

OPTIMIZATION OF THERMAL PERFORMANCE OF A BUILDING WITH GROUND COUPLED HEAT PUMP SYSTEM

Olympia Zogou and Anastassios Stamatelos*

University of Thessaly, Department of Mechanical Engineering
Pedion Areos, 383 34 Volos, Greece

ABSTRACT

Component optimization studies during the last twenty years, point to the use of ground source heat pump systems to minimize building heating and cooling costs. Modern computational tools enable building energy simulation for a typical year with a time step of the order of minutes. This allows improved insight in the details of its transient operation and may significantly affect the form of the objective function employed in the component optimization procedure, as demonstrated in this paper. A 3-zone residential building located in Volos, Greece, is modelled along with its chiller - boiler or heat pump, hydronic distribution system and their controls, in the TRNSYS 16 environment. Yearly performance of the building with the reference, chiller-boiler system, is compared to that of the alternative, ground source heat pump system. 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.

Keywords: Heat Pumps, Building Energy Simulation, Optimization, Systems Design.

NOMENCLATURE

ACH Air changes per hour
COP Coefficient of performance
TMY Typical Meteorological Year
GSHP Ground source heat pump

INTRODUCTION

The minimization of energy consumption for space heating and cooling is crucial nowadays due to increasing energy costs and CO₂ 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. Should voluntary compliance with the standards not be forthcoming, then mandatory standards should be considered in a future amended version of the buildings directive [2]. Especially with regard to electrical energy, it is important to minimize also peak demand, by avoiding equipment oversizing. On Thermodynamics grounds, the use of heat pumps for space heating and cooling is advantageous, due to the reduced pumping temperature difference.

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 [3,4,5]. 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 [6,7]. However, the installation cost is also higher for the GSHPs and thus proper sizing of the equipment is crucial to the amortization of the investment. Proper sizing needs to be based on detailed system simulation, including building envelope, HVAC equipment and control system.

FORMULATION OF THE SIMULATION

Building energy simulation can be carried out in two levels: (I) simulation mainly of the building envelope with simplifying assumptions

* Corresponding author: Phone: +30 24210-74067, Fax: +30 24210-74096, E-mail: stam@uth.gr

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 [8]. 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 [9].

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 [10,11]. 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 m² of building space, deduced from installation experience and commercial literature.

Table 1 Indicative economic performance data for alternative HVAC systems (€/m² of building space)

SYSTEM COMPARED	ANNUAL MAINTEN. EXPENSE	ANNUAL OPER. EXPENSE	INSTALLATION COST
FAN COIL, CHILLER/BOILER 4-PIPE	1.2	12.	100
VARIABLE AIR VOLUME	1.2	8.	80
GEOHERMAL HEAT PUMP	0.6	6.	90
WATER LOOP HEAT PUMP	0.9	8.	70

One of the objectives of the present study 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 Figure 1 - a two store building with basement. 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.

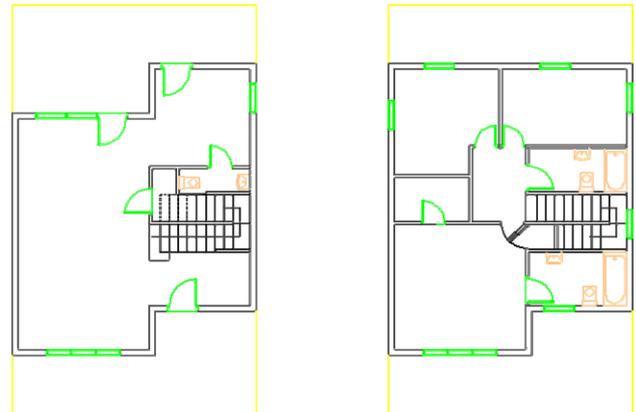


Figure 1 Layout drawing of the residential building employed in the simulations (ground and 1st levels)

HVAC SYSTEM MODELING DETAILS

Heating capacity for both system A and system B was set to 11 kW. The ground source heat pump system uses a ground coil of 180m 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.

The system's model, (Figure 2 and Figure 3, respectively, for the alternative systems A and B), comprises a 3-zone building model, air-cooled chiller and water-source heat pump model, boiler, pump, fan coils, controls, ground coil model, TMY and ground temperature models, psychrometric model, shading model, is used to determine the annual performance of the building.

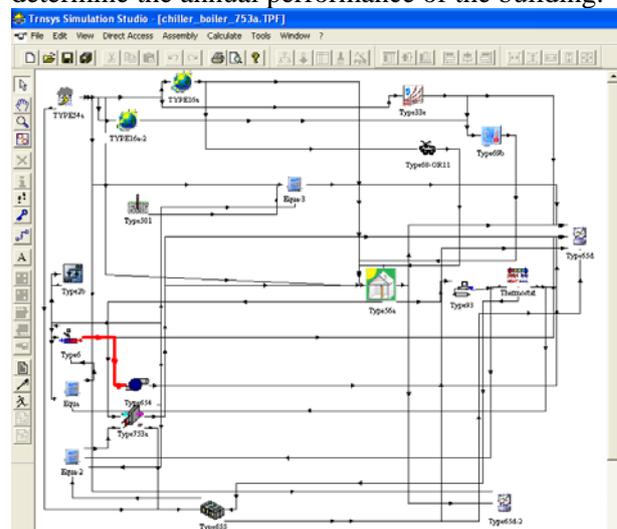


Figure 2 TRNSYS 16 project file, system A (fan coils, chiller/boiler system)

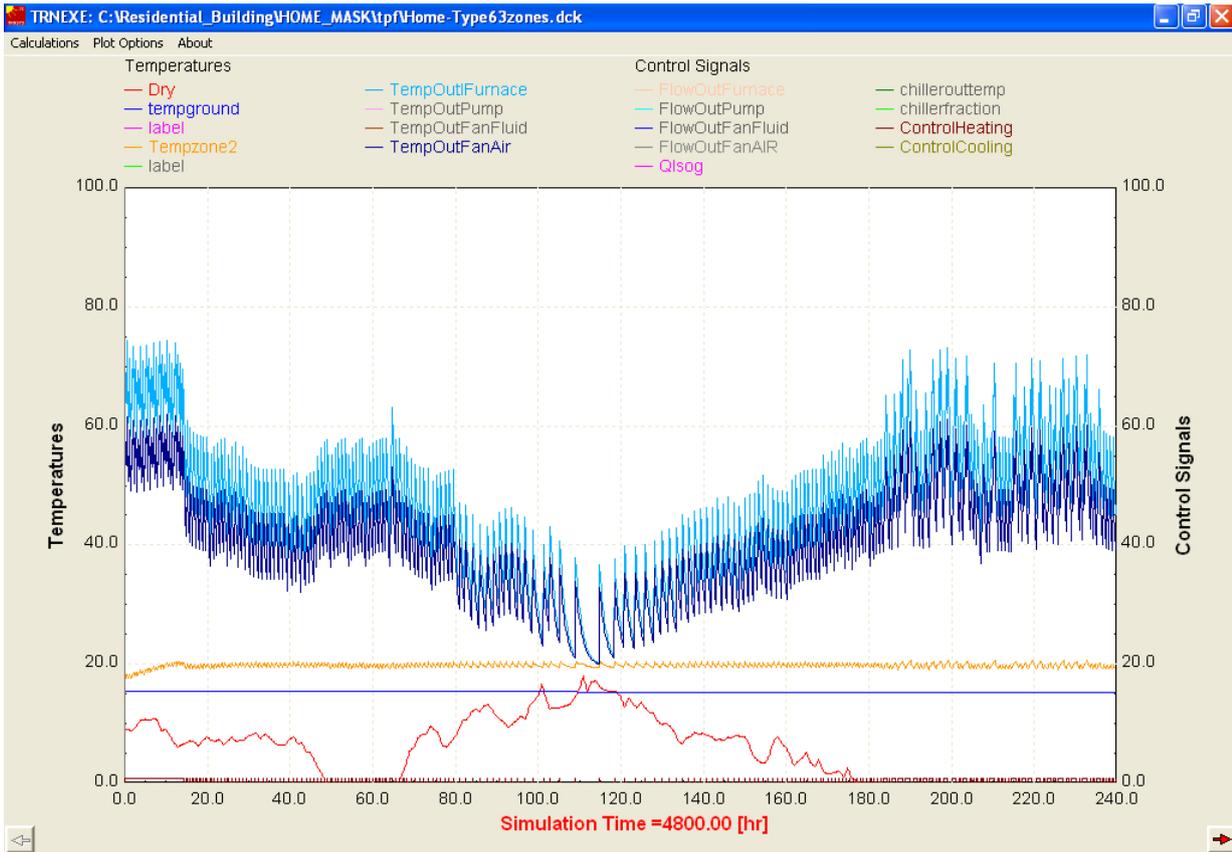


Figure 4 Transient performance of system A (fan-coil, chiller-boiler), during the first 10 days of January. Room thermostat, which controls furnace operation, is set to 20°C. Boiler thermostat is set to 60°C.

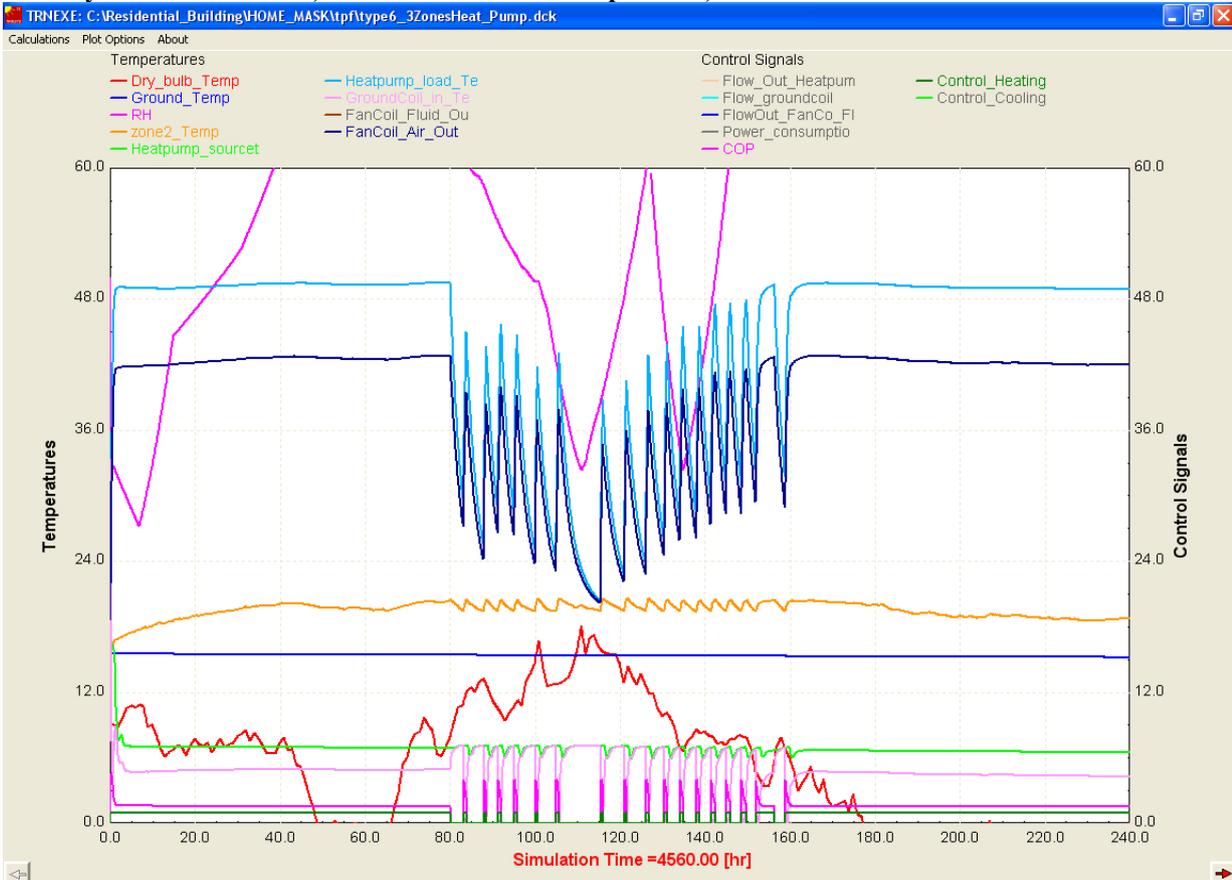


Figure 5 Transient performance of system B (fan-coil, ground source water-to-water heat pump), during the first 10 days of January. Room thermostat, which controls heat pump operation, is set to 20°C.

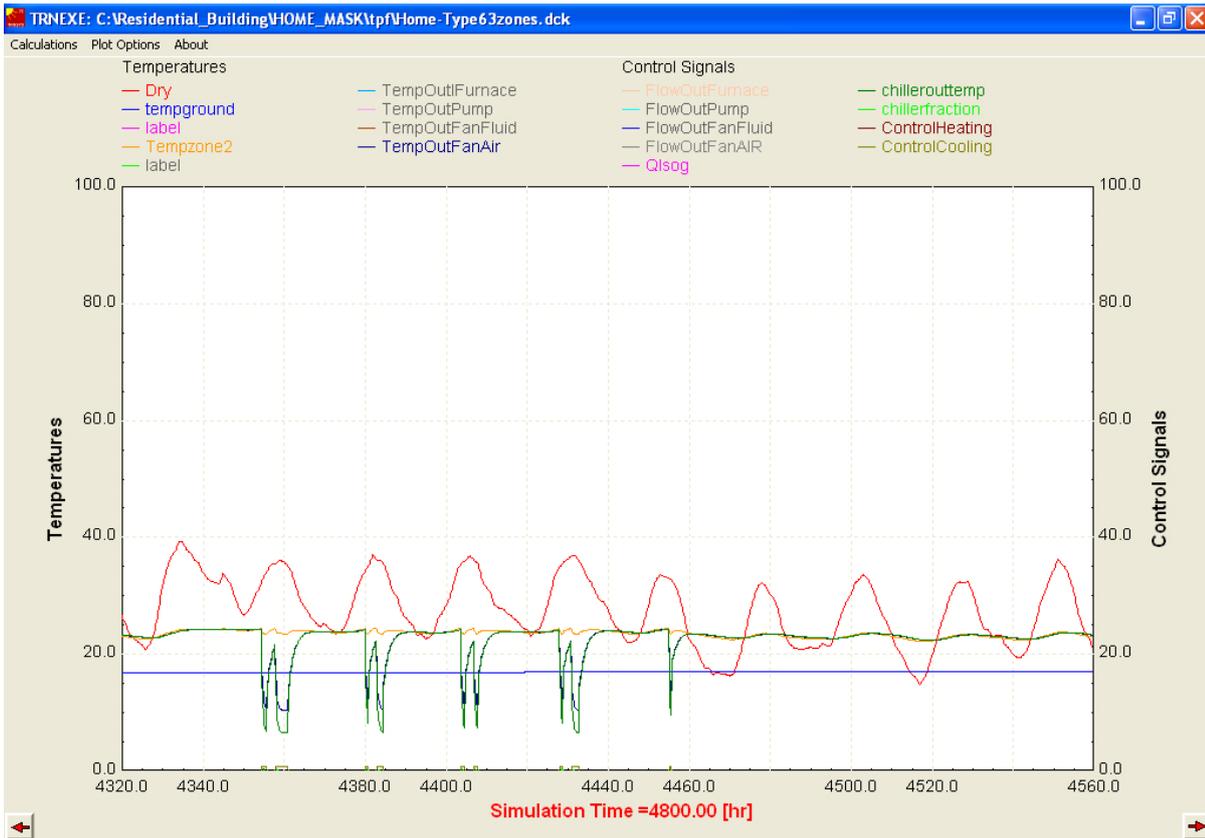


Figure 6 Transient performance of system A (fan-coil, chiller), during the first 10 days of July. Room thermostat, which controls chiller operation, is set to 24°C.

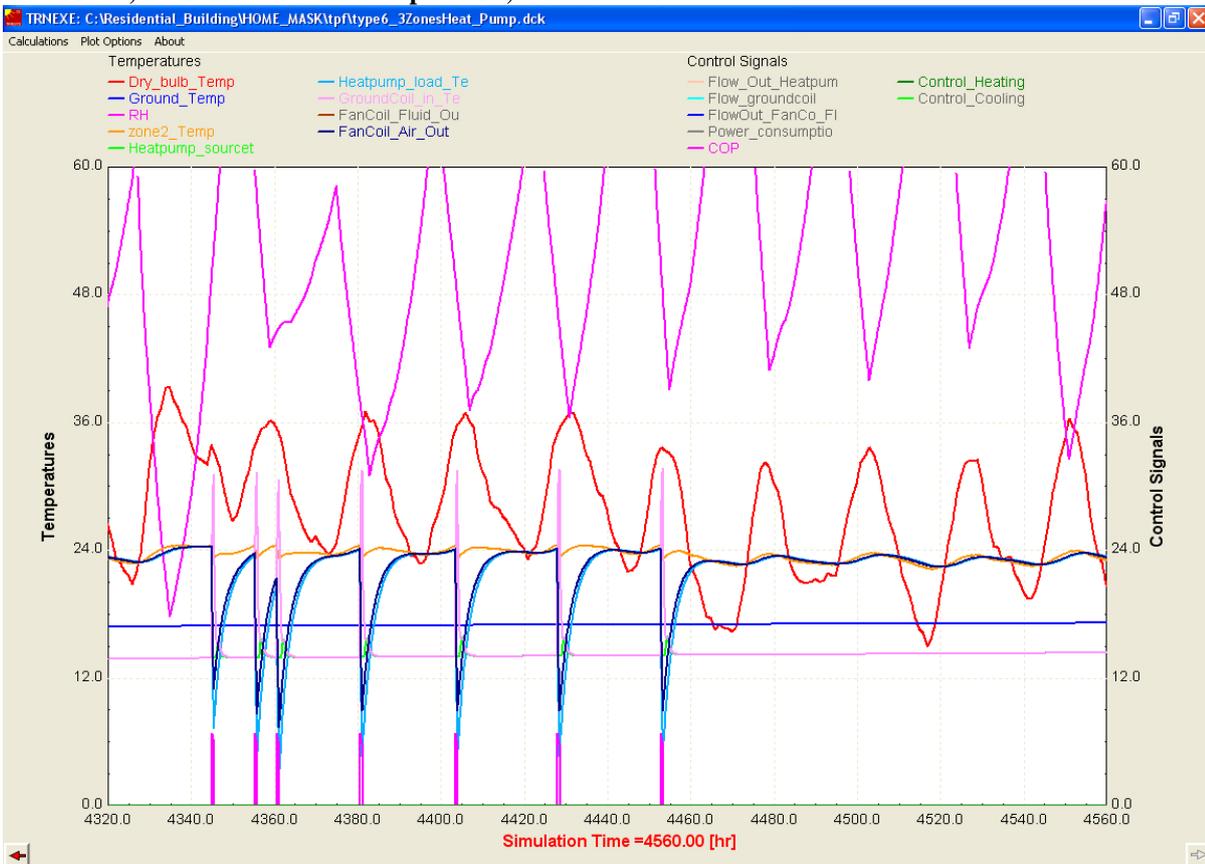


Figure 7 Transient performance of system B (fan-coil, ground source water-to-water heat pump), during the first 10 days of July. Room thermostat, which controls heat pump operation, is set to 24°C.

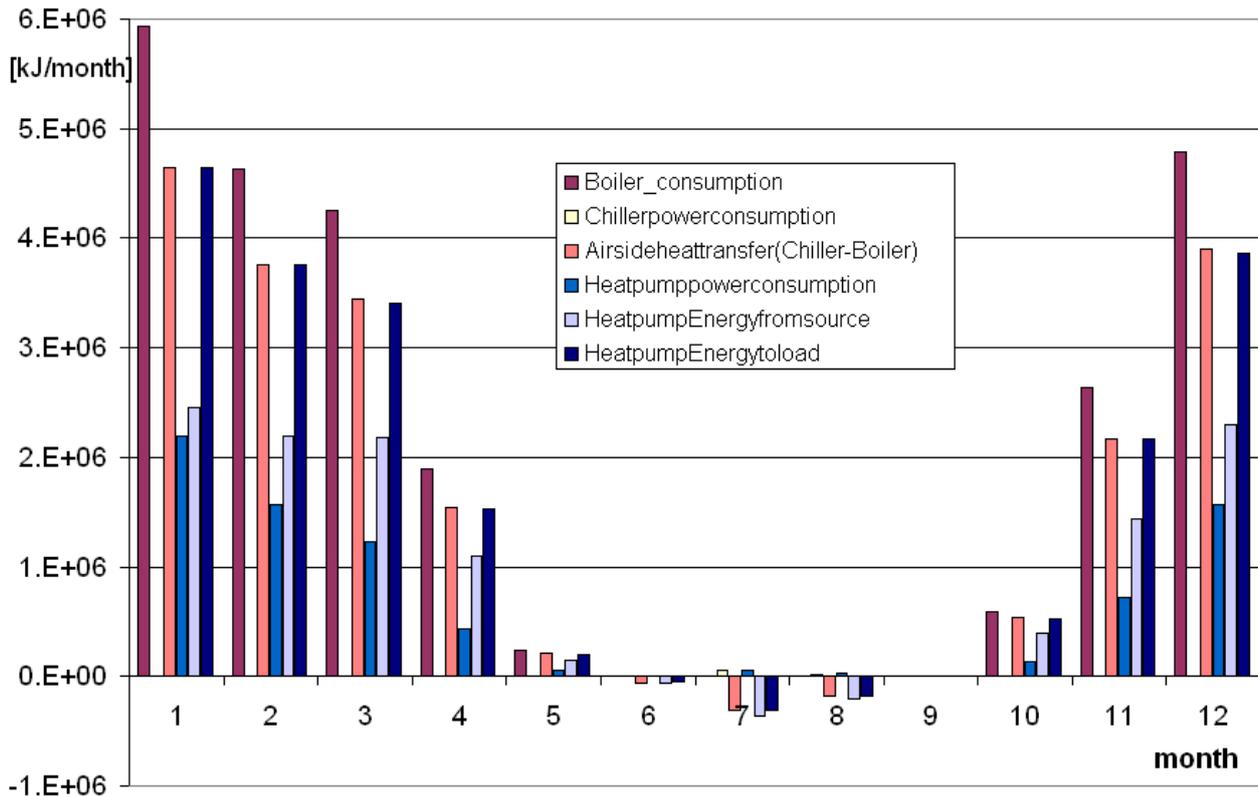


Figure 8 Yearly performance comparison between systems A (chiller-boiler) and B (ground source heat pump).

Figures 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 Figure 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 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 high boiler cycling).

A typical graph of summer operation of system B is presented in Figure 8 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 Figure 8. In interpreting this Figure, we should keep in mind that boiler consumption kWh's are thermal, while chiller and heat pump consumption kWh's are electrical.

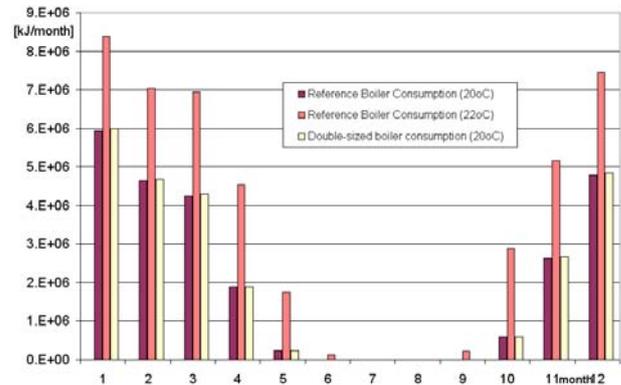


Figure 9 Summary of system A heating performance: effect of thermostat setting (20 versus 22 °C) and boiler size (11 vs 22 kW).

EFFECT OF CONTROL SETTINGS AND EQUIPMENT SIZING

The performance summary for the heating season is compared in Figure 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 m² 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 systems designers tend to overdimension the equipment. Apart from the operation expenses, this practice naturally 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.

EFFECT OF CHILLER COP - CONTROL

A high efficiency chiller is expected to significantly improve system's performance [15]. Figure 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.

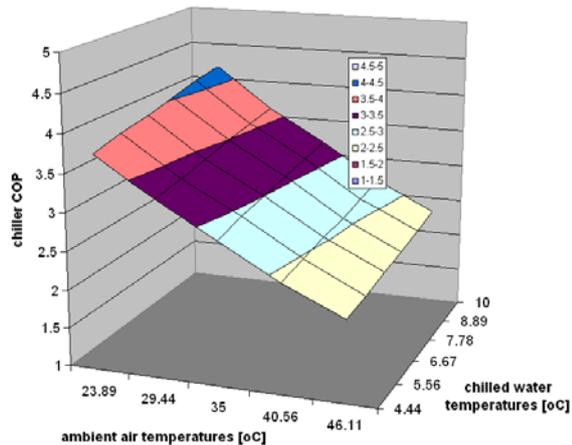


Figure 10 COP characteristics of standard chiller employed in system A

Before considering the adoption of a better chiller, one should check the total electricity consumption for cooling in system A. Before this, 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 extremely

low thermostat setting of 24°C, very low electricity consumption is predicted for system's A chiller (Figure 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 [16]. Of course, a chiller with 50% overall increase in COP, compared to the standard chiller of Figure 10, would demonstrated even lower power consumption according to Figure 11. However, there would be no hope for payback of the added cost. Even the necessity of compressor cooling for this house is questionable.

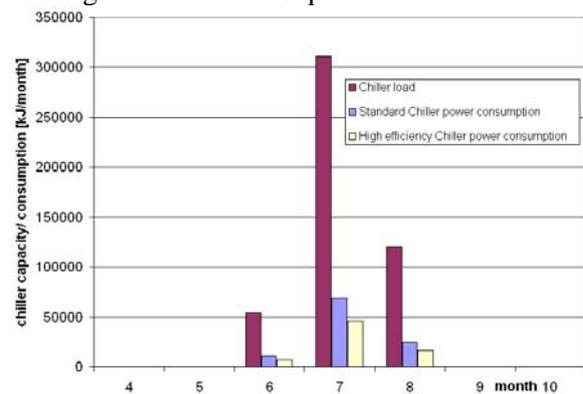


Figure 11 Summary of performance in cooling mode: system A with standard –versus- high efficiency chiller.

EFFECT OF HEAT PUMP COP

Comparative computations were carried out to assess the effect of high efficiency heat pumps in system B. Figure 12 presents the COP characteristics of the reference GSHP in heating and cooling mode. We may readily assess the effect of installing a high efficiency heat pump, say with a 50%- higher overall COP in heating mode. Indicative results of this type of computation are presented in Figure 13. Remarkable gains in yearly energy consumption are predicted.

CONCLUDING REMARKS

- Detailed simulation of the building envelope and HVAC equipment, despite its increased complexity, is increasingly applied in building HVAC systems design optimization.
- In this paper, a detailed simulation of the HVAC system operation of a residential building is carried out, which allows good understanding of its transient operation and allow 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.

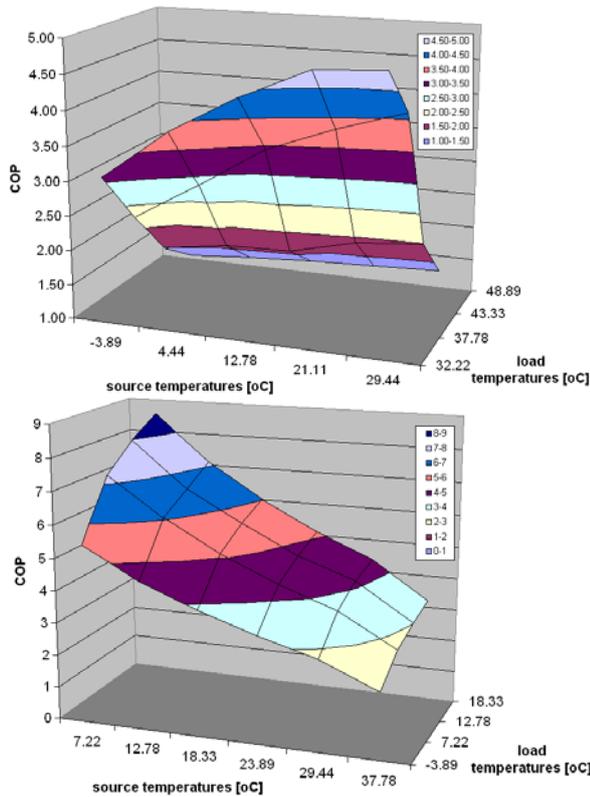


Figure 12 Heating and cooling mode characteristics of the reference ground source heat pump.

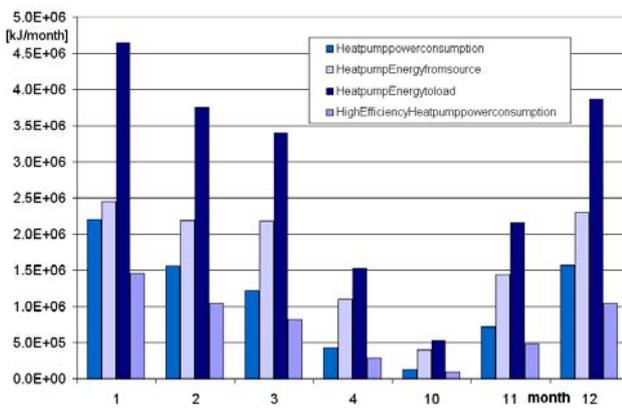


Figure 13 Summary of heating performance system B with standard –vs- high efficiency heat pump.

- In general, the computations confirm what is known from experience. Only the fuel consumption penalty of the oversized boiler seems to be underestimated.

- Further development of building systems' models, despite its complexity, is proven worthwhile in providing more realistic routes of system optimization.

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