Energetic and economic aspects of seasonal heat storage in single and multifamily houses

Henner Kerskes, Harald Drück

Institute for Thermodynamics and Thermal Engineering (ITW)
Research and Testing Centre for Thermal Solar Systems (TZS)
University of Stuttgart
Pfaffenwaldring 6, 70550 Stuttgart, Germany
Tel.: +49 (0)711 / 685-63536, Fax: +49 (0)711 / 685-63503
Email: kerskes@itw.uni-stuttgart.de

1. Introduction

Solar assisted space heating systems are well introduced to the market and have an increasing market share. In typical single and two family houses today's solar combisystems reach an annual energy saving of about 20 to 30 % of the total heat demand required for hot water preparation and space heating. The largest solar gains are reached during the transitional months in the spring and autumn. At these periods solar radiation and heat demand coincide in large parts. The challenging task, now and in future is the solar only heating system providing 100% of the total heat demand by means of solar energy. Towards this goal, great technological improvements have already been achieved in the last few years. Today, there is already a trend towards the “Solarhouse50+” with solar fractions of more than 50 % and towards the “Solar Active House” which is totally heated by solar thermal energy. Certainly one of the main difficulties in using solar energy for space heating is the seasonal variation of solar radiation. To overcome this problem, long term heat storage is required for storing the solar heat from summer to winter. Large heat storage capacities, low heat losses and good heat transfer characteristics are the key factors for developing efficient long-term heat stores. Hence the implementation of compact energy stores with higher efficiencies will be the next innovation step. This can be achieved by using physical mechanisms like adsorption processes as well as chemical reactions, for instance the hydration/dehydration process of inorganic salts. Both technologies are becoming more and more the focus of scientific interest.

In this paper, the thermal, energetic and economic aspects of solar space heating systems with seasonal heat storage to achieve high solar fraction are investigated. The shown results are based on simulation studies and energetic calculations described in the following sections.

2. Determination of the thermal performance and storage efficiency

The calculation of the thermal performance has been carried out by dynamic system simulations with the simulation software TRNSYS. Concerning the calculation of the space heating demand two building types were considered: A standard building (called Type A) and a low energy building (called Type B). Both buildings have a living area of 128 m^2, a 45° inclined and south oriented roof. The standard building is thermally insulated according to the current German regulation, which results in a space heating demand of 9090 kWh per year. The low energy building has an about 50 % lower heat demand corresponding to an annual specific space heating demand of approx. 35 kWh/m^2. The heat demand for hot water preparation amounts to 2945 kWh per year in both cases.

To interpret the results of the numerical simulation, two characteristic figures are introduced, namely the yearly fractional energy saving and the storage efficiency. The yearly fractional energy saving f_{sav} is calculated according to equation 1:

$$f_{\mathrm{sav}} = \frac{Q_{\mathrm{conv,net}} - Q_{\mathrm{aux}}}{Q_{\mathrm{conv,net}}} \qquad \text{(eq. 1)}$$

Whereas $Q_{conv,net}$ (kWh/a) is the total heat demand of a conventional (non-solar thermal) heating system to cover the space heating and hot water demand. Q_{aux} (kWh/a) is the residual heat demand which is required to cover the space heating and hot water load completely and is delivered by the backup heater. The difference between $Q_{conv,net}$ and Q_{aux} is the heat provided by solar thermal energy. The storage efficiency η_{sto} is the ratio of the solar heat discharged from the store to the solar heat fed into the store. It is calculated according to equation 2:

$$\eta_{\mathrm{sto}} = \frac{Q_D - Q_{\mathrm{aux}}}{Q_{\mathrm{col}} - Q_{\mathrm{lp}}} \qquad \text{(eq. 2)}$$

Here, Q_D (kWh/a) is the total heat demand, Q_{col} (kWh/a) is the heat delivered by the collector array and Q_{lp} (kWh/a) the heat loss of the piping in the collector loop.

3. Determination of the energetic payback time

The energetic payback time (EPBT) can be determined by comparing the primary energy embodied in the system with the amount of primary energy that will be saved by the thermal solar system during its estimated lifetime /1/. Here the primary energy embodied in the system comprises the cumulative energy demand for the production (incl. transport, assembly and installation), for the operation and for the maintenance of the system.. The amount of primary energy saved by the thermal solar system is determined by the difference of the total primary energy demand of a conventional (non solar thermal) heating system that is necessary to meet the total heating demand and the auxiliary primary energy demand required by the solar thermal system.

4. Determination of the heat price and the financial payback time

In order to calculate the solar heat prices and the financial payback time (FPBT) the net present value method is applied. For the determination of the investment costs the following positions were included: the system costs, the assembly costs, a cost credit of 2000 € for not required conventional components such as the conventional hot water store as well as their proportionate assembly costs. For the return of invest an interest rate of 3 % was chosen according to a fixed term deposits. The time of operation is assumed to 25 years. Because the energy price increasing rate for fossil fuels can not be predicted exactly for the next 25 years, annual price increasing rates of 5 %, 7 % and 11 % were taken into consideration.

5. Small solar combisystem

As a first step a relatively small solar combisystem, as it is representative for the majority of systems installed today, is considered. The system consists of a 14 m^2 flat plate collector area (FPC) and a combistore with a volume of V_{sto}= 900 litres. The domestic hot water is prepared via an immersed heat exchanger. For this system a fractional annual energy saving of 27.0 % is achieved for the building Type A. This represents a saving of 3408 kWh heat per year

respectively 4009 kWh of gas or oil per year (boiler efficiency of 85 %).
The solar heat price of 0.14 €/kWh is only 17 % higher than the current cost of heat provided by fossil fuels. For an assumed annual energy price increasing rate of only 5 % the financial payback (FPBT) is around 15 years. If the price increasing rate is set to 11 % which represents the average of the last 10 years in Germany, the financial payback time is only 10 years. The energetic payback time (EPBT) is with 2.7 years significantly shorter. During the assumed operating time of 25 years approx. 89000 kWh of primary energy can be saved with the system.
The reduction of the space heat demand (building Type B) leads to a proportional increase in fractional energy savings to 36.4 %. However, the total energy saved decreases to 3481 kWh per year due to the lower heat demand. This results in slightly higher values for the solar heat price, FPBT and EPBT. For the storage efficiency values of 69 % and 64 % are achieved for building Type A and Type B respectively. That means about 1/3 of the stored solar energy is lost during the year. The results are summarized in Table 1.

building type	total heat demand [kWh/a]	f_{sav} [%]	energy savings [kWh/a]	η_{sto} [%]	system costs [€]	heat price [€/kWh]	EPBT [year]	FPBT [year] 5 %	7 %	11 %
Type A	12,675	26.9	4,009	69	8,400	0.14	2.7	15	13	10
Type B	8,130	36.4	3,481	64	8,400	0.16	2.9	16	14	11

Table 1: Key figures of a small solar combisystem (V_{sto} = 0.9 m³, A_C = 14 m² FPC)

6. Large solar combisystems with seasonal heat storage

To achieve higher solar fractions (>50 %) in general a larger technical effort is necessary compared to small combisystems. The imbalance between heat demand and solar radiation requires either correspondingly large collector areas to generate enough heat during the transition and winter months for direct heating or alternatively a sufficient energy storage capacity to store the heat from the summer period into the winter month.

6.1 Combisystem with large hot water stores

In order to analyse the thermal performance of a solar combisystems with a large hot water store, a system with 30 m^2 of evacuated tube collectors (ETC) and a 10 m^3 hot water store made out of steel has been simulated with TRNSYS. The domestic hot water is prepared via an external heat exchanger (fresh water station). For the store including fresh water station, costs of 14900 € were estimated. For the evacuated tube collectors 550 €/m^2 were assumed without installation. The results for the combisystem with the large water store are summarized in Table 2.

building type	total heat demand [kWh/a]	f_{sav} [%]	energy savings [kWh/a]	η_{sto} [%]	system costs [€]	heat price [€/kWh]	EPBT [year]	FPBT [year] 5 %	7 %	11 %
Type A	12,675	53.4	7,947	58	36,500	0.31	5.2	25	22	17
Type B	8,130	63.0	6,025	47	36,500	0.41	5.9	25	34	20

Table 2: Key figures of a solar combisystem with large hot water store
(V_{sto} = 10 m³, A_C = 30 m² ETC)

The solar combisystem with a large hot water store reaches an energy saving of about 8000 kWh per year for Building type A and 6000 kWh per year for building Type B. Compared to the small solar combisystem this is almost a doubling of the energy saving. Due to the relatively long time period of storage and the high water temperature inside the store relatively large heat losses occur. Hence the storage efficiency drops to 47 % and 58 % respectively. The investment costs are much higher compared to the small combisystem. That results in significantly higher solar heat prices and longer financial payback times. The energetic payback time, however, remains with about 5 to 6 years, relatively low. Assuming an operating life time of 25 years 160 MWh or 120 MWh respectively of primary energy can be substituted by solar energy.

6.2 Combisystem with thermo-chemical heat store

Thermo-chemical heat stores (TCES) represent an extremely interesting alternative to large hot water stores. The principle of the thermo-chemical heat storage described in this paper is based on the reversible exothermic solid/gas reaction. For example, the hydration of salts like magnesium sulphate ($MgSO_4$) or calcium chloride ($CaCl_2$) is suitable. During the hydration reaction water molecules are deposited on a salt molecule (anhydrate) to form the salt hydrate. The released heat of the exothermic reaction can be used for heating purposes. By feeding the same amount of energy to the reaction product at a higher temperature level, the reverse reaction is stimulated. If the two reaction components (anhydrate and water) are stored physically separated from each other, loss free energy storage can be realized for an unlimited period of time. A more detailed description of the concept is given by Mette in “Design of a thermo-chemical energy store integrated in a solar combisystem” /2/.

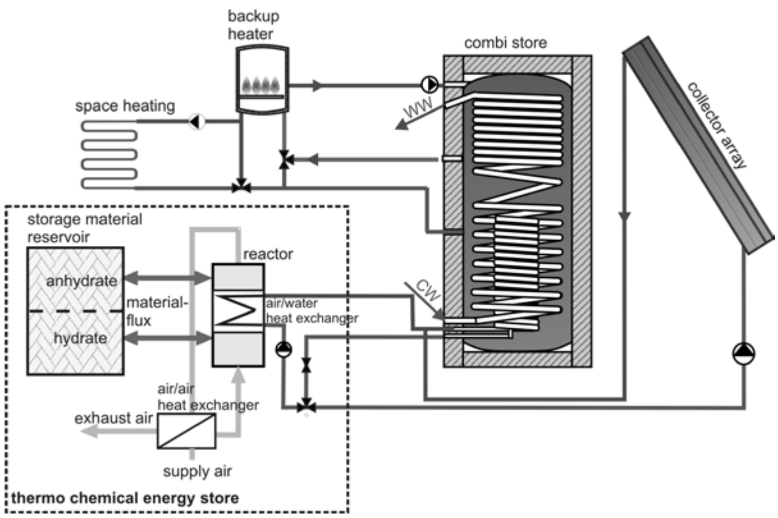

Figure 1: Schematic of a solar combisystem with thermo-chemical energy store.

As part of the research project “chemical heat storage by reversible gas-solid reactions” (Chemische Wärmespeicherung, CWS) a system concept, shown in Figure 1, for thermo-chemical energy storage is developed and tested at ITW. To determine the thermal performance, annual system simulations have been carried out. Therefore a detailed model of the thermo-chemical energy storage has been developed and implemented in the TRNSYS-software. In this model the chemical reaction behaviour of calcium chloride ($CaCl_2$) applied on bentonite as storage material is implemented. This material is characterized by a high storage density of about 250 kWh/m^3. With approximately 0.5 €/ kg it is very inexpensive to manufacture.

Despite the storage material is still more expensive than water, the costs for the entire store are in the same range as for a conventional steel tank of a hot water store of equal volume. The costs for the thermo-chemical store were estimated by 9.675 € /3/. However, the energy storage capacity is about four times higher and the heat losses are much smaller.
Compared to the system with the hot water store the system with the thermo-chemical heat store is cheaper. Due to the higher storage efficiency, the collector area needed for high solar fraction is much smaller. A solar combisystem with a thermo-chemical heat store of 6.25 m^3 and an energy storage density of 250 kWh/m^3 combined with 23 m^2 of vacuum tube collectors reaches an energy saving of 50 % for building Type A and even 70 % for the Type B building. The heat price is with 0.28 €/kWh only twice as high as for the small combisystem providing a much lower energy savings. However, the financial payback time is longer. In the best case a financial payback can be achieved after about 16 years. In contrast to this the energetic payback time is much shorter, with 5.8 years for building Type A and 6.5 years for Type B (see table 2). The efficiency of the thermo-chemical heat store is evidently higher and amounts to approximately 68 %, which almost corresponds to the value of short-term hot water store. The advantages of the thermo-chemical heat stores are outstanding, especially for applications with very high fractional energy savings.

building type	total heat demand [kWh/a]	f_{sav} [%]	energy savings [kWh/a]	η_{sto} [%]	system costs [€]	heat price [€/kWh]	EPBT [year]	FPBT [year]		
								5 %	7 %	11 %
Type A	12,675	50.2	7,486	68	30,300	0.28	5.8	23	20	16
Type B	8,130	69.0	6,700	66	30,300	0.31	6.5	25	21	17

Table 3: Key figures of a large solar combisystem with TCES (V_{sto} = 10 m³, A_C=23 m² ETC)

For the system shown in Figure 1 and the Type B building the annual fractional energy savings are shown as a function of storage volume and collector area. The collector area was chosen in a way that the corresponding store volume can be regenerated during an annual cycle. In comparison, the results of an identical system with a hot water store instead of the thermo-chemical energy store (TCES) are also shown in figure 2. It becomes obvious that the system with the thermo-chemical heat store achieves significantly higher energy savings. The difference is even more significant if the required system size is compared to the achievement of equal energy savings. For example, to achieve an annual energy saving of 75 % the TCES system requires a store volume of approximately 7 m^3 and 25 m^2 of evacuated tube collectors. In the case of the water-based system savings of 75 % are achieved with a collector area of approximately 44 m^2 and a store volume of about 15 m^3. As can be seen both, the required storage volume and the required collector area can significantly be reduced by the using thermo-chemical heat stores.

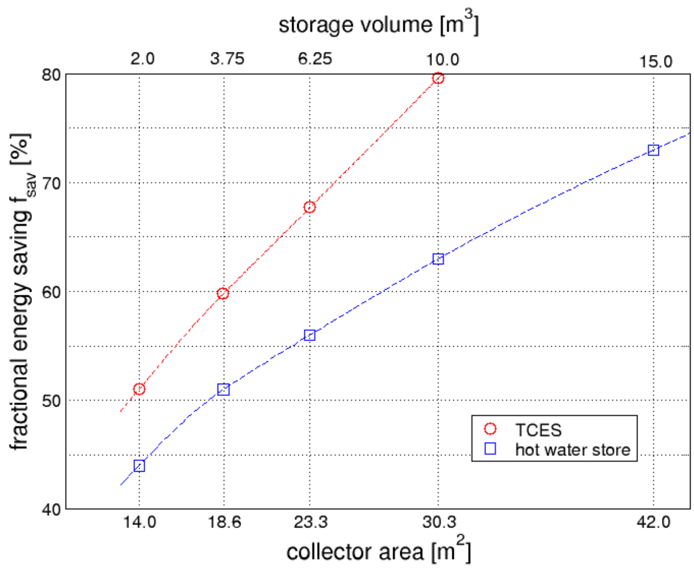

Figure 2: Fractional energy savings of a large solar combisystem with hot water store and a thermo-chemical energy store (TCES)

7. Conclusion

The presented results clearly show that water-based storage systems as well as solar combisystems with thermo-chemical store are able to achieve very high fractional energy savings. Efficient seasonal heat storage is possible in particular by using thermo-chemical heat storage. The high storage density and low thermal losses lead to high solar energy savings at reasonable storage and collector sizes. The high thermal performance, despite the low charging and discharging cycles, is reflected by a high storage efficiency, which comes with about 65 % close to short-term storage efficiency. With energetic payback times far below the expected lifetime of the systems both concepts are without any doubts an appropriate technology to contribute to the savings for natural resources and the reduction of greenhouse gas emissions. From the economic point of view an important prerequisite for seasonal heat storage is a low cost storage material with high storage density. Providing composite materials based on low-cost carriers and salts rates of 0.5 €/kg can be realized.

To bring the promising technology of thermo-chemical energy storage to marketability, extensive research and development activities in all sections (storage material, reactor design and system integration) have to be performed. Moreover, demonstration projects are necessary to investigate and optimize the complete system and especially the thermo-chemical energy store under realistic operation conditions.

8. References

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