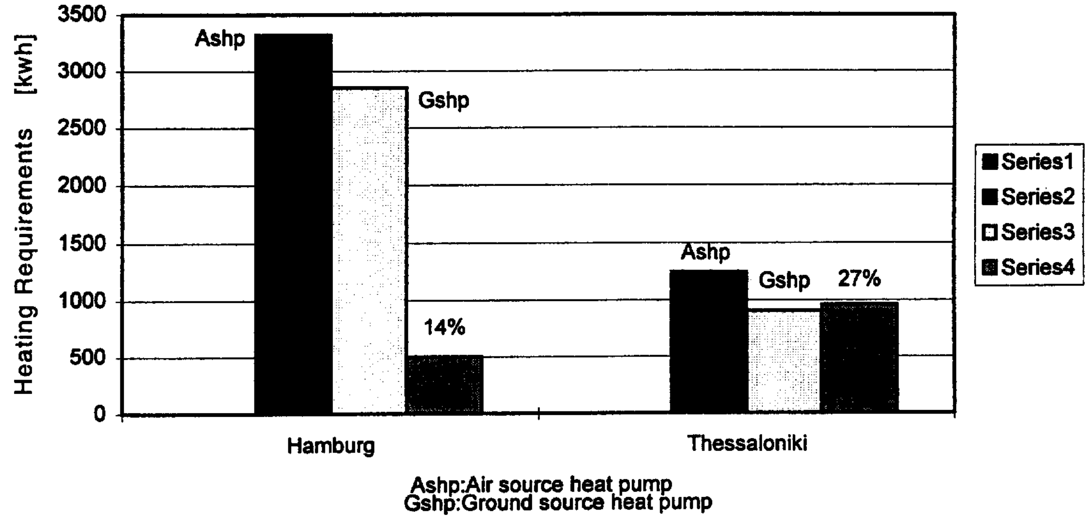

Fig. 5. Comparison of the heating mode performance of a high efficiency residential space conditioning unit for the reference house (air source vs ground source), in Hamburg and Thessaloniki. Operation point shifted to 40°C condensation temperature (for floor heating applications).

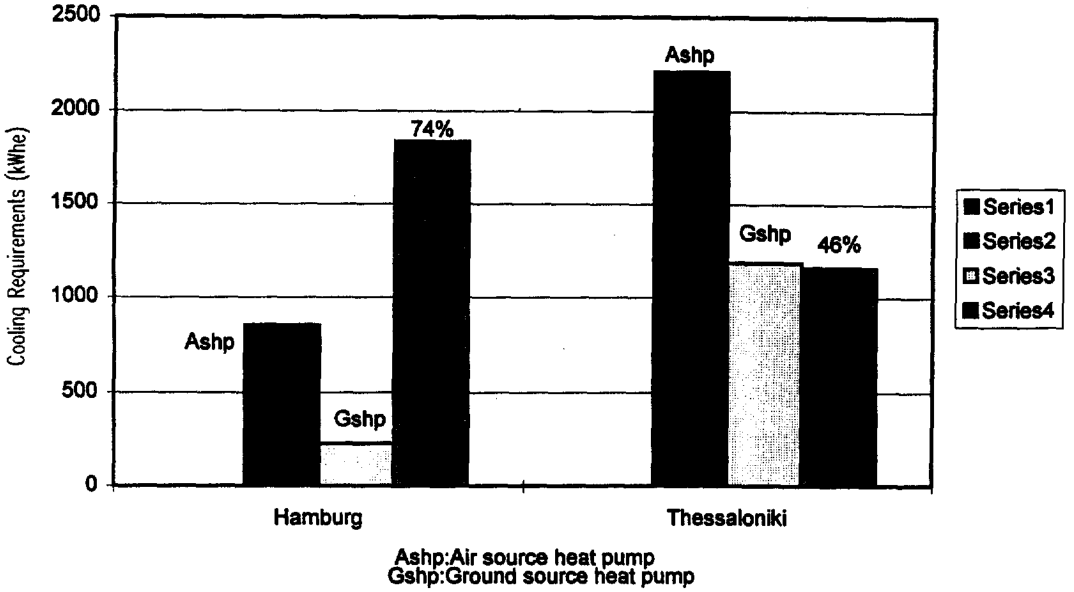

Fig. 6. Comparison of the cooling mode performance of a high efficiency residential space conditioning unit for the reference house (air source vs ground source), in Hamburg and Thessaloniki (0°C evaporator inlet).

of the curve in Fig. 1. In Thessaloniki (mean annual temperature: 16.0°C), the mean temperature lift is equal to 34°C and lies in a range of the curve with a steeper slope.

Figure 4 presents the results with a more advanced heat pump (higher efficiency curve in Fig. 1). For the higher efficiency heat pump COP curve of Fig. 1, average air temperatures in Hamburg lie again in a lower slope region. Thessaloniki temperatures lie in an even steeper region, and thus the gains reach 21%. Even higher gain may be attained by employing lower temperature lifts, for example, by shifting to floor heating with a 40°C condensation temperature for the heat pump. This is shown in the results of Fig. 5, where a 27% reduction of electricity consumption is attained in Thessaloniki and a respective 14% in Hamburg.

The above-mentioned calculation procedure may also be extended to cover cooling operation of the heat pump. Figure 6 compares the performance of a high efficiency residential space conditioning unit for the reference house (air source vs ground source) in Hamburg and Thessaloniki (0°C evaporator inlet). The calculation follows the six steps described in Section 3. However, the cooling energy requirements computation must be checked by the ASHRAE "bin" method to avoid significant errors that are possible with the cooling degree-day methodology. Although percentage gains are higher in Hamburg, absolute values of gains are significantly higher in the Mediterranean climatic conditions. The calculated cooling requirements and loads are shown in Table 6. COP dependence on temperature lift is assumed to follow the tendency of Fig. 1. However, in the cooling mode, the COP is one unit less due to the necessary rejection of the electricity consumed by the compressor.

Apparently, despite the fact that the ground source system's gains are lower, due to the more uniform air temperature variation during summer compared to winter, high gains are again observed in the Thessaloniki climatic conditions, thus raising even more the profitability of shifting to the ground source application.

5. CONCLUSIONS

- Ground source heat pumps present a serious alternative for heating energy conservation in buildings.
- However, this potential is highly dependent on the heat pump technology employed in conjunction with the climatic conditions of the place of application.

Table 6. Spreadsheet with the calculations of cooling energy requirements of the house under consideration with the high efficiency residential heat pump version in Hamburg, Germany and Thessaloniki, Greece. Heat pump operation points are at 0°C evaporation temperature

	Hamburg						Thessaloniki					
Month	Cooling requirements	Monthly average temperature °C	COP air source	Cooling kWhe air source	COP ground source	Cooling kWhe ground source	Cooling requirements	Monthly average temperature °C	COP air source	Cooling kWhe air source	COP ground source	Cooling kWhe ground source
		0°C Evaporation							*0°C Evaporation*			
Jan.		1.5						5.50				
Feb.		2.0						7.00				
Mar.		5.5						9.90				
Apr.		5.50						14.60				
May	464	12.0	4.3	107	16.40	28	1394	19.70	4.3	321	8.00	174
Jun.	986	16.0	4.3	227	16.40	60	1934	24.10	4.3	445	8.00	242
Jul.	900	17.5	4.3	207	16.40	55	2253	26.70	4.2	537	8.00	282
Aug.	1014	16.5	4.3	233	16.40	62	2204	26.30	4.3	515	8.00	276
Sep.	343	14.0	4.3	79	16.40	21	1701	22.20	4.3	392	8.00	213
Oct.		7.5						16.70				
Nov.		5.0						11.90				
Dec.		2.0						7.40				
	3707			853		226	9487			2210		1186

- For the heat pump types considered in this paper, higher percentage gains are calculated for the milder climates of the Mediterranean and subtropical types.
- Thus, also in these cases, the attainable electricity consumption reduction may counterbalance the higher initial investment costs involved, provided that a good selection of the heat pump operation characteristics is made to match the climatic conditions.
- Additional gains are observed during cooling operation of the heat pump. These reduce even more the electrical energy consumption of the reversible cycle heat pump in the climatic conditions of southern Europe.
- The significant advantages of ground source heat pumps calculated in this paper for the Mediterranean climatic conditions may be even more enhanced by installation of water-to-air heat pumps in place of the usual fan coil units used in hydronic systems.
- As a final conclusion, the well established (in the norhtern part of U.S.) technology of ground source heat pumps may be adapted with even more advantages to milder climates like that of the Mediterranean type, provided that a careful selection is done of the system's layout and the heat pump operating variables.

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