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Solar active building with directly heated concrete floor slabs

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Abstract

A new concept for solar active houses is presented within this paper. In contrast to existing solar house solutions, the solar collector heat gains are distributed in a temperature-optimized way to three different heat sinks – a significantly smaller storage tank, concrete floor elements directly fed by the solar circuit and a ground heat exchanger which also serves as the heat source of a heat pump, which is the backup heater. This new layout should reduce the today's usual extra system costs of solar houses by about 25%.

System simulations prove the functionality of the concept and show even higher solar fractions and energy savings as simulated for the existing solar active house concept. One of the main components in the new concept is the controller which has to decide which heat sink will be charged. A control strategy was developed which evaluates the potential outputs of the collector operating to each heat sink. Simulations allow determining the optimal control parameters for this approach. While the thermal activation is able to compensate the decreasing solar input to the smaller storage tank, the effects of the regeneration of the ground heat exchanger are significantly smaller. However, the regeneration avoids a long-term temperature decrease in the ground and may allow a reduction of the heat exchanger area.

Keywords: Solar active house; thermally activated building systems, heat pump; ground heat exchanger; storage heat losses

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1. Introduction

Currently, solar houses with solar fractions of more than 50% are usually built with a central buffer storage (typical volumes in single family houses are between 5 to 10 m³[1]), which is charged by the solar thermal system. Thus, part of the solar heat gained in the summer may be stored for the heating period. The storage tank is installed within the heating zone of the building, so that the storage heat losses serve as internal gains during the heating period. In fact, many solar active houses of this type have been built and are operated successfully, achieving a high solar fraction. However, the large storage volume shows some disadvantages: It leads to high system costs, requires space inside the building and the heat losses in summer are undesired internal loads, which may cause overheating.

The Institut für Solarenergieforschung Hameln (ISFH) and the manufacturer of residential buildings, HELMA Eigenheimbau AG, are developing a new heat supply concept for solar houses. In contrast to typical solar buildings, the buffer storage is not the center of the system. Instead, the solar heat gains are distributed in a temperature-optimized way to feed different heat sinks. These are a buffer storage, a ground heat exchanger and thermally activated concrete elements of the ground and upper floor. Thus, the buffer storage may be designed significantly smaller. The concept should decrease the today's usual extra system costs of solar houses by about 25% while achieving at least the same solar fraction.

Nomenclature

c_p	Specific heat capacity (Wh/kgK)
f_{Sav}	Fractional energy savings (-)
f_{Sol}	Solar fraction (-)
$\dot{m}$	Mass flow rate (kg/h)
Q	Annual heat amount (kWh/a)
$\dot{Q}$	Thermal power (W)
Sig	Signal (-)
SPF	Seasonal performance factor (-)
ϑ_C	Collector temperature (°C)
t	Time step (s)
W	Ratio of potential collector output (-)
W_{el}	Electrical energy demand (kWh/a)
C	Index for collector
GHX	Index for ground heat exchanger
HP	Index for heat pump
Ref	Index for reference system
SH	Index for solar active house
St	Index for storage
TA	Index for thermal activation

2. Description of the concept

In the new system, the solar heat gains are distributed in a temperature-optimized way to feed different heat sinks. The scheme in Fig. 1 gives an overview of the system concept with its main components. A more detailed hydraulic scheme can be found in [2].

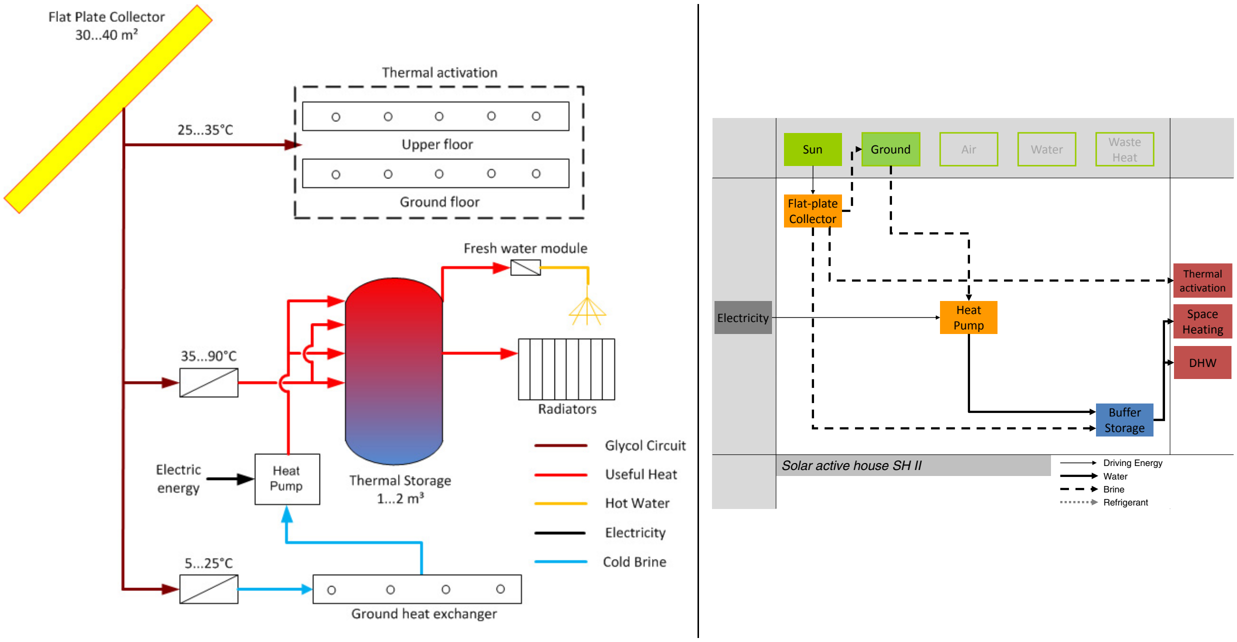

Fig. 1. Left: Scheme of heat sources and heat sinks in the new heating concept for solar houses (the lines indicate energy flows). Right: Flow chart of the concept according to IEA SHC Task 44 – Solar and heat pump systems

2.1. Thermal activation (in upper and ground floor concrete slabs)

The thermal activation in usual applications covers the whole buildings heat load. In contrast, the solar heated thermal activation in this building concept serves as a basic heat source besides the additional conventional space heating. Thus, the dimensioning differs from standard sizing methods. According to a detailed parameter study, carried out with finite elements simulations [4], the thermal activation can be designed with higher pipe distances, fewer distribution circuits and thus lower costs than in usual applications. Due to the different heat resistances between slab and ceiling, the ground and upper floor are charged independently via a parallel connection.

2.2. Buffer storage

The buffer storage supplies its heat to a fresh water module and the radiators of the space heating circuit. Because of the two different temperature ranges the upper part of the storage is divided into two zones heated by the heat pump, each for one consumer. The heat pump loads the heat zones with different set temperatures – constant for hot water, depending on ambient temperature for space heating. The actual connection heights, the zone volumes and additional dead volumes are the result of a comprehensive investigation in simulations.

2.3. Heat pump and ground heat exchanger

The power of the heat pump is 5 kW to cover the buildings heat load. The dimensioning of its heat source – the ground heat exchanger – has to consider the heat input of the solar collectors. Thus, system simulations in TRNSYS let us find the minimum necessary area to cover the buildings heat load without any use of the electric back-up heater. Since there is no reasonable model available to simulate horizontal ground heat exchangers the simulations are conducted with a model for borehole heat exchangers. The resulting borehole length was converted in heat exchanger area by means of the specific heat extraction power of borehole and ground heat exchanger. A further reduction of the area is possible since the simulations do not consider latent heat gains which may have a considerable amount.

2.4. Control

The solar heat can be used for three different heat sinks – buffer storage, thermal activation and ground heat exchanger. Thus, the controller has not only to decide if the collector circuit is active but also which heat sink has to be charged. In contrast to a solar system with one heat sink, it is not possible to control the system with just a measurement of the current collector outlet or absorber temperature. During operation such a measurement cannot provide enough information whether a heat sink on a higher temperature level may be charged or not.

Therefore, the controller has to consider the different operating conditions depending on the mass flow and temperature level of each heat sink. The development and realization of this control strategy is one of the main issues of the current project stage (see Section 4). The system simulations in Section 3 include an idealized control, which considers three collector temperatures (one for each heat sink) calculated with three additional virtual collectors. Based on a comparison of these potential collector temperatures with the heat sinks combined with additional criterions for protection (maximum temperatures) and demand (thermal activation only if room temperature and ambient temperature below limit) the controller decides if charging of the respective heat sink is possible.

If charging of more than one heat sink is possible the control has to decide which one is the most effective. The ground heat exchanger has the lowest priority, thus it is only used if both the storage tank and the thermal activation have no demand. Contrary to that, no constant priority is used between thermal activation and storage tank. Instead, the potential collector output power is calculated based on the determined outlet temperatures of both heat sinks.

$$\left.\begin{array}{l}\dot{Q}_{C,TA} = \dot{m}_{Coll,TA} \cdot c_p \cdot (\vartheta_{C,in,TA} - \vartheta_{C,out,TA}) \\ \dot{Q}_{C,St} = \dot{m}_{Coll,St} \cdot c_p \cdot (\vartheta_{C,in,St} - \vartheta_{C,out,St})\end{array}\right\} \; W = \frac{\dot{Q}_{C,TA}}{\dot{Q}_{C,St}} \tag{1}$$

The potential heat outputs are compared to each other and a value W is calculated, defined as the ratio of the collector output in case of charging the thermal activation to the collector output in case of storage charging. The collector charges the storage ($Sig_{St,t} = 1$) if this ratio is above a defined limit under consideration of an upper and lower control hysteresis.

$$SIG_{St,t} = 1 \;\; \text{if} \;\; \begin{cases} SIG_{St,t\text{-}1} = 0 \text{ and } W > W_{Set} + \Delta W_{up} \\ SIG_{St,t\text{-}1} = 1 \text{ and } W > W_{Set} - \Delta W_{lo} \end{cases} \tag{2}$$

W_{Set}-values below 1 and low values for the control hysteresis indicate a higher priority for the thermal activation while values above 1 result in a higher priority for storage charging. The optimal values of W_{Set} (with the lowest energy demand) and its control hysteresis have been determined with simulations (see Section 3.2).

3. System simulations

The thermal behavior of the concept introduced in Section 2 (now defined as SH II) is calculated in TRNSYS [5]. The aim is to optimize the system performance and compare it to existing standard solutions for solar active houses with a large storage tank (defined as SH I). Both concepts are simulated with the same boundary conditions. For a better comparison SH I is also simulated with a heat pump and a ground heat exchanger although most of the existing solar active houses use other heat sources (mainly basing on wood combustion).

The building is parameterized according to the intended design of an exemplarily solar house planned by HELMA Eigenheimbau AG. The house is divided mainly into two heating zones (upper floor and ground floor) which are equipped with radiators. The hot water draw off profile has been generated based on IEA Task 44 [6], the location is Zurich in order to ensure a better comparability with other research studies (e.g. IEA Task 32 [7]). Table 1 gives further main parameters for both systems.

Table 1: Boundary conditions for the solar active house concepts simulated in TRNSYS

	Standard concept (SH I)	New concept (SH II)	TRNSYS Type/Model used
Location	Zurich, Switzerland		Weather data from Meteonorm [8]
Building			
Heated area	184 m²		Type 56 [5]
Heat demand	7150 kWh/a (constant infiltration rate 0.4 h^{-1}/20 °C room temperature)		
Space heating			
Type	Radiators		
Design temperatures (Flow/return)	55 °C / 45 °C at -14 °C ambient temperature 35 °C / 30 °C at 20 °C ambient temperature		Type 362 [9]
Hot water demand	2200 kWh/a		Based on Task 44 [6]
Collector	32 m² selective flat plate collector/tilted 45°, orientated south		Type 832 [10]
Storage tank			
Volume	7.3 m³ (situated within heat zones)	1.5 m³ (situated in heating room)	Type 340 [11]
Heat loss rate	6.6 W/K	3.3 W/K	
Thermal activation (TA)	-	Concrete slabs of ground/upper floor	Within building (Type 56)
Auxiliary heater			
Heat pump	5.9 kW (condensator output), COP 4.9 (35 °C heat sink/0 °C heat source)		Type 401 [12]
Heat source	Ground heat exchanger, simulated as a borehole with 55 m depth (SH I) and 50 m depth (SH II) equal to 110 m²/100 m² horizontal collector		Type 557 [13]

The main indicators to evaluate the systems and its variants are the solar fraction f_{Sol} and the fractional energy savings f_{Sav}. The solar fraction is defined by the ratio of the collector output (if charging storage tank or thermal activation) to the sum of the collector output to both heat sinks and the condensator output of the heat pump. The collector output to the ground heat exchanger is not considered.

$$f_{Sol} = \frac{Q_C}{Q_C + Q_{HP}} = \frac{Q_{C,St} + Q_{C,TA}}{Q_{C,St} + Q_{C,TA} + Q_{HP}} \tag{3}$$

As pointed out in [14] this definition is disadvantageous when comparing systems and their simulation results since increasing storage heat losses may lead to higher solar fractions. Otherwise, other possible definitions of the solar fraction consider the thermal activation output only as a reduced space heating demand resulting in considerably lower values for the concept SH II. Since the storage volume and its insulation are constant for all variants, the definition in (3) can be used for the comparison of both concepts.

However, the preferable values for the evaluation are the fractional energy savings which consider the overall electrical energy demand of the solar active house (heat pump and all circulation pumps) and of a reference system without any solar collectors. The energy demand of the reference system (heat pump, ground heat exchanger and small storage tank) was simulated in TRNSYS under the same boundary conditions (building, hot water profile, location, heat pump and ground heat exchanger) as shown in Table 1.

$$f_{Sav} = 1 - \frac{W_{el,SH}}{W_{el,Ref.}} \tag{4}$$

The seasonal performance factor for the heat pump is the ratio of the annual condensator heat output and the electricity demand of the compressor.

$$SPF_{HP} = \frac{Q_{out,HP}}{W_{el,HP}} \tag{5}$$

3.1. Importance of the storage tank and its heat losses

The heat losses of the large storage tank in standard solar active houses (SH I) may lead to a significant reduction of the buildings heat demand during the heating period. This uncontrolled heat input decreases with a reduced storage volume (as intended in the new solar house SH II). The significance of the storage heat losses is analyzed in simulations of system SH I shown in Fig. 2. Apart from the storage volume (7.3 m³ and 1.5 m³) the simulations treat the storage heat losses differently. The heat losses act as an energy input to the respective heat zone in the variants "wQ" while the variants "noQ" only consider the heat losses in the energy balance of the storage tank.

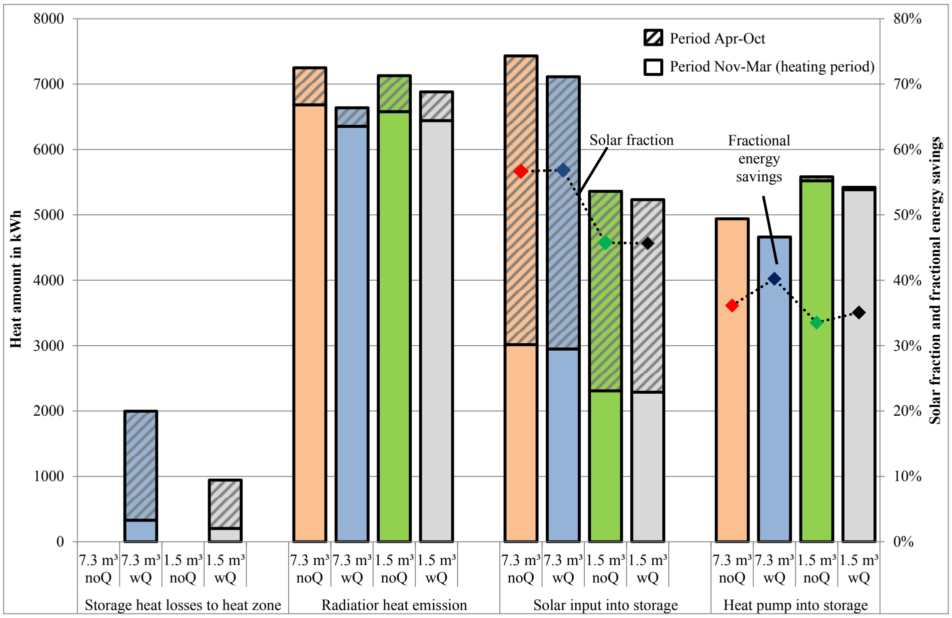

Fig. 2. Simulation results of the standard solar house concept SH I with a storage volume of 7.3 m³ and 1.5 m³, storage heat losses considered in the buildings heat load (wQ) or not (noQ).

The figure points out the main results of the simulations:

- The radiator emission for the variants without considering storage heat losses in the heat zones (noQ) is 7200 kWh/a, 92% of it emitted during the heating period from November to March.
- The storage heat losses at a storage volume of 7.3 m³ are 2000 kWh/a, most of the heat losses (84%) occur in the period Apr-Oct. This explains that the annual radiator output is only reduced by 600 kWh (8.5%) while the reduction in period Nov-Mar is 300 kWh (5%) and 300 kWh (50%) in the period Apr-Oct. The same trend occurs with the smaller storage tank (annual reduction is 250 kWh/3.8%).
- Since the heat losses in the variants "wQ" lead to higher room temperatures and less heat demand the solar input to the storage is a bit lower. The heat output of the heat pump is 300 kWh (6%) less.
- The solar input into the storage tank decreases with smaller volumes. The heat input is 3000 kWh for 7.3 m³ and 2300 kWh for 1.5 m³ (both wQ). The relative decrease is a bit less (-24%) for the smaller storage in the heating period than during the rest of the year (-30%).
- During the period April to October there is almost no demand for the heat pump in all variants. Thus, only the heat losses during the heating period lead to a decreasing energy demand of the heat pump. The heat pump input increases by 860 kWh (18.5%) if the smaller storage tank is used.

- The solar fraction with 1.5 m³ is only 40% compared to 56% with the larger storage. There is almost no effect on the solar fraction when the storage heat losses are considered in the building (affects both solar and heat pump input).
- Fractional energy savings reach considerably higher values if the heat losses are considered in the building, especially with the large storage tank. Without this, the difference between large and small storage tank is only 2.5%-points.

According to the simulations the heat demand may be reduced by almost 10% in a solar active house due to storage heat losses. Thus, the heat losses cover a significant part of the heat demand. But it has to be kept in mind that this heating is uncontrolled and cannot be turned off if necessary. By this means, the storage heat losses lead to higher temperatures in summer. The simulations show that all important parameters evaluating the room comfort (operative temperature, predicted mean vote/PMV) are higher compared to a reference system without solar. A concept for shading is strongly recommended in all cases especially with a large storage (as used in SH I).

3.2. Control optimization

Section 2 gives an explanation of the control strategy used in the solar active house SH II, which has to decide which heat sink should be charged. If both storage and thermal activation may be charged the ratio of the potential collector output is calculated and compared to a fixed value under consideration of a hysteresis, see Eq. 2. Simulations allow the evaluation of different combinations of factor W_{Set} and its hysteresis as shown in Fig. 3.

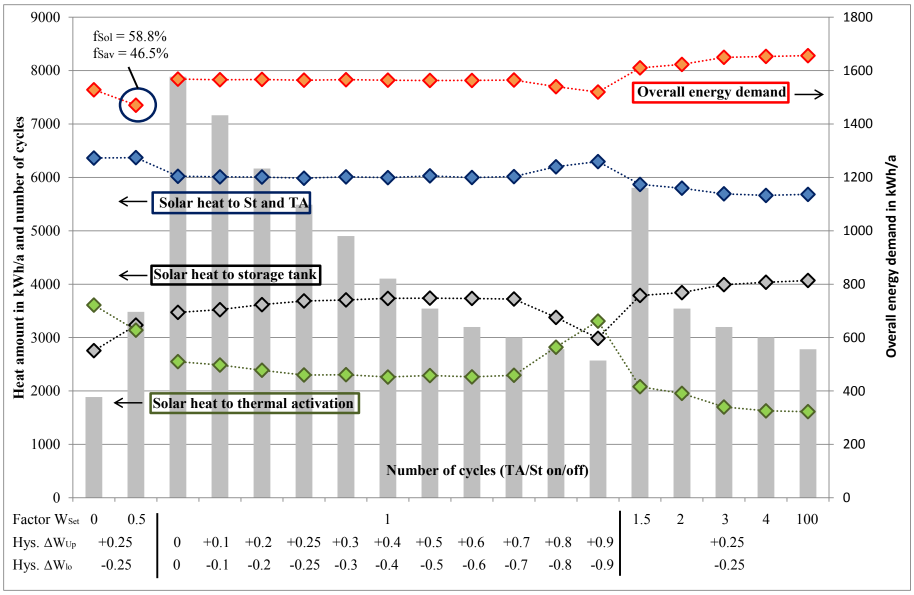

Fig. 3. Solar input to storage tank and thermal activation as well as overall energy demand for different factors W_{Set} and control hysteresis. Factor W_{Set} is varied from 0 (priority on thermal activation) to 100 (priority on storage charging).

The main results are:

- The solar input to the storage increases with higher values of W_{Set} while the amount of the thermal activation decreases. The sum of both is not constant with a maximum difference of 600 kWh/a. The lowest values are reached with high portions of buffer storage charging. A priority for storage charging (W_{Set} = 100) leads to the lowest energy savings. Thus, it is more reasonable to increase the room temperature directly via the thermal activation than to increase the storage temperature.

- The control hysteresis affects mainly the number of cycles (the smaller the hysteresis the higher the number of cycles). But the hysteresis may even influence the overall energy demand as seen at a factor of 1 and higher hysteresis values.
- There is still a considerable amount of energy delivered to the storage tank at a priority for thermal activation ($W_{Set} = 0$) and vice versa ($W_{Set} = 100$). The reason is that the controller receives a demand signal from storage and thermal activation at the same time only at 400 h/a. This is almost the same as the demand signal coming only from the storage (400 h/a) and only from the thermal activation (500 h/a).
- The lowest overall energy demand is reached at limit of 0.5 with control hysteresis of ±0.25. This corresponds to fractional energy savings of 46.5 compared to the reference system without solar collector. Also the configuration of $W = 1$ and $\Delta W = 0.9$ leads to good results. It may be concluded, that the relative hysteresis $\Delta W/W$ should have a rather high value of between 0.5 and 0.9, indicating that a once selected operation mode should be kept, as any change would lead to capacitance losses.

3.3. Performance of the system

The evaluation of the new system SH II and its comparison with the standard solar house concept SH I is one of the main goals of the simulations. Table 2 shows the main results. SH II is represented in three variants differing by the potential solar heat sinks. While the storage charging is possible in all variants, thermal activation and the regeneration of the ground heat exchanger are switched on or off. For the variants with thermal activation the control is set to the optimal combination of W_{Set} and its hysteresis according Fig. 3.

Table 2. Comparison of solar active house concept SH I with the new concept SH II, SH II is simulated with and without thermal activation (TA) and regeneration of the ground heat exchanger (GHX); also shown is the fraction of each solar input occurred in the heating period (Nov-Mar)

	SH I (conventional concept)	SH II (new concept)			Difference		
		No TA No GHX	With TA No GHX	With TA With GHX			
Solar heat (total)	6140 kWh/a	4560 kWh/a	6280 kWh/a	9180 kWh/a	-26%	+2%	+49%
In period from Nov-Mar	(48%)	(50%)	(54%)	(38%)			
Solar heat input to storage	6140 kWh/a	4560 kWh/a	3250 kWh/a	3250 kWh/a	-26%	-47%	-47%
In period from Nov-Mar	(48%)	(50%)	(39%)	(38%)			
Solar heat to TA							
In ground floor slab	-	-	950 kWh/a	970 kWh/a			
In period from Nov-Mar	-	-	(71%)	(71%)			
In upper floor	-	-	2080 kWh/a	2110 kWh/a			
In period from Nov-Mar	-	-	(70%)	(70%)			
Storage heat losses	2000 kWh/a	950 kWh/a	930 kWh/a	930 kWh/a	-53%	-54%	-54%
Emission of radiators incl. piping							
Lower floor	3010 kWh/a	3140 kWh/a	1510 kWh/a	1490 kWh/a	+4%	-50%	-51%
Upper floor	3630 kWh/a	3750 kWh/a	3170 kWh/a	3160 kWh/a	+3%	-12%	-13%
Solar heat to ground heat exchanger	-	-	-	2860 kWh/a			
In period from Nov-Mar	-	-	-	(2%)			
Heat output of heat pump	4660 kWh/a	5420 kWh/a	4510 kWh/a	4480 kWh/a	+16%	-3%	-4%
Seasonal performance factor SPF_{HP}	3.37	3.59	3.57	3.62	+6%	+6%	+7%
Heat extracted from GHX	3260 kWh/a	3890 kWh/a	3230 kWh/a	3210 kWh/a	+19%	-1%	-2%
Overall electricity demand	1640 kWh/a	1780 kWh/a	1490 kWh/a	1470 kWh/a	+9%	-9%	-10%
Fractional energy savings f_{Sav}	40.2%	35.1%	45.9%	46.4%	-13%	+14%	+15%
Solar fraction f_{Sol}	56.9%	45.7%	58.2%	58.5%	-20%	+2%	+3%

The results allow an evaluation of the new concept and the significance of each heat sink:

- The conventional concept SH I has a solar yield of almost 200 kWh/m²a (collector aperture area is 32 m²) leading to a solar fraction of 57%. The remaining energy is delivered from the heat pump with a seasonal performance factor of 3.3. Compared to the system without solar collectors 40% less electricity is needed. Remarkably, almost 50% of the solar heat is generated during the heating period, when the solar collectors preheat the storage water (e.g. in January the solar heat is mainly delivered with an inlet temperatur of 28 °C while the space heating demands a temperature of 43 °C).
- In SH I, without thermal activation and regeneration of the ground heat exchanger the solar fraction drops to 46% (140 kWh/m²a) and the energy savings to 35%. The thermal activation is able to compensate the smaller storage, the values for solar fraction (58%) and fractional energy savings (46%) are even a bit higher than in SH I. Almost 50% of the solar heat is used for the thermal activation, mainly in the upper floor (heats upper floor and ground floor via ceiling). This reduces the heat demand of the radiator by 50% (ground floor) and 12% (upper floor), respectively. This mismatch is the result of the double heating of the ground floor (TA in ground floor and ceiling).
- The regeneration of the ground heat exchanger increases the collector yield to 287 kWh/m²a. Since this heat amount is not considered in the solar fraction, the fraction does not increase significantly. Likewise, the fractional energy savings increase only slightly by less than 1%-point. Even the seasonal performance factor of the heat pump is almost unaffected. This may be explained that the solar collectors charge the ground heat exchanger only in summer (app. 98% of the annual energy) in contrast to a regeneration during the whole year (e.g. as analyzed in [15]). Actually, it is possible that heat pump and solar charging of the ground heat exchanger occur at the same time. But over the year this happens only at 1 h/a while the regeneration without heat pump operation happens at 280 h/a. Moreover, the heat pump is not in operation during summer, thus there may be a considerable amount of natural regeneration.
- Surprisingly, the solar energy delivered to the thermal activation increases slightly if the regeneration of the ground heat exchanger is active. This is because of the low temperature level of the ground heat exchanger which cools down the collector in case of regeneration. This way, the maximum inlet temperature to the thermal activation (used for protection of the pipes) is reached less frequently.
- The energy balance of the ground heat exchanger is almost even in the regenerated system (heat extraction 3200 kWh/a, heat input 2900 kWh/a). In case of boreholes, such an even balance avoids a long-term temperature decrease in the ground and allows a shortening of the borehole [15]. The validity for horizontal ground heat exchangers is not known and this should be analyzed in the future. Apart from the energetic view, the solar input to the ground heat exchanger reduces the amount of stagnation from 133 h/a to 6 h/a (not shown in Table 2).
- In all variants the solar heat used in the heating period from November to March is almost the same as in the summer. Only in the complete system of SH II (with TA and GHX) this value drops to 38% due to the high percentage of ground heat exchanger regeneration in summer. The thermal activation is mainly in use during the heating period (around 70%) in contrast to the storage charging which mainly happens in summer (60%). Overall (GHX-charging not considered), the solar yield during the heating period is in SH II with 3490 kWh (38% of 9180 kWh/a) higher than in SH I (2950 kWh).

4. Conclusions and outlook

A new concept of solar active houses with a considerably smaller buffer storage is developed. The main goal is the reduction of the solar house system costs. A thermal activation of upper and ground floor increases the solar yield during the heating period due to lower collector temperatures and is able to compensate the decreased solar input to the smaller buffer storage. The solar charging of the ground heat exchanger (simulated as a borehole) does not lead to a significant improvement of the system performance. Though due to the even energy balance of the ground heat exchanger it may be possible to decrease the system costs by reducing the heat exchanger area. A more detailed analysis is necessary but difficult since there is no model for ground heat exchangers available in TRNSYS.

The simulation results presented in Section 3 prove the functionality of the concept and show that high solar fractions and energy savings are reached. After a promising comparison of the system costs for both concepts (SH I and

SH II) the project partner HELMA Eigenheimbau AG has decided to build a first test house situated in Hanover, Germany, planned completion in spring 2014. The house will be equipped with a monitoring system for a detailed system analysis. During the measurement period a family will live in the house thus ensuring a realistic demand.

The dimensioning of the main components was made with conventional planning tools and the simulation results. The ground heat exchanger will be divided into four parts which can separately be operated. Thereby, it is possible to test different heat exchanger areas. One of the main tasks is the development of the control setup which will be done by RESOL and bases on the approach developed with system simulations in TRNSYS. Before the implementation in the test house, the controller will be included in the TRNSYS simulations to test the functionality and determine the system performance in comparison to the (idealized) control which is used in TRNSYS so far.

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