Conference Proceedings

EuroSun 2016
Palma de Mallorca (Spain), 11 – 14 October 2016

COMBINATION OF SOLAR THERMAL COLLECTORS AND HORIZONTAL GROUND HEAT EXCHANGERS AS OPTIMIZED SOURCE FOR HEAT PUMPS

Fabian Hüsing, Hauke Hirsch and Gunter Rockendorf

Institut für Solarenergieforschung Hameln GmbH (ISFH), Emmerthal (Germany)

Abstract

Heat pumps coupled to thermal ground sources, such as Horizontal Ground Heat Exchangers (HGHX), represent an efficient option to supply heating demands of single- and multi-family houses. However, the high land-use yet often prevents HGHXs from installation. The combination with solar thermal energy promises reduction of the HGHX area while retaining high system efficiencies. Our contribution studies the combination of HGHXs and solar thermal collectors, focusing on solar thermal regeneration of the soil. This is analyzed through both numerical modelling and experimental investigations. Modelling rests on a novel TRNSYS type for the HGHX, developed at ISFH. A test facility, installed on the premises of ISFH in Lower Saxony / Germany is used to validate the model. System simulations extrapolate the perceptions on differently configured heating systems.

Keywords: *horizontal ground heat exchanger, TRNSYS Type, system simulations, regeneration, bivalent source, HGHX area reduction*

1. Introduction

HGHX systems are integrated into the shallow subsurface at depth of 1-2 meters below surface. They represent flat, extended heat exchangers which extract naturally stored energy from the ground. To withdraw the heat from ground, heat pumps (HP) are used, which face the HGHX system as cold heat source and the buffer storage of a supplied building as heat sink. Characteristic performance quantity is the temperature shift between cold and hot ends of the heat pump. Especially, the coefficient of performance of the heat pump is related to this shift. One advantage of ground coupled heat pumps over ambient-air based systems is the fact that the temperature shift changes little during the course of the year as a result of the thermal inertia of the ground, provided that the HGHX size is properly designed. The existing technical guideline in Germany (VDI 4640-2) is presently under revision. The current draft (Verein Deutscher Ingenieure 2015) gives advice for the design of HGHX systems: The size (land-use) of an HGHX system for a given heating demand, soil type and climate zone. However, for typical heat pump systems in residential buildings the land-size recommended often exceeds the existing potential.

The combination of HGHX and solar thermal collectors provides a solution, as the land-use of the HGHX can be reduced significantly while maintaining high system efficiencies. This contribution deals with the investigation of this combination, analyzing solar regenerated HGHX heat pump systems through both numeric modelling and experimental investigations. A model of the HGHX developed at ISFH as a type for the modelling suite TRNSYS (Klein et al. 2010) and it's validation are presented. The validation is performed using a 150 m^2-sized HGHX, installed on the premises of ISFH in Lower Saxony / Germany as part of a test facility. We explain the model and evaluate different system configurations studied.

doi:10.18086/eurosun.2016.04.18 Available at http://proceedings.ises.org

2. Horizontal ground heat exchanger model

2.1 Numerical model

To represent the dynamic behavior of a HGHX precisely, the model includes the following physical components: It is based on a two dimensional formulation of transient conductive heat transport problem. Fourier's Law is employed to model conductive heat transport from and to soil, which is in contact to a pipe axially streamed by a heat carrier fluid. The model reduces the heat transport between soil and pipeline to a plane perpendicular to the pipe, see Figure 1. The plane is discretized by a rectilinear mesh, which refines towards the pipe and the soil surface. The selected boundary conditions are adiabatic to the lateral edges of the plane (as explained below), radiative heat exchange and convective heat transport at the surface edge and a constant temperature at the lower edge of the plane. The interior boundary to the pipe domain is represented by a convective heat transfer condition which takes into account the carrier flow regime. The temperature of the fluid results from an axial energy balance of the pipeline. The transport equations for soil and pipe are numerically solved by the method of (explicit) finite difference, coupled through the thermal conditions at the interior boundary between soil and pipeline.

The TRNSYS type distinguishes two soil domains, see Figure 1. Soil domain A represents an inner segment of the HGHX, which is enclosed by adjacent pipes. Symmetry is assumed and thus left and right boundaries are adiabatic, which leads to significantly lower computational effort. Soil domain B represents a fluid pipe at the HGHX edge or a supply pipe. In contrast to soil domain A, it extends to a variable distance (parameter b) on one side, which can be considered as undisturbed soil if parameter b is chosen sufficiently large.

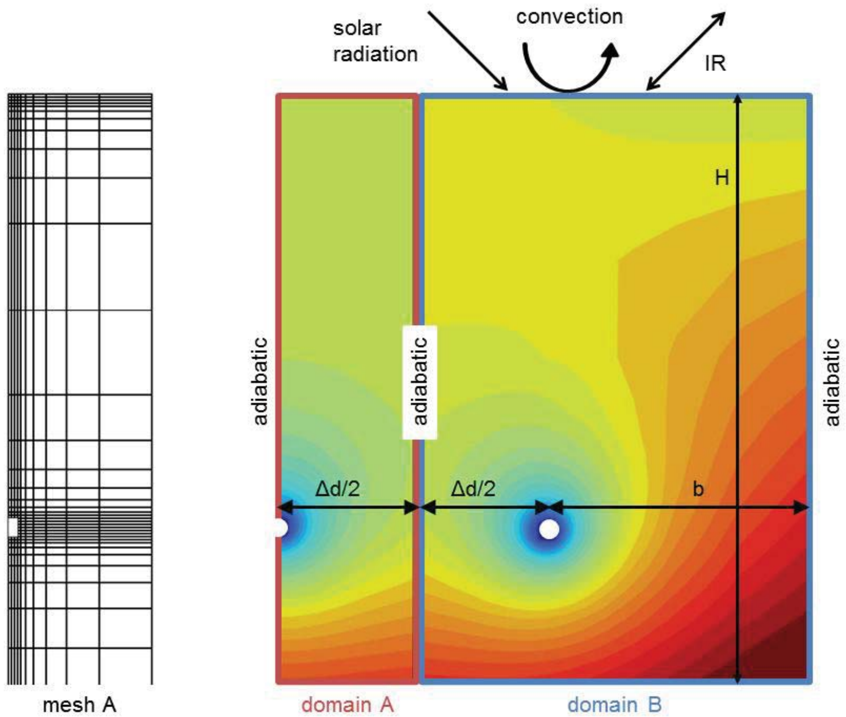

Fig. 1: Soil domain and discretization of HGHX model. Left: Discretization of soil domain A. Right: Charactersitic temperature contour plots for both soil domain A and B as well as indicated boundary conditions.

In comparison to previously published HGHX models (e.g. by Giardina 1995, Ramming 2007 or Glück 2009), the presented model has the advantage of combining all of the following properties:

- Sufficiently fine discretization of the soil domain
- Modelling of latent heat extraction and change of soil properties during freezing
- Consideration of the fluid capacity inside the HGHX, in both situations with and without massflow

- Consideration of heat gains through HGHX lateral edges
- Implementation as computation time optimized TRNSYS Type

An extended experimental validation for the presented model was conducted at ISFH for which exemplary results are presented in the following paragraph.

2.2 Model validation

For validation of the numerical model under static and dynamic operation conditions, a test facility was installed on the premises of ISFH, Figure 2 (left). It includes a shallow horizontal ground heat exchanger covering 150 m², a compressor heat pump and a resistant heater to emulate heat generation by solar thermal collectors. On the condenser side of the HP, a load module is installed, which emulates pre-defined thermal load profiles. Monitoring equipment is installed at the test facility to measure soil, brine and water temperatures, as well as meteorological data (ambient air temperature, solar irradiation, and infrared radiation (IR)) during and also between individual test runs.

Different experiments were performed to assess the quality of the model. For the simulations, measured operation data (heat transfer rate at the HPs evaporator, mass flow, and start temperature of the soil domain) and meteorological data are used as inputs to the model. The results for a selected experiment and the associated simulation are shown in Figure 2. The experiment is conducted using only a single out of four fluid circuits of the HGHX. The pipe length is 65 m. Constant mass flow of 0.278 kgs^{-1} and a heat extraction rate of 1.2 kW were the operating conditions of the experiment. The setup is chosen to validate the ability of the HGHX model to represent impacts of lateral heat gains at HGHX edges. Two model configurations are compared: A 2d model, using only soil domain A (neglecting HGHX edges) and a virtual 3d model, using a series connection of soil domain A and B and thus taking into account HGHX edges.

For both model configurations, Figure 2 confirms acceptable coincidence between measurement and simulation at the beginning of operation (see inset subfigure for first half hour). Especially for long periods of heat extraction the effects of the border segments are of significant magnitude. The virtual 3d model allows an accurate representation of this effect, as the deviation is only 0.2 K after 80 hours of operation.

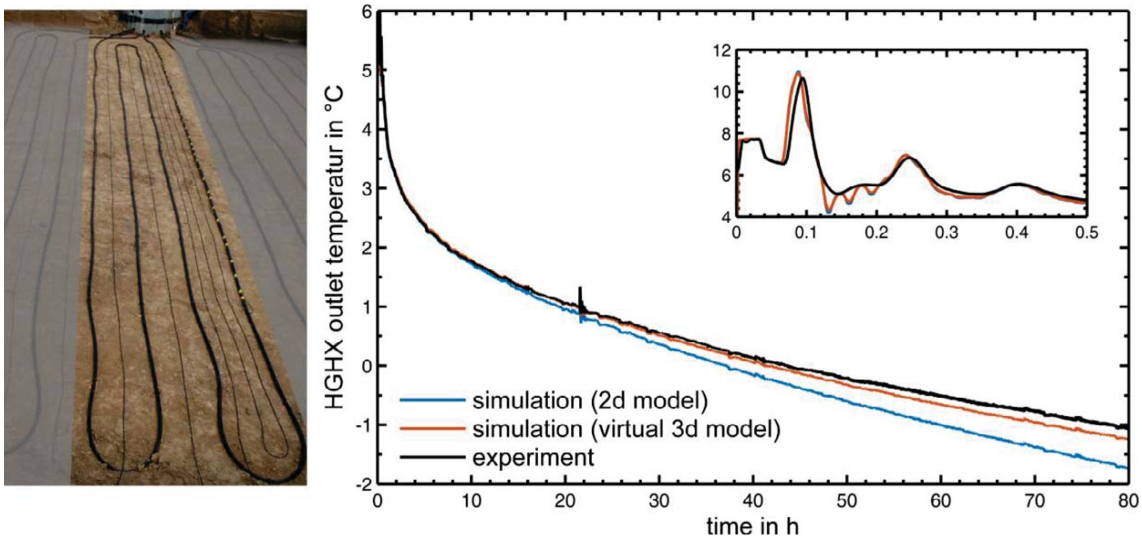

Fig. 2: Experimental setup and comparison of measured and simulated temperatures

Therefore the TRNSYS-Type can be regarded as a precise model for a HGHX for application in heat pump coupled system simulations. Further information on the HGHX model can be found in Hirsch et al. 2016.

3. System simulations

To investigate performance and efficiency of HGHX supplied heat pump systems and subsequent integration routes of solar thermal energy, TRNSYS simulations employing the presented HGHX model are evaluated.

3.1 Boundary conditions

The boundary conditions of the system simulation model are, in large part, taken from the Task 44 (Solar and Heat Pump Systems) of the Solar Heating and Cooling (SHC) program of the International Energy Agency (IEA) (Haller et al. 2012). This concerns the examined reference buildings (a newly constructed building: SFH45 and an existing building: SFH100) as well as internal load profiles for heat gains (Dott et al. 2012). The SFH45 uses a floor heating system while the SFH100 is equipped with radiators. At the chosen location of Zurich the buildings have annual heating demands of approximately 8500 kWh (SFH45) and 18000 kWh (SFH100), respectively. The domestic hot water tapping cycle adds an annual heat demand of approximately 2200 kWh. Supply configurations are equipped with two zone buffer storages for domestic hot water (DHW) and space heating (SH), each of which can be supplied with the connected heat pump.

The subsurface is characterized by three soil types according to 2015's draft of VDI guideline 4640-2 (Verein Deutscher Ingenieure 2015). Table 1 gives an overview over the properties of the three soil types used as parameters for the HGHX model. The total simulation time period is two years for each configuration, while only the data of the second year is used for evaluation.

Tab. 1: Parameters of the soil types used for the simulations

Soil nr.	**1**	**2**	**3**
Soil type (acc. to USDA)	Sand	loam	sandy clay
λ in $Wm^{-1}K^{-1}$ (unfrozen)	1.2	1.52	1.76
λ in $Wm^{-1}K^{-1}$ (frozen)	1.37	2.35	2.85
c_p in $Jkg^{-1}K^{-1}$ (unfrozen)	802	1218	1319
c_p in $Jkg^{-1}K^{-1}$ (frozen)	687	880	886
ρ in kgm^{-3}	1512	1815	1820
h_F (heat of fusion) in Jkg^{-1}	17648	51457	65977

3.2 System configurations

Two different HGHX-equipped supply configurations are studied, with and without solar thermal system, as shown in Figure 3. The HGHX is installed at a depth of 1.5 m in all cases. The simulations employ type 401 to model the heat pump. Parameters are taken from data determined by experimental testing of a commercially available heat pump at ISFH by Pärisch et al. 2014.

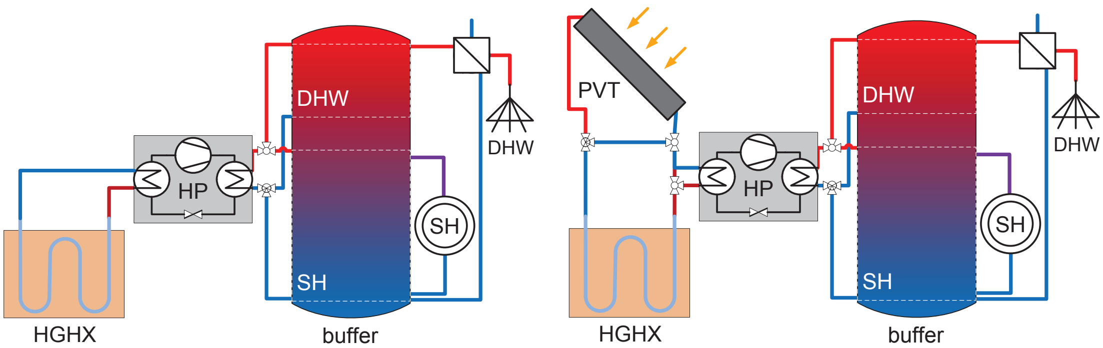

Fig. 3: System schemes for configurations without (left) and with (right) use of solar thermal energy on the source side

An unglazed photovoltaic thermal hybrid collector (PVT) is assumed as solar thermal supply system. The hydraulic layout allows different operation modes: (1) stand-alone HP/HGHX, while there are no (sufficient) solar thermal gains; (2) serial connection of the PVT and HGHX/HP, while heat demand and solar thermal gains coincide; (3) recharging of the HGHX by PVT (at lower mass flow), if solar thermal gains allow regeneration of HGHX and there is no present heat demand. The state of the system is monitored during the simulations and the specific operation mode is selected by a controller developed for this purpose. The upper limit of 25 °C for fluid entering the HGHX is observed in all operation modes to avoid overheating of the ground.

3.2 Performance indicators

To assess the quality of the simulated system configurations a set of performance indicators is defined. For a ground coupled heat pump system there are two classes of quality to assess: efficiency and sustainability.

Sustainability of a HGHX means to avoid states of exhaust as well as securely avoiding critical frost conditions. An HGHX is exhausted if the temperature of the carrier fluid on influx to HP evaporator falls below -5 °C during operation. This is the temperature at which the HP is no longer operated and an electric auxiliary heater is used instead. Accordingly the amount of heat supplied by the auxiliary heater (Q_{aux}) is used as an indicator for HGHX exhaustion. The critical frost conditions affect the biosphere as well as important soil properties like rainfall infiltration etc. To detect states of induced frost two gauges are implemented, vertical and horizontal. The “vertical” frost indicator, referred to as vertical FI, is activated once the frost around the HGHX pipe collides with the surface frost. The horizontal frost indicator, referred to as ISFH FI, is activated once the frozen domains around adjacent HGHX pipes grow horizontally into contact, in absence of surface frost.

The efficiency of a heat pump system is assessed by the seasonal performance factor of the system (referred to as SPF_{SHP} following a definition by D’Antoni (2013)). This indicator takes into account the useful heat divided by the total electric energy spent for its generation:

$$SPF_{SHP} = \frac{\text{useful heat}}{\text{electric energy}} = \frac{\int (\dot{Q}_{DHW} + \dot{Q}_{SH})dt}{\int (P_{HP\_compressor} + P_{aux} + P_{pumps} + P_{control})dt} \qquad \text{(Eq. 1)}$$

3.3 Results

Figure 4 depicts the seasonal performance factor for different soil types as function of HGHX area. The results are based on the spacing between HGHX pipes (dx) recommended for each soil by 2015’s draft of VDI guideline 4640-2 (Verein Deutscher Ingenieure 2015) for laminar flow. The size recommended for each soil type by the guideline is marked by a black diamond. Furthermore the occurrence of critical frost conditions is displayed by the frost indicators for vertical and ISFH criteria.

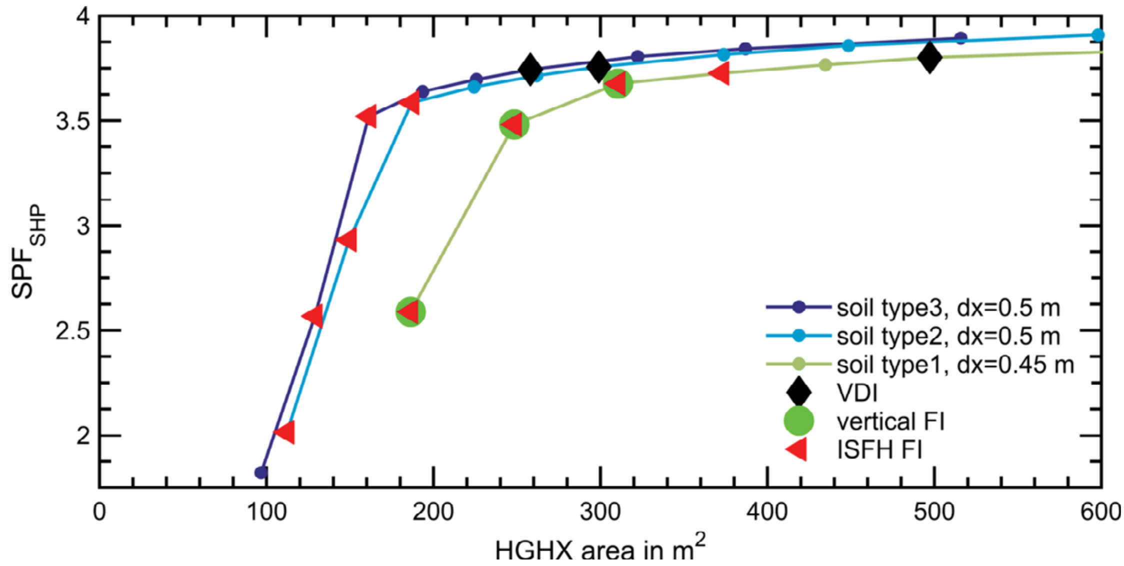

Fig. 4: Seasonal performance factor SHP for different soil types over HGHX area

The shapes of the graphs are characteristic of HGHX systems. From their curvatures follows, that the reduction of the HGHX area below a critical size causes significant degradation of the system performance, while beyond this critical value only moderate efficiency wins are possible. The designs recommended by the VDI guideline are always well beyond the critical size, securely avoiding critical frost conditions and reaching seasonal performance factors of approximately 3.75. The ISFH frost indicator is the strongest frost criteria limiting small HGHX areas. The vertical frost indicator is only activated for soil type 1 (sand), which has the lowest enthalpy of fusion (h_F).

To analyze the underlying effects responsible for the characteristic shape of these graphs, the auxiliary power and energetically weighted evaporator inlet temperatures are plotted as function of the HGHX area in Figure 5. The occurrence of high demands for auxiliary power, Figure 5 (left), correlates with the significantly reduced seasonal performance factors below the critical systems size. Because electric auxiliary heaters have a lower thermal efficiency than heat pumps, exhausted HGHX systems cause break-in of overall system efficiency. The VDI 4640-2 avoids the necessity for auxiliary heating for all three soil types by sufficiently large design recommendations.

The energetically weighted mean evaporator inlet temperature, defined in Eq. 2, takes into account which amounts of energy are extracted at which temperature. Therefore it represents a good indication of the averaged condition of the heat source during heat pump operation throughout the year.

$$\overline{T}_{evap,\ energetically\ weighted} = \frac{\int (T_{evap}(t) \cdot \dot{Q}_{evap}(t))dt}{\int \dot{Q}_{evap}(t)dt} \qquad \text{(Eq. 2)}$$

The energetically weighted mean evaporator inlet temperature over HGHX area is shown in Figure 5 (right). For small HGHX areas, where auxiliary power demands cannot be avoided, the temperature stays in an interval from 0 to 1 °C, uncorrelated to HGHX area variations. This is explainable, as the extraction of heat from the HGHX is limited by states of exhaustion. Additionally produced heat near the state of exhaustion mainly originates from latent heat extraction at constant temperatures. Above the critical size, the increase of HGHX area increases the source temperature levels. Here, the natural soil temperature is the theoretical limit for the evaporator inlet temperature; hence the decreasing slopes of the respective curve branches. The small size-sensitivity of the source temperature for larger HGHX sizes is reflected by the HP performance. The detected performance gains are in agreement with values published earlier by Pärisch et al. 2014. The designs according to VDI recommendations reach energetically weighted mean evaporator inlet temperatures in a range from 3 to 4 °C.

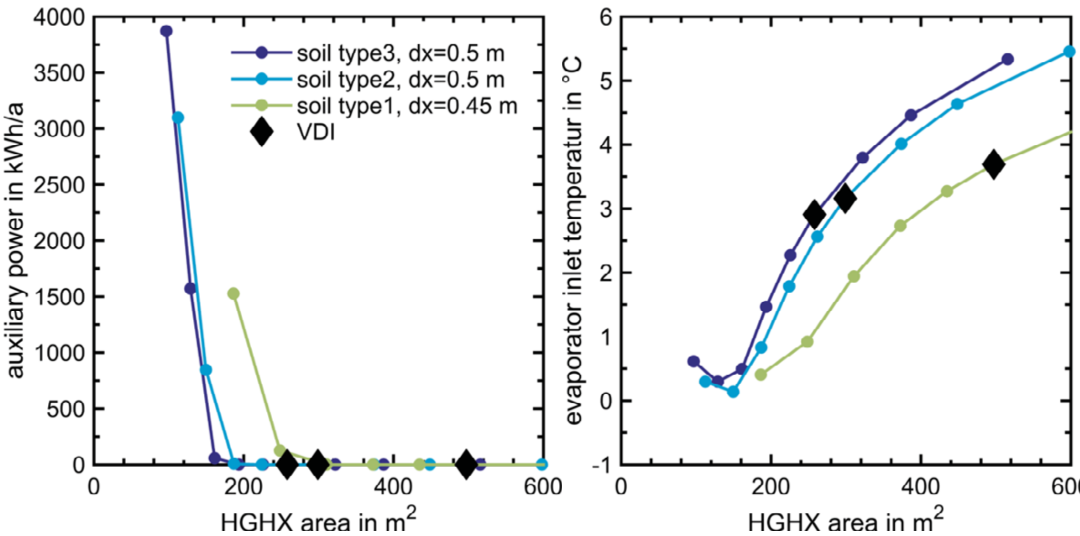

Fig. 5: Auxiliary power and energetically weighted evaporator inlet temperature for different soil types over HGHX area

Figures 6 and 7 present the seasonal performance factors for soil type 2 (loam) as function of the HGHX area, parametric in the pipeline spacing and for ascending sizes of the PVT collector. The VDI 4640 design recommends, under assumption of laminar flow, a pipeline spacing of 0.5 m. Figure 6 (left) shows the results for a system without solar thermal regeneration. The shapes of the graphs are therefore similar to the ones shown in Figure 4. All plots confirm that narrower pipeline spacing enables higher efficiencies in general. We see that a size reduction of 28 % (A_{HGHX} from 311 m² to 224 m²) of the HGHX relative to the VDI 4640 design recommendation may be tolerated at almost missing efficiency losses.

In the second diagram (Figure 6 right) results for systems equipped with 6.7 m² of PVT collector area are depicted. To focus on the thermal/regeneration process, electrical energy yield of the PVT collector is not included in the calculation of seasonal performance factors at this time. At high HGHX areas, the seasonal performance factors are lowered, due to the added electric energy demand of the collector pumps. At lower HGHX areas the seasonal performance factors increase. The main reason therefor is that the HGHX is less frequently exhausted and thus the demand for auxiliary power is lower. Also the occurrence of critical frost conditions is slightly limited.

With increasing PVT collector areas (Figure 7), the described trends proceed, until at 26.6 m^2 of PVT collector area critical frost conditions are completely prevented, even for the smallest HGHX areas simulated. At this PVT collector size the HGHX area may be as much as 64 % smaller (A_{HGHX} from 311 m^2 to 112 m^2), while achieving almost the same system efficiency as an unsupported system. Only 5 % efficiency losses (SPF_{SHP} from 3.76 to 3.60) are predicted in this case.

Similar results are obtained for soil types 1 and 3. For narrower spacing between the HGHX pipes and with solar thermal regeneration the simulations predict possible HGHX size reductions between 49 to 66 %, taking into account limited efficiency losses below 5 %. Note that Soil type 3 (sandy clay) has greater potential for area reductions (66 %) than soil type 1 (sand, 49 %) due to both higher heat conductivity and higher heat capacity.

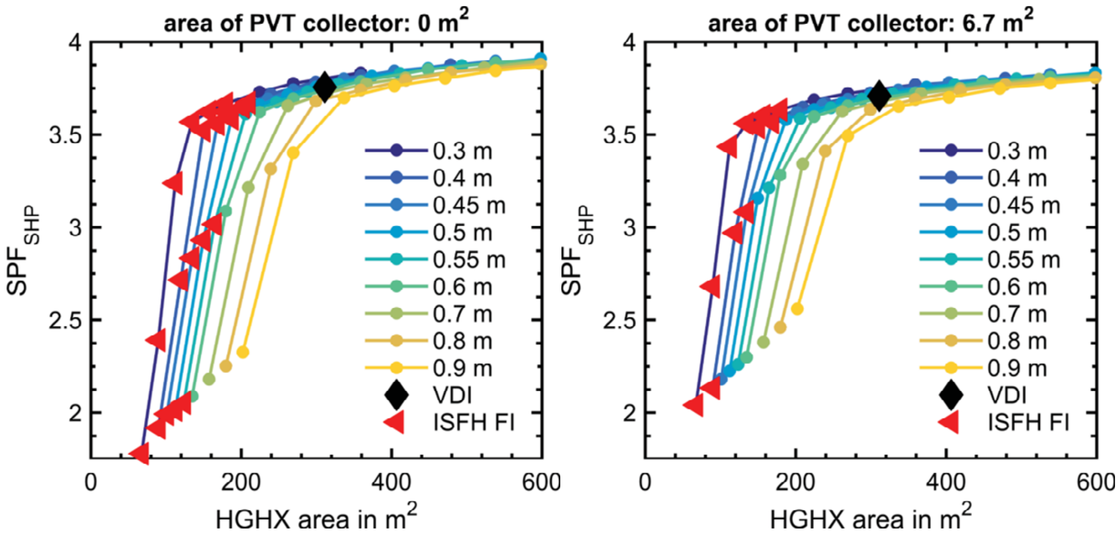

Fig. 6: Seasonal performance factor for soil type 2 over HGHX area for different spacing between HGHX pipes

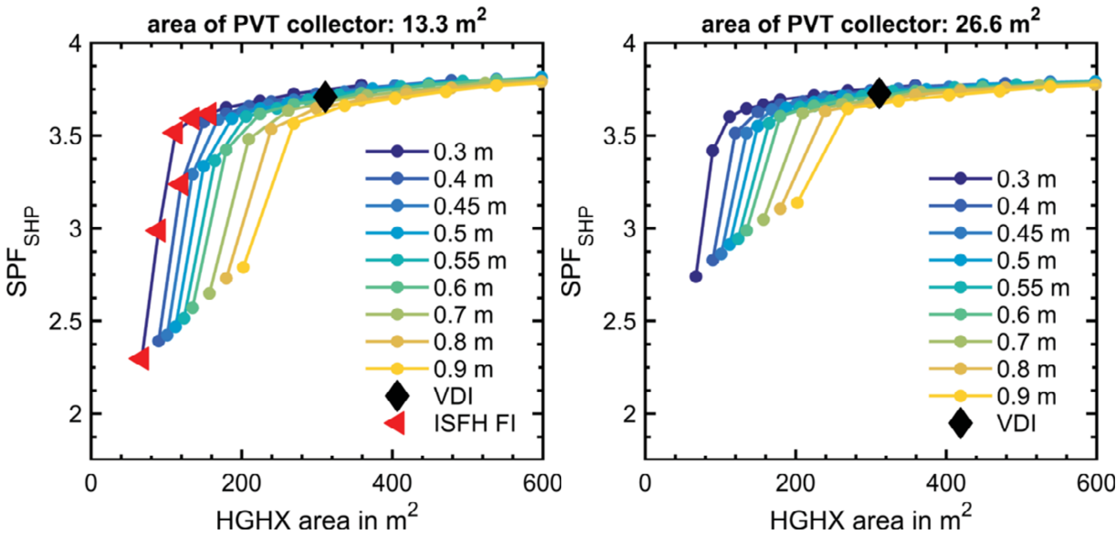

Fig. 7: Seasonal performance factor for soil type 2 over HGHX area for different spacing between HGHX pipes

In the following we analyze the operation of the HGHX fluid cycle with and without solar thermal regeneration. For this purpose the progression of energy quantities of the HGHX and the PVT collectors is considered in time on a monthly basis. The considered HGHX system has a size of 134.6 m^2 comprising a pipe separation of 0.3 m. It is supported by PVT collectors of two selected sizes (13.3 and 26.6 m^2).

Figure 8 provides the monthly net heat extraction from the HGHX with and without the PVT collectors of respective sizes. Net heat extraction is defined as heat extraction subtracted by solar thermal heat supplied to the soil. For the system without active solar regeneration (purple graph), the net heat extractions resembles a typical domestic HP heat demand progression. High heat demands in the winter oppose low demands in the summer, when domestic hot water preparation is the only demand.

Systems with solar thermal regeneration (blue and green graphs) show a slightly different progression. While the differences in net heat extraction are reduced for October (month 10) to December (month 12), i.e. the beginning of the heating season, the difference grows significantly larger towards March (month 3). Solar regenerated systems exhibit negative net heat extractions, once more heat is fed into the HGHX than extracted. The model predicts maximum regeneration heat inputs between March (month 3) and July (month 7), dependent on the size of the PVT collectors.

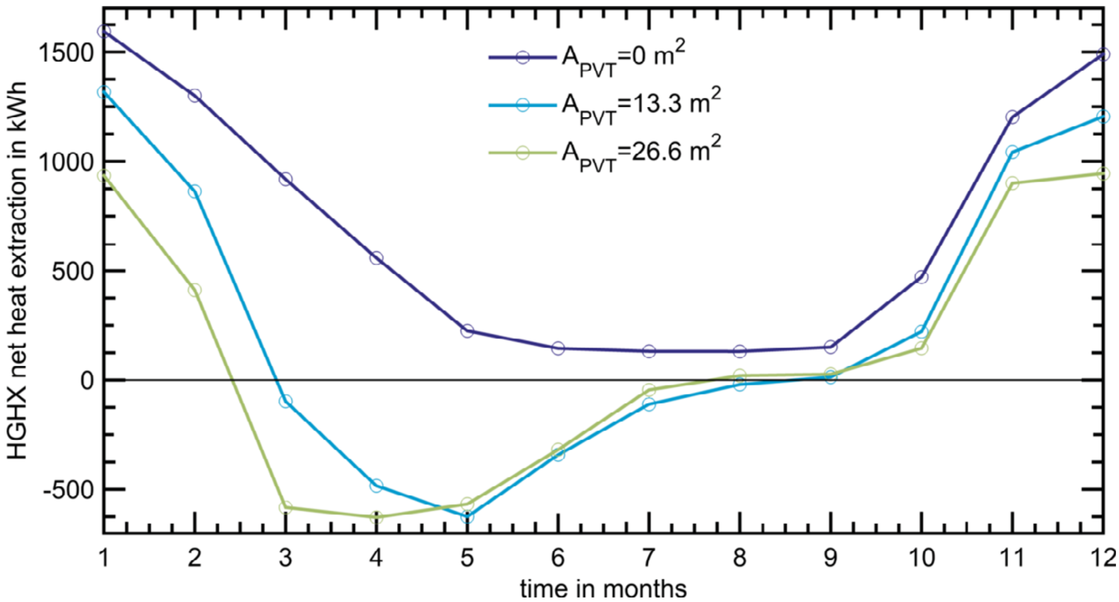

Fig. 8: Monthly distribution of HGHX net heat extraction

Figure 9 provides the monthly progression of the related solar yields, the quantity thereof fed to the soil (regeneration heat) and the solar irradiation on the collector plane. The maximum yield occurs in March (month 3, for A_{PVT} = 26.6 m^2) and April (month 4, for A_{PVT} = 13.3 m^2), respectively and coincides with the lowest net heat extractions shown in Figure 8. This shows that regeneration mainly takes place at the end of the heating season, when the HGHX tends to be exhausted.

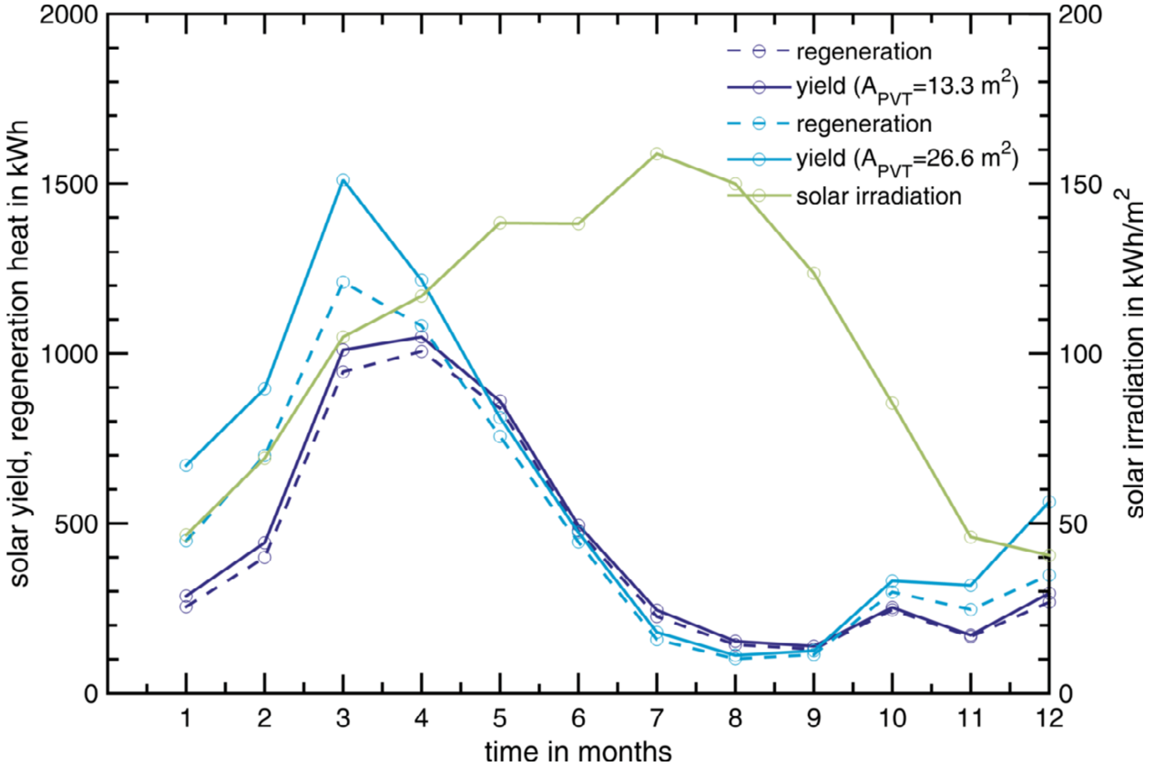

Fig. 9: Monthly distribution of solar yields, regeneration heat and insolation

For the smaller PVT collector area ($A_{PVT} = 13.3$ m^2) almost the entire solar yields are used for soil regeneration. Only systems with the larger PVT collector size exhibit tangible differences between solar thermal yield and regeneration heat from November (month 11) to April (month 4). In this case, the solar yield suffices to directly supply the heat pump during the heating season.

Comparing the yield and solar irradiation curves over the year, we see that significant solar irradiations (from May (month 5) to October (month 10)) remain unused in configurations connected only to the HGHX. The time period during October (month 10) to May (month 5) offers great potential for using solar thermal yields at low temperatures efficiently. Furthermore optimal synergy conditions exist for the solar/HGHX system, because of reduced competition between direct use and HGHX recovery.

Figure 10 illustrates the effects of regenerating a possibly undersized HGHX system. It shows energy quantities in the fluid carrier cycle along with auxiliary energy and energetically weighted evaporator inlet temperatures on a yearly basis. A HGHX system with a size of only 89.7 m^2 with a pipe separation of 0.3 m is considered.

The blue column represents the energy extracted from the fluid carrier cycle in the heat pumps evaporator (symbol Q_evap). This quantity scales with the PVT collector area size, because the source is less often exhausted. The auxiliary power demand (symbol E_aux, red column) shows the opposite behavior. This quantity scales inverse to the PVT collector area size. The second column shows the heat quantities delivered from the HGHX to the evaporator (symbol Q_HGHX->evap / dark green), from the PVT collectors to the evaporator (Q_PVT->evap / light green) and from the PVT collectors to the HGHX (symbol Q_PVT->HGHX / yellow). The diagram shows that while the system without PVT collector extracts the entire heat from the HGHX, the PVT supplied system may use the solar yields partially in the evaporator. Hence the heat extraction from the HGHX can be reduced, while most of the solar yields are used to actively regenerate the HGHX. The energetically weighted evaporator inlet temperature increases from -0.74 °C without PVT collectors to 2.32 °C with a PVT collector size of 26.6 m^2.

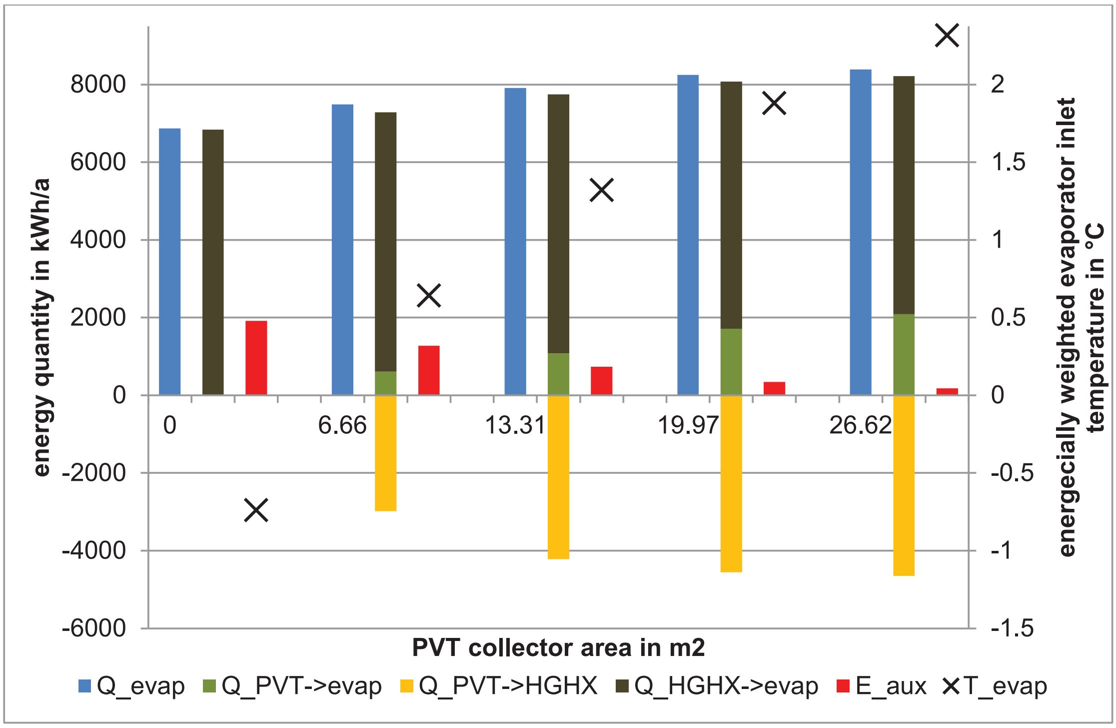

Fig. 10: Energy quantities of the source cycle, auxiliary energy and evaporator temperatures over PVT collector area

The simulations predict that the integration of 26.6 m^2 of PVT collectors on the source side allows the seasonal performance factor of an undersized HGHX (~29 % of VDI's recommendation) to be increased from 2.4 to 3.4. When taking into account the potential of electricity co-generation of the PVT modules (using only electricity obtained from grid for the calculation of the seasonal performance factor) the overall systems seasonal performance factor may even reach 3.7, which means the PVT-supported, undersized HGHX system is as efficient as the standard VDI design – but two thirds smaller.

4. Conclusion and prospect

A TRNSYS model for HGHX has been developed and successfully compared against measurement data. For analysis of system configurations including a heat pump and solar thermal regeneration it is successfully integrated into a system model. The ability to use the model in differently configured heat supply systems in TRNSYS allows a variety of future applications.

The presented results of system simulations show that critical frost conditions and exhaustion are the limiting factors in lowering the area of a HGHX. Solar thermal regeneration is able to avoid critical frost conditions and strongly limit exhaustion at small HGHX areas, if smaller separation between the HGHX's pipes is used.

Analysis of monthly solar yields and HGHX heat extraction reveals that a HGHX is not a seasonal storage. Still its comparatively large heat capacity allows to smoothen solar thermal heat generation and supply peak loads as a combined source for a heat pump. Unglazed and presumably even low-end collectors can be used, because of the low temperatures needed. As a result promising applications for solar thermal heat at low temperatures are enabled, while only sparsely affecting the potentials to directly use yields in the summer.

Ongoing research concerns the utilization of low-end and façade integrated collectors for regeneration of HGHXs as well as an additional connection to the buffer storage to make direct use of possible solar yields in the summer. For these configurations suited control strategies are being developed.

After demonstrating the technological potential of the combination of solar thermal collectors and HGHXs, analysis of the feasibility of differently configured solutions is the next important step towards a comprehensive assessment.

5. Acknowledgement

The project "Ground collectors and solar collectors as optimized bivalent heat sources for high efficiency heat pump systems (Terra-Solar-Quelle)", FKZ 03ET1275A, was carried out in cooperation with the companies tewag-Technologie-Erdwärmeanlagen-Umweltschutz GmbH and Bundesverband Wärmepumpe (BWP) e.V. and funded by the German Federal Ministry for Economic Affairs and Energy on the basis of a decision of the German Federal Parliament. The authors are grateful for the financial support. The content of this publication is the sole responsibility of the authors.

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