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Solar assisted heat pump systems with ground heat exchanger–simulation studies

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Abstract

Different concepts of solar assisted heat pump systems with ground heat exchanger are simulated according to IEA SHC Task44/HPP Annex38 reference conditions. Two aspects of the concepts are investigated using TRNSYS simulations. First, the solar impact on system efficiency is assessed by the seasonal performance factor. Second, the solar impact on the possible shortening of the ground heat exchanger is evaluated by the minimum temperature at the ground heat exchanger inlet.

The simulation results reveal diverging optimums for the concepts. The direct use of solar energy clearly achieves the best effect on the efficiency improvement. A simple domestic hot water system reaches a seasonal performance factor of 4.5 and solar combi-systems seasonal performance factors up to 6. In contrast, the use of solar energy on the cold side of the heat pump achieves the best effects on the shortening of the ground heat exchanger of up to 20%.

Two highly sensitive influences are investigated with the developed transient system model. First, the minimum allowed heat source temperature is varied. Here 1 K equals a variation of 0.25 in the seasonal performance or of around 10% ground heat exchanger length. Second, the ground heat exchanger model is simulated without and with a pre-pipe that improves the transient model behavior. The influence of this pre-pipe on the SPF is small for conventionally designed ground heat exchangers, but of around 2 K for the minimum inlet temperature. Therefore, the dynamic model quality reveals potential to reduce the size of the ground heat exchanger corresponding to investment costs.

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Keywords: Ground heat exchanger design; dynamic system model, solar ground regeneration

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1. Introduction

Highly efficient electric heat pump systems are a cornerstone of a future renewable heat supply. They allow supplying multiple parts of heat from one part of renewable electricity. Systems with high and constant efficiency are of special interest in the context of electrical peak load and the connected investments for the electrical power reserve in winter. Ground coupled heat pump systems are the most efficient and weather independent systems due to the constant heat source temperatures in the ground. Measured seasonal performances of up to 4 are possible [1, p. 51] and performances of up to 6 are reported for systems in combination with solar thermal collectors [2], [3].

From this starting point five different system concept with ground heat exchanger are analyzed in simulations with particular regard to the system performance, the influence of solar heat to the ground heat exchanger temperatures and possible shortening of the ground heat exchanger.

Nomenclature

l	depth of ground heat exchanger in m
l^*	Specific length of ground heat exchanger related to the useful energy m MWh^{-1} a^{-1}
T_{min}	Minimum inlet temperature of ground heat exchanger in °C
T_{prot}	Protecting temperature for ground heat exchanger (bivalence point) in °C
SPF_{SHP+}	Seasonal performance factor of heat pump system including all pump energies and penalties in -

2. Description of System Model

2.1. Simulation Setup, Boundaries and Definitions

The comparison of complete heating system concepts cannot be measured and must be determined in simulations. Besides, in system simulations the outcome strongly depends on the simulation settings as the choice of input parameters as the location or the applied simulation tool. Accordingly, the well documented boundary conditions and parameter specifications for a new single family house of IEA SHC Task44/HP Annex38 [4, p. 44] have been used, to allow a maximum of traceability, repeatability and comparability.

Special focus is laid on the detailed modeling of all components of the heat source side of the heat pump. The heat pump parameterization includes measured performance description at higher heat source temperatures and time constants for the internal heat exchangers [5, 6]. The applied model parameters are derived from measurements at ISFH over an extended temperature range of the evaporator temperatures according to the European standard EN 14511-3. The uncovered collector model [18] includes condensation heat gains. A brief overview of the applied parameters and reference conditions is given in Table 1. An overview of the applied sub- models and their implementation is given in Table 2.

Vertical ground heat exchangers can show strong long-term temperature decreases. This effect can take several years and the temperature drop can be several Kelvin. However, in most cases this effect is negligible for single ground heat exchangers. Nonetheless, a cross-check was made for twenty years of the reference system without solar. Compared to the 2nd year it revealed an additional temperature drop of 0.38 K in the 20th year of operation. This temperature drop is neglected to reduce the simulation runtimes and only applies to systems without regeneration. To conclude, the systems are simulated for two years and all presented results represent the data of the second year. The ground heat exchanger is modified with adiabatic pre-pipe to improve the modeling of dynamic effects and is parameterized according to measurements, too [8, 9].

The definition of the seasonal performance factor also influences the simulation results. In the following the seasonal performance (SPF_{SHP+}) is also calculated according to the definitions of IEA SHC Task44/HP Annex38. It is calculated of the heat demand for domestic hot water (DHW) and space heating divided by the overall electrical effort. The electrical effort includes all pumps (space heating, DHW charging, ground heat exchanger, solar etc.), the heat pump compressor, an electric back-up heater, the consumption for a controller unit and penalties that that are added to the electric consumption, if the heat demand for DHW and space heating cannot be fully satisfied at any time [10, p. 5].

Temperature limits for the operation of components can have a crucial impact on the simulation results, as will be seen later in this paper. The controller settings in the simulation permit operation of the ground heat exchanger below -3°C and for the collector below 0°C as freeze protection. The maximum operating temperature for the uncovered collector on the evaporator side is set to 35°C. This protects the ground heat exchanger and the heat pump from too high temperatures.

Table 1. Applied parameters and boundary conditions

Description	Value
Location	Strasbourg, France
Building living area	140 m²
Heating demand building	6.7 MWh = 47.8 kWh/m²a (Floor heating)
Heating demand DHW	2075 kWh/a
Volume DHW storage	Without solar 150 l, with solar 300 l
Collector	Parameters according to EN 12975-2
Parameters flat plate collector	η_0=0.8, a_1=3.5 W $m^{-2}K^{-1}$, a_2=0.05 W $m^{-2}K^{-2}$
Parameters uncovered collector	η_0=0.8, b_u=0.1 s m^{-1}, b_1=13.5 W $m^{-2}K^{-1}$, b_2=2 J $m^{-3}K^{-1}$
Orientation	South, slope 45°
Heat pump	
Heating capacity	7.9 kW (35°C heat source / 0°C heat sink)
COP	4.8 (35°C heat source / 0°C heat sink)
Ground heat exchanger	
Heat conductivity of the ground	2 W m^{-1} K^{-1}
Type of heat exchanger	Ground heat exchanger, double U pipe DN32
Borehole resistance	0.08 K m W^{-1}

Table 2. Component models applied in the TRNSYS system model.

Description	Typ	Reference / comment
Hot and cold storages	340	[11], cold storage recompiled to allow operation below 0°C
Ground heat exchanger	557a	[12] TESS + modification according to [13]
modified with pre-pipe	604	[12] TESS
Hydraulic components: pipes, valve, multi-valve, pump	709, 11, 469, 803	[12] TESS, [14] standard, [12] TESS, [14] standard
Controller: On-off, DHW storage, W-interpreter, forcing function, value recall (1), value recall (2)	911, 890pro, (-), 14, 93, 899	[12] TESS, Source [15,16], [17], [14] standard, [14] standard, ISFH
Output: Bin-sorter, printer, integrator (1), integrator (2)	1576, 24, 339, 55	[12] TESS, [14] standard, [14] standard, [14] standard
Building	56	[14] standard
Internal loads and applied types are used according to task44 template	-	[15,16] non-standard
Covered collector	832v500	[7] non-standard
Uncovered collector including condensation	203	[18] non-standard
Radiator, PID controller	362	[19] non-standard
Weather reader, dew-point calculation, sky temperature	109, 33, 69b	[14] standard

2.2. Investigated Systems

The simulated systems represent common solutions for integration of solar heat into ground coupled heat pump systems on the hot and on the cold side. For solar heat on the hot side of the heat pump a covered collector is applied. The solar heat on the cold side of the pump is provided by an uncovered collector, because of the lower operating temperature level. The square views of the principle energy flow charts for the solar thermal systems are presented in figure 1. The simulated systems are described in the following:

- REFERENCE system is a conventional heat pump system with ground heat exchanger as heat source. The domestic hot water tank has a volume of 150 l.

Solar on the HOT Side (covered Collector)

- DHW system is identical to the reference system, but has a solar collector connected to the domestic hot water storage. The bivalent DHW- storage has a volume of 300 l.
  BUFFER system is identical to the REFERENCE system, but is extended by a solar assisted buffer storage of 800 l, which supplies all heat for the fresh water unit for DHW and the space heating.

Solar on the COLD side (uncovered Collector)

- REGENERATION system is identical to the REFERENCE system, but an uncovered collector is added, that can be connected in series to the ground heat exchanger as additional heat source. In summer, the ground heat exchanger is thermally regenerated by the collector.
- REGEN+COLDSTOR system is identical to the REGENERATION system, but the uncovered collector is connected to the ground heat exchanger via a glycol storage. The volume of the glycol storage is 1 m³.

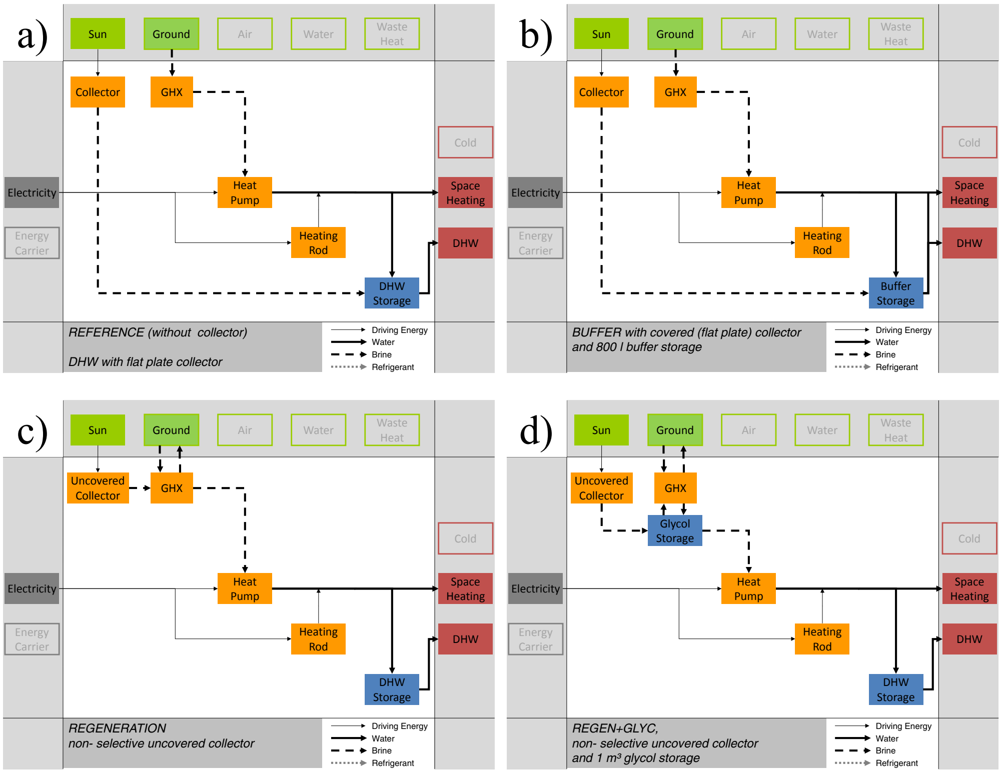

Fig. 1. Flow charts for four different systems with solar heat and ground heat exchanger. Hot side: (a) is the solar heat support for DHW preparation (b) is the buffer solution with DHW and space heating. Cold side: (c) is the REGENERATION of the ground heat exchanger (d) the REGEN+GLYCOL system, which combines the regeneration with a cold glycol storage.

3. Results of System Comparison

The simulation results for five solar thermal system designs are presented for different ground heat exchanger lengths in fig. 2 for the seasonal performance factor and in fig. 3 for the minimal inlet temperature of the ground heat exchanger. The system design represents typical design examples. The concepts strongly influence the impact of solar heat on the system and in particular the temperatures of the ground heat exchanger. The systems are categorized by the place where solar heat is injected to the system, either on the hot or on the cold side of the heat pump. (In terms of characterization by Duffie & Beckman [20, p. 526] hot side is equivalent to a parallel system and cold side injection correlates to a dual-source solar energy system.)

3.1. Seasonal Performance

The conventional use of solar energy on the hot side (see Fig. 2, left) of the heat pump results in a significant increase of the seasonal performance factor. Conventionally designed systems with 110 m ground heat exchanger and 5 m² flat plate collector for domestic hot water preparation improve the SPF by 1 from 3.5 to 4.5. The system with a buffer storage and 15 m² collector for space heating and DHW raises the SPF even to 5.5 with. The further augmentation of the collector to 30 m² nearly doubles the performance to 6.2 compared to the reference system without solar. This performance off-set however decreases significantly for shorter ground heat exchangers. Even with 30 m² collector area the seasonal performance is below an annual performance factor of 3 in case of a very short (50 m) ground heat exchanger.

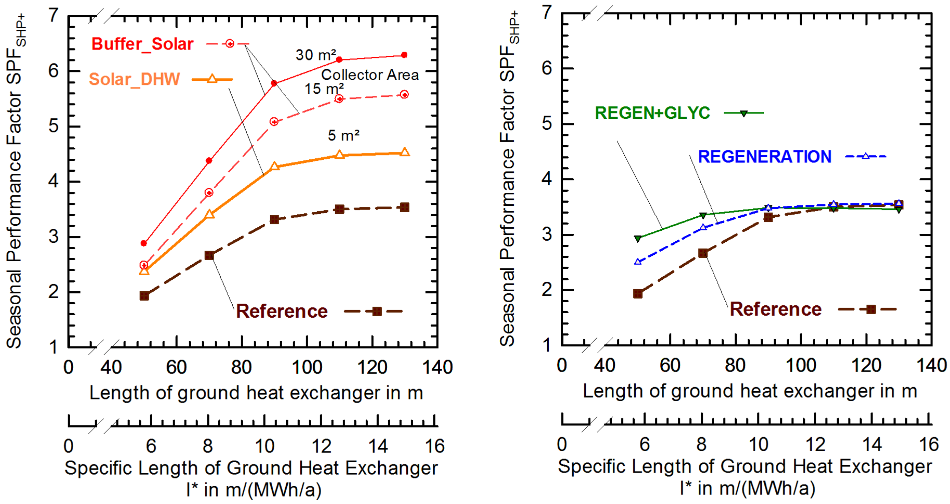

Fig. 2. Left: Seasonal performance for different system concepts with use of solar energy on the hot side and ground heat exchanger lengths; Right: Seasonal performance for different system concepts with use of solar energy on the cold side and ground heat exchanger lengths

Moreover, attention should be drawn to the fact, that the overall electrical consumption is in the inverse ratio to the performance numbers. Accordingly, the absolute savings compared to the additional effort make large collector fields economically unattractive, although high performance numbers can be achieved. In fact, the first five square meter flat plate collector correspond to 533 kWh^{-1} or approx. 100 kWh a^{-1} m^{-2} savings, while the increase from 15 m² to 30 m² correspond to specific savings of 179 kWh a^{-1} or approx. 10 kWh a^{-1} m^{-2}. The correlation of decreasing specific savings with higher solar fraction is well known, but has to be highlighted as the increase of the SPF suggests otherwise.

In contrast, the injection on the cold side of the system (see Fig. 2, right) shows the opposite behavior. It does not improve the seasonal performance factor for conventionally designed ground heat exchangers, whereas it clearly improves the efficiency for short ground heat exchangers. Here, significant improvements are achieved. In an undersized system with 50 m ground heat exchanger the SPF raises from 2 to 3 through 15 m² uncovered solar collector in combination with a glycol storage tank.

3.2. Minimum inlet temperature of ground heat exchanger

Reducing the ground heat exchanger length is an attractive goal; because it can save investment costs. Limiting criterion for the sizing is the inlet temperature of the ground heat exchanger to protect the filling material from damages. The legal specifications differ depending on the country specific guidelines and even change within a country. While the VDI guideline [21] limits the minimum peak temperatures to +/-17 K compared to the undisturbed ground temperature, many other guidelines demand absolute minimum temperatures. In Germany values of -3°C up to +1°C can be mandatory, depending on the specific region. In the simulations an electrical back-up heater substitutes the heat pump below the temperature limit of -3°C until higher temperatures are reached again.

The minimum temperatures at the ground heat exchanger inlet are presented in Fig. 3 for the simulated systems.

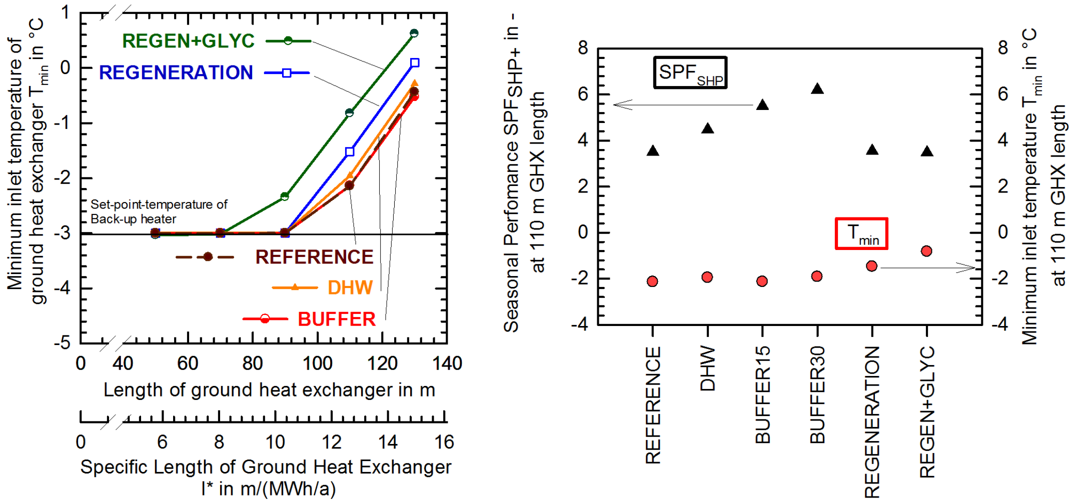

Fig. 3. left Minimum inlet temperature for different system concepts and ground heat exchanger lengths; right: SPF_{SHP+} and minimum inlet temperature T_{min} for 110 m ground heat exchanger length

The minimum temperature of the ground heat exchanger is not affected for systems that use solar heat on the hot side. In contrast, systems using solar heat on the cold side do increase the minimum temperatures. To a first approximation, this temperature lift is constant over the heat exchanger length. Nonetheless, the absolute temperature increase of 15 m² uncovered collector is 1 K with glycol storage and 0.5 K without storage. Therefore, the length of the ground heat exchanger can be shortened without significant impact on the seasonal performance. The ground heat exchanger can be reduced to 90 m with 15 m² collector and to 70 m with additional cold storage compared to a typical dimensioned system with the length of 110 m. This corresponds to a reduction of ~20% or ~40% without loss of performance. The influence of solar heat on the hot side is the opposite of that on the cold side. A reduced thermal load on the hot side does not affect the source temperatures at all. Therefore, the reduced heat exchanger length leads to a significant performance decrease (Fig. 2, left).

This opposing trend is illustrated in Fig. 3 right, comparing all systems with 110 m ground heat exchanger length. Increasing solar fraction on the hot side injection (DHW→BUFFER15→BUFFER30) shows increasing performance while the minimum inlet temperatures stay constant. Solar heat on the cold side does not raise the performance, but reduces the necessary ground heat exchanger length by lifting its minimum temperatures. Cold thermal storages are beneficial for this effect.

3.3. Discussion of System Concept and Conclusion

To conclude, solar thermal heat on the hot side significantly improves the performance, whereas solar heat on the cold side allows shortening the ground heat exchangers length. Both investigated system approaches for solar heat have their field of application, depending on the particular application. Aiming at high performances the hot side injection is clearly the most beneficial solution, yet at the price of a rapidly growing effort compared to the achieved absolute electricity savings. The cold side injection of solar heat and solar regeneration of the ground allows shortening of the ground heat exchanger. Apart from the aspect of investment costs two effects are highlighted in this context: (1) legal restrictions for the permitted drilling depth, because of ground and ground water protection and (2) the suppression of long-range interference, that arise for multiple interacting systems in residential areas.

The investigation of systems obviously raises the question of systems that switch between hot and cold side and benefit from both effects, down-sizing and improved efficiency. These optimized systems would find an optimum between downsizing the ground heat exchanger and using solar heat on the hot side. However, first very simple simulations of conventionally dimensioned systems showed that combination of hot and cold side always bear the danger of performance losses [22]. Further simulation studies and economic optimization must, in the opinion of the author, always include the following three aspects to find reasonable systems solutions:

1. System efficiency or performance corresponding to running expenses
2. System dimensioning corresponding to investment costs
3. System impact on the electrical peak load in the public grid.

Especially ignoring No. 3 leads most probably to recommendation of down-sized systems with reasonable performance that use occasionally direct electric heating during cold winter periods, but increase the temperature sensitivity of the electric grid, resulting in costly current peaks.

4. Limiting Temperature of Ground Heat Exchanger (Bivalence Point)

The installation of a ground heat exchanger requires an administrative permission that ensures the long-term safety for the ground, the ground water and the system components. In this context, the administrative guidelines define an allowed minimum ground heat exchanger inlet temperature. Additional requirements are set for the fluid polluting potential and in some areas operation is permitted for water only. This significantly influences the design and performance of the ground heat exchanger, which will be discussed in the following.

Within the system model a direct electric back-up heater can supply the demanded heat instead of the heat pump. The switching point of this back-up heater depends on the inlet temperature at the ground heat exchanger for protecting it from too cold temperatures. This protecting temperature T_{prot}, or bivalence point, is varied for the described system REFERENCE and REGENERATION. The results are presented in Fig 4.

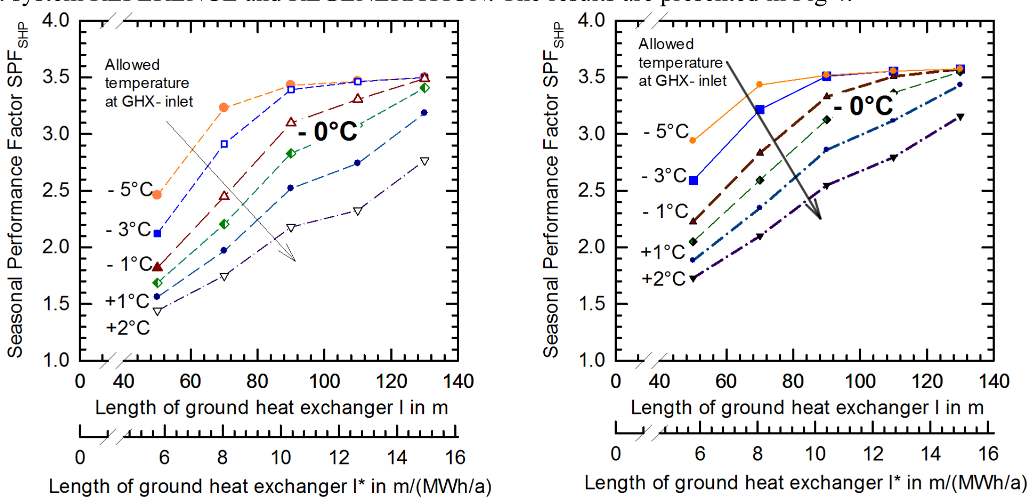

Fig. 4. Seasonal performance factor for different protecting temperatures that activate a direct electric back-up heater instead of the heat pump, left REFERENCE system without solar regeneration, right REGENERATION system with solar regeneration (The ground heat exchanger is simulated as two GHX above a length of 100 m. This explains the shallow dip of the curves between 90 m (= 1 x 90 m) and 110 m (= 2 x55 m.)

The simulation results presented in Fig. 4 allow the following conclusions:

- The seasonal performance of the system is highly dependent on the permitted minimum ground heat exchanger protection temperature $T_{prot.}$ At 90 m ground heat exchanger length the SPF sensitivity is 0.25 per K and therefore equal to 10 m of ground heat exchanger.
- The solar regeneration does slightly improve the characteristic of the system. With regeneration the temperatures are approx. shifted by 1 K and the sensitivity is reduced to 0.2 per K.
- The possibility to use water instead of a water glycol mixture as a fluid (T_{prot}) demands very long ground heat exchangers. In this example more than 130 m are required, especially if the necessary 2 K safety distance for measurement uncertainty and inhomogeneous mass flow in the evaporator heat exchanger is considered. A frozen evaporator heat exchanger is a total loss of the complete heat pump! Water therefore is in most cases an exclusion criterion.

5. Thermal Capacity Effects within the Ground Heat Exchangers

The established system model focusses on the detailed dynamic description of the heat pump, collector and ground heat exchanger. The dynamic parameters have been determined on the basis of measurements and the ground heat exchanger model is extended with an adiabatic pre-pipe to improve the transient model quality [13]. This pipe is inserted within the simulations between heat pump and GHX inlet in order to improve the modeling of the dynamic behavior The impact of this model change is demonstrated by comparing simulations with and without adiabatic pre-pipe and presented in Fig. 5. The ground heat exchanger lengths have been varied in agreement with all other simulations from 50 to 130 m in steps of 20 m.

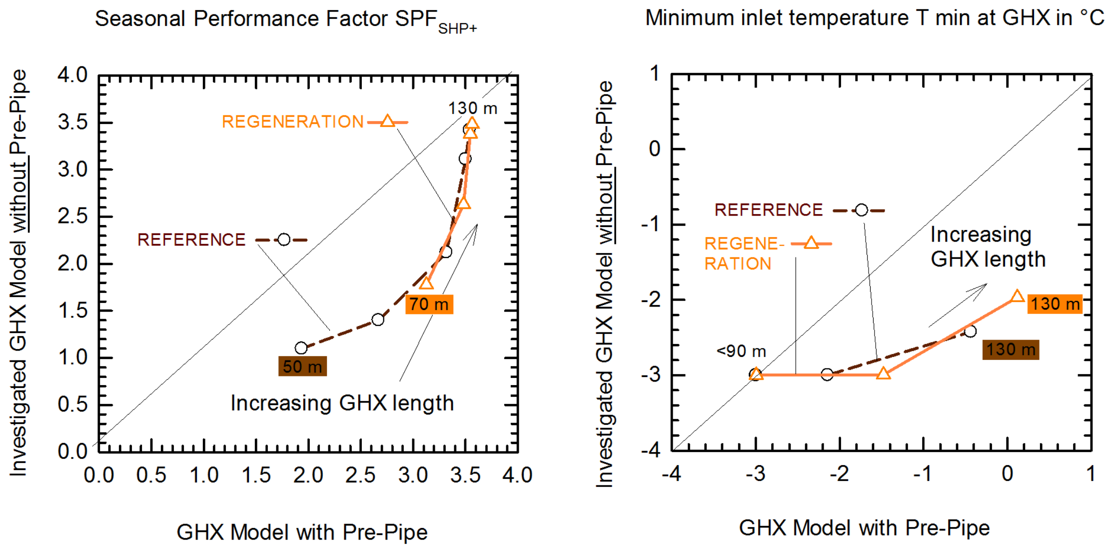

Fig. 5. Simulation results with and without adiabatic pre- pipe for the systems REFERENCE and REGENERATION. Left: seasonal performance factor SPF. Right minim inlet temperature T_{min}

The results reveal the impact of the pre-pipe before of the ground heat exchanger model in the system model. The comparison is an indicator for the influence of dynamic effects in the inner part of the ground heat exchanger.
The model extension with pre-pipe has an impact on the simulated seasonal performance. Furthermore, the influence is dependent on the ground heat exchangers length. This difference is small for long ground heat exchangers, while the SPF is significantly influenced by the model choice for shorter ground heat exchangers. This effect is explained

by the shifted temperature level with additional capacities. This shifted temperature level, as can be seen in section 4.1, results in additional operation of the back-up heater and therefore in specially high performance losses.
With preppie the minimum temperature at the ground heat exchanger inlet is roughly 2 K higher. Regarding dimensioning aspects this would allow 20% to 30% shorter ground heat exchangers. For small ground heat exchangers both models reach the minimum temperature limit of -3°C, where the differences disappear.
The reason for the model induced shift of the minimum temperatures is presumably the dynamic thermal heat extraction- often below 30 min. The additional thermal capacities of the adiabatic pre-pipe fluid and pipe wall provide "additional" heat during the beginning of the heat extraction period compared to pure heat conduction. During the standstill the capacities are recharged from the ground at low heat flow rates and therefore at low temperature differences. Especially for the dynamic simulations with smaller time steps and a pulsing heat pump these capacity effects have an influence on the fluid temperatures.

6. Results and discussion

The best performance of the presented results is achieved with conventional heat pump systems including solar heat on the hot side. Here, seasonal performance factors of up to 6 are possible. But even lower dimensioned solar DHW systems can achieve seasonal performances of 4.5 with 5 m² collector area. In contrast, solar thermal heat on the cold side does not lead to a performance improvement for conventional dimensioned systems with sufficiently dimensioned ground heat exchangers.

Nevertheless, the solar heat on the cold side allows shortening the ground heat exchanger. The length of single ground heat exchangers could be reduced by 20% and by 40% in combination with a glycol-storage. Furthermore, undersized ground heat exchangers actually do benefit from solar support on the cold side. However, for most applications the improved system stability and the possible shorting will not justify the additional costs. The reasons for regeneration are an even heat balance in the ground, suppressing any long-term temperature development and avoiding the interaction of adjacent ground heat exchangers. These influences are a barrier for the broad dissemination of ground heat exchangers in residential areas. To conclude, solar heat should be used on the hot side of the heat pump, unless aspects as shortening of the ground heat exchanger or systems or areas with multiple ground heat exchangers are concerned.

Apart from the shortening and performance aspects the developed system model allows to quantify the influence of the boundary conditions and the impact of dynamic effects. Both investigated influences, the minimum inlet temperature and the ground heat exchanger model, prove: The quality of dynamic system models with a heat pump are not only obtained by connecting adequate sub-models, but also by the precise settings of control strategies and boundary conditions.

The parameter variation of the minimum inlet temperature reveals the sensitivity of the performance to this temperature limit. The applied limit of -3°C seems acceptable. Higher limits however quickly lead to increased operation of the direct electric heater or require longer ground heat exchangers. An operation with water seems unrealistic due to the immense necessary enlargement of the ground heat exchanger.

The differences of the ground heat exchanger models highlight the sensitivity of dynamic simulations using short time steps, here 1 min. Depending on the applied model 2 K difference appear for the minimum temperature of the ground heat exchanger inlet. This improvement arises from including the heat capacities within the ground heat exchanger, which reduce the heat conduction peak loads. As a result, including this more detailed calculation method to dimensioning tools of designers would offer a significant saving potential, because common planning tools do not respect the inner thermal heat capacities or calculate with hourly load files, where dynamic effects are not respected [23–25]. Current planning tools, which use hourly load files, will therefore lead to a ground heat exchanger overdesign.

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