THERMODYNAMIC ANALYSIS OF GROUND COUPLED HEAT PUMPS WITH SOLAR THERMAL REGENERATION - MONITORING AND SIMULATION RESULTS

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Abstract: Combined solar and heat pump systems exist since some years in a large variety on the market. There exist so-called parallel and serial configurations. Ground coupled heat pumps work parallel sometimes with regeneration of the ground source using solar thermal. Such solar and heat pump systems have the potential of performing very efficiently compared to standard heat pump systems. However, the technical effort and thus the investment costs increase significantly. In addition, the installation and operation are more likely to be subject to errors and failures. In order to optimize control strategies and to evaluate the benefit of these systems simulations have to be performed. Eventually, the costs per saved kWh have to be competitive.
Monitoring data and system simulation results are presented and a thermodynamic analysis of regeneration of the ground is conducted for different types and designs of ground heat exchangers by means of simulation with Matlab/Simulink. For such an investigation, detailed models of the ground heat exchanger that are validated against measured data are presented. Results of system simulations with different ground heat exchangers are compared.

Key Words: solar and heat pump systems, ground heat exchanger, simulation models

1 INTRODUCTION

Combining solar thermal and heat pump technologies is relevant in several aspects (see e.g. Ruschenburg et al. 2012): a high renewable fraction can be achieved, the solar heat can help enhance the performance of the heat pump by raising the evaporation temperature and the solar heat can be stored. Ground coupled heat pumps work in parallel to a solar thermal system sometimes with regeneration of the ground source using solar thermal collectors or uncovered absorbers. These solar and heat pump systems have higher performance compared to standard heat pump systems. However, the investment costs increase significantly because of the higher technical effort. Due to the higher complexity of the system, the installation and operation are more likely to be subject to errors and failures. An appropriate control strategy is obligatory which has to be determined by means of dynamic system simulation. One example of a complex solar and heat pump system was investigated by means of an in-situ monitoring (Loose et al. 2013). In this contribution, in addition, simulation results are presented and a general discussion on solar regeneration is given.

2 MONITORING OF A GROUND COUPLED HEAT PUMP WITH SOLAR THERMAL REGENERATION

2.1 Description of the project

The multi-family house in Füssen, Bavaria (Germany) with 3 flats and 5 persons (until July 2013, then move-out and sale of the house) was constructed in 1960 and refurbished in 2011. Heated living area is 280 m^2. A radiator heating system is operated with low flow temperatures (radiators are oversized after retrofit of the building). The supply and return temperatures for space heating are 29°C/27°C (measured). The measured annual space heating demand is 18 890 kWh/a (corresponding to 67.5 kWh/(m^2 a)). The measured annual DHW demand with a design tapping temperature of 45°C is with 1 345 kWh/a (or 4.8 kWh/(m^2 a)) comparatively low.

2.2 Ground coupled heat pump with solar thermal regeneration

The bivalent system for heating and domestic hot water preparation works with a solar roof tile collector and so-called energy baskets as ground heat exchangers, which feature less investment costs compared to vertical ground heat exchangers. The source of the heat pump is either the roof absorber or the ground heat exchanger. Depending on the temperature of the absorber, the ground source and the store the control of the system chooses between regenerating the ground and bringing the store temperature to a higher level, see Figure 1. The control of the system also distinguishes between summer, winter and transition times. While during summer direct domestic hot water preparation is favored, during winter solar thermal heat is offered to the heat pump directly as heat source, if possible and the temperature is high enough, and during autumn and spring the regeneration of the ground is prioritized.

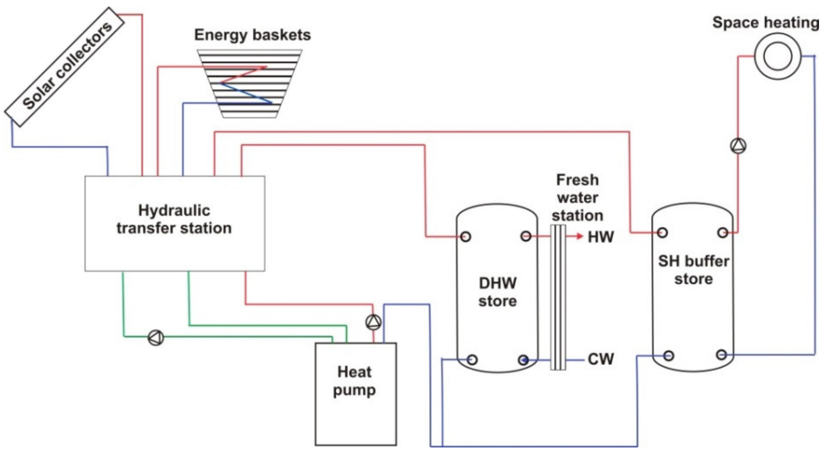


Figure 1: Simplified hydraulic scheme of the solar and heat pump system with energy baskets, domestic hot water (DHW) store and space heating (SH) store (Loose 2013)

The brine/water heat pump with a COP of 4.7 at B0/W35 (EN 14511) is driven with refrigerant R410a and has a nominal capacity of 12 kW (scroll compressor). There was no cooling during monitoring. As source of the heat pump four geothermal energy baskets are used with a nominal capacity of 1.5 kW each. The collector area of the solar roof tile collectors oriented to south is 35 m^2. There is a 400 l DHW and a 400 l SH buffer store.

2.3 Monitoring Data

The system has been monitored from September 2012 until August 2013 (see Loose 2013 for a detailed analysis). The average ambient temperature during the monitored period was 8.5°C. Space heating demand was 18 890 kWh/a and DHW demand including heat losses

due to circulation 1 752 kWh/a, respectively. The performance of the system was determined to SPF_{HP} = 3.8 for the heat pump as component and SPF_{SHP} = 3.5 (SPF according to IEA SHC T44 A38 definitions) over the period of one year (see Figure 2). This is comparable to a conventional brine to water heat pump with borehole heat exchangers (without solar).
The minimum flow temperature (inlet to basket type ghx) was about -10 °C while the return temperature (outlet of basket ghx) was only rarely below -5°C (see also section Validation of the ground heat exchanger model, below, for measured flow and return temperatures.)

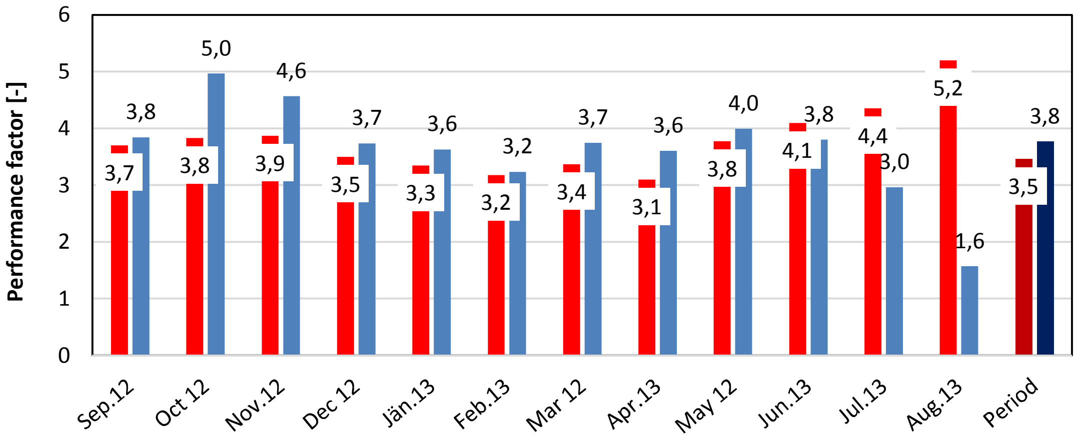


Figure 2: Heat pump (SPF_{HP}, blue bars) and system performance factors (SPF_{SHP}, red bars) (Loose et al. 2013)

3 MODELLING OF GROUND HEAT EXCHANGERS

3.1 General Aspects

To investigate the potential of solar regeneration, several types of ground heat exchangers (GHX) are investigated as summarized in Figure 3.

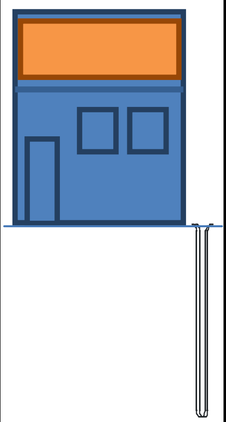
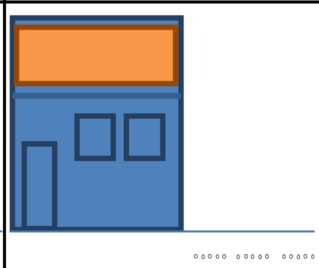
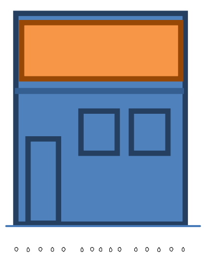
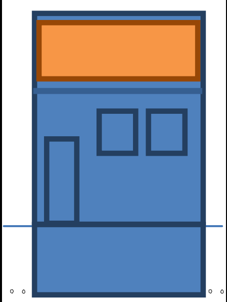
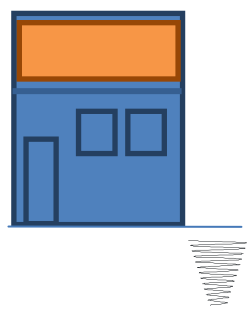
VGHX	HGHX	HGHX int.	GHX int.	energy basket
1 probe (2U) 25 … 125 m	meander type 10 … 200 m², 1, 2, 4 parallel pipes, depth 1.5 m spacing 0.2 m	integr. into basement, 2 parallel, 70 m², spacing 0.175 m, 30 cm insulation	building integrated (trench), surrounding, with cellar 2 parallel pipes with 44 m each	1, 2, 4 parallel baskets 200 m, depth 2.5 m
				

Figure 3: Types of ground heat exchangers with double U-pipe (2U) vertical ground heat exchanger (vghx), horizontal ground heat exchanger (hghx) and building integrated (int.) ghx and energy basket

Ground heat exchanger models have been developed by the authors based on finite difference (HGHX, VGHX) or finite element method (basket, trench) and have been validated against measured data and/or cross validated against other simulation models (HGHX: Peper et al. 2011, Ochs et al. 2011, Ochs et al. 2011 (b); VGHX Ochs et al. 2013, basket type Ochs 2012).
The ground heat exchanger is modelled as a semi-isothermal heat exchanger where the heat transferred from the fluid (i.e. brine) with the temperature ϑ_m to the ground with the temperature ϑ_{hx} is

$$\dot{Q} = UA \cdot \Delta\vartheta_{log} \approx UA \cdot (\vartheta_m - \vartheta_{hx}) \quad (1)$$

The overall heat transfer coefficient is calculated with the internal and external diameter d_i and d_e, respectively, as well as with the heat transfer coefficient h_i and the conductivity of the pipe λ_p as follows:

$$U = \left(\frac{1}{h_i} + \frac{d_i}{2\lambda_p} \cdot \ln \frac{d_e}{d_i} \right)^{-1} \quad (2)$$

In case of non-geometric models, i.e. 1D-models, the real behavior can be approximated applying a heat transfer efficiency η_{hx}.

$$\dot{Q} = \eta_{hx} \cdot UA \cdot (\vartheta_m - \vartheta_{hx}) \quad (3)$$

This heat transfer efficiency η_{hx} can be either determined by means of measurements or by means of 2D FE simulations. In case of shallow GHX such as basket type GHX and HGHX freezing has significant influence. Freezing is considered using the capacity method (Ochs 2013), see also section Validation of a basket-type ground heat exchanger, below.
Remarks: Initialization has significant influence. In particular for the VGHX quasi steady-state is reached after more than some 10 years. In order to avoid very long simulation time simulation is performed for one year with an additional initial phase of 4 month starting from quasi steady-state conditions.

3.2 Modelling of a basket type ground heat exchanger

Parabolic PDEs (in 2D) can be solved in Matlab with the PDETOOL using the form

$$d \cdot u' - div(c \cdot grad(u)) + a \cdot u = f \quad (4)$$

where the coefficients d, c, a and f are a function of the position x and time t and are independent from the variable u. Applied to heat transfer, Eq. (4) forms to:

$$\rho \cdot c_p \cdot \frac{\partial \vartheta}{\partial t} - div(\lambda \cdot grad(\vartheta)) = \dot{q} \quad (5)$$

The temperature ϑ is a function of the position x, the time t and the heat source q. The thermal conductivity λ and the volumetric capacity $C = \rho \cdot c_p$ can be functions of space and time but not of temperature.
With a radial symmetric formulation of the PDE, a basket ground heat exchanger can be modelled (Figure 4). The heat transfer equation is formulated to:

$$r\rho c_p \frac{\partial \vartheta}{\partial t} - \frac{\partial}{\partial r}\left(r\lambda \frac{\partial}{\partial r} \vartheta \right) - \frac{\partial}{\partial z}\left(\lambda \frac{\partial}{\partial z} \vartheta \right) = \dot{q} r \quad (6)$$

with radius r and depth z. The reduction of the extraction energy and power of neighboring baskets might be considered by reduced extension of the domain (or distance of the radial boundary, respectively). However, the reduction is overestimated if a neighboring basket is located only on one two or three sides.

Using the method of lines, the thermal conductivity λ, and the volumetric capacity ($\rho \cdot c_p$) can be functions of space, time and temperature. Using the method of lines the PDE can be transformed in an ODE that can be solved using Simulink (see Ochs 2012, Ochs 2013).

$$\frac{d}{dt}U = M^{-1}(F + G + R + KU + QU + HU) \qquad (7)$$

Here, U is the dependent variable, K is the stiffness matrix, M is the mass matrix, F is the right side vector, Q is for the system matrix and G is the u related term. H and R are zero in case of Neumann BC and nonzero in case of Dirichlet BC. The process is schematically shown in Figure 5.

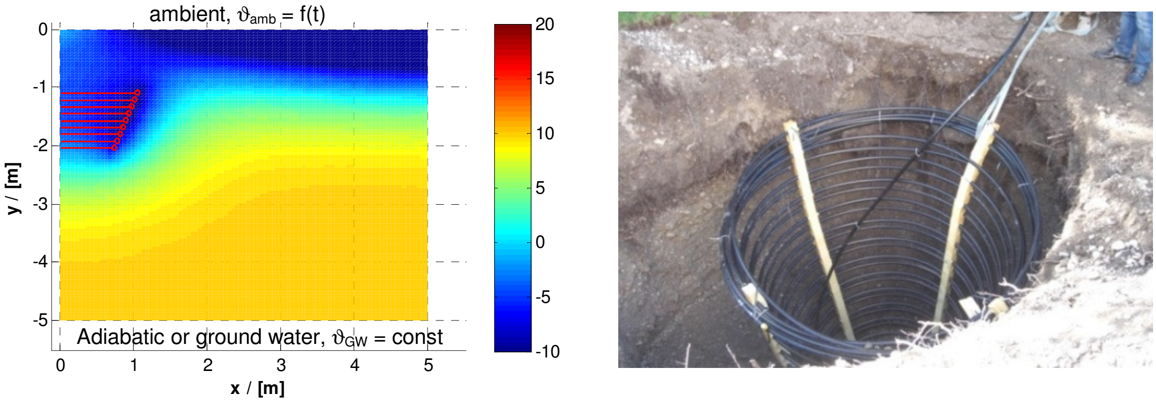


Figure 4: (left) temperature distribution in °C for a basket type ground heat exchanger, arbitrary point of time, ϑ_{brine} = 0°, (right) installation of a basket (source A. Drexler)

Simulink solves ODEs. These ODEs are generated from PDEs with the Method of Lines. The PDE parameters are updated with time, the integration is performed by Simulink. A Level-2 S-function can be used. In the block *Initialization* the states of the PDE are initialized (one state for each node). The update of the derivatives (method of lines) is performed in the *Derivatives* Block. The Outputs are e.g. the temperatures at the nodes, the fluid outlet temperature (with given inlet temperature and mass flow) or the heat flow.

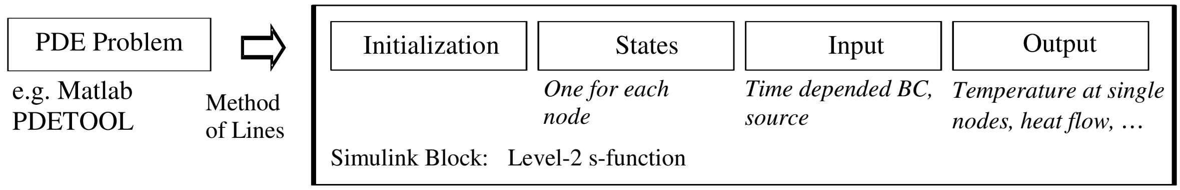


Figure 5: Schematic approach of solving PDEs within the Simulink environment

3.3 Validation of a basket-type ground heat exchanger

The monitoring data (see section above) serve very well for the purpose of validation as in the monitoring period both discharging (i.e. heat extraction) and charging (i.e. heat injection) cycles are included. Charging periods can be recognized by the higher mass flow.
Applying the 2D-FE model with cylindrical formulation of the PDE the geometry of the basket (depth, width, pipe size and distance) can be depicted as built in reality.
However, usually the exact properties of the ground as well as the level and velocity of ground water are not known. Furthermore, there are unknown influences such as e.g. rain or melting of snow, which are not considered in the model.
In such a model due to the large number of unknown parameters the degree of freedom is relatively high. However, for most parameters the values can be limited to a reasonable range based on experience. For the validation the following properties have been assumed

for the ground. The porosity of the ground is assumed to be 20 % and the volumetric water content is varied between 0 and 20 %. A volumetric water content of 15 % to 20 % was found to yield relatively good agreement between measurement and simulation. The water content of the ground has significant influence if freezing is considered. For the freezing (capacity method, see Ochs 2013) a ΔT of 2 K is assumed. (The latent heat of fusion is Δh_{sl} = 333 kJ/kg). For the cases without freezing the water content has been set to zero with otherwise same material properties.

Table 1: Ground properties

	Density [kg/m³]	**Thermal conductivity [W/(m K)]**	**Heat capacity [J/(kg K)]**
Air	1.24	0.026	1007
Water liquid	997	0.613	4179
Water solid	918	2.31	2052
Solid	1500	2	800

Simulation times are relatively high using Matlab Level 2 S-functions. Simulation speed can be increased by some 20 % using C S-functions instead (see also Siegele 2013). However, in particular if freezing is considered for long periods the 2D FE approach is hardly feasible. Therefore, in addition, a simplified 1D-model has been used with the approach of the heat transfer efficiency (see section above). For the 1D model an efficiency of η_{hx} = 0.75 has been found to be appropriate where in a range of 0.7 to 0.8 the influence on the result is of minor significance. However, further optimization including material properties and boundary conditions (BC) - such as solar absorption and long-wave radiation - might possibly further improve the results.

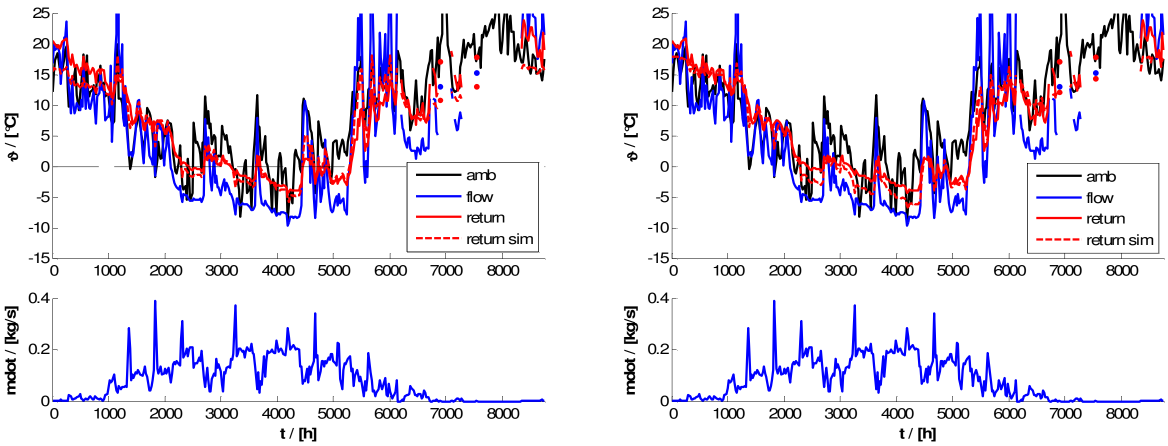


Figure 6: Measured ambient and flow temperature taken as BC as well as measured and simulated return temperature for (left) 2D FE model, (right) 1D FD model with a η_{hx} = 0.75

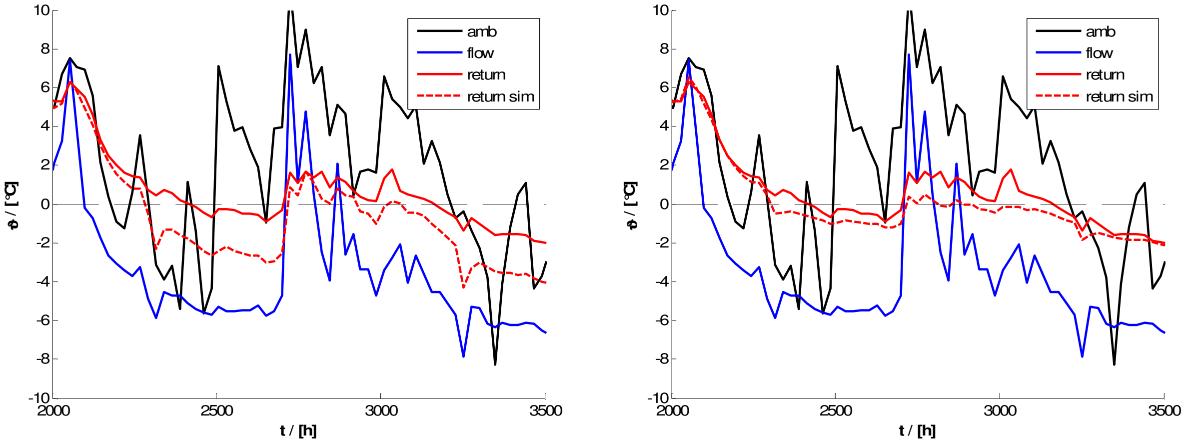


Figure 7: Detail of measured and simulated return temperature for the 1D model without icing (left) and with icing (right) with a moisture content of 20 %

Both simulation models deliver relatively good results, while the 2D model predicts the measured data slightly better. The seasonal trends are followed relatively precise, however charging peak powers are underestimated by both models. The behavior at freezing conditions can be predicted also with good accuracy with a moisture content of the ground in the range of 15 to 20 %.

4 SYSTEM SIMULATION – THERMODYNAMIC ANALYSIS OF REGENERATION OF THE GROUND

4.1 Overview of investigated concepts

With the validated models a thermodynamic analysis of solar thermal regeneration of the ground is conducted for different types and designs of ground heat exchangers by means of simulation with Matlab/Simulink using the CARNOT blockset (Hafner 2005).
As reference an air source HP and solar domestic hot water preparation is investigated. Solar domestic hot water preparation is operated with a direct electric backup heater with tapping profile defined in (IEA SHC T44 HP A 38, Dott et al. 2013, Haller et al. 2013). The air source heat pump is directly connected to a floor heating system and controlled with zone temperature (on-off). Set point temperature is 20 °C. As building the SFH15 reference building of IEA SHC T44 HP A38 is used.
The ground source HP is simulated with different types of ghx according to Figure 3. The performance map of a standard heat pump is taken and scaled to match the required heating power. The hydraulic scheme is shown in Figure 8. Solar domestic hot water preparation with direct electric backup is identical to the reference system, regeneration of the ground with solar thermal energy is considered optionally. The heat pump is directly connected to the floor heating system and the control of heat pump (on-off) uses the zone temperature of the house. The benefit of an optional regeneration of the ground with solar collectors is investigated.

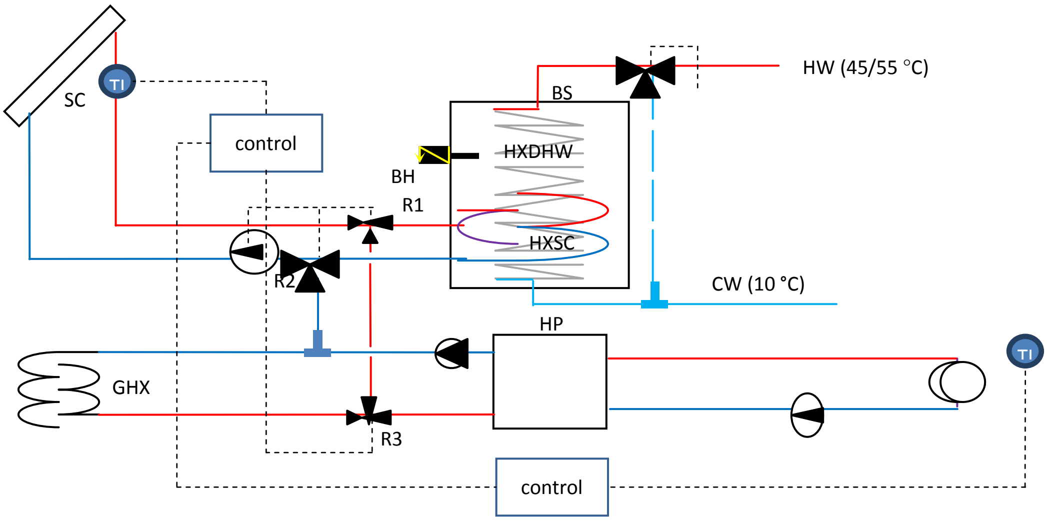


Figure 8: Hydraulic scheme of system with ground source HP with solar regeneration and solar domestic hot water preparation

Remarks: Solar regeneration and DHW preparation are simulated independently. For the solar regeneration it is assumed that the collectors deliver energy to the ground if the flow temperature of the collector is between 20 °C and 30 °C, but only if the 24 h floating average of the ambient temperature is smaller than 12 °C (i.e. in winter). Variants are investigated where the solar regeneration is increased (flow temperature of the collector between 20 and 40 °C or 20 and 50 °C, respectively).It is further assumed that the solar domestic hot water preparation is not (significantly) influenced by this.

4.2 Results for solar domestic hot water preparation

Solar fraction and specific collector yield for the domestic hot water preparation as a function of the collector area are plotted in Figure 9. For the further investigation a collector area of 10 m² is assumed, which delivers reasonable to good solar fraction of 73 % (1-Backup/DHW). Considering the direct electric backup including aux. energies (solar pump and controller) a $SPF_{DHW} = Q_{DHW}/P_{el,DHW} = 3.42$ is obtained.

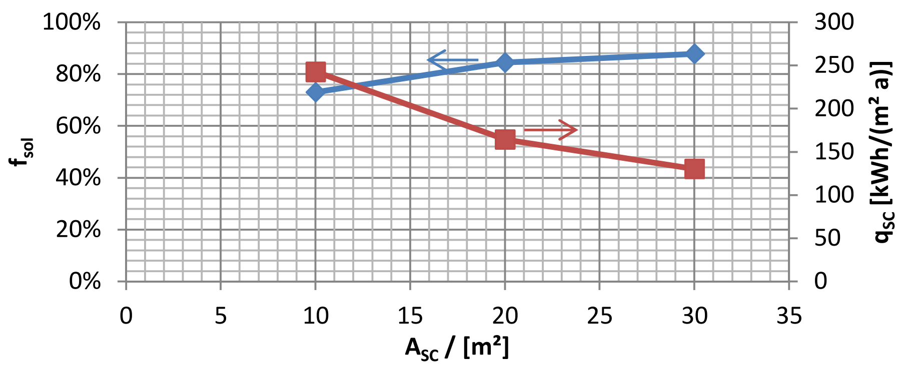


Figure 9: Solar fraction (1-Backup/DHW) and specific collector yield for the domestic hot water preparation as a function of the collector area

4.3 Results for space heating

For very efficient buildings such as a Passive House (SFH15) cost effective heating systems can be realized. The investigated system consists of an air or ground source heat pump for heating. With a heat pump directly connected to the floor heating system very low flow

temperatures can be realized resulting in good performance for all types of sources (air and ground). However, in particular for ground coupled heat pumps a well dimensioned system (heat pump power matched to load of the building and ground heat exchanger size as well as very efficient circulation pump) is required.
Independent of the type of ground heat exchanger, ground source heat pumps with tightly dimensioned GHX do perform as good/bad as air sourced heat pumps. The main advantage of ground coupled heat pumps is that they are invisible and silent. Figure 10 shows the total electric consumption for different lengths of GHX (VGHX and basket type GHX).

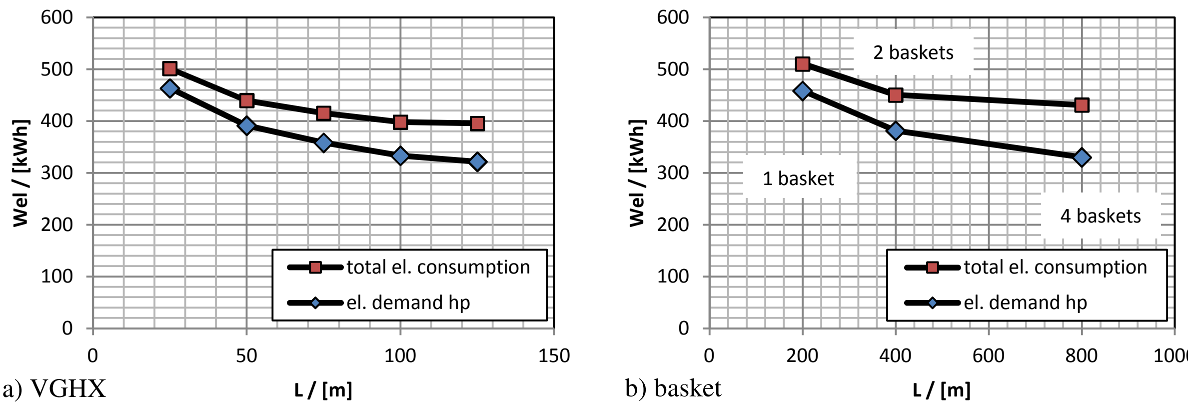


Figure 10: Electric consumption with and without brine pump and control as (a) a function of the borehole depth (b) a function of the number of parallel baskets (1: 200, 2: 400 and 4: 800 m)

The monthly electrical energy consumption for domestic hot water and heating inclusive auxiliary energies is shown in Figure 11.

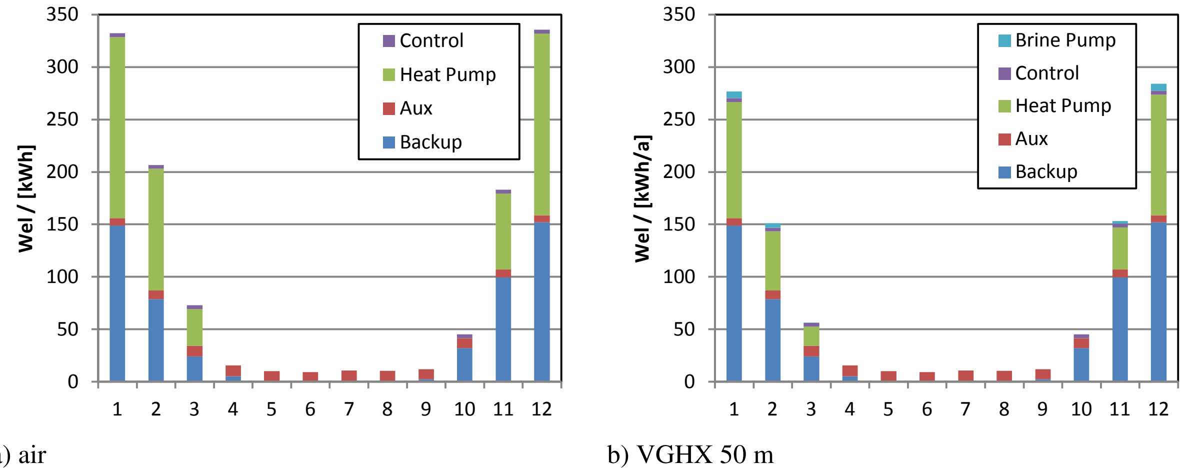
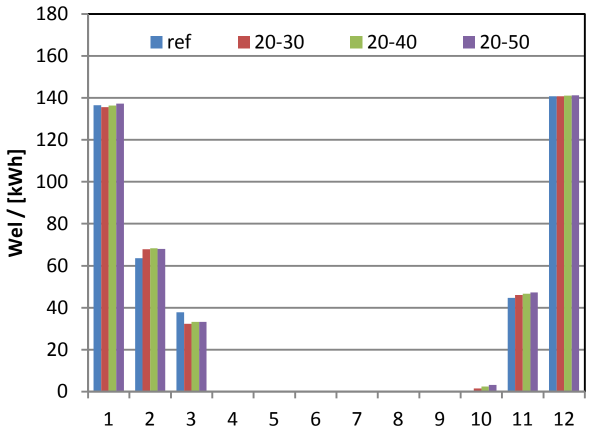
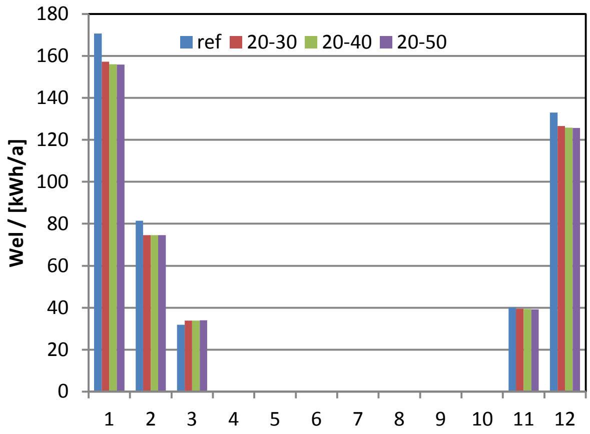


Figure 11: Monthly electrical energy consumption for DHW and SH inclusive auxiliary energies for (a) the air source heat pump (b) a ground source heat pump (50 m VGHX).

4.4 Solar regeneration

Different regeneration set points were investigated: 20-30: Solar injection if flow temperature of solar collector is between 20 °C and 30 °C (only if heat pump is not in operation and if the floating average of the ambient temperature is below 12 °C, i.e. in winter). 20-40 and 20-50: if the flow temperature is between 20 °C and 40 °C or 50 °C, respectively. Figure 12 shows the monthly el. energy consumption of the heat pump with and without solar regeneration for 50 m VGHX and a basket type GHX.



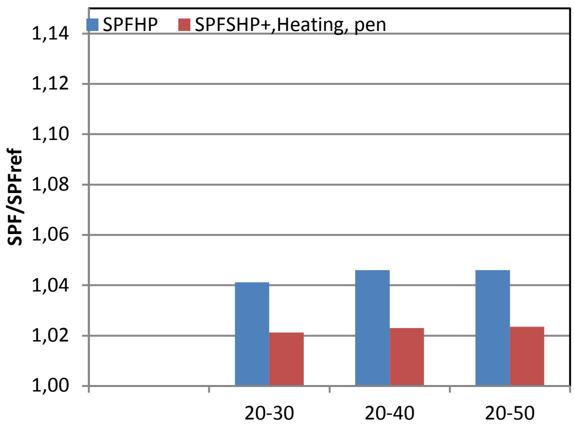


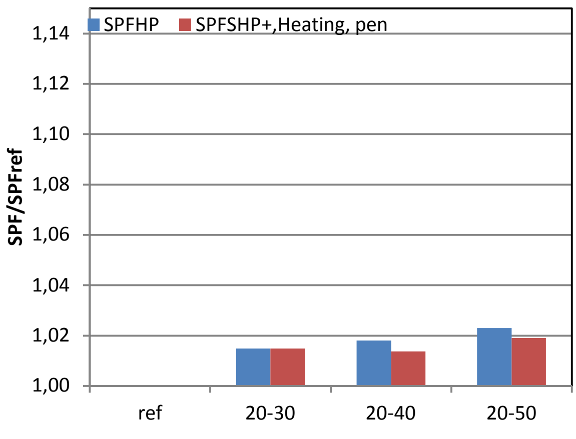
a) VGHX (50 m)
solar injection:
20-30: 355 kWh, 20-40: 354 kWh, 20-50: 493 kWh

b) basket type GHX (single)
solar injection:
20-30: 437 kWh, 20-40: 639 kWh, 20-50: 837 kWh

Figure 12: Monthly electricity demand of the heat pump for heating (W_{el}) for the reference case (without solar regeneration) and for three different control set points for (a) 50 m VGHX and (b) basket type GHX

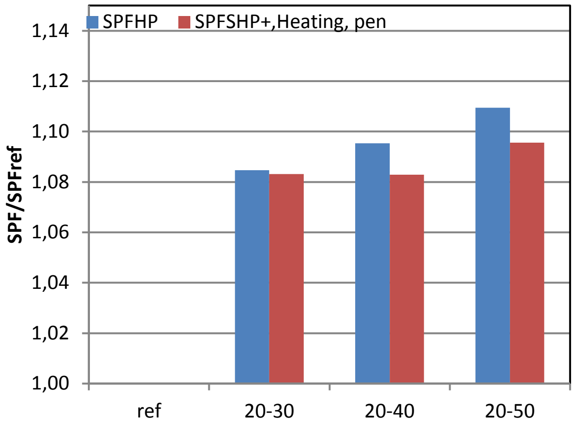
Solar regeneration cannot be recommended generally. Solar regeneration should only be applied in case of compact ground heat exchangers such as basket type GHX or building integrated HGHX. If the heat pump is used for heating only (or used in combination with a solar thermal system which delivers DHW demand to a significant share in summer), solar regeneration is only beneficial in autumn and winter (i.e. as heat dissipates if injected into the ground no more than 1 month before heating season starts). Minimization of aux. energies (brine/solar pump and control) is of major importance. Even if the heat pump SPF can be slightly improved, the system SPF is not necessarily increasing due to parasitic energies.
In Figure 13 the relative change of SPF_{HP} (i.e. heat pump SPF) and $SPF_{SHP+(Heating),pen}$ (i.e. system SPF for heating) for different regeneration set points is shown for different types of ground heat exchanger.



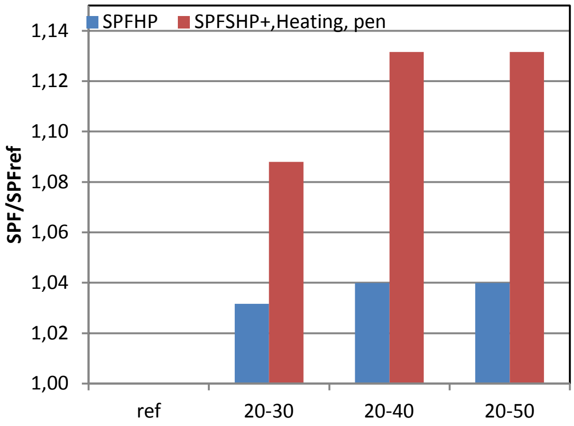


a) HGHX 200 m

b) VGHX 50 m



c) basket type GHX



d) building integrated HGHX

Figure 13: relative change of SPF_{HP} and $SPF_{SHP+(Heating),pen}$ for three different control set points of solar regeneration for (a) HGHX, (b) VGHX, (c) basket and (d) building integrated HGHX

4.5 Special case of building integrated HGHX

In case of the building integrated HGHX the heating demand increases ("ref" compared to "air", see Figure 14) due to the decreased ground temperature as a result of the operation of the heat pump. With solar regeneration the heating demand decreases again.

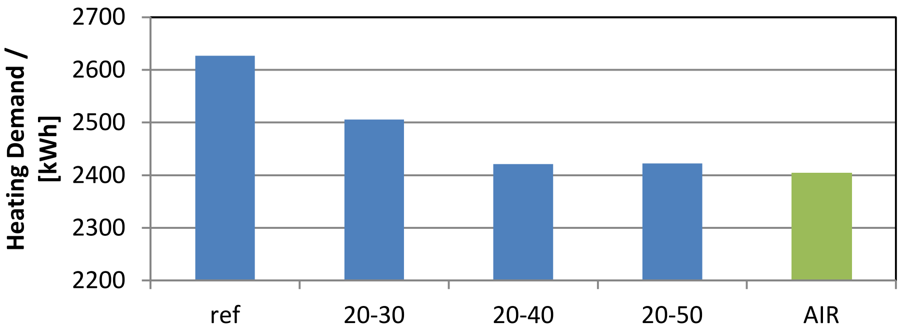


Figure 14: Heating demand in case of the integrated HGHX without solar regeneration (ref) and with regeneration (20-30, 20-40, 20-50) and the HD of the SFH15 with air sourced HP (Air).

5 SUMMARY AND CONCLUSION

The suggested system of a solar domestic hot water preparation with direct electric backup and an air source or ground coupled heat pump directly connected to the floor heating system is feasible for the SFH15. For very efficient buildings such as the Passive House, very low total electric consumption can be obtained. The suggested system is simple and relatively low cost.

Several types of GHX have been compared. If for a house with very low energy demand the GHX is efficiently, i.e. tightly dimensioned, the performance of the different GHX types differs only slightly. In this case the borehole hx does only perform slightly better than the bsket type ghx and ground coupled heat pumps do not perform much better than air source heat pumps. Over-dimensioned heat pumps (or under-dimensioned sources) lead to poor performance.

Solar regeneration is not generally recommendable. Minor improvement can be obtained in case of compact GHX (such as basket) and building integrated HGHX. For the latter one the heating demand increases due to the lower ground temperature. This effect can be reduced

or compensated by solar regeneration. Optimized control strategy and set points are required. Solar injection should be limited to autumn and winter (and early spring). Very efficient circulation pumps (brine and solar) are required.
In future work the investigations should be extended to different climates.

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