Depletion and regeneration behaviour of a large solar-assisted ground source heat pump system (SAGSHP) for 156 units multi-dwelling.

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Abstract

Geothermal heat pumps can contribute to the transition to 100% renewable energy. Thermal depletion of the soil can be a constraint to this application for large heating-dominated buildings. A large solar assisted ground source heat pump system (SAGSHPS) is analysed for an apartment building located in Belgium. For this specific case a simulation set-up of the system (SAGSHPS) is developed in the software environment TRNSYS. All the components of this system have been dimensioned by hand and then tested in the simulation set-up in order to validate the sizing. No sustainable large heating system can be designed without regeneration of the soil. Geothermal storage with a volume 30% above the calculated volume still encounters thermal depletion problems. Solar collectors to inject solar heat into the ground is a proven technology to reduce depletion of the soil. A SAGSHPS containing 390 boreholes of 107 m deep combined with 100 solar collectors with an absorber area of 303m² is the sustainable set-up calculated at first in this research. The last system SAGSHPS resulted with 48 boreholes of 107m deep combined with 450m² solar collectors. Furthermore, this research encloses few design guidelines. This leads to a conclusion that a SAGSHPS can be a sustainable heating system for large buildings in specific cases.

Introduction

The 2020 strategy of Europe wants to tackle the climate change. Currently, the buildings contribute with up to 40% of the energy use and 36% of the CO_2 emissions in the European Union (EC, 2015).From 2021 onwards, all new constructions should be near zero energy buildings. In the pathway to 100% renewable energy, described by Connolly(2014), solar energy, heat pumps and energy storage are a few of the key technologies to make the transition possible.

Europe has an old building stock in which 75% of the buildings are energy inefficient (EU Directive 2016/0381). Those buildings will be refurbished in time where the building envelop and the HVAC system must comply with the new regulations. In Belgium 28% of the dwelling stock are multi-family buildings (EU, 2010). There are many available technologies in the market. However air to water heat pumps can have noise pollution in urban high-density areas. The geothermal heat pumps are high efficient systems. The scope of this research is to check the viability of geothermal heat pumps for apartments in Belgium.

The total amount of solar radiation reaching the roof of a building (1000kWh/m²a for Belgium) is more than its annual heating demand. Unlikely solar energy is not continuously available and the heating peak loads and the production of renewable energy do not match. In order to overcome this mismatch a seasonal thermal storage can/should be integrated to the system. Hence, the stored solar energy from the summer can be used during the winter. The model analysed in this work is a solar assisted ground source heat pump system (SAGSHPS).

The SAGSHPS is dimensioned for a multi-dwelling building consisting of 156 units located in Brussels. The building has a heated surface of 10787m². The actual aim of the refurbishment is a heating demand of 647244kWh/a (60kWh/m²a). The energy demand for the production of domestic hot water (DHW) is 163845kWh/a where 60% of this demand is produced by the solar collectors. A simulation model for this specific SAGSHPS is made in the simulation software TRNSYS to test the sustainability and efficiency of the system. Gradual improvement of the design and verification of the dynamic simulation was done in TRNSYS.

SAGSHPS

Geothermal heat pump systems consist of vertical borehole heat exchangers, which allow injecting or extracting heat from the soil. The HP produces domestic hot water (DHW) of 60°C and water at approximately 35°C for the floor heating.

Geothermal heat pumps have a coefficient of performance (COP) close to 5 for a heating supply temperature of 35°C and a source temperature of 0°C (Burkhard Sanner, 2003). That means that 80% of the energy is extracted from the soil or 648871kWh for the reference project. The extraction during winter takes 90% for its account.

When the HP is activated heat is extracted from the soil. In non-solar assisted systems the recharging of the soil happens by natural regeneration. The whole year, heat is flowing from the surrounding ground towards the geothermal heat exchanger. An ideal case is when the natural regeneration covers the heat extraction completely. Trillat (2006) noted that heating-dominated buildings can suffer from insufficient natural regeneration. The surface of the geothermal storage volume (GSV) is proportional to the heat flux to regenerate the soil. The surface to volume ratio is smaller for large storage volumes which results in a reduced regeneration capacity. Large storage volumes will sooner suffer from depletion than small storage volumes. This yields to a temperature decrease of the soil. Every year the temperature will decrease further until the soil is frozen and the system is unable to operate anymore. Besides, a lower soil temperature causes a decrease of the coefficient of performance (COP) of the HP. Therefore, extra heat should be injected in the soil. In this way a sustainable system can be obtained, as well as a better efficiency of the system. The additional heat injection for this project is obtained by adding thermal solar collectors.

These solar collectors will also produce DHW, hereby reducing the working load of the HP and the heat extracted from the soil. Additionally, the excess heat from the solar collectors is supplied to the borehole heat exchangers to regenerate the soil. Enough solar heat should be injected into the soil to create a balance between the heat extracted, the heat injected and the natural regeneration.

Furthermore, two water buffer tanks are used in a SAGSHPS. The first tank stores the DHW produced by the solar collectors. The solar energy is maximal around noon, while the use reaches peaks in the evening and the morning. The volume of the DHW tank is designed to match heat supply and heat demand. Next to the production of DHW the HP is producing the heating water for the central heating system (CHS). To limit the ON/OFF frequency of the HP, a central heating tank (CH) is added in which the heating water is stored before flowing to the building.

Figure 1 shows an example of a SAGSHPS for a residential house. A large number of borehole heat exchangers and solar collectors are needed for an apartment building.

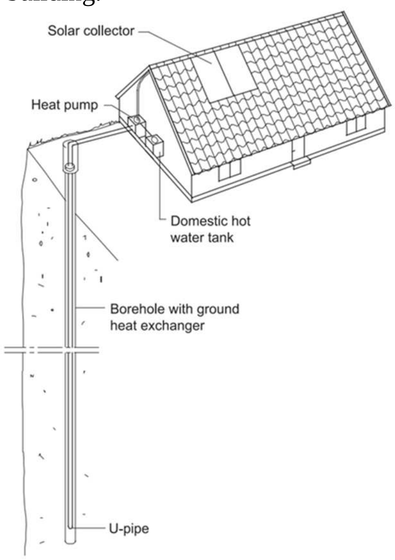

Figure 1: Overview of a SAGSHPS for a residential building (Kjellsson, 2010)

The measurements and simulations done by Eugster (2000) show that the recovery duration after depletion of the soil roughly equals that of the operation, e.g. for 30 years of borehole heat exchanger (BHE) operation the thermal recovery of the ground needs 30 years.

The authors found no references in literature about available solutions to cope with the depletion when depletion occurred for systems with an operation period longer than 30 years.

Eugster defines a sustainable geothermal system where the long-term performance of the BHE/HP system stabilizes after a few years.

The limitations on soil depletion are described in several standards such as VDI 4640 (1998), ISSO publication 73 (2005) and the UK standard MIS 3005 (2015).

The VDI (Verein Deutscher Ingenieure)4640 limit the inlet water temperature to the heat pump to 1°C for permanent operation and to -5°C for peak load conditions. The ISSO publication 73 (Institute for Study and Stimulating Research, Netherlands) limits the decrease of the average temperature of the storage volume up to 5°C after 25 years of operation. The UK standard is similar to the German approach: the temperature of the thermal transfer fluid at the inlet of the heat pump shall be designed to be higher than 0ºC at all times for 20 years in normal operating conditions.

These guidelines and standards aim to avoid freezing of the soil to keep a sustainable system. Nevertheless, VDI 4640 guidelines advice for installations bigger than 30kW as well as for underground thermal energy storage to perform computer simulations. The standard describes also a measurement method for the determination of thermal properties of the underground and the heat transfer characteristics of the ground. Many of the simulations executed during this research compiled with the three standards. However, not all of them resulted in a balanced system for an operation time of 25 years. Compiling with the mentioned standards is not a guarantee to have a sustainable system.

Many authors such as Trillat (2007) and Ionescu (2013) investigated geothermal heat pumps with thermal solar collectors for small applications. Those researches are limited to a residential building. The conclusion is that the extension with thermal solar reduces the depletion and that a balance is (or is almost) achieved.

Burkhard (2003) verified five simulation software packages. The versions of 1996 gave a variation of 30% on the design length of the boreholes. In contrary, the versions from 1999 gave a variation of 11%. TRNSYS was among the investigated simulation tools.

Comparing the different versions from 1999, TRNSYS resulted in the highest design length of the borehole. As mentioned before, large geothermal storage volumes suffer from the reduced capacity for natural regeneration. Capozza (2012) calculated a ‘penalty temperature’ for large borehole fields. Wang (2012) simulated an office building where the regeneration was supplied by the cooling system during summer and the thermal solar collectors. His project is comparable in capacity with the research presented in this article. Wang reduced the distance between the boreholes to improve the thermal energy storage. The results show a sustainable system resolving the ground thermal energy imbalance problem.

TRNSYS simulation

A simulation model is made for the SAGSHPS coupled to the apartment building in the simulation software TRNSYS. This model enables to analyse the efficiency of the system and the heat balance of the GSV.

SAGSHPS simulation components

Building

The apartment building is 13 stories high and every floor consists of three identical blocks of four apartments. In order to limit the simulation calculation time, only one identical block of four apartments is implemented in TRNSYS. The heat demand of those four apartments is multiplied with 39 to simulate the whole building.

The implementation is done by model type 56 in which the original building specifications are adapted to obtain a heating demand of 60kWh/m²a. The component is equipped with active layers simulating the floor heating system. In this research the simulation tool TRNFLOW is used to calculate the infiltration and exfiltration of the building. The building is provided with a balanced ventilation system with heat recovery.

Heat pump

The HP is a 4-stage water-to-water type. Two 2-stage HP models type 1221 are used. This model uses a data file containing the heating capacity *Cap* and power consumed (*P)* for different inlet temperatures at the evaporator and outlet temperatures at the condenser side. Based on these values the model calculates the heat extracted in the evaporator Q_{ab} and the outlet temperatures in the evaporator and condenser according to equations (1) to (4).

$$COP = Cap/P \quad (1)$$

$$Q_{ab} = Cap - P \quad (2)$$

$$T_{o,evap} = T_{i,evap} - \frac{Q_{ab}}{\dot{m}_{evap}\, C_{p,evap}} \quad (3)$$

$$T_{o,cond} = T_{i,cond} + \frac{Cap}{\dot{m}_{cond}\, C_{p,cond}} \quad (4)$$

Borehole heat exchanger

The borehole heat exchanger has a depth of 107m. To reduce the pressure losses, the pipes are connected in a Tichelmann circuit with 6 boreholes per branch to keep a turbulent flow. The used fluid is an antifreeze mixture of 25% mono-propylene glycol and water, which results in a freezing point of -9°C. The storage volume, containing the boreholes is simulated in TRNSYS by using model type 557. The model assumes that the boreholes(N_b) are placed uniformly within the storage volume V_{st}. This volume is calculated according to equation (5):

$$V_{st} = \pi \cdot N_b \cdot L_b \cdot (0.525 \cdot B)^2 \quad (5)$$

A storage volume is based on the interaction between the local thermal process around a pipe and the global thermal process of the storage volume and the surrounding ground. The local process calculates the heat flow from the pipe to the ground surrounding the pipe. The heat flow will thereby influence the global thermal process, but on the other hand the local values of the global temperature field are necessary to calculate the local heat flow (Hellström, 1989). The total temperature at a specific location is calculated as the superposition of three temperature contributions: the global problem, the redistribution of heat (steady-flux problem) and the local heat transfer from the fluid to the surrounding region.

The average thermal conductivity of the soil is 1.64W/mK. Depending on the location in Brussel the average thermal conductivity of the top 100m varies between 1.6 and 2.3W/mK. Detailed maps are provided by the Belgian government (Goosse, 2015).

Solar collector

Evacuated tube collectors have the ability, in cold climate conditions, to produce hot water up to temperatures of 60°C. Hence, the production of DHW is realized without much auxiliary heating. Model type 71 is used in the set-up to simulate the evacuated tube collectors. This model is based on the Hottel-Whillier equation, calculating the useful energy of the collector with equation (6). The overall heat removal factor F_R used in this equation is given by Eq.(7)

$$Q_u = F_R A_c \left((\tau\alpha) \cdot I - U_L\,(T_i - T_a)\right) \quad (6)$$

$$F_R = \frac{\dot{m}\, C_p\,(T_o - T_i)}{A_c\,((\tau\alpha) \cdot I - U_L\,(T_i - T_a))} \quad (7)$$

Hot water storage tank

To obtain the most efficient set-up, the SAGSHPS is equipped with thermal stratified storage tanks.

The tanks are implemented in the simulation set-up by model type 4. The stratification is obtained by assuming that the tank consists of a number of fully-mixed volume segments N_s. The up and downwards flows between adjacent segments are fully mixed before they enter a segment. The energy balance of segment *i* is defined by equation (8). S_{si} and S_{li} are control functions that adopt the value 1 if in segment *i* fluid from the heat source or load enters.

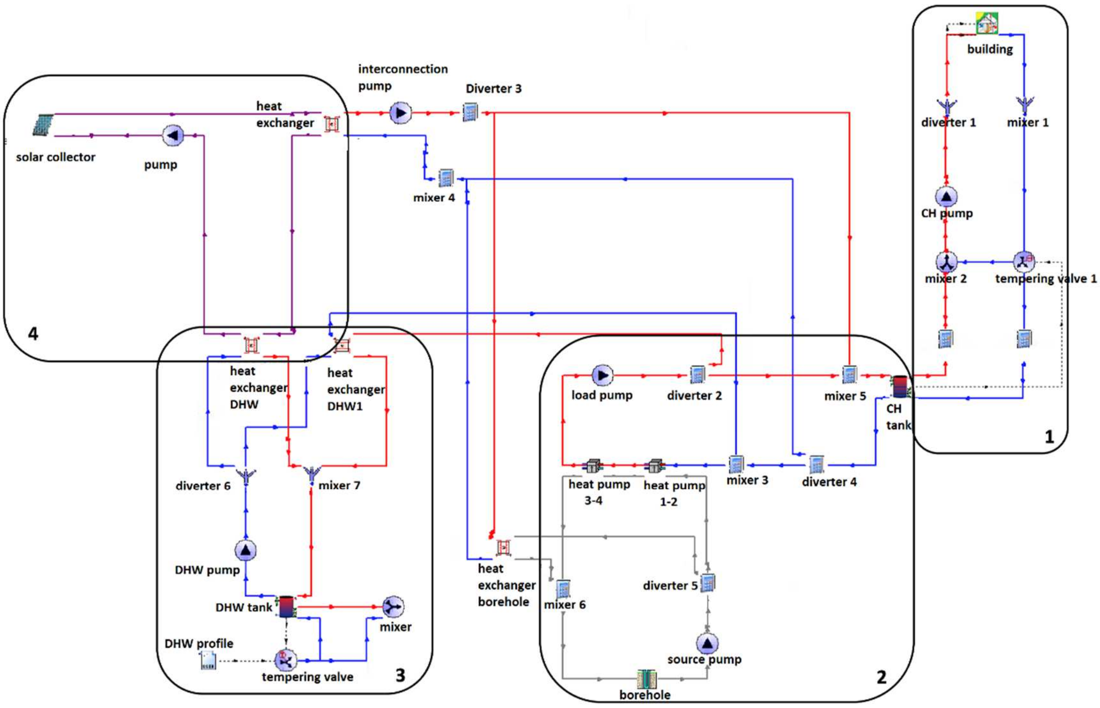

Figure 2: Global overview of TRNSYS simulation set-up

$$\dot{m}_i C_p \frac{dT_i}{dt} = s_{si}\dot{m}_s C_p (T_s - T_i) + s_{li}\dot{m}_l C_p (T_l - T_i) + U_L A_i \,(T_a - T_i) + \gamma_i C_p (T_{i-1} - T_i) \quad \textit{if resultant flow is downwards} \quad + \gamma_i C_p (T_i - T_{i-1}) \quad \textit{if resultant flow is upwards} \tag{8}$$

$$\gamma_i = \dot{m}_s \sum_{j=1}^{i-1} s_{sj} - \dot{m}_l \sum_{j=i+1}^{N_s} s_{lj} \tag{9}$$

Simulation set-up

The components explained above are connected with each other to obtain a SAGSHPS simulation set-up, shown in Figure 2. A colour code is used in the connections between the components for a better clarity:

- Red line: hot water
- Blue line: cold water
- Purple line: heat carrier medium flowing through the solar collectors
- Grey line: heat carrier medium flowing through the borehole heat exchanger; mono-propylene glycol
- Dotted line: control signal, no psychical transportation

The complete set-up is divided into four subsystems, where each one is handling one specific task of the system. Subsystem 1 contains the building component that generates as output the heating demand of the four apartments based on the ambient weather conditions and the internal activities of the residents. This heating demand is multiplied by 39 to simulate the whole building. With heating water stored in the CH tank, the rooms are heated by the floor heating system. The CH tank is loaded by the HP in subsystem 2. This HP is simulated by two components, one representing stage 1 and 2 while the other represents stage 3 and 4.

The evaporator side of the HP is connected to the borehole heat exchangers. Additionally, the HP also produces DHW for subsystem 3 stored in the DHW tank. This subsystem is separated from the rest of the set-up by two heat exchangers, causing the legionella measures only to be applicable to this part of the system. The last subsystem 4 contains the solar collectors whose main task is to produce DHW. The excess heat from the solar collectors can be transported by the interconnection pump to the borehole heat exchangers.

Control strategy

The control strategies for the pumps, flow diverters, flow mixers and the heat pump are subdivided. There is a control strategy for the summer months and one for the winter months. In the model it is decided the summer to start on May 15 and to end on October 1. During this period, the building will not be heated and the CH tank cools down. There is no cooling provided. The solar collectors will produce most of the DHW during the summer. However when there is a cloudy sky for a longer period the support of the HP is necessary. When the DHW tank is fully loaded the excess of solar energy will be used to recharge the ground storage volume.

In the winter months DHW should be produced as well as heating water for the building. The priority of the HP is to make sure that the DHW tank is fully loaded. When this condition is met, the HP will produce heating water for the building.

The control strategy exists of several working modes:

- Mode 1: When the outlet temperature of the solar collector is 7°C higher than the outlet source temperature of the DHW tank, solar energy will be used to produce DHW. The production is stopped when the temperature difference drops below 2°C or the temperature of volume segment 7 in the DHW tank is above 80°C. (Segment 10 is on top of the tank).
- Mode 2: Firstly, when the outlet temperature of the solar collector is 15°C higher than the outlet temperature of the borehole heat exchangers and secondly the temperature of volume segment 7 in the DHW tank is above 80°C, solar energy will be used to recharge the ground storage volume. The recharging stops when the temperature difference drops below 5°C or the average temperature of the ground storage volume is above 25°C according to the Flemish legislation VLAREM II 5.53.6.2.
- Mode 3: When the temperature of the water coming from the DHW tank, supplying the tap points, is below 60°C, the HP is activated and DHW is produced. The controller of the HP works with a temperature dead band range of 2°C.
- Mode 4: When the temperature of the water in volume segment 7 of the DHW tank is below 60°C when there is no demand of DHW, the HP is activated to produce DHW.
- Mode 5: When the temperature in volume segment 3 of the CH tank is below the set temperature of the heating curve, hot water is produced and transported to the CH tank. The set temperature imposed by the heating curve is related to the ambient temperature defined by two working points: leaving water temperature of 26.4°C for 16°C outdoor temperature and a leaving water temperature of 42°C for -10°C outdoor temperature.
- Mode 6: When the temperature in a room of an apartment is below the desired 20°C, the floor heating system is activated. Heating water from the CH tank is supplied to the concerning room. However when the temperature of the water is 4°C below the set temperature according to the heating curve, the floor heating system will not be activated and priority is given to heat up the CH tank.

Mode 1 and 2 will be active during the whole year, while mode 3 is only active during the summer months. In the winter months mode 4, 5 and 6 can be activated, however mode 5 can only be used when mode 4 is turned off.

Component sizing

The preliminary design for a refurbishment to a 60kWh/m²a apartment was executed. In this case the design of the solar thermal was focussed on the energy demand of the DHW. Gradually the sizing of the solar thermal and the BHE are adjusted to avoid depletion of the soil. During the second part of the research a refurbishment to a 15kWh/m²a apartment is investigated.

Solar collector area and DHW tank

The first parameter for determining the number of solar collectors is the DHW consumption profile. The daily consumption of DHW in litres per day, $\dot{V}$, in function of the number of apartments, x, is given by equation (10) according to the research of De Schutter (2014). For the apartment building, containing 156 apartments, the daily consumption is 7721 l. The yearly energy demand for the production of DHW at 60°C thereby equals 163845kWh/a. The solar collectors are sized to obtain a solar fraction of 60% of the DHW production, which yields a total production by the solar collectors of 98307kWh/a.

$$\dot{V} = 28.995 \cdot x + 0.1314 \cdot x^2 \qquad (10)$$

The installed evacuated tube collectors in this work have a solar gain in Belgium of 475kWh/m²a. So at least 207m² collector area has to be available. Therefore 72 collectors with an absorber area of 3.03m² are installed on the roof. The DHW tank is dimensioned in accordance to the solar collector area. According to the Flemish EPB reference (Flemish Government, 2016), 50 l storage volume per square meter solar collector area results in a volume of 10900l.

Heat pump and central heating tank

The HP is dimensioned for the worst-case scenario to make sure that it is capable of preserving a room temperature of 20°C on the coldest winter days and to produce enough DHW to handle the peak moments. On January 12 the heat demand reaches a maximum value of 389kW for the entire building. However most of the time, the bedrooms will not be heated, allowing the HP to be dimensioned for a somewhat lower peak demand.

A four stage water to water HP is considered, the specifications are represented in Table 1, for full load operation under following conditions: evaporator 5/0°C, condenser 40/45°C.

Table 1: Technical specification HP at full load operation

Heating capacity	367 kW
Power input heating	102 kW
COP	3.61
Evaporator side flow rate	14 l/s
Condenser side flow rate	17.8 l/s

The central heating tank is sized to limit the number of starting moments of the HP compressors. The volume of the tank is calculated according to equation (11), based on design rules of the manufacturer.

$$V = \frac{Cap_{min} \cdot t \cdot 0.7}{C_p \cdot \Delta T \cdot 2} = \frac{92\ kW \cdot 600s \cdot 0.7}{4.186\ \frac{kJ}{kg \cdot K} \cdot 2°C \cdot 2} \qquad (11)$$

$$V = 2308\ l$$

Borehole heat exchanger

The number of borehole heat exchangers is calculated in accordance to ISSO-publication 73, using the method for office buildings (Geelen, 2005) since no special design rules are available for multi-dwelling buildings. However this approach is only accurate for systems with a heating capacity of the HP up to 100 kW. With the help of the simulation set-up, the dimensioning can be done correctly for larger capacities by making sure that the average temperature of the storage volume does not decrease below 5°C after 25 years of operation.

The HP has to produce 40% of the DHW and has to heat up the building. This yields to a total heat production of 712782kWh/a. Therefore 513203kWh/a of heat is extracted from the storage volume. In a first stage, no solar energy will be injected into the soil. Only natural regeneration will occur. According the ISSO-publication 73, based on the stated values above, the necessary borehole length is 32806m. The authorized borehole depth at the location in Belgium is 107m (VLAREM Section 55.1, 2016). Therefore the cylindrical storage volume contains 306 boreholes that are uniformly positioned with 7m distance between each other.

$$Q_{hp} = Q_{DHW} \cdot 0.4 + Q_{hd} \qquad (12)$$

$$Q_{hp} = 163845\ kWh/a \cdot 0.4 + 60\ kWh/m^2a \cdot 69.15m^2 \cdot 156$$

$$Q_{hp} = 712782\ kWh/a$$

Pumps

Proper selection of the pumps in terms of fulfilling the requirements for the mass flow rate of the fluid and overcoming the pressure drop in the system was performed. The pressure drops are however estimated, as no hydraulic schedule for the system is made. The solar collector pump and the interconnection pump are fixed flow rate centrifugal pumps. The other pumps have a variable flow rate. In Table 2, the specifications of the different pumps are shown.

Table 2: Specifications of centrifugal pumps

Pump	Flow rate	Pressure drop	Power
	[l/h]	[kPa]	[W]
Solar collector	6546	60.76	317.7
Interconnection	6545	25.64	165
DHW	70625	48.6	1523
Load	64080	46.82	1192
Source	50400	430	9210
Central heating	49764	50	1163

Simulation results

The ISSO-publication 73 dimensions the borehole heat exchangers in function of 25 years of operation. Therefore, for all the simulations this is the accepted operation range in order to make sure that the temperature of the ground storage volume stays above the 5°C limit. The used time step is 5 minutes. The first simulation set-up uses the dimensions of the previous calculated components and the system is working without extra heat injection from the solar collectors. The average temperature of the storage volume containing 306 borehole heat exchangers is represented in Figure 3 by the red line.

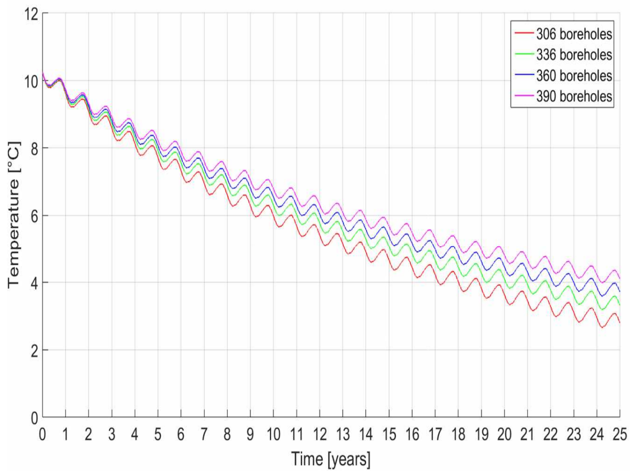

Figure 3: Average temperature of storage volume over 25 years for different number of borehole heat exchangers without regeneration

As expected the temperature of the storage volume after 25 years of operation is below the limit of 5°C. The amount of heat extraction from the storage volume is not in balance with the natural regeneration. To cope with the thermal depletion effect, the size of the storage volume is systematically increased with 10%. The results for the storage volume containing 336, 360 and 390 borehole heat exchangers are presented on the same figure. Even with the biggest storage volume of 390 boreholes the temperature limit is exceeded. This storage volume is 1770569m³ and has a diameter of 145m, which is already double the size of the apartment length so it cannot be increased any further. Without regeneration of the soil, a geothermal heat pump with one borehole field is not a sustainable solution for an apartment building in Belgium.

The excess of solar energy that will be used for the regeneration is crucial to obtain a sustainable system.

The storage volume of 390 boreholes is left untouched and the excess of solar energy is used for the regeneration of the soil. The 72 solar collectors with a total absorber area of 218m² will produce 60% of the yearly DHW demand. When the DHW tank is fully loaded, the incoming solar energy is supplied to the ground. This is achieved when volume segment 7 has a temperature of 80°C. A higher average temperature in the ground storage volume is obtained as presented in Figure 4 by the green line. However, the temperature after 25 years of operation is still below the limit. Therefore the number of solar collectors is increased with 20% to 88 with an absorber area of 266.64m² going up to 100 collectors with an absorber area of 303m². The 100 collectors result in an operational system as the temperature after 25 years of operation is 5.203°C. The SAGSHPS is working with a solar regeneration of 20%.

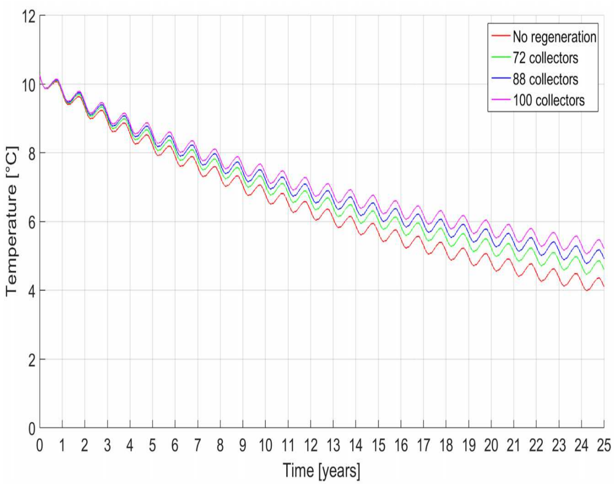

Figure 4: Average temperature of storage volume over 25 years for the storage volume containing 390 borehole heat exchangers with different number of solar collectors

The temperature of the storage volume is still a decreasing line as the years pass. This is still no sustainable system as described by Eugster (2000). To understand the working principle of the storage volume, the heat transfers are analysed and shown in Figure 5. The green line represents the heat extraction which is a slowly decreasing line, as less heat can be extracted due to the temperature drop in the storage volume. The red line visualizes the amount of solar energy injected into the ground, which is a yearly constant. The blue, purple and cyan lines represent the heat transfers trough the bottom, edges and the top of the storage volume. As the temperature of the storage volume yearly decreases, the heat transfers from the surrounding ground to the storage volume increases. The black line is the sum of all the heat transfers to the storage volume and the heat injection from the solar energy. It is clear that in the first years of operation there is a large difference between the yearly heat storage and extraction, causing the ground temperature to decrease rapidly. As the years pass, the yearly heat flux to the storage volume increases due to the increasing temperature difference between storage volume and surrounding soil. It will however always be lower than the yearly heat extraction, which makes that the temperature of the storage volume keeps decreasing but less fast.

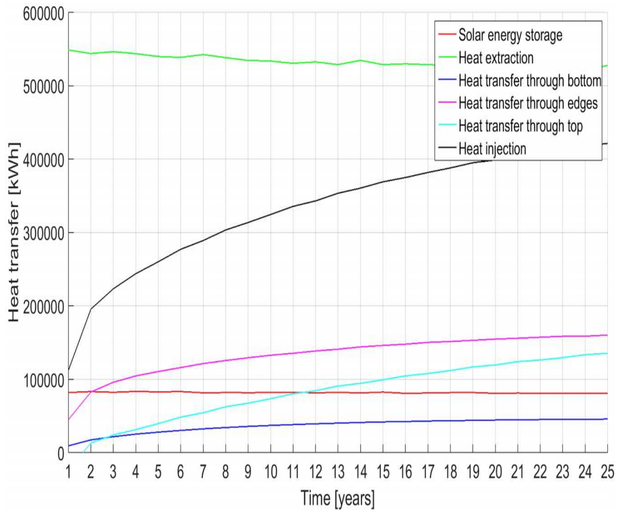

Figure 5: Yearly heat transfers in ground storage volume containing 390 boreholes and a solar collector area of 303m²

The yearly electrical energy use of the SAGSHPS is increased from 166829kWh/a during year 1, to 182381kWh/a in year 25. The enlargement of the energy use is due to the temperature decrease of the ground storage volume which results in a lower COP of the HP. The average COP during operation year 1 is 5.085, but decreases to 4.608 in year 25.

To obtain a SAGSHPS where the ground storage volume is in complete balance and the balanced soil temperature is raised, more solar collectors should be added. Besides, a higher COP for the HP will be obtained, as well as a better efficiency of the whole system.

The discussion above explains the problems encountered during the design of a SAGSHPS for an apartment building. The required number of solar collectors and borehole heat exchanger are large, which increases the cost of such a system. The cost of boreholes in Belgium is between 35€/m and 75€/m to drill depending the composition of the soil. Thermal solar collectors have a cost of 500€/m². With an average cost of 55€/m borehole and 500€/m² thermal solar collector, an investment of 2445650€ makes this design economical not viable. As mentioned in the introduction, the European Directive 2010/31 requires that all new buildings will be near zero energy buildings in 2020. The next step is to improve the building envelop to the passive house standard with a heating demand of 15kWh/m²a.

Besides the cost of the geothermal heat pump system, the necessary available space is huge which makes the practical installation very difficult. A possible solution is to implement a cooling system in the apartment building which injects the extracted heat into the soil. However the cooling load of an apartment is small which makes the influence rather limited.

Improved building envelope

Table 3: Improvements made to achieve the passive house standard:

	60kWh/m²a	15kWh/m²a
Wall insulation	3 cm	10 cm
Glazing	1,1 W/m²K	0,52 W/m²K
g-value	0,624	0,585
Airtightness	6,9 1/h	0,6 1/h
Effectivity air to air heat exchanger	60%	80%

Improving the apartment to a heating demand of 15kWh/m²a results in a total heating demand (inclusive DHW) of 4.2E6kWh/a instead of 16.8E6kWh/a.

Simulations were executed for 60, 90 and 150 boreholes and the results are shown in Figure 6.

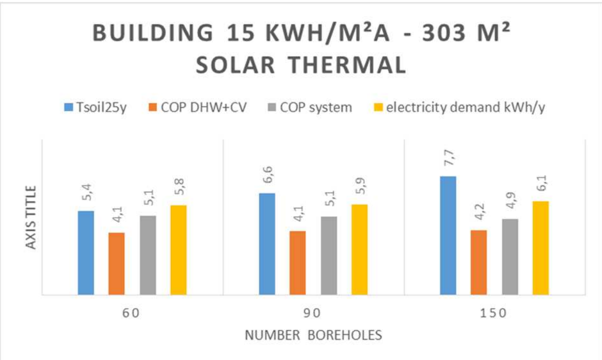

Figure 6: Average storage temperature after 25 years, the COP of the heat pump without pump energy, the COP of the total system and the total electricity demand in kWh/m²a for different boreholes

The system with 60 boreholes compiles with the ISSO publication 73 and has the best COP system, eq.(13).

$$COPsystem = \frac{\text{Qhp+Qsolar}}{\text{Php+Ppumps}} \qquad (13)$$

The lower COP system for the 90 and 150 boreholes is due to the extra energy for the source pump. The COP value increases proportionally with the enlarged number of the boreholes. None of these systems resulted in a balanced system after 25 years.
All previous simulated systems were with a borehole distance of 7m which is common used in geothermal heat pump systems in Belgium. Figure 7 shows the results for different distances between the boreholes.

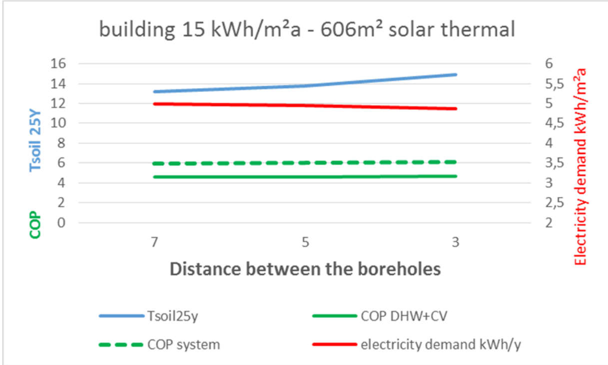

Figure 7: system results for different distances in m between the boreholes – system with 60 boreholes

Decreasing the distance between the boreholes, increases the storage temperature after 25 years from 13.19°C to 14.88°C for a distance of 7m to 3m respectively. The 1.7°C temperature increase of the storage volume gives no significant increase of the system COP. The small increase of the storage volume temperature results in a small increase of the COP of the heat pump. Only the system with 3m distance results in a balanced system as indicated in Figure 8.

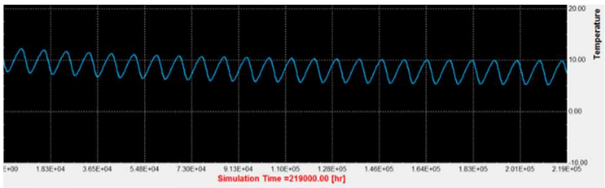

Figure 8: average storage volume temperature for the 15kWh/m²a building with 60 boreholes and 606m² thermal solar collectors

The best results are shown in Figure 9.

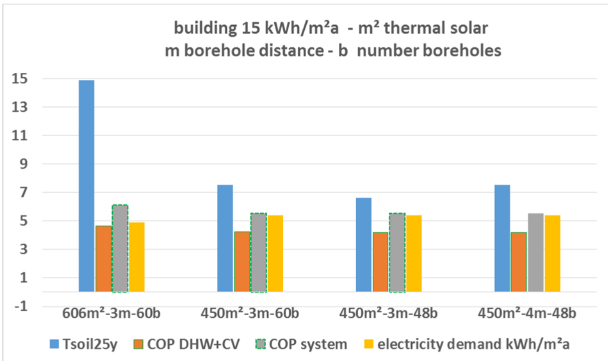

Figure 9: Economical optimisation of the system

Reducing the number of boreholes to 48 and the thermal solar collectors to 450m² results in systems that compile with the ISSO publication 73. The system with a borehole distance of 3m has sometimes a heat pump inlet temperature of 0°C which does not compile with the VDI4640. The most economical and sustainable solution is the system with 450m² solar, 48 boreholes and a borehole distance of 4m. This system has a system COP of 5.55 and the needed surface for the geothermal field is reduced to 576m² which is in most cases available next to a 13 stories high apartment. The investment per apartment for the boreholes and the solar collectors is in the range of 3250€. Net present value calculations must be made to compare this installation to other heating solutions.

Conclusion

For an apartment building located in Belgium, containing 156 apartments with a living area of 69.15m² per apartment, a SAGSHPS is designed and tested for a heating demand of 60 and 15 kWh/m² (exclusive heating demand DHW) . The large BHE must be regenerated by thermal solar energy to limit the storage volume temperature and to get a balanced sustainable system. A solar system that is too small results in depletion of the soil. A solar system that is too large results in continues increasing soil temperatures. The minimum needed BHE to get a sustainable system is determined by the surface of the solar thermal collectors, the number and length of the boreholes and the borehole distance. Not only the outlet temperature of the BHE and the minimum outlet temperature of the BHE has to be checked but also the balance of the system after 25 years to get a sustainable system.

A SAGSHPS for not very low energy buildings is economical not viable. The first approach has to be the improvement of the building envelop to the level of a passive building. Simulations are needed to optimize the three important parameters: number of boreholes, distance between the boreholes and the surface of the thermal solar collectors. A SAGSHPS can be a sustainable heating system for large heating-dominated buildings in specific cases.

Nomenclature

A_c	[m²]	Collector surface area
B	[m]	Borehole spacing
Cap cond	[kW]	Capacity of the HP condensor
C_p evap	[kJ/kgK]	Specific heat evaporator
F_R	[--]	Overall collector heat removal factor
I	[W/m]	Solar radiation
L_b	[m]	Borehole depth
$\dot{m}$	[kg/s]	Mass flow rate
$\dot{m}_l$	[kg/s]	Mass flow rate at load side
$\dot{m}_s$	[kg/s]	Mass flow rate at source side
N_b	[--]	Number of boreholes
P	[kW]	Power
Q_{ab}	[kW]	Heat extracted at the evaporator
Q_u	[W]	Useful energy gain
T_a	[°C]	Ambient temperature
T_i	[°C]	Inlet temperature
T_l	[°C]	Fluid temperature from the load
$T_{i,evap}$	[°C]	Inlet temperature evaporator
T_o	[°C]	Outlet temperature
$T_{o,evap}$	[°C]	Outlet temperature evaporator
T_s	[°C]	Fluid temperature from the heat source
U_L	[W/m²K]	Overall thermal loss coefficient
V	[l]	Tank volume
$\dot{V}$	[l/day]	Daily hot water consumption
V_{st}	[m³]	Storage volume
x	[--]	Number of apartments
α	[--]	Absorption coefficient of absorber
τ	[--]	Transmission coefficient of glazing

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