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Key Facts for High Efficient Solar Ice Storage Heat Pump Systems

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Abstract

Focus of this paper is to show the key facts for high efficient solar ice storage heat pump systems, their appropriate application area and furthermore includes their classification within solar heat pump system combinations.

Simulation models for the solar-ice-storage system were developed and validated with field and laboratory measurements. The solar-ice-storage system has been optimized for high efficiency and reduced system expenditure with four buildings of same size but different insulation quality by simulation. Heat pump systems with heating capacities of 6, 8, 10 and 13 kW and solar absorbers between 10 m^2 and 30 m^2 show seasonal performance factors SPF_{bSt} between 3.7 and 4.5. The convective heat transfer rate of the solar absorber is of key importance if used as heat source for the heat pump. A reduced convective heat transfer due to lower wind speed or unfavourable design of the absorber reduces the seasonal performance by 6.5% to 11% and shows the biggest influence on the seasonal performance. The yearlong availability of the heat pump as heat generator and avoidance of need for direct electric backup is assured by the latent heat gains in the ice-storage to secure the minimum heat pump inlet temperature in combination with ground heat gains in coldest winter month. Further improvement of the system performance is possible with PVT absorbers as heat source for the heat pump in the sense of generating more surplus electrical energy that is available for other appliances as long as the high convective heat gains of the existing solar absorber can be maintained as well.

Keywords - solar-ice-storage; heat pump; photovoltaics

1. Introduction

Combinations of solar technology and heat pump shall be used for new and existing buildings.

The results presented here are an excerpt of the work in the project SOFOWA [1] on "solar heat, fotovoltaics and heat pump system combinations" which has been conducted as one Swiss national contribution in the framework of the IEA SHC Task44 / HPT Annex 38 "Solar and Heat Pump Systems" [2].

This paper deals with single family houses with heat generation for space heating and domestic hot water generation by heat pumps combined with solar technology (c.f. Figure 1), especially using ice storage and solar absorber as heat source for the heat pump. The use of PV production to cover the heat demand is analysed. The household electricity demand and its influence on the self-consumption of PV energy are not in the scope of the study.

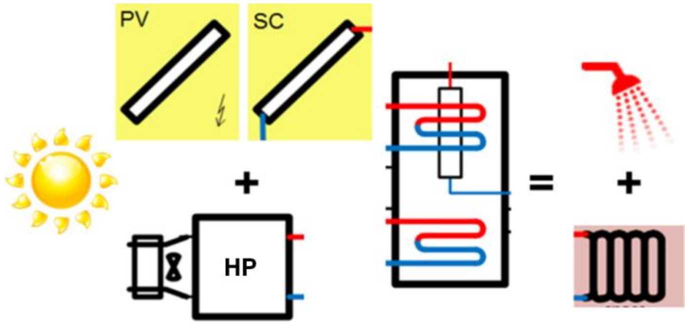


Fig. 1 Interaction of solar technology with heat generation and usage

First a general view on combinations of heat pump with solar thermal collectors (SC) or photovoltaics (PV) or combined photovoltaic thermal collectors (PVT) shows advantages / disadvantages of the technologies as well as the question on the potential added value of such combinations. This general comparison in chapter 2 has amongst other results shown that there is a potential of combined solar heat and electricity generation with high specific energy gain of combined PVT collectors, if there is a good integration of the solar collector as heat source for the heat pump.

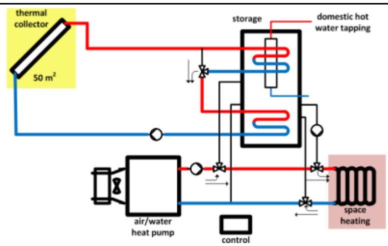
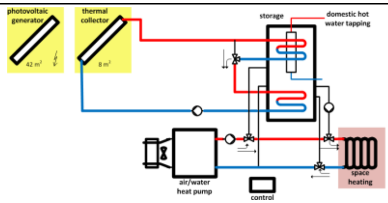
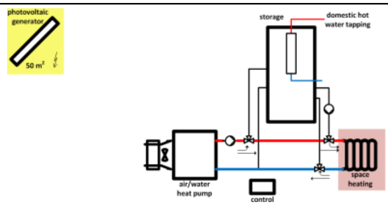
What good integration of solar collector as heat source for the heat pump does mean in detail, has been shown with the evaluation of solar ice storage heat pump systems. A more detailed view on efficiently using solar collectors/absorbers as heat source for the heat pump gives chapter 3 of this paper, which also tries to answer the question of the papers title: "What are the key facts for high efficient solar ice storage heat pump systems?"

The heating systems are applied to seven different buildings. Three of these buildings were defined in the framework of the IEA SHC Task44 / HPT Annex 38 "Solar and Heat Pump Systems" [5], A38T44. These buildings are named SFH15, SFH45 and SFH100, where SFH is the abbreviation for SingleFamilyHouse and the following numbers refer to the space heating demand in $kWh/m^2/a$. They have an energy reference area of 140 m^2 and are used for the general evaluation of solar and heat pump system combinations in chapter 2 of this paper. Furthermore four additional buildings have been defined for the evaluation of heat pump with ice storage heating systems. They are based on the A38T44 buildings, but have an energy reference area of 250 m^2 and space heat demand of 25 $kWh/m^2/a$, 45 $kWh/m^2/a$, 60 $kWh/m^2/a$, 100 $kWh/m^2/a$ and are named SFH25*, SFH45*, SFH60* and SFH100*.

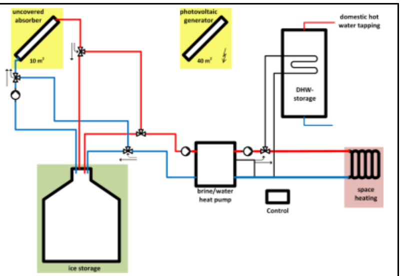
2. Solar & Heat Pump System Combinations

For this paper the impact of solar heat generation and solar photovoltaic electricity used by heat pump on the electricity demand of a heat pump as additional heat generator in the heating system is in focus. Therefore five solar heat pump heating systems, described in Table 1, have been defined and analysed using heat from solar irradiation or the near environment of the building. The final report of the project gives more details also on ecological and economical aspects for all three A38T44 buildings. Here only the energetic results for SFH45 are shown, that are exemplary also for the other building types.

Table 1. Short description and pictogram of compared solar heat pump systems

System 1 uses the whole roof area of the building of 50 m^2 for direct heat generation with glazed thermal collectors (ST50FK) and seasonal heat storage of 10 m^3. Hence no roof area is left for PV (PV00). Backup heat generator is an air/water-heat pump.	
System 2 uses glazed solar thermal collectors of 8 m^2 aperture area for heat generation (ST08FK) with a buffer of 900 liters. Additional heat generator is an air/water-heat pump. The PV surface fills up the roof area and hence covers 42 m^2.	
System 3 comes without solar thermal collectors (ST00) and uses the whole roof area for PV (PV50). The heat is generated by an air/water-heat pump.	

System 4 is described in more detail in chapter 3 of this paper and uses 10 m² of uncovered solar absorber (ST10UK) combined with a 10 m³ buried ice storage as heat source for a brine/water-heat pump. The remaining 40 m² of the roof area are covered with PV (PV40).



System 5 is generally equal to system 4 but here the whole roof area of 50 m² is covered with combined photovoltaic thermal collectors (PVT50).

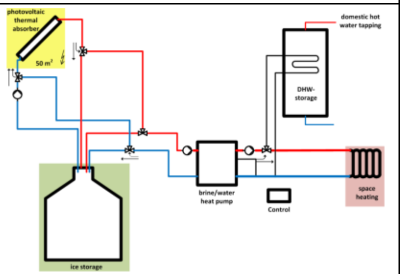


Figure 2 shows the energy balance for these five systems for the SFH45 building. Therein, the red frame shows the generated heat in comparison to the heat demand depicted by the dashed line. The hatched area to the negative ordinate shows the grid electricity demand, the green hatched area to the positive ordinate the self-generated and used PV electricity. The filled green area depicts the surplus PV electricity.

The results show that a combination of PV and heat pump in system 3 can reduce the grid electricity demand to a comparable amount than a system with smaller solar thermal collector as e.g. in system 2 and furthermore provides more surplus PV electricity. A system using a big solar thermal collector area as system 1 can reduce the grid electricity demand further but no extra roof area for PV electricity generation is left. Only a system with a heat generation system with higher seasonal performance factors SPF_{bSt}, c.f. (1), like system 4 and 5, using a brine/water-heat pump with a good heat source, can reduce the grid electricity demand to a low level.

$$SPF_{bST} = \frac{\int (Q_{SC,H}+Q_{HP,H}+Q_{BU,H})dt}{\int (E_{el,SC,H}+E_{el,SC,C}+E_{el,HP}+E_{el,HP,C}+E_{el,BU}+E_{el,CU})dt} \qquad (1)$$

with:

		SPF	seasonal performance factor		
Q	thermal energy	E	electric energy	el	electric
C	cold side of heat pump	SC	solar collector	HP	heat pump
H	hot side of heat pump	bSt	before storage	BU	backup unit
DHW	domestic hot water	SH	space heating	CU	control unit

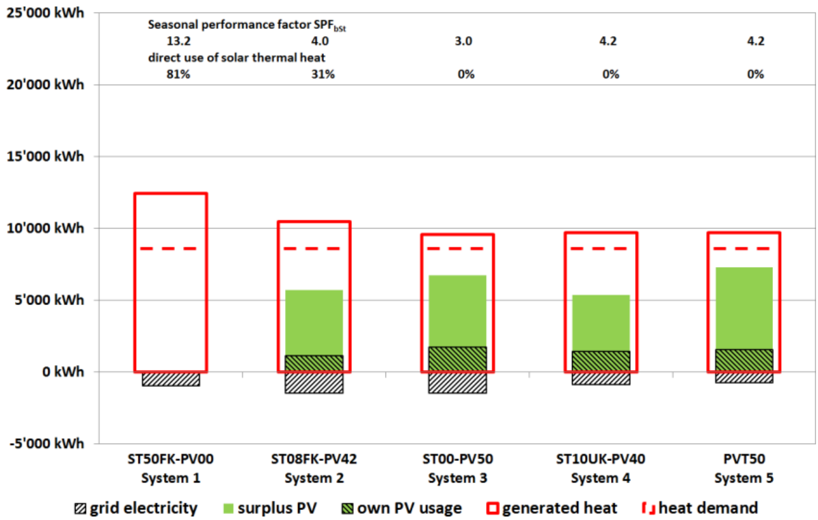


Fig. 2 Energy balance of five solar heat pump systems for SFH45

Generally, for the summer situation, as Figure 3 shows for the weeks 15 to 40, it is more important to well operate solar technology than the type of technology. The difference on the electricity demand of a heat pump as alternative heat generator is small between heat from solar collectors as primary heat generator or electricity generated by PV and used in a heat pump.

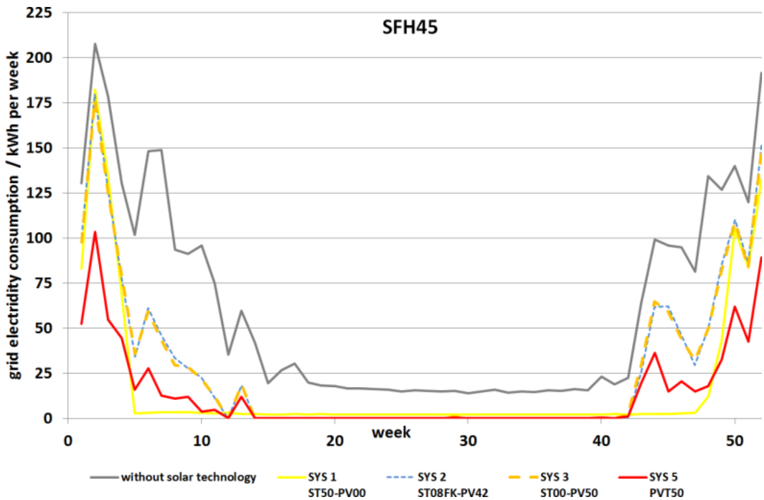


Fig. 3 Annual devolution of the electricity demand for four out of five systems for SFH45

On top of this, solar technology which improves the winter system performance is more useful in the sense of sustainable future heat supply systems than summerly solar thermal heat generation since herewith the efficiency of the heat generator providing the bigger amount of heat is improved.

3. Solar Ice Storage System

The solar ice storage heat pump system (system 4 in chapter 2) uses an uncovered thermal absorber and a buried ice storage as heat source for a brine/water heat pump. Figure 4 shows a schematic of the system including hydraulics. The uncovered solar absorber consists of two layers of parallel pipes which gain heat from solar irradiation and the ambient air by convection. A ground-buried ice storage with 10 m^3 of water volume serves as secondary heat source in times when the absorber isn't able to deliver heat or if the use of the ice storage is more efficient. The absorber and the ice storage are connected in parallel to the source side of the heat pump and are in operation alternatively. There is a separate heat exchanger with hydraulic circuit to heat the ice storage from the absorber.

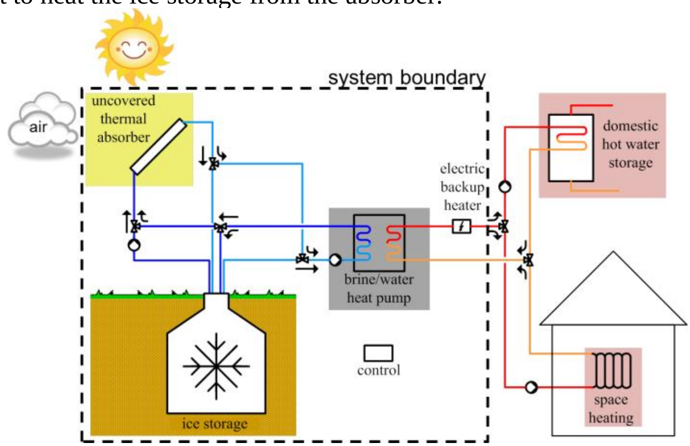


Fig. 4 Solar ice storage system hydraulics and evaluation boundary for SPF_{bSt}

The solar ice storage heat pump system has been optimised in dimensioning of collector area and number of ice storages as well as the control for four heat pump thermal capacities, 6 kW for SFH25*, 8 kW for SFH45*, 10 kW for SFH60* and 13 kW for SFH100*. The simulation results for these systems show good heat generation system performance factors SPF_{bSt} around 4 as depicted in Table 2. The SPF_{bSt} generally correlates with the required temperature level of the heat supply system. Only in very well insulated buildings the SPF_{bSt} drops slightly due to a higher share of domestic hot water demand and hence higher supply temperature level and furthermore a higher share of auxiliary electrical power. This high system efficiency can also be confirmed for the three A38T44 buildings even if the heat generation system is not especially adapted. Especially compared to former heat pump systems using solar collectors as heat source for the heat pump, these SPF_{bSt} values are significantly higher [3].

Table 2. System simulation results for the solar ice storage heat pump system

building	space heating load in kW	ice-storage volume in m^3	solar-absorber area in m^2	capacity of HP in kW	generated heat in kWh	flow- / return flow temp. in °C	total electrical energy use in kWh	SPF_{bSt}
SFH25*	5.5	10	10	6	9'558	30/25	2'254	4.24
SFH45*	7.5	10	13	8	15'257	33/28	3'413	4.47
SFH60*	9.5	10	20	10	19'784	41/31	4'800	4.12
SFH100*	12.5	20	30	13	31'439	48/38	8'428	3.73
SFH15	1.8	10	10	6	5'250	30/25	1'412	3.73
SFH45	4.0	10	10	6	9'731	34/29	2'301	4.23
SFH100	7.3	10	20	10	20'249	48/38	5'040	4.02

Now, what are the reasons for such high performance factors? First step has been to find an answer to the question of where the source heat comes from. Figure 5 shows an annual Sankey-diagram for SFH45* with the solar ice storage heat pump system. It shows that the biggest part of the source heat comes directly from the uncovered solar absorber. Figure 6 shows the annual energy balance of the heat generations sources.

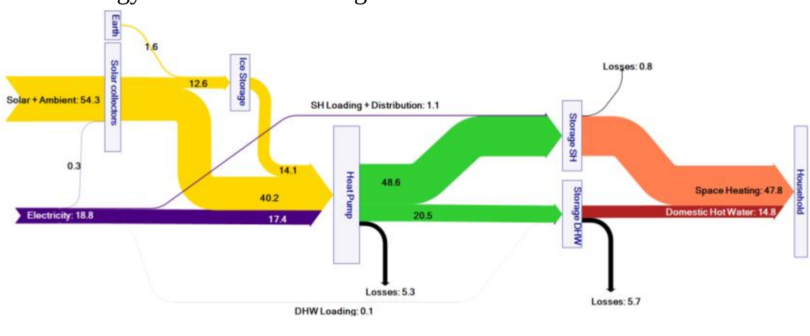


Fig. 5 Annual sankey-diagram for SFH45* with solar ice storage heat pump system

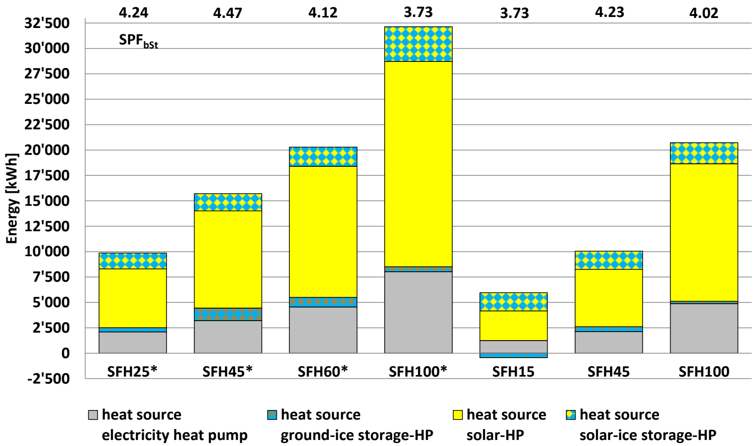


Fig. 6 Annual energy balance of the heat generations heat sources (heat pump, solar absorber and ice storage)

In all systems the biggest amount of heat goes directly from the uncovered solar absorber to the heat pump, second biggest part is the electricity used in the heat pump and third part is heat from the solar absorber via the ice storage to the heat pump. The heat balance between ground and ice storage includes for the annual balance as well heat gains from the ground to the ice storage as also heat losses. Hence this part is not shown with its real impact in this picture. Therefore, in Figure 7, a monthly heat balance of only the ice storage is shown.

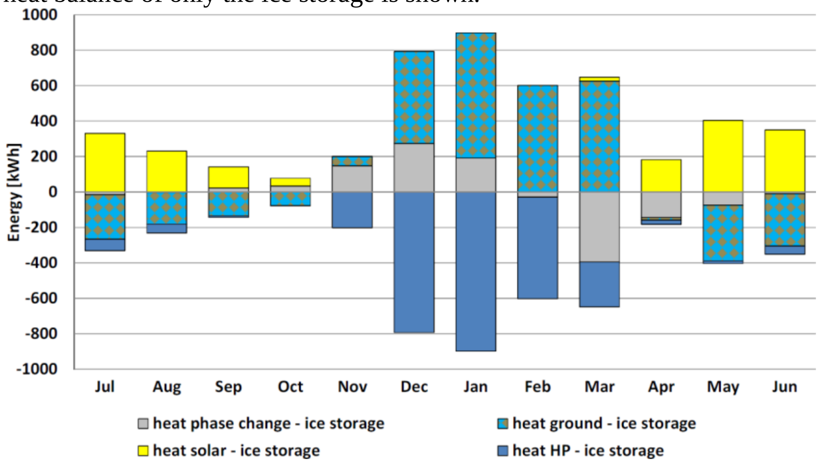


Fig. 7 Monthly energy balance of the ice storage of simulation SFH45*. Heat exchange is depicted on the ordinate axis, subdivided into the different energy ratios. Positive values

indicate heat flow to the ice storage. Phase change gains (losses) describe energy released (lost) through cooling (heating) or freezing (thawing) of water/ice.

Between May and October the ice storage loses heat to the ground, which on the other hand is charged into the ice storage from the solar absorber. In the winter month November until March the heat pump mainly draws from the ice storage which is supplied on the one hand from phase change heat gains and on the other hand by the surrounding ground. Here the importance of the ground heat gains is visible since in December to March most of the heat that is taken out of the ice storage comes from the ground.

As it can be seen in Figure 5 and Figure 6, most of the heat used as heat source for the heat pump comes directly from the solar absorber. Question is, what are the most important characteristics of the absorber or how does the absorber gain heat from? To evaluate this, two cases with deteriorated properties have been evaluated.

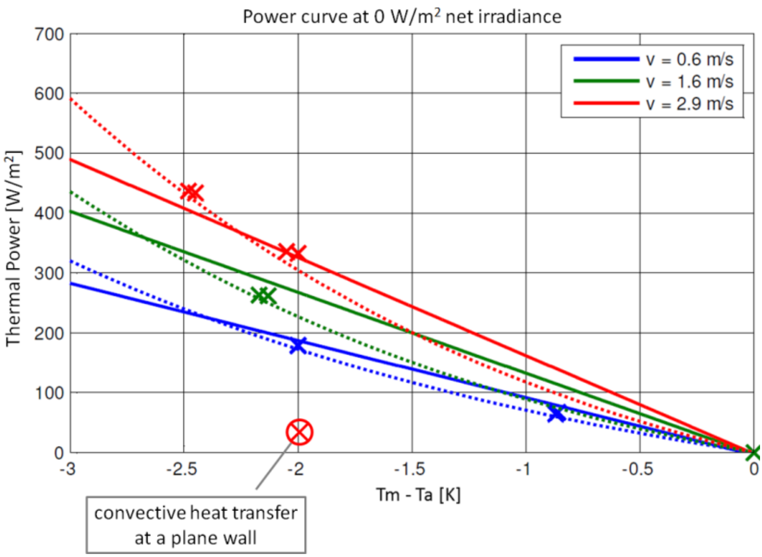


Fig. 8 Thermal power curves for test without irradiance and three different wind speeds. Measurement points are marked with an 'x', dashed lines indicate a polynomial fit and the results from the simulation model are shown as solid line.

In the first case the influence of the solar irradiation is tested by a total shading of the absorber so that no solar irradiation comes to the absorber and it can only gain heat by convection. This reduces the SPF_{bSt} for the SFH45* from 4.47 to 4.45 and hence shows a negligible influence.

In the second case the convective heat gains are tested. The first test reduces the wind speed at the collector to constant 1.5 m/s where the average wind speed in the climate data is 5.5 m/s. This reduces the SPF_{bSt} for the

SFH45* from 4.47 to 4.18, a significantly higher reduction of 6.5%. In the second test of convective heat gains, a different absorber design is used, where the convective heat gain coefficient is approximately half of the original value. This reduces the SPF_{bSt} for the SFH60* comparatively strong from 4.12 to 3.66 or by 11%.

Figure 8 shows these good convective properties of the solar absorber with a comparison of the measured power curve without irradiation compared to the convective heat transfer at a plane wall.

4. Conclusion

It has been shown that a solar absorber and ice-storage system can reach almost similar SPF as a ground source heat pump with a conventional drilling (SPF up to 4.5) and can be significantly above an air source heat pump (SPF ~3). The capacity of the storage cannot cover the whole winter, so ambient gains are relevant also during the heating season. A solar absorber with a high convective gain from ambient temperature is favourable.

Acknowledgment

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