Computational Analysis of Two Arrangements of a Central Ground-Source Heat Pump System for Residential Buildings

Ehab Foda, Ala Hasan, Kai Sirén
Helsinki University of Technology, HVAC Technology, FI-02015 TKK, Finland
ehab.foda@tkk.fi

Abstract

This study aims at obtaining a computational comparison between the performance of two different ground-source heat pump (GSHP) central system arrangements used for heating, cooling and domestic hot water (DHW) energy production for a residential area. The required space heating and cooling energy for the buildings is calculated using dynamic building performance simulation, ground heat exchange simulation and a GSHP model created to study the hourly performance of the system. The system performance is determined and the total required electrical energy is calculated for the two arrangements. The results obtained from this case study show that the seasonal performance factor (SPF) for the arrangement that totally uses the GSHP in the DHW energy production is considerably higher than the partial use of GSHP for that purpose.

1. Introduction

Ground-source heat pump (GSHP) has become a popular method for producing heating, cooling and domestic hot water (DHW) energies for residential buildings using centralised or decentralised systems. The objective of this study is to develop basic concepts and perform computational comparisons to serve as a starting point for the energy and HVAC system design of a residential area at Nupuri-Espoo, Finland.

In this study, the GSHP system performance is analysed based on two different system arrangements, where the main variant is the method of DHW energy production. System *Arrangement 1* partly uses the GSHP system in the DHW energy production along with a local storage tank in each house, which is equipped by a back-up electrical heater to provide the DHW at a proper final temperature. System *Arrangement 2* totally produces the DHW energy using a 2-stage or cascade GSHP system. The simulation of the building energy performance is carried out using IDA ICE 3.0 (IDA Indoor Climate and Energy) software [1] while the ground side simulation is obtained using EED 2.0 (Earth Energy Designer) software [2]. Then, the output results from IDA ICE 3.0 and EED 2.0 are entered to a GSHP model that is created to analyse the performance of the system. The hourly energy consumption of the GSHP system is calculated then the coefficient of performance (COP) and the seasonal performance factor (SPF) for the two arrangements are compared for better energy performance of the system.

2. Nupuri residential area

Nupuri residential area is an area of 40 hectares located in Hista region at Espoo city. It consists of 219 houses of different types (attached, semi-detached, cluster and single family houses). The buildings are arranged into 17 residential blocks. The number of buildings per each block varies from a single building to several buildings including service buildings such as day-care, gas-station and food stores. The building blocks are divided into 4 groups and each group has its own energy production system. In this study, one of those 4 groups is selected as a case study and is named *Group1*.

2.1 Nupuri house

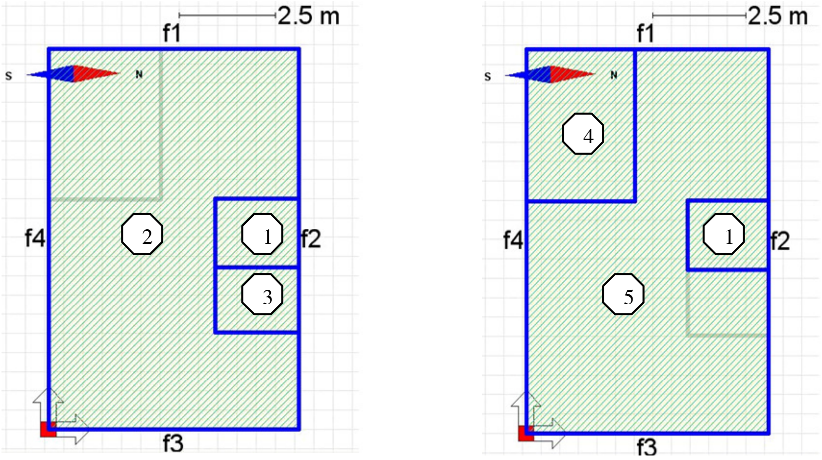
A typical Nupuri house is a two-floor attached or semi-detached house. The net area of the houses varies from 80 m² to 158m². The construction overall heat transfer coefficients (U-values) are as shown in **Table 1**; these are 30% lower than the maximum values stated in the Finnish building code for thermal insulations (C3 for the year 2007) [3].

Table 1. U-values of the construction.

Item	U-value (W /m^{2}K)
External walls	0.17
External roof	0.10
External floor	0.17
Windows	1.10
External doors	1.10

2.2 IDA ICE 3.0 model house

Preliminary architecture drawings are used in this study as the basis for the building energy calculations. A typical house is considered from those drawings to construct the model house on IDA ICE 3.0 [1] and as shown in **Fig. 1**. The specifications of the house are shown in **Table 2**. The house net area is 128 m^2 with a room height of 2.5 m. The number of occupants is five. The house is divided into five main zones according to different heating and cooling system settings in each zone. The fresh and exhaust air are mechanically maintained according to the common approach for residential houses in Finland, which is supplying the fresh air into bedrooms and living room while the exhaust is taken through the bathrooms and the kitchen ventilation hood. Profiles of internal heat gains in the house are assumed for occupants, appliances and lighting, as well as DHW consumption. IDA ICE 3.0 hourly simulation results are used to calculate the space heating and cooling energies per square meter. Then, the heating and cooling systems losses are added according to the Finnish building code (D5) [4]. The DHW energy and the electrical energy consumption for domestic appliances are directly estimated according to the D5 code [4].



(a) Ground Level *(b) Upper Level*

Fig.1. Zones in IDA ICE 3.0 Model House: 1. Staircase, 2. Living room + kitchen + one bedroom, 3. Bathroom, 4. Bathroom, 5. Three bedrooms + corridor.

The heating system of the house is under-floor heating system. The water supply temperature from GSHP is linearly proportional to the outdoor air temperature (supply temperatures of 35 °C and 20 °C at outdoor air temperatures of -26 °C and 20°C, respectively). The same heating water is also supplied to the ventilation air handling units. The under-floor water piping is used for cooling during summer, where cooling water is supplied at 18 °C by a free cooling heat exchanger. However, this is not applicable for the bathrooms zones whereas the heating is always used in all seasons. The final DHW temperature at consumers is 55 °C that is provided by two different system arrangements.

Table 3. IDA ICE 3.0 Model specifications

Item	**Specifications**
Windows Type	Pilkington Sun-cool HP Brilliant 50
Internal shading	Blinds between panes 50% open
External shading	145 mm windows recess and balcony on western façade
Heating system	Under-floor water heating
Heating set point temperature	21 °C for rooms and 22°C for bathrooms
Cooling system	Under-floor water cooling
Cooling set point temperature	26 °C
Internal heat gains	According to D5 code [4]
Ventilation system	Mechanical system (supply air at 18°C)
Ventilation flow rate	53.3 l/s = 0.6 air change per hour (ACH)
Heat recovery system efficiency	0.7 (Annual average value)
Tightness n50	1.5 ACH
Outdoor conditions	Helsinki 2001 weather file

2.3 EED 2.0 Ground model

EED 2.0 software is used for the GSHP ground heat exchange simulation. EED software uses algorithms that have been derived from modelling and parameter studies with a numerical simulation model (SBM) resulting in analytical solutions of the heat flow with several combinations for the bore hole pattern and geometry (g-functions) [2].

The monthly average heating and cooling loads, the key ground parameters (thermal conductivity and specific heat) as well as properties of pipe materials, a preliminary configuration (g-function) and a heat carrier fluid are the input data to the EED. The borehole thermal resistance is then calculated in the program, using the borehole geometry, grouting material, pipe material and geometry. A fluid temperature constraint in the software is used to be 0/15 ˚C as min/max values. Calculations of the boreholes depth (in meters) was carried out by Geological Survey of Finland (GTK) [5] to fulfil that constraint. The number of boreholes for *Group1* buildings is estimated to be 40 boreholes with diameter of 114 mm and using single U-tube 40mm with average depth of 189 m and boreholes spacing of 7 m.

3. GSHP System arrangements

The GSHP system is studied based on two different arrangements for heating and cooling energy production. The main difference between the two systems is related to the DHW production. The GSHP compressor (for both arrangements) is sized to cover 80% of the heating power. An auxiliary system will then be needed to cover the peak loads. The main reason for that is to avoid over-sizing of the GSHP system and to ensure the performance of the GSHP close to its full load performance. In addition, covering 100% of the heating demand by the heat pump may slightly lower the heating cost but the savings may not offset the added cost for a larger GSHP system. The cooling load is planned to be totally covered by free cooling, that is heat exchange with the ground fluid without using the heat pump.

3.1 Arrangement 1

Arrangement 1 uses a GSHP to produce the space heating energy and it is sized to produce part of the DHW energy by passing part of the supply water through a DHW heat exchanger. The DHW heat exchanger is used to preheat the city water. Then, the local back-up heater provides the DHW at the fixture temperature (i.e. 55°C). The circulation of the DHW is maintained locally. *Arrangement 1* main components (as shown in **Fig. 2**) are: a stationary GSHP that is mainly producing the space heating energy; a DHW heat exchanger; a free cooling heat exchanger as the main cooling system; pumps for the circulation of heating and cooling water as well as a local DHW circulation pump at each consumer and a back-up electrical heater storage tank at each consumer. *Arrangement 1* is thought to be a flexible arrangement to assure the temperature of the DHW supply.

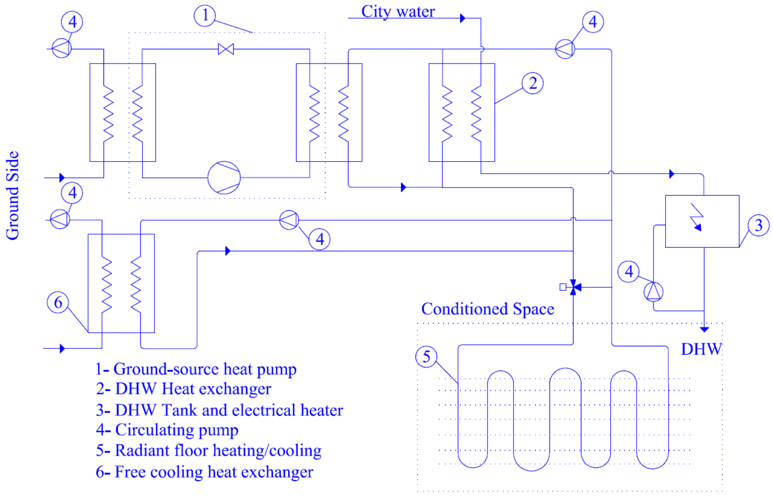


Fig.2. GSHP System Arrangement 1

3.2 Arrangement 2

Arrangement 2 uses a two-stage or a cascade GSHP to produce the space heating and the DHW energies. The DHW plant supply temperature is designed to be 60°C to compensate

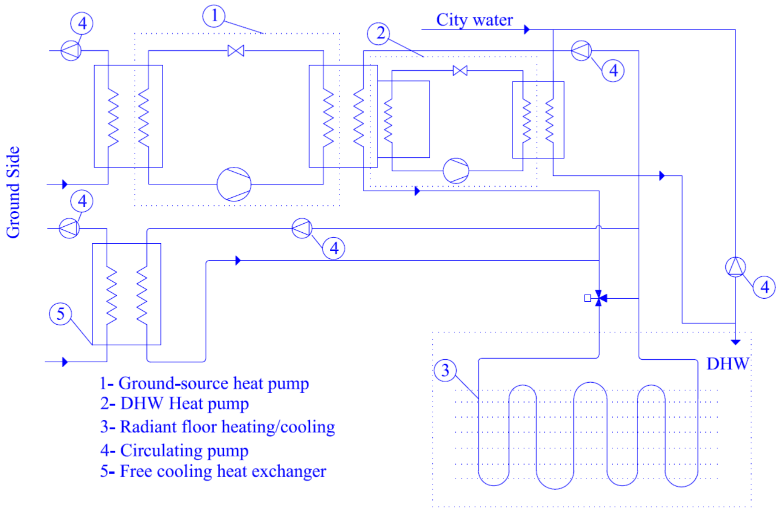


Fig.3. GSHP System Arrangement 2

for the circulation losses and also to obtain peak hours central storage at 55°C. The DHW circulation is one of the disadvantages of *Arrangement 2* since the water will keep circulating between the plant and the group of houses to maintain the DHW fixture temperature or storage temperature always at 55°C. *Arrangement 2* main components (as shown in **Fig.3**) are: 1st stage GSHP that is mainly producing the space heating energy; 2nd stage heat pump to supply the DHW at 60 °C; a free cooling heat exchanger as the main cooling system; pumps for the circulation of the heating, cooling and DHW water.

4. GSHP Modelling

The GSHP model for each system arrangement includes a similar approach in most of the calculations. The hourly load (Q_c) from IDA ICE 3.0 calculations and the hourly outdoor air temperature (T_o) from Helsinki 2001 weather data are used as hourly input data.

The supply water temperature (T_s) varies linearly with the outdoor air temperature (T_o). An estimation of the conductance of the space heating system (G_r) is made based on the peak heating power. Then, the return temperature (T_r) is calculated iteratively with the water mass flow rate (m) from

$$T_r = T_{room} + \exp\left[\ln(T_s - T_{room}) - \frac{G_r}{mc_p}\right] \tag{1}$$

$$m = \frac{Q_c}{c_p}(T_s - T_r) \tag{2}$$

The mass flow rate is then calculated based on the produced power. The compressor is sized to cover 80% of the peak power. The condenser conductance (G_c) is calculated at the peak power by assuming that the condenser temperature (T_c) is 5 K higher than the water supply temperature (T_s)

$$T_c = \frac{\exp\left(\frac{G_C}{mc_p}\right)T_s - T_r}{\exp\left(\frac{G_C}{mc_p}\right) - 1} \tag{3}$$

The brine mean temperature is taken from EED 2.0 results as hourly input data. It is adjusted in the model to have a constant brine temperature difference ($T_{b1} - T_{b2}$) equal to 5°C. The conductance of the evaporator (G_e) is calculated at the peak power assuming that the evaporator temperature is 5 K lower than the brine return temperature (T_{b2}). The calculation of the evaporator temperature involves an iterating operation with other parameters as the *COP*, compressor power (*P*) and the brine mass flow rate (m_e) from

$$T_e = \frac{\exp\left(\frac{G_e}{m_e c_{pb}}\right)T_{b2} - T_{b1}}{\exp\left(\frac{G_e}{m_e c_{pb}}\right) - 1} \tag{4}$$

where C_{pb} is the brine heat capacity in kJ/kg. The *COP* is calculated from

$$COP = \eta_c \frac{T_c + 273.15}{T_c - T_e} \tag{5}$$

where η_c is the compressor power factor or cycle efficiency (equals 0.6 according to Bitzer™ scroll compressor data sheet). The compressor power (*P*) is calculated from

$$P = \frac{Q_c}{COP} \tag{6}$$

The calculation of the cooling mode is based only on the free cooling. The sizing of the free cooling heat exchanger is based on the peak cooling load. The plant supply temperature of the cooling water is constant (18°C) that the temperature will be adjusted at each zone by the 3-way control valve. A similar approach to the heating mode is used to calculate the return temperature. The mass flow rate is directly calculated from the water temperatures and the cooling load.

The pumping energy for the brine circuit is calculated based on two different alternatives for boreholes distribution in paved streets or forest walkways. However, the pumping energy for both options does not much vary from each other since the pressure drop in the circuit is mainly through the borehole U-tube. The calculation is done by first sizing the circuit based on the maximum flow rate and then calculating the circuit constant that is used to calculate the hourly pressure drop and thereby the pumping energies. The heating and cooling water circuits are calculated in a similar approach.

5. Results

Fig. 4 shows results from IDA ICE 3.0 simulation software for the hourly performance of *Group 1* buildings around the year. **Fig 4a** indicates the sum of space heating and DHW as well as the cooling power demand while **Fig. 4b** shows the space heating, DHW and cooling powers on a duration diagram for the two arrangements. The duration diagram sorts the hourly power data for one year in a descending order. The negative values refer to the cooling power. It shows the power demand for heating and the covered power by the GSHP, where the auxiliary system handles the difference. **Fig. 5a** shows the results from EED for the monthly brine temperatures between the boreholes and the GSHP evaporator while **Fig.5b** indicates the brine pumping power for *Group1* buildings based on two different options for the boreholes distribution in surrounding paved streets or forest walkways. **Fig. 6** shows the GSHP model results. **Fig. 6a** gives the compressors power for the two arrangements in a duration diagram while **Fig. 6b** shows hourly heating COP for the two arrangements.

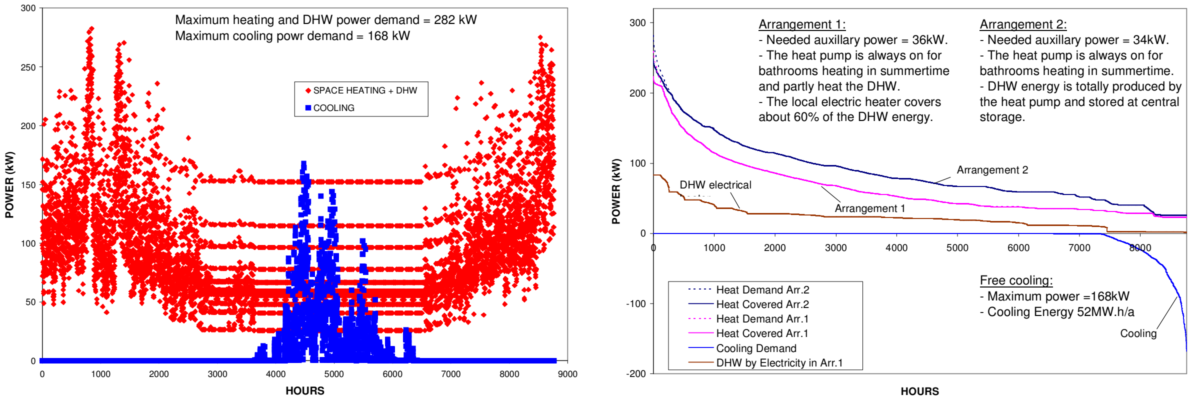
The comparison between the two system arrangements based on the seasonal performance factor SPF is necessary due to the use of the back-up electrical heater in *Arrangement 1.* The SPF is basically the sum of the annual system output energies divided by the annual needed electrical energies on the whole system boundary including compressors, pumps, fans, and electrical heaters. The SPF is calculated as:

$$SPF = \frac{Q_C + Q_{DHW.E.H}}{E_{compressor} + E_{pump} + E_{DHW.E.H}} \quad \text{(Arrangement 1)} \tag{7}$$

$$SPF = \frac{Q_C}{E_{compressor} + E_{pump}} \quad \text{(Arrangement 2)} \tag{8}$$

where, Q_C is the total condenser output for space heating and DHW in kWh, $Q_{DHW.E.H}$ is the DHW back-up electrical heater output in kWh, $E_{compressor}$ is the electrical consumption of the

GSHP compressor in kWh, E_{pump} is the electrical consumption of the brine and water pumps in kWh and $E_{DHW.E.H}$ is the DHW back-up electrical heater consumption in kWh.


Maximum heating and DHW power demand = 282 kW
Maximum cooling powr demand = 168 kW

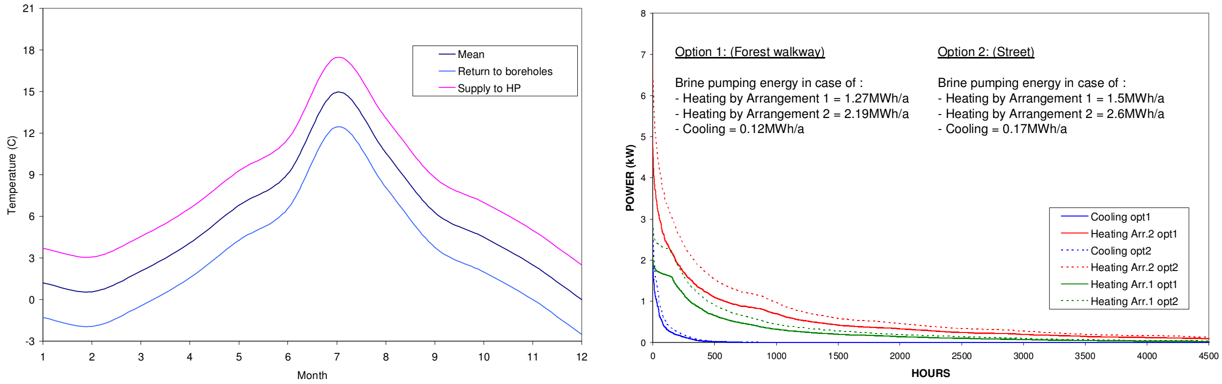
Arrangement 1:
- Needed auxillary power = 36kW.
- The heat pump is always on for bathrooms heating in summertime and partly heat the DHW.
- The local electric heater covers about 60% of the DHW energy.

Arrangement 2:
- Needed auxillary power = 34kW.
- The heat pump is always on for bathrooms heating in summertime.
- DHW energy is totally produced by the heat pump and stored at central storage.

Free cooling:
- Maximum power =168kW
- Cooling Energy 52MW.h/a

(a) ***(b)***

Fig.4. IDA ICE simulation results (a) Space heating + DHW and cooling power demand, (b) Space Heating, DHW and cooling power demand/covered in a duration diagram


Option 1: (Forest walkway)

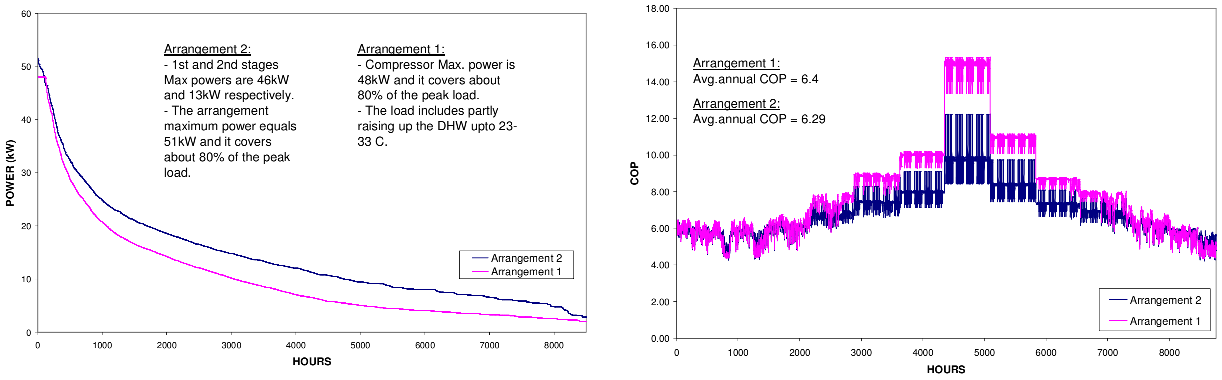
Brine pumping energy in case of :
- Heating by Arrangement 1 = 1.27MWh/a
- Heating by Arrangement 2 = 2.19MWh/a
- Cooling = 0.12MWh/a

Option 2: (Street)

Brine pumping energy in case of :
- Heating by Arrangement 1 = 1.5MWh/a
- Heating by Arrangement 2 = 2.6MWh/a
- Cooling = 0.17MWh/a

(a) ***(b)***

Fig.5. EED output and Brine pumping (a) Brine monthly temperatures from EED simulation, (b) Brine pumping powers in a duration diagram


Arrangement 2:
- 1st and 2nd stages Max powers are 46kW and 13kW respectively.
- The arrangement maximum power equals 51kW and it covers about 80% of the peak load.

Arrangement 1:
- Compressor Max. power is 48kW and it covers about 80% of the peak load.
- The load includes partly raising up the DHW upto 23-33 C.

Arrangement 1:
Avg.annual COP = 6.4

Arrangement 2:
Avg.annual COP = 6.29

(a) ***(b)***

Fig.6. GSHP model output (a) Compressors power for both arrangements in a duration diagram, (b)Hourly heating COP for both arrangements.

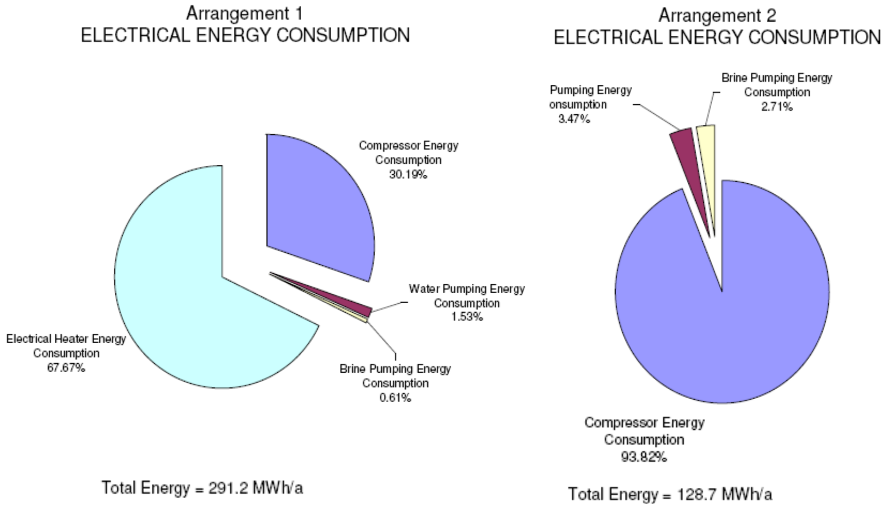


Fig.7. Electrical energy consumption for the two system arrangements

The electrical energy consumption for the two arrangements is illustrated by the pie-charts shown in **Fig. 7**. It is found that, the total electrical energy consumption for *Arrangement 1* is more than twice the consumption for *Arrangement 2.* Additionally, it can be noted that the electrical energy consumption in *Arrangement 1* by the electrical heater is also more than twice by the compressor. Calculation of SPF for both system arrangements shows that SPF for *Arrangement 2* equals 5.9, while SPF for *Arrangement 1* equals 2.6.

6. Conclusions

This study presents the dynamic performance of the GSHP when linked to the building load on one side and the ground heat exchanger on the other side. This analysis has shown a considerably higher heating seasonal performance factor SPF with the system *Arrangement 2* (two-stage or cascade heat pumps) compared to *Arrangement 1* (DHW is partly heated by GSHP before it is finally heated by an electrical heater in a local water tank). *Arrangement 2* seasonal performance factor value is near to its average annual COP since the system electrical energy consumption is mainly by the heat pump compressors. System *Arrangement 2* is therefore the preferable system arrangement from the energy conservation perspective. The circulation of the domestic hot water between the consumers and the central plant and related losses would not affect the SPF of the system because it is minor energy consumption. However, to ensure that *Arrangement 2* will cover the instantaneous DHW peak demands and to reduce the DHW heat pump size and operation cycling, the use of central storage tanks for groups of houses may be necessary. Further studies may include an optimization study to identify each component relative importance with respect to operational conditions.

References

[1] IDA ICE (IDA Indoor Climate and Energy) http://www.equa.se/eng.ice.html .
[2] Earth energy designer EED 2.0 manual.
[3] Finnish code for thermal insulation C3 – 2007, Ministry of the Environment.
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