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Optimization of thermal performance of a building with ground source heat pump system

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Abstract

Component optimization studies during the last twenty years, point to the use of carefully optimized ground source heat pump systems as a means of reducing building heating and cooling energy costs. Modern computational tools enable building energy simulation with a time step of the order of minutes. This allows improved insight in the building HVAC system's transient operation and may affect the form of the objective functions employed in the component optimization procedure. In this paper, the yearly performance of a 3-zone residential building located in Volos, Greece, equipped with a conventional chiller–boiler system, compared to that of an alternative, ground source heat pump system, are simulated in the TRNSYS 16 environment. Comparative year-round simulations are employed to demonstrate the expected transient and overall energy balance effects of control settings, chiller or heat pump COP characteristics, equipment sizing and other design parameters. It is concluded that detailed simulation of the HVAC system operation further improves our understanding of its transient operation. Furthermore, it allows more realistic system's sizing, better assessment of the effect of control settings, chiller or heat pump COP characteristics and other design parameters.

Keywords: Heat pumps; Building energy simulation; Optimization; HVAC systems design

1. Introduction

The minimization of energy consumption for space heating and cooling is crucial nowadays due to increasing energy costs and CO_2 penalties [1]. Around 30 European (CEN) standards have been developed to provide Member States with the necessary tools for developing the framework for an integrated calculation methodology of the energy performance of buildings [2]. Should voluntary compliance with the standards not be forthcoming, then mandatory standards should be considered in a future amended version of the buildings directive [3]. Especially with regard to electrical energy, it is important to minimize also peak demand, thus avoiding equipment oversizing. On exergoeconomic grounds, the use of heat pumps for space heating and cooling is advantageous [4]. However, the overall attainable reduction in energy costs is additionally dependent on a variety of factors, starting from the sizing of the HVAC installation, insulation, building heat capacity, ventilation strategy, heating and cooling schedules, control system, climate of the site etc. Also, the exploitation of ground seasonal storage of solar thermal energy with the so-called ground source heat pump (GSHP), is a proven technology in Northern Europe and US [5–7]. GSHPs reduce peak electrical demand compared to conventional heat pumps. Preliminary calculations with vertical closed-loop ground-coupled heat pumps showed 30–70% reduction of yearly heating and cooling electrical energy consumption of the ground-coupled system compared to an air-to-air system in a southern climate [8,9]. The installation cost is higher for the GSHPs and thus proper sizing of the equipment is crucial to the payback of the investment. Proper sizing needs to be based on detailed system simulation, including building envelope, HVAC equipment and control system. The required modelling detail will be demonstrated in a case study presented in this paper.

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Nomenclature

ACH	air changes per hour
COP	coefficient of performance
TMY	typical meteorological year
GSHP	ground source heat pump

2. Building and HVAC system simulation

The numerous building energy simulation methodologies in-use today, can be categorized as follows:

(I) Simulation mainly of the building envelope with simplifying assumptions regarding operation of the HVAC equipment and
(II) detailed transient simulation of the building envelope and the HVAC equipment and its control.

Due to increased complexity and need for additional performance and control system data, most studies employ the first approach [10]. On the other hand, simulations of the, so-called, ''typical day operation'' type, are nowadays carried out with advanced HVAC control system modelling [11]. A few years ago, a ''level **I**'' simulation of a single zone house, combined with a component model of an air-to-air (split type) heat pump, was carried out to study performance optimization of heat pump operation by varying refrigerant pressure levels to minimize outdoor unit temperature differences [12].

The results of this study suggested that the attainable gains in heat pump COP values were not directly transferable as gains in total yearly energy costs. The study was based on the assumption of ideal control of zone temperature. Nowadays, more detailed investigation with ''level **II**'' system simulations is increasingly employed to assess the overall effects of COP improvements. They are usually based on software with standardized modules, like the DOE-2 [13]. However, fully transient simulations are also possible [14,15]. As demonstrated in this paper, ''level **II**'' simulations enable realistic prediction of reduction in yearly heating and cooling energy costs for a typical residential building by improved heat pumps and how this is affected by equipment sizing, climatic conditions, operating schedule and specific control system implementation. As a starting point, competing building HVAC systems in the market are presented in Table 1, along with estimated installation and yearly operating and maintenance costs per m^2 of building space, deduced from installation experience and commercial literature.

One of the objectives of the continuing study presented here is to check the extents of validity of some of these indicative cost figures, as well as their sensitivity to various component's and system characteristics.

This is a computational study for the reference residential building of Fig. 1 – a two store building with basement.

Table 1
Indicative economic performance data for alternative HVAC systems (€/m^2 of building space)

System compared	Annual maintenance expense	Annual operation expense	Installation cost
Fan-coil,chiller/boiler4-PIPE	1.2	12.	100
Variable air volume	1.2	8.	80
Geothermal heat pump	0.6	6.	90
Water loop heat pump	0.9	8.	70

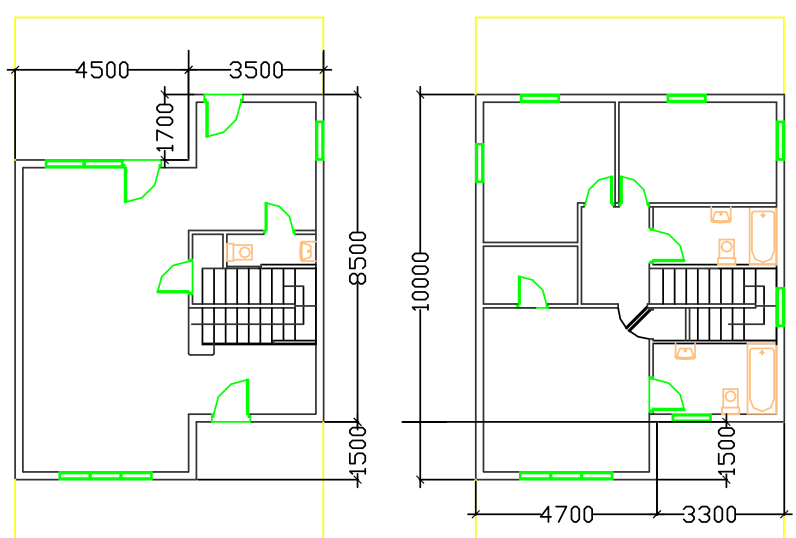

Fig. 1. Layout drawing of the residential building employed in the simulations (ground and 1st levels).

Comparative energy simulation runs were carried out for this building equipped with the following two alternative systems:

(A) Fan-coil, chiller/boiler 2-pipe system and
(B) ground source, water-to-water heat pump with horizontal ground coil.

3. Building and HVAC system modeling approach

Maximum heating power for both system A and system B was set to 11 kW. The ground source heat pump system uses a ground coil of 180 m length. TRNSYS 16 software was employed in the building energy simulation study to predict thermal performance and economic aspects of the reference building, which is located in Volos, Greece.

4. TRNSYS software

TRNSYS is a transient systems simulation program with a modular structure that was designed to solve complex energy system problems by breaking the problem down into a series of smaller components. TRNSYS components (referred to as "Types") may be as simple as a pump or pipe, or as complicated as a multi-zone building model. The components are configured and assembled using a fully integrated visual interface known as the TRNSYS Simulation Studio, and building input data is entered through a dedicated visual interface. In simulation studio, the user specifies the components that constitute the system and the manner in which they are connected. The simulation engine then solves the system of algebraic and differential equations that represent the whole system. In addition to a detailed multi-zone building model, the TRNSYS library includes components for solar thermal and photovoltaic systems, low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells, etc. The modular nature of TRNSYS facilitates the addition of new mathematical models to the program. In addition to the ability to develop new components in any programming language, the program allows to directly embed components implemented using other software (e.g. Matlab/Simulink,

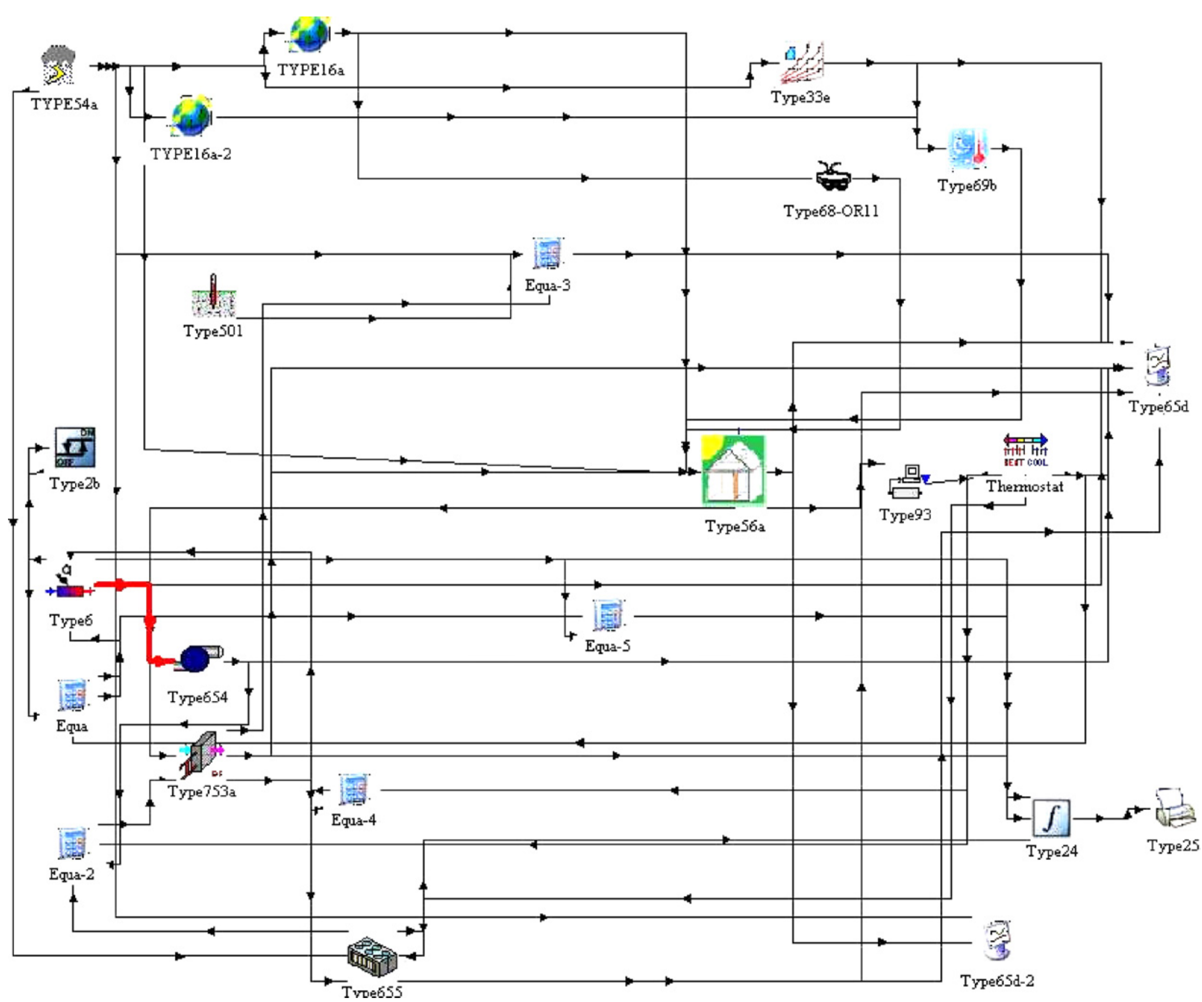

Fig. 2. TRNSYS 16 project file components, (types): system A (fan coils, chiller/boiler system).

Excel/VBA, and EES). The TRNSYS library (in Fortran source code), includes many of the components commonly found in energy systems, as well as component routines to handle input of weather data or other time-dependent forcing functions and output of simulation results. The software is well suited to detailed analyses of any system whose behaviour is dependent on the passage of time and has become reference software for researchers and engineers around the world. Main applications include: solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells. TRNSYS is one of the listed simulation programs in the recent European standards on solar thermal systems (ENV-12977-2). The level of detail of TRNSYS' building model, known as "Type 56", is compliant with the requirements of ANSI/ASHRAE Standard 140–2001. The level of detail of Type 56 also meets the general technical requirements of the European directive on the energy performance of buildings [1]. During the last two decades, TRNSYS is widely employed in building energy systems simulations [16–19]. There exist systematic studies comparing the performance of this software against experimental results, as well as comparing the results of TRNSYS to other industry standards for building energy simulation [20,21].

5. Building and HVAC system simulation details

The two alternative systems A and B are modelled in simulation studio, (Figs. 2 and 3, respectively). Both systems models comprise a 3-zone building model of the reference house. System A uses a boiler and an air-cooled chiller model. System B employs a water-source heat pump and ground coil model. Both systems use fan coils to distribute heating and cooling in the different parts of the house.

Apart from the standard utility components of the program, the following standard TRNSYS component models (Types) were employed in the simulations:

Type 56, Multi-zone building;
Type 2, ON/OFF differential controller;
Type 3, Pump;
Type 6 Auxiliary heater (modified);
Type 108, Five-stage room thermostat;
Type 54, Weather generator;
Type 16, Solar radiation processor: total horizontal only known;
Type 33, Psychrometrics: dry bulb and relative humidity known;
Type 69, Effective sky temperature for long-wave radiation exchange;
Type 68, Shading mask.

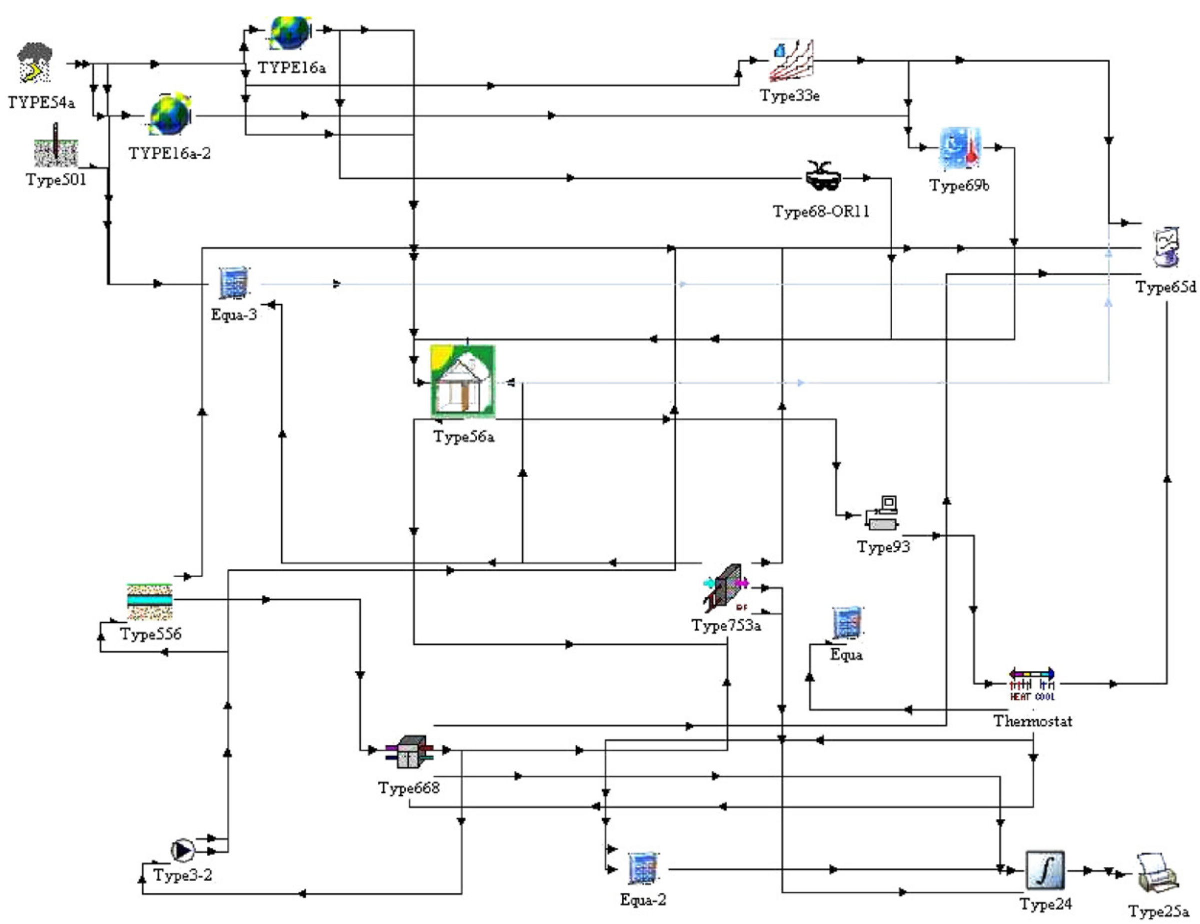

Fig. 3. TRNSYS 16 project file components (types): system B (fan coils, ground source heat pump).

The following TRNSYS types belonging to the TESS library [22] are employed:

Type 753a Heating coil using bypass fraction approach – free floating coil (modified)
Type 655 Air-cooled chiller (modified);
Type 654, Single speed pump;
Type 556, Horizontal ground-coupled heat exchanger;
Type 668 Water to water heat pump (modified);
Type 501, Soil temperature profile.

The modification to certain types indicated above, was necessary to add dynamic characteristics that are essential to the realistic simulation of the control system and start/stop operation.

As regards the building envelope characteristics inserted in Type 56 building model, insulation values are inserted based on the Greek standard under preparation (Table 2).

As regards ventilation, 0.5 air changes per hour (ACH) are assumed, a figure which surpasses the requirements of ASHRAE 62.2–2004 [23]. Internal heat gains are taken according to ASHRAE [24]. For the sake of comparison, the building operation schedule is simplified to provide heating or cooling day and night. Also, the shading effect of two neighboring houses in the same complex is taken into account. Climatic data in the form of a typical meteorological year for the city of Volos are employed. Hourly values of the following data for the full TMY are employed in the simulation: DB temperature, RH, wind direction and speed, total and direct solar horizontal radiation.

As regards the control systems employed, for heating operation in system A the boiler's exit temperature is set to 60 °C. The room thermostat controls zone temperature to 20 °C with a tolerance of ±1 °C. This is accomplished by switching on and off the boiler or heat pump. For cooling operation in system A, the air-cooled chiller's water exit set-point temperature is 6.5 °C. Again, the room thermostat controls zone temperature to 24 °C with a tolerance of ±1 °C. For heating and cooling operation in system B, the fan-coil is again assumed to be free-floating and the room thermostat controls zone temperature by switching on and off the water-source heat pump. Simulation of ground source heat pump system is carried out by employing type 668 (water-to-water heat pump, modified type) and type 556 (horizontal ground loop) [22]. A full year's performance simulation with a time step of 0.1 h, takes a few minutes total computation time on a Pentium 4, 3.06 GHz pc.

Table 2
Insulation data for the building envelope of the house under study

Shell type	Layers	K(W/M2K)
DECK_INSUL	BET240GREC, ROOFMATE, LEICHTBETON, KERAMIK	0.391
DOKOSINSUL	BET240GREC, STYROFOAM	0.551
FUSBMARMOR	MARMOR, BET240GREC	3.385
TIXIA_INSU	BET240GREC, STYROFOAM	0.551
W_OUTINSUL	VOLLKLINKE, WALLMATE, VOLLKLINKE	0.463

6. Simulation results and discussion

A typical graph of simulated winter operation for the first 10 days of January of the TMY is presented in

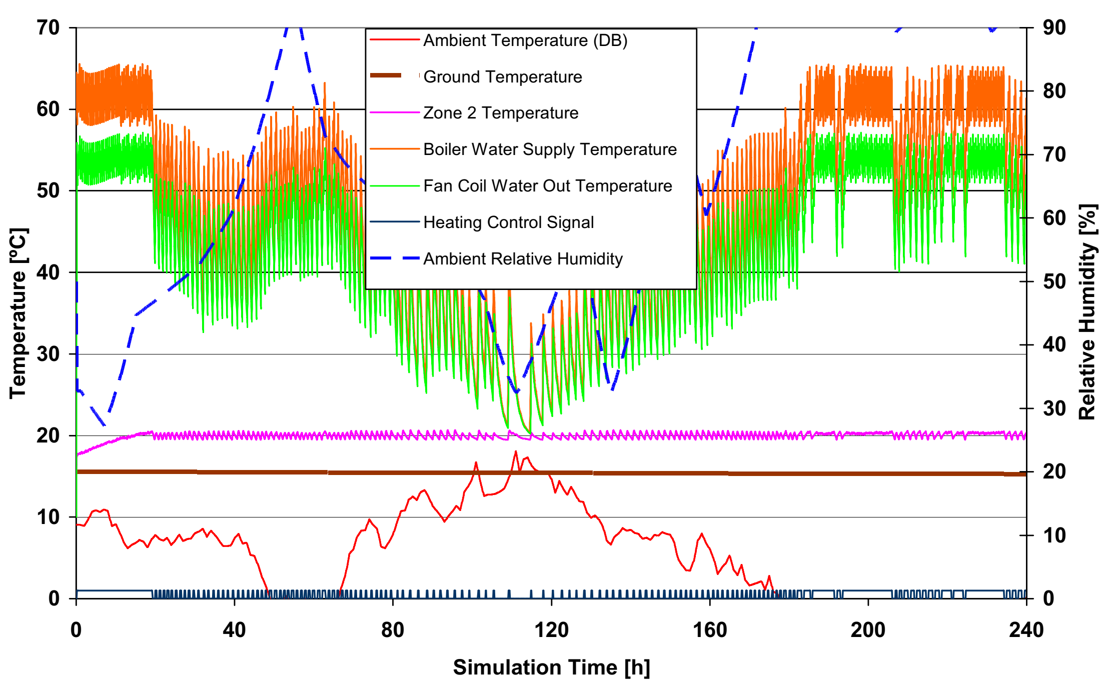

Fig. 4. Transient performance of system A (fan-coil, chiller–boiler), during the first 10 days of January. Room thermostat, which controls furnace operation, is set to 20 °C. Boiler thermostat is set to 60 °C.

Fig. 4. The system's and control operation in heating mode is apparent in this Figure. During hours 0–20, the room thermostat commands the boiler to be always on, to heat up the house. During this period, the boiler is set on and off according to its own thermostat, which is set to 60 °C. After this initial heating-up period, the room thermostat starts to cycle on/off, keeping the room's temperature to 20 °C within ±1 °C. During the very cold days (e.g. hours 190–210), the room thermostat stays always on, and the boiler's operation is controlled by its own aquastat. On days with higher temperatures, the room thermostats cycle quickly on and off and do not allow the boiler to stay on for enough time to reach its aquastat setting of 60 °C.

A typical graph of winter operation of system B is presented in Fig. 5 for the first 10 days of January. During hours 0–80, the room thermostat commands the heat pump

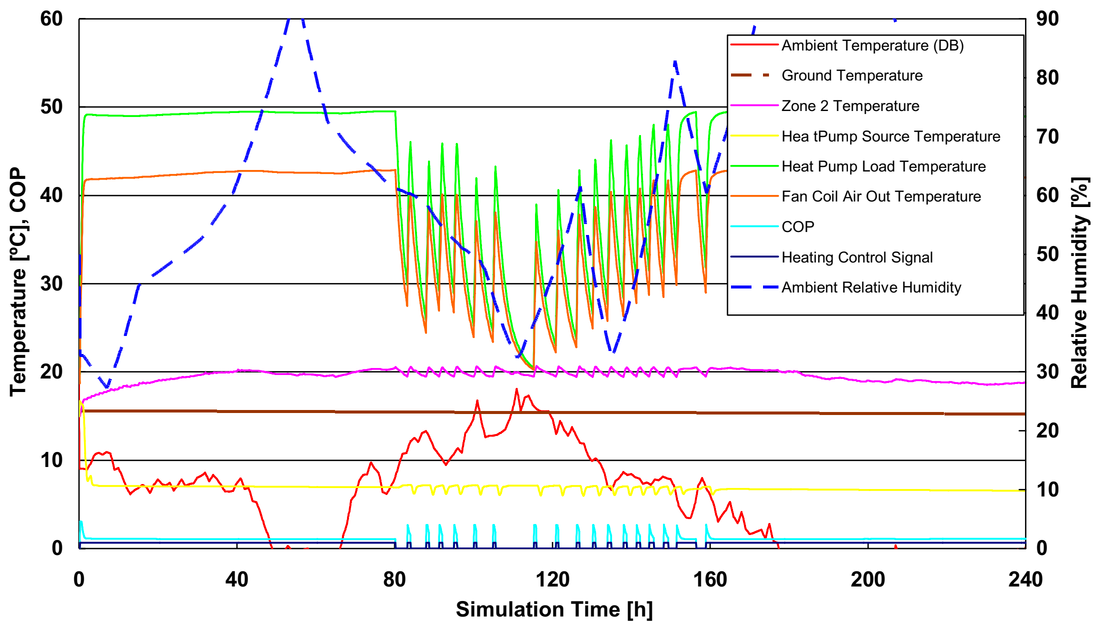

Fig. 5. Transient performance of system B (fan-coil, ground source water-to-water heat pump), during the first 10 days of January. Room thermostat, which controls heat pump operation, is set to 20 °C.

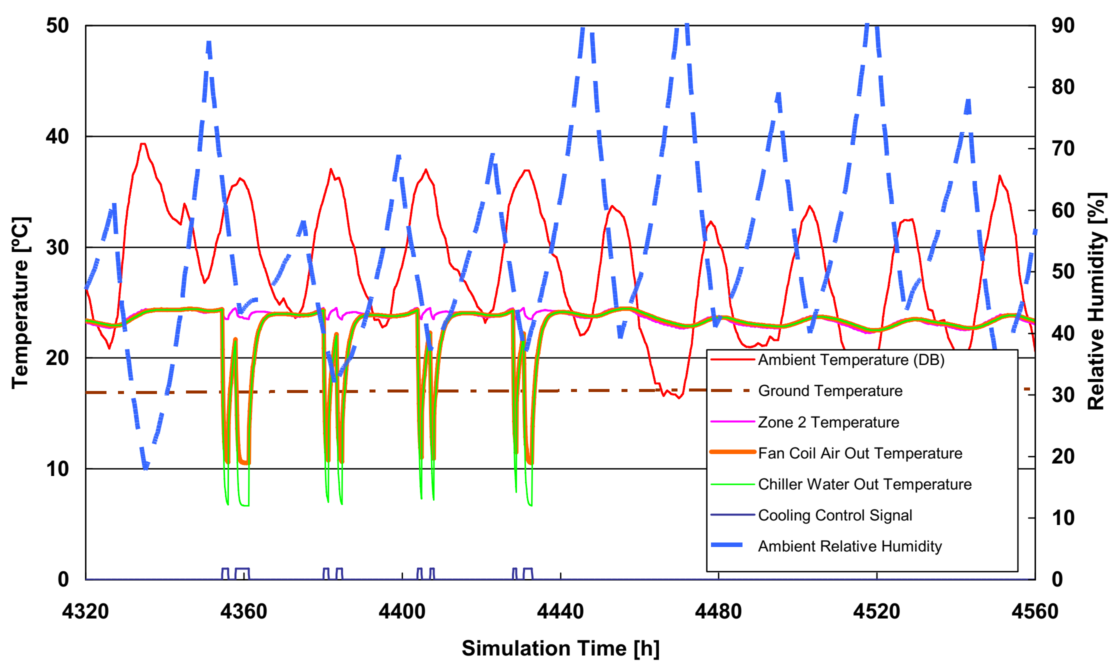

Fig. 6. Transient performance of system A (fan-coil, chiller), during the first 10 days of July. Room thermostat, which controls chiller operation, is set to 24 °C.

to be always on, to heat up the house. After this initial heat-up period, the room thermostat starts to cycle between on/off. During the very cold days (e.g. hours 45–70, 180–240), the room thermostat stays always on, and the heat pump is continuously working. Figs. 4 and 5 reveal much less on/off cycling of the ground source heat pump system.

A typical graph of summer operation of system A is presented in Fig. 6, for the first 10 days of July of the Typical Meteorological Year. The system's and control operation in heating mode is apparent in this Figure. The onset of high ambient temperatures at about 4330 h will require, after a time lag of several hours, the starting of the chiller operation. The chiller stays on during the hot hours of each

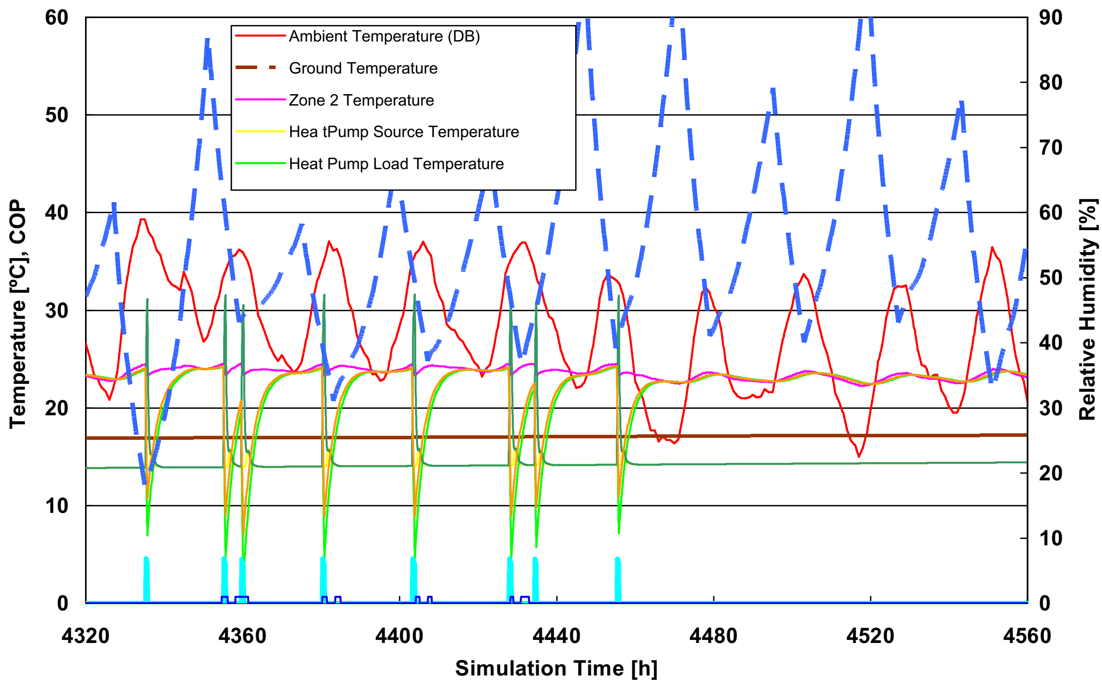

Fig. 7. Transient performance of system B (fan-coil, ground source water-to-water heat pump), during the first 10 days of July. Room thermostat, which controls heat pump operation, is set to 24 °C.

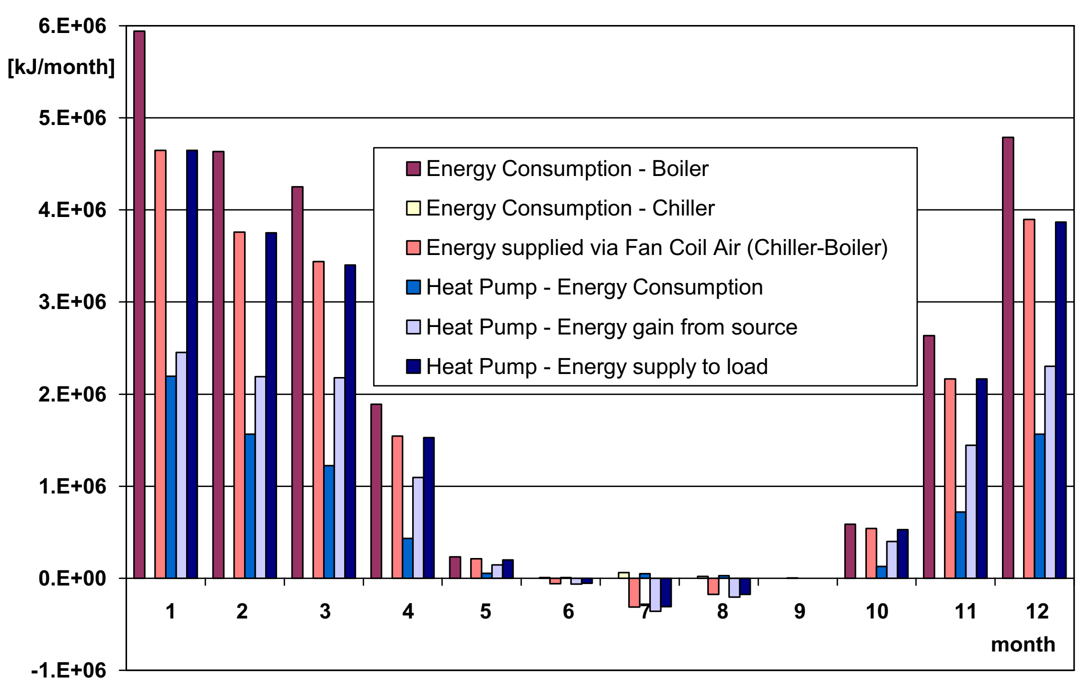

Fig. 8. Yearly performance comparison between systems A (chiller–boiler) and B (ground source heat pump).

day, until the ambient temperature levels drop after 4460 h. The small size of the chiller is responsible for the presence of only two on/off cycling during one day (in contrast to the frequent boiler cycling).

A typical graph of summer operation of system B is presented in Fig. 7 for the first 10 days of July of the TMY. The ground source heat pump's operation in cooling mode is apparent in this Figure. It must be noted that also in the cooling mode the ground source heat pump presents very little on/off cycling (one cycle each day). This presents important advantages in energy consumption as shown in the comparison of yearly performance of the alternative systems in Fig. 8. The comparative energy consumption results of this Figure agree with the empirical estimates that ground source heat pumps have 50% lower operation costs to the standard chiller–boiler HVAC systems (Table 1). In interpreting the economics of this Figure, we should keep in mind that boiler consumption kWh's are thermal, while chiller and heat pump consumption kWh's are electrical. The full thermodynamic benefits of the exploitation of heat pumps instead of boilers are only gained through cogeneration [25].

7. Effect of control settings - equipment sizing

The performance summary for the heating season is compared in Fig. 9 for the reference system A (11 kW boiler, thermostat set to 20 °C), a variation with the room thermostat set to 22 °C and another variation with a 22 kW boiler. According to these results, increasing the thermostat setting by 2 °C would significantly increase yearly heating energy consumption.

On the other hand, the oversized boiler is predicted to result in a relatively low fuel consumption penalty. However, the detail of simulation of boiler operation in the specific model is not adequate to assess the full penalty (starting losses of the boiler etc). Good engineering practice results to normal area per cooling unit of about 25–35 m^2 per ton (3.6 kW) for commercial buildings in Greece. Lower values correspond to higher ventilation rates (e.g. classrooms, laboratories etc). Higher values are indicative also of residential buildings. However, building HVAC sys-

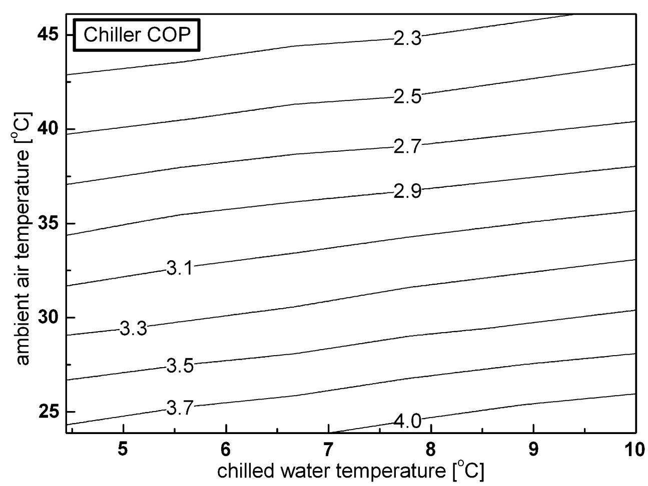

Fig. 10. COP characteristics of standard chiller employed in system A.

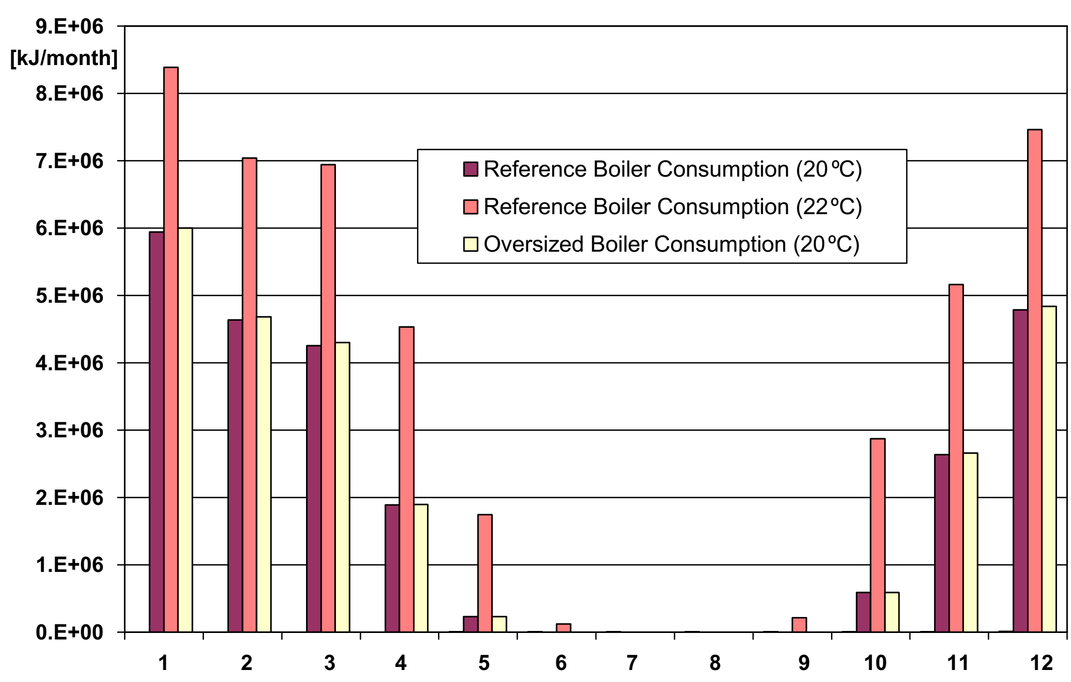

Fig. 9. Summary of system A heating performance: effect of thermostat setting (20 versus 22 °C) and boiler size (11 versus 22 kW).

tems designers tend to overdimension the equipment. Obviously, apart from the operation expenses, this practice penalizes installation and maintenance cost, and could damage the overall payback time advantage of ground source heat pump. ''Level II'' systems simulations, as those demonstrated here, allow exact sizing of the equipment with good estimates of percentage of failure to cover heating and cooling load peaks. In this way, they can be a valuable tool for the building design process [26].

8. Effect of chiller cop – control settings

A high efficiency chiller is expected to significantly improve system's performance [27]. Fig. 10 presents a map of COP characteristics of the standard air-cooled chiller employed in system A, as function of chilled water temperature level and ambient dry bulb temperature levels. Before considering the adoption of a higher efficiency chiller, one should check the total electricity consumption for cooling in system A. To this end, we perform a comparative check for two different room thermostat settings: 24 and 26 °C respectively. It is interesting to note that no compressor cooling is necessary when the room thermostat is set to 26 °C. Even for the very low thermostat setting of 24 °C, very low electricity consumption is predicted for the chiller of system A (Fig. 11). This could be attributed to the mild climate of Volos, the high degree of insulation of the house and the heavy construction that leads to a high heat capacity [28]. Of course, a chiller with 50% overall increase in COP, compared to the standard chiller of Fig. 10, would demonstrate even lower power consumption according to Fig. 11. However, there would be no hope for

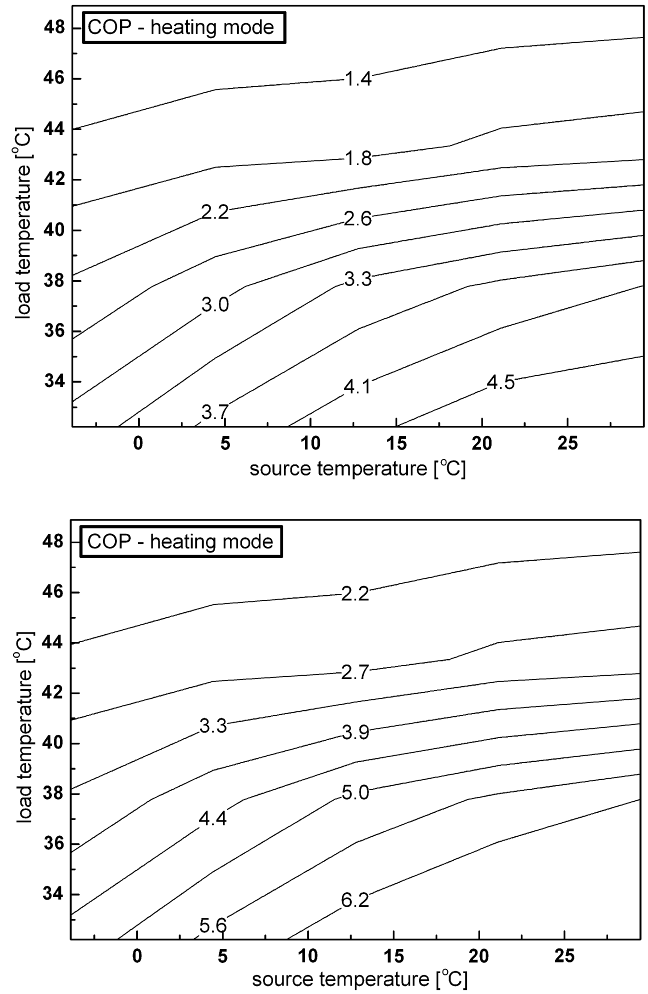

Fig. 12. Heating mode characteristics of the reference, (up) and a high efficiency (down) ground source heat pump.

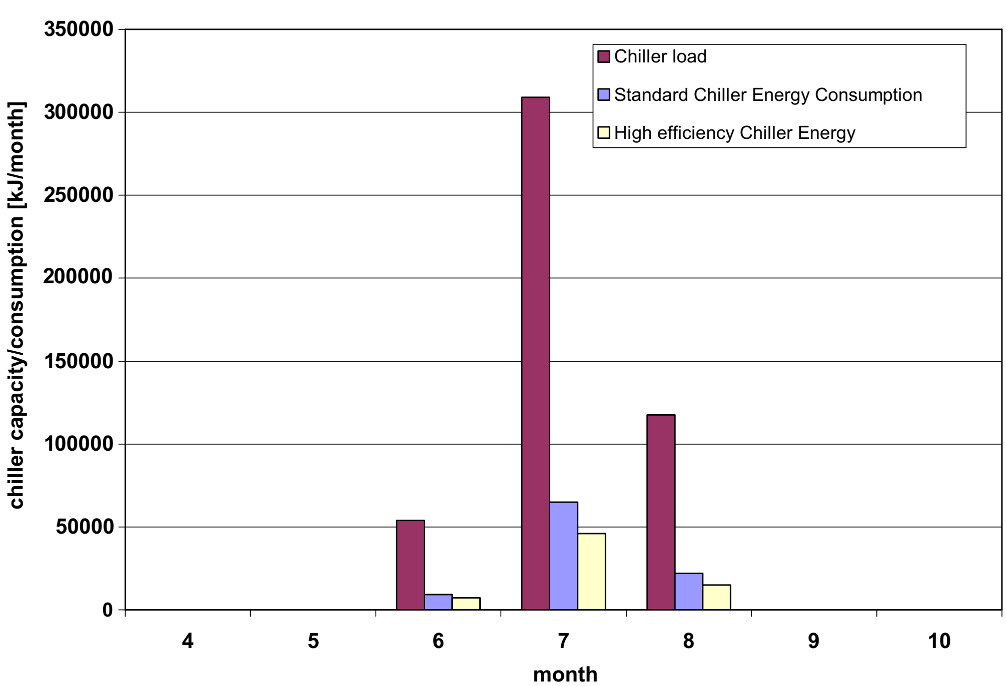

Fig. 11. Summary of performance in cooling mode: system A with standard – versus - high efficiency chiller.

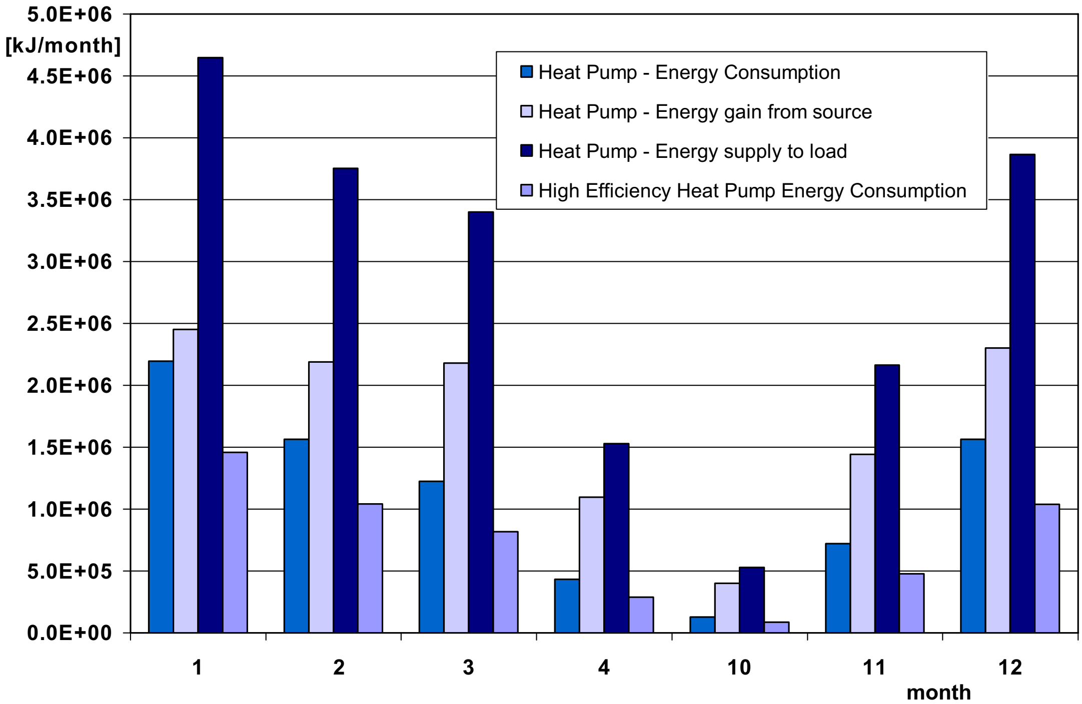

Fig. 13. Summary of heating performance system B with standard –versus-high efficiency heat pump.

payback of the added cost. The mere necessity of compressor cooling for this house is questionable.

9. Effect of heat pump cop

Comparative computations were carried out to assess the effect of high efficiency heat pumps in system B. The upper graph of Fig. 12 presents the COP map of the reference GSHP in heating mode. We may readily assess the effect of installing a higher efficiency heat pump, with the COP map of the lower part of Fig. 12 in heating mode. Indicative results of this type of computation are presented in Fig. 13. Remarkable gains in yearly energy consumption are predicted in this case. The heat pump efficiency improvement is a measure that pays back in heating mode.

10. Concluding remarks

- Detailed simulation of the building envelope and HVAC equipment, despite its added complexity, is increasingly applied in building HVAC systems design optimization. A demonstration case study is presented here.
- A detailed simulation of the HVAC system operation of a residential building is carried out, which improves understanding of its transient operation and allows more realistic system's sizing.
- "Level **II**" modelling allows good assessment of the effect of control settings, chiller or heat pump COP characteristics, equipment sizing, ventilation rates and other design parameters.
- The already reported by others, increased advantage of GSHPs in southern climates, is confirmed in the specific case study, where system's design optimization was assisted by detailed building energy simulations.
- In general, the computations confirm what is known from experience. Only the fuel consumption penalty of the oversized boiler seems to be underestimated.
- The study presented in this paper is continuing, with further development of the systems models, economic analysis and optimization.
- The proposed methodology, despite the added modeling complexity, is proven worthwhile in providing more realistic routes of system optimization.

References

[1] NN, Directive 2002/91/EC. 2002.
[2] NN, CEN/TC 89/WG 4 N 249: Energy performance of buildings – calculation of energy use for space heating and cooling; 2004.
[3] NN. Doing more with less: Green paper on energy efficiency COM(2005); 2005.
[4] Hepbasli A, Akdemir O. Energy and exergy analysis of a ground source (geothermal) heat pump system. Energy Convers Manage 2004;45:737–53.
[5] Hepbasli A, Akdemir O, Hancioglu E. Experimental study of a closed loop vertical ground source heat pump system. Energy Convers Manage 2003;44(4):527–48.
[6] Doherty PS et al. Ground source heat pump – description and preliminary results of the Eco House system. Appl Therm Eng 2004;24:2627–41.
[7] Sanner B, Karytsas C, Mendrinos D, Rybach L. Current Status of ground source heat pumps and underground thermal energy storage in Europe Geothermics; 2003;32: p. 579–88.

[8] Zogou O, Stamatelos A. Effect of climatic conditions on the performance of heat pump systems for space heating and cooling. Energy Convers Manage 1998;39(7):609–22.
[9] Sauer HJ, Howell RH. Heat pump systems. New York: J. Wiley & Sons; 1983.
[10] Florides GA et al. Measures used to lower building energy consumption and their cost effectiveness. Appl Energy 2002;73:299–328.
[11] Zhen Huang W, Zaheeruddin M, Cho SH. Dynamic simulation of energy management control functions for HVAC systems in buildings. Energy Convers Manage 2006;47:926–43.
[12] NN, Exergo-economic optimization of air-to-air heat pumps for space heating and cooling. Volos: LTTE/University of Thessaly; 1999.
[13] Dhakal S, Hanaki K, Hiramatsu A. Heat discharges from an office building in Tokyo using DOE-2. Energy Convers Manage 2004;45: 1107–18.
[14] Sakellari D, Lundqvist P. Energy analysis of a low-temperature heat pump heating system in a single-family house. Int J Energy Res 2004;28:1–12.
[15] Sakellari D. Modeling the dynamics of domestic low-temperature heat pump heating systems for improved performance and thermal comfort-a systems approach, in PhD thesis. Royal Institute of Technology, Stockholm; 2005.
[16] Cheung CK, Fuller RJ, Luther MB. Energy-efficient envelope design for high-rise apartments. Energy and Buildings 2005;37:37–48.
[17] Lazzarin RM, Castellotti F, Busato F. Experimental measurements and numerical modelling of a green roof. Energy and Buildings 2005;37:1260–7.
[18] Mei L et al. Thermal modelling of a building with an integrated ventilated PV facade. Energy and Buildings 2003;35:605–17.
[19] Lindenberger D et al. Optimization of solar district heating systems: seasonal storage, heat pumps, and cogeneration. Energy 2000;25: 591–608.
[20] Neymark J et al. Applying the building energy simulation test (BESTEST) diagnostic method to verification of space conditioning equipment models used in whole-building energy simulation programs. Energy and Buildings 2002;34:917–31.
[21] ANSI/ASHRAE, Standard 140-2001, Standard method of test for the evaluation of building energy analysis computer programs, R. American Society of Heating, and Air-Conditioning and Engineers, editors. ASHRAE, Atlanta, GA; 2001.
[22] NN, TESS. Component libraries for TRNSYS, version 2.0. User's Manual,. 2004, Madison WI: http://www.tess-inc.com/services/software.
[23] NN. ANSI/ASHRAE Standard 62.2–2004: Ventilation and acceptable indoor air quality in low-rise residential buildings. 2004. pp. 18.
[24] NN, ASHRAE Handbook. Fundamentals. 2005;1.
[25] NN, EDUCOGEN CA. The european educational tool on cogeneration. In: Commission E, editor. 2001, http://www.cogen.org/projects/educogen.htm.
[26] Bachman L. Integrated buildings: the systems' basis of architecture. Hoboken, NJ: John wiley & Sons, Inc.; 2003. pp. 480.
[27] Brodowicz K, Dyakowski T. Heat pumps. Butterworth-Heinemann. 1993.
[28] Kalogirou SA, Florides G, Tassou S. Energy analysis of buildings employing thermal mass in Cyprus. Renew Energ 2002;27: 353–68.