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Solar-Active-Houses: Simulation based analysis of building concepts with high solar thermal fractions

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Abstract

Within this contribution a comprehensive simulation study regarding the dynamic thermal behaviour of Solar-Active-Houses is presented. These buildings cover at least 50 % of their space heating and domestic hot water demand by solar thermal energy. To take into account the dynamic interaction between the heat supply system and the building, extensive simulation studies were performed with the software TRNSYS. The simulation studies were focused on the optimization potentials regarding several major issues of Solar-Active-Houses, namely the integration of the hot water store, the solar thermal heat production and the integration and operation of the heat distribution system. The results show, that the identified optimization measures can increase the feasible energy savings and hence contribute to the cost reduction of such building concepts.

Keywords: Solar-Active-House, solar heating, high solar thermal fraction, building simulation, TRNSYS

1. Introduction

Regarding the established goal of the European Union to cover 20 % of the final energy demand of its member states in the year 2020 by means of renewable energy sources, the reduction of the non-renewable energy consumption in private households and office buildings has become a fundamental objective. As stated by the European Solar Thermal Technology Panel (ESTTP) of the European Technology Platform on Renewable Heating and Cooling (RHC-platform), a convenient way to cover the heat demand of buildings and to prevent or reduce CO_2-emissions at the same time is the utilisation of solar thermal heat supply systems (Stryi-Hipp et al., 2012). Named Solar-Active-Houses, these buildings cover at least 50 % of their total heat demand including space heating (SH) and domestic hot water (DHW) preparation with solar thermal energy (Bestenlehner et al., 2011). The practical functionality of the Solar-Active-House concept has already been proven as a result of an extensive measurement analysis of nine existing buildings in Germany within the project “HeizSolar”. As the potential to compare and optimize the buildings based on the measured data is restricted, a simulation based investigation of the dynamic thermal behaviour of the Solar-Active-House concept was carried out.

In literature, almost exclusively simulation studies about “typical” solar combisystems in Central Europe with solar thermal fractions of 20 % to 30 % are available. However, compared to the investigation of these systems, the interaction between the solar thermal heat supply system and the building itself has a much higher influence on the dynamic thermal behaviour of Solar-Active-Houses. This can be primarily attributed to the integration of relatively large hot water stores as well as other components into the building envelope.

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Therefore, a simulation model was elaborated enabling the dynamic coupling between heat supply system and building. The model was validated by a comparison of specific simulation results to measured data of real buildings. In order to examine the issues concerning Solar-Active-Houses by means of a simulation study, several typical buildings with different geometric and thermo-physical characteristics as well as different market available solar thermal system configurations were defined. Finally, the thermal performance of the Solar-Active-House concept was analysed by systematic parameter variations and optimization potentials were identified. Within this contribution, the results of the simulation study concerning a typical single family (SFH) Solar-Active-House and its solar thermal heat supply system are presented and discussed.

2. Modelling and methodology

A dynamic system simulation model was implemented in the transient system simulation software TRNSYS (version 17). The development was focused on the following aspects concerning the dynamic thermal behaviour of Solar-Active-Houses:

- dynamic interaction of heat generation (solar thermal collector and auxiliary boiler), the hot water store and the heat consumption (space heating system and domestic hot water preparation)
- realistic thermal performance of the large collector field and the large hot water store
- dynamic coupling of heat supply system and building to incorporate heat losses of the store and the hydraulics as internal gains into the building
- validation of the model by a comparison of specific simulation results to measured data from real buildings
- operation conditions of the auxiliary heating system for different boiler types such as wood fired ovens as well as chip and gas fired boilers
- operation conditions of different types of space heating systems such as panel heating and radiator heating

2.1. Building characteristics

To represent typical Solar-Active-Houses, a generic building geometry was defined based on the reference buildings developed in the IEA-Task 32 (Heimrath and Haller, 2007). This building geometry was used in the present study, whereas the thermal properties of the building envelope were altered. Different insulation standards were incorporated according to the German regulation “Energieeinsparverordnung 2009” (EnEV 2009) and the corresponding enhanced insulation standards. An overview of the characteristics of the evaluated single family Solar-Active-House is given in tab. 1. Different space heating systems were considered, having different design flow and return temperatures. The characteristics of the heating systems are shown in tab. 2. With respect to the DHW load, a dynamic load profile according to IEA-Task 32 was used. No hot water circulation was taken into account.

Tab. 1: Characteristics of the simulated Solar-Active-House

building type	single family house (SFH)
gross building volume	504.0 m³
heated floor area	140.0 m²
building location	Passau, Germany
yearly space heating load / specific heating load per floor area	10,440 kWh/a 75 kWh/(a m²)
room set temperature	20.0 °C
domestic hot water heat load specific DHW load per floor area	1,707 kWh/a 12 kWh/(a m²)
daily hot water draw-off volume	0.115 m³
hot water draw-off temperature	45 °C
cold water supply temperature	10 °C
hot water circulation	none

Tab. 2: Characteristics of the considered space heating distribution systems

	efficient panel heating	standard panel heating	efficient radiator heating
nominal flow temperature	35 °C	42 °C	55 °C
nominal return temperature	26 °C	30 °C	45 °C

2.2. Solar thermal heat supply system

The basic hydraulic layout of the solar thermal heat supply system is shown in fig. 1. For the shown configuration, all generated or consumed heat is charged to or discharged from the hot water store. As mentioned above, heat losses of the store and the hydraulics during the heating season were accounted as internal gains of the building, hence reducing the effective heat load of the solar thermal system. For the presented results, the heat losses of the hot water store as well as of the solar circuit piping were considered, both being situated inside the thermal zone.

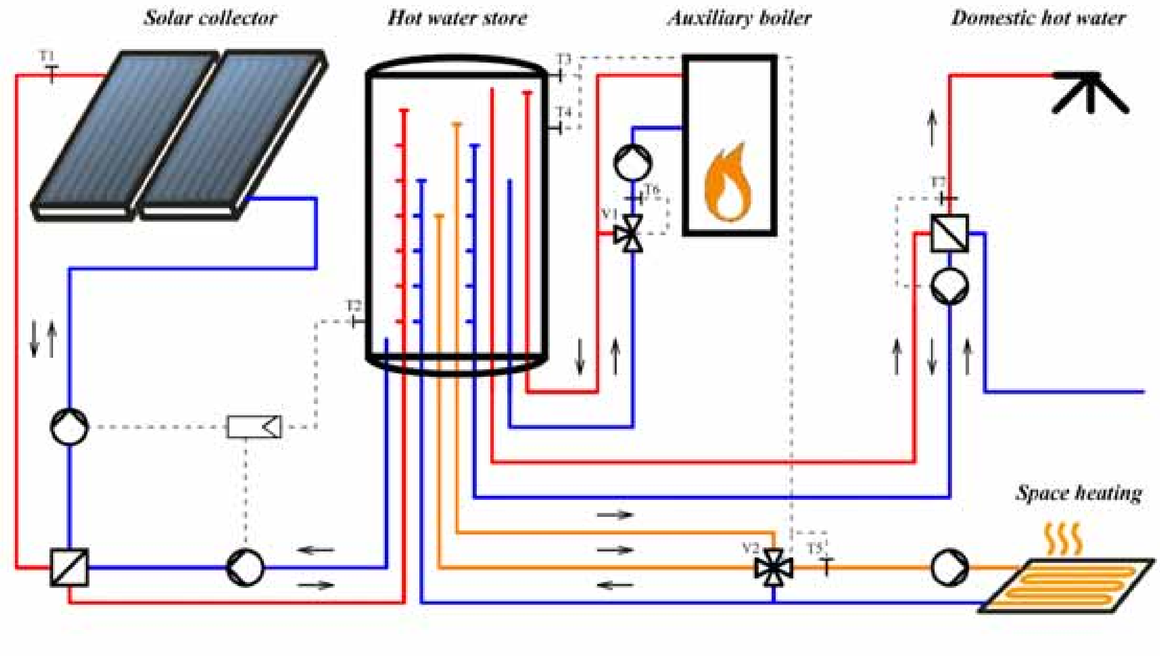

Fig. 1: Basic hydraulic layout of the solar thermal heat supply system

Concerning the solar circuit, the specific mass flow rate of the primary circuit with a water-glycol mixture was 25 kg/h per m² aperture area for all simulations. The flow rate of the secondary circuit, operated solely with water, was adapted according to the ratio of the specific thermal capacities of the fluids. The solar circuit piping was insulated according to the European standard EN 12977-2:2012-06. In order to assess the suitability of different collector technologies for their utilisation in Solar-Active-Houses, two different collector types were taken into account. Namely a generic standard flat plate collector with a selective coating according to IEA-Task 32 and an existing high end evacuated tubular collector with CPC-reflectors according to Solar Keymark licence no. 011-7S2031 R[1]. The characteristics of the two collectors are given in tab. 3. Since the collector gross area is the relevant size for the installation of large collector fields on a roof or facade, this parameter should generally be taken into account for the comparison of different collector types. However, since the ratio of the collector aperture to the collector gross area of the evacuated tubular collector with CPC-reflectors is in the range of a flat plate collector, in this contribution only the aperture area was taken into account.

Regarding the characteristics of the hot water store, the ratio between height and diameter of the hot water store was calculated according to IEA-Task 32. The heights of ports and sensors were derived from the

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[1] The test data sheet is publically available on http://www.estif.org/solarkeymarknew/certification-bodies/sk-certified-products

experience with existing stores for Solar-Active-Houses and are schematically shown in fig. 1. Some features were implemented to avoid adverse effects regarding the charging and discharging of the store by either suboptimal control strategies or dimensioning of the store. Firstly, the flow from the solar circuit into the store is assumed to be ideally stratified. Secondly, the return inlets from the SH and DHW circuit are also assumed to be ideally stratified. Moreover, two discharging outlets for the space heating circuit were implemented. Presumably, with these features, the maximal solar thermal fraction for a certain system configuration will be reached (Glembin and Rockendorf, 2012). The overall heat loss rate UA_{sto} in W/K of the store was calculated with respect to the store volume with eq. 1, which corresponds to class C defined in the Directive 2010/30/EU of the European Parliament[2]. In the equation V_{sto} in litres denotes the store volume.

$$UA_{\mathrm{sto}} = \frac{1}{45} \cdot \left(16.66 + 8.33 \cdot V_{\mathrm{sto}}^{\ 0.4}\right) \left[\frac{\mathrm{W}}{\mathrm{K}}\right] \qquad \text{(eq. 1)}$$

Tab. 3: Characteristics of the considered solar thermal collector types

	unit	**flat plate**	**evacuated tubular with CPC**
ratio of collector aperture to gross area	[-]	0.91	0.91
conversion factor	[-]	0.800	0.688
heat loss coefficient	[W/m² K]	3.500	0.583
temperature dependence of the heat loss coefficient	[W/m² K²]	0.015	0.003
effective thermal capacity of collector and fluid	[J/(m² K)]	7,000	8,790
IAM* for diffuse radiation	[-]	0.900	0.940
IAMs* for direct radiation	[-]	1st order equation according to ASHRAE	see SK licence no. 011-7S2031 R
IAM* equation coefficient	[-]	0.180	-

* IAM…incidence angle modifier

2.3. Evaluated parameters

An important performance indicator of solar thermal heat supply systems is the solar thermal fraction. This is the share of the total heat demand of a Solar-Active-House that is covered by solar thermal energy. The solar thermal fraction $f_{\mathrm{sol,th}}$ is calculated according to eq. 2. In the equation, Q_{aux} in kWh represents the heat delivered by the auxiliary boiler, $Q_{\mathrm{SH,load}}$ in kWh the heat load of the building for space heating without incorporation of the heat supply system's losses and Q_{DHW} in kWh the heat supplied to the hot water circuit.

$$f_{\mathrm{sol,th}} = 1 - \frac{Q_{\mathrm{aux}}}{Q_{\mathrm{SH,load}} + Q_{\mathrm{DHW}}} \, [-] \qquad \text{(eq. 2)}$$

3. Results of the simulation based studies and discussion

A typical heat and temperature profile of an entire year of operation of a Solar-Active-House's heat supply system is shown in fig. 2. With the standard flat plate collector and the standard panel heating, this system configuration reaches a solar thermal fraction of 61 %. As described in an earlier work (Kramer et al., 2014), the characteristic phases regarding the operation of the thermal store, namely the four phases of discharging, auxiliary heating, charging as well as solar excess, are clearly observable. Moreover, the figure shows that in the decisive phase when auxiliary heating is required, the return temperatures from the store to the solar thermal collector $T_{\mathrm{sol,ret}}$ are predominated by the return temperature from the SH circuit $T_{\mathrm{SH,ret}}$ to the store. In contrast, the heat consumption of the DHW circuit seems to be too low, to significantly influence the store's

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[2] Directive 2010/30/EU of the European Parliament and of the Council of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products

bottom temperature $T_{\mathrm{sto,bot}}$. Furthermore, the aforementioned useful heat losses of the heat supply system $Q_{\mathrm{loss,use}}$, in particular the store's heat losses, can cover a significant part of the space heating demand of the building. For the system configuration shown in fig. 2, 7 % of the building's heating demand is covered by useful heat losses of the hot water store and the solar circuit. Regarding all simulations considered in this contribution, this fraction varies between 5 % and 15 %. With respect to the total heat losses which occur in the building, the useful losses account for around 20 % to 30 %. It is denoted, that the non-useful heat losses of the heat store and the solar circuit range between 2,000 kWh/a and 4,000 kWh/a for the evaluated system configurations. The resulting additional cooling load will lead to an increased temperature of the building in the summer period and hence preventive measures may be required. This aspect is not further assessed within this contribution.

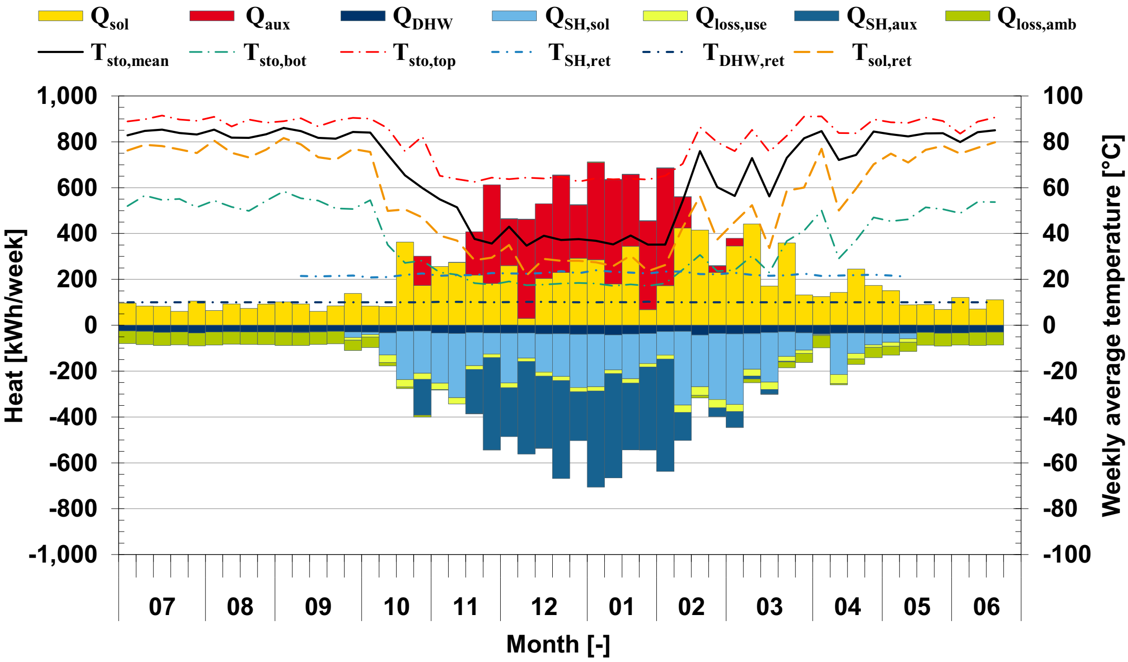

Fig. 2: Weekly heat demand and average temperatures for the SFH with 50 m² of the standard flat plate collector, 4 m³ store volume and the standard panel heating (simulation results). On the left ordinate, positive values correspond to generated heat, negative values to heat demand incl. heat losses.

3.1. Influence of the store volume and the collector area

With respect to the dimensioning of the solar thermal system, the size of the hot water store and the solar thermal collector field are essential. Fig. 3 shows the dependency of the solar thermal fraction on the store volume and the collector area for different system configurations with the standard flat plate collector. Generally, the solar thermal fraction increases with increasing both the collector area and the store volume. However, if the ratio between store volume and collector area (further denoted as the specific store volume) becomes either too low or too high, a distinct saturation behaviour is observed regarding the increase of the solar thermal fraction. Meaning that for specific store volumes below 50 l/m², an increase of the collector area does not result in a considerable increase of the solar thermal fraction anymore. Similarly, for specific store volumes above 200 l/m² or 300 l/m² an increase of the store volume does not result in a considerable increase of the solar thermal fraction. As a result of the simulations, an optimal value of about 100 l/m² and an acceptable range of specific store volumes between 50 l/m² and 150 l/m² was identified, where an alteration of either the collector area or the store volume leads to a distinct change of the solar thermal fraction and where a desired solar thermal fraction may hence be reached most effectively. In order to find an optimal specific store volume to reach a desired solar thermal fraction, ecologic or economic criteria should be taken into account as well. The curves in fig. 3 are characteristic for each Solar-Active-House and presumably depend on the following factors: local climate conditions, heat demand of the building regarding both load and temperature profiles, the characteristics of the collector and the store as well as the realizable orientation of the collector field and the integration of the store into the building.

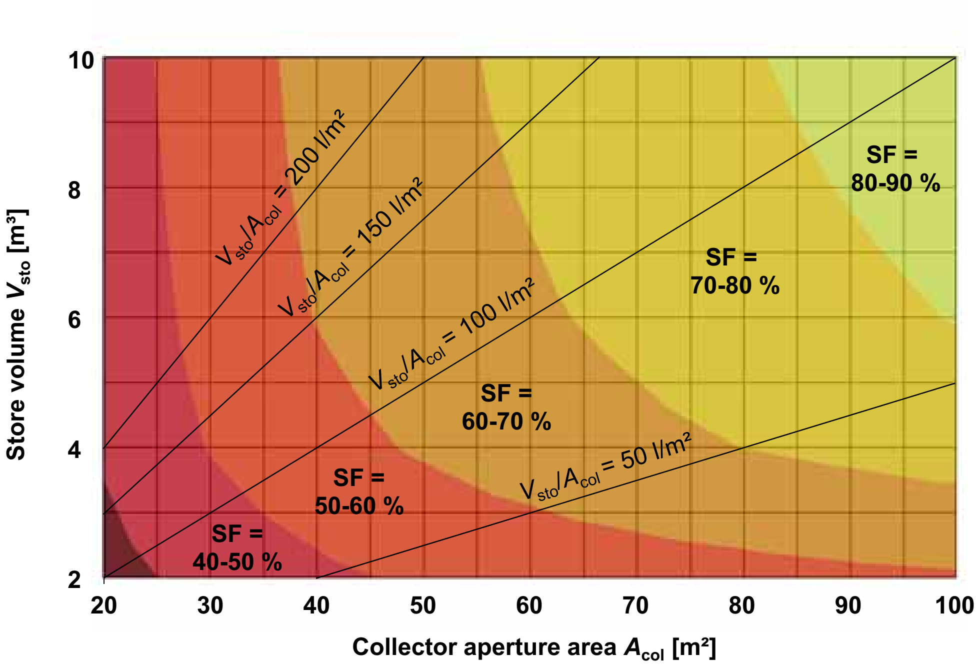

Fig. 3: Solar thermal fraction (SF) plotted against collector aperture area and store volume for the SFH with the standard flat plate collector (simulation results)

3.2. Influence of the tilt angle and characteristics of the solar thermal collector

It is already well known, that the characteristics, the dimensions and the orientation of the solar thermal collectors are decisive for the energy savings of solar thermal systems. Regarding the orientation, obviously a collector plane facing south ensures the maximum solar irradiation yield. However, regarding the tilt angle of the collector plane, the optimum depends on the desired solar thermal fraction and the sun's ecliptic at a certain location. Fig. 4 shows the influence of the tilt angle of the collector plane on the solar thermal fraction for two different solar thermal collector types at the location of Passau, Germany.

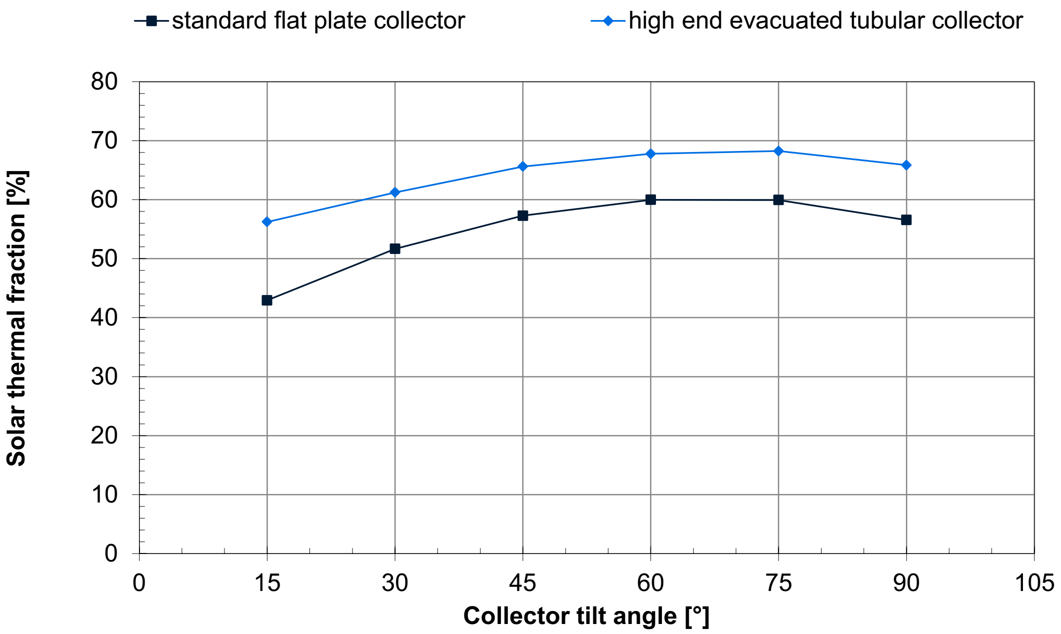

Fig. 4: Solar thermal fraction versus collector tilt angle for two collector types (simulation results)

The characteristics of the two considered collectors are presented in section 2. The collector field is facing south with a collector aperture area of 40 m² for both collector types. The store volume is 6 m³. With both collector types (standard flat plate and the high end evacuated tubular collector with CPC reflector), a maximum solar thermal fraction is reached at a tilt angle of around 60° and 75° respectively. Hence, a collector tilt angle of 60° was used to generate the following simulation results. Regarding the influence of the collectors' characteristics, the absolute enhancement of the solar thermal fraction reached by the evacuated tubular collector compared to the flat plate collector is equal to or larger than 8 % for all tilt angles. The further the tilt angle differs from its optimum, the higher is the enhancement. This implies that the usage of evacuated tubular collectors may be particularly advantageous for such buildings, where the realization of optimal tilt angles between 60° and 75° is not possible. In fig. 5 the correlation between the solar thermal fraction and the collector area is shown for the two collector types and for different store volumes. Depending on the specific store volume, the high end evacuated tubular collector with CPC reflector achieves an absolute enhancement of the solar thermal fraction ranging between 7.2 % and 11.4 % for the 4 m³ store and 6.7 % and 13.6 % for the 10 m³ store respectively compared to the standard flat plate collector. The enhancement increases with decreasing specific store volumes. This implies that the usage of evacuated tubular collectors may be particularly advantageous, if only small stores can be realized. However, once a certain specific store volume is underrun – in this case 4 m³ with a collector area larger than 60 m² – the enhancement deteriorates again. Overall, the highest enhancements are reached with large store volumes and large collector areas. It is denoted, that if not prohibited, the stagnation times of the system configurations with the evacuated tubular collector during the summer period are significantly increased compared to the flat plate collector.

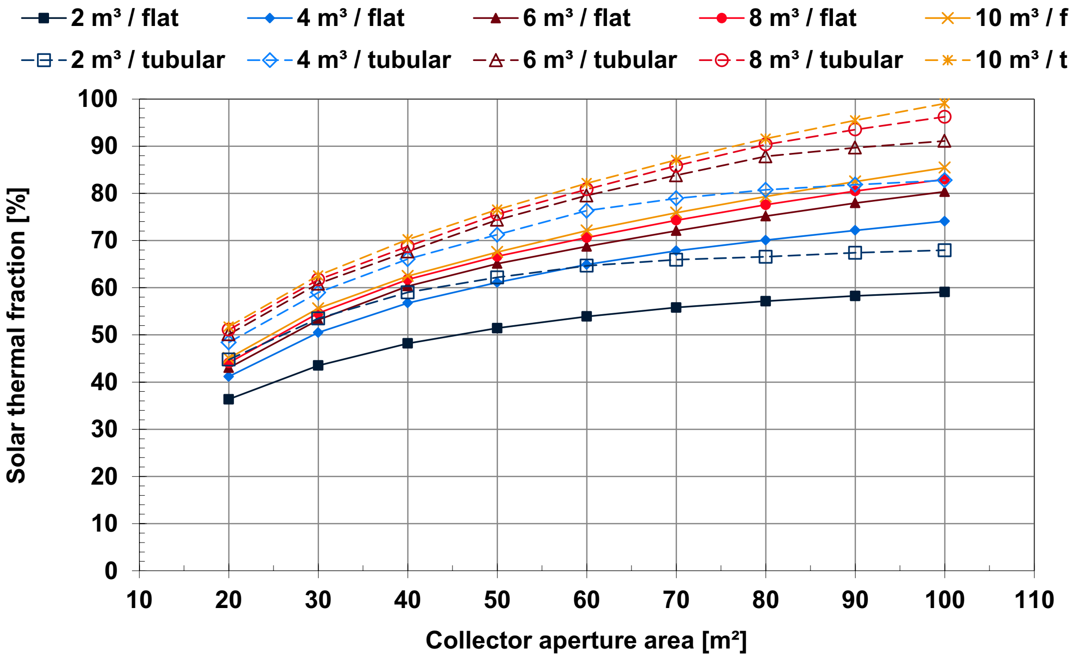

Fig. 5: Solar thermal fraction versus collector area for the SFH with different store volumes and two types of solar thermal collectors for the standard panel heating (simulation results)

3.3. Influence of the space heat distribution system

Another aspect covered in the present contribution is the influence of the space heat distribution system's operating conditions. The characteristics of the considered space heating systems are given in section 2. Fig. 6 shows the achieved solar thermal fractions for different system configurations. The solar thermal fraction clearly decreases with an increasing temperature level of the space heating system. While the difference between the efficient panel heating and the standard panel heating is small, the solar thermal fraction deteriorates significantly with the radiator heating. The maximum absolute decrease of the solar thermal fraction with the radiator heating compared to the efficient panel heating is 4.6 % for the flat plate collector and 1.9 % for the evacuated tubular collector. As already stated, for solar thermal systems of Solar-Active-Houses the return temperatures from the store to the collector field during the heating period are predominated by the return temperature from the space heating circuit to the store. Thus, the efficiency of the collector is decreasing with the rising temperature level of the space heating system. Due to the collector characteristics, this effect is stronger for the flat plate collector. Therefore, the utilization of a low temperature space heat distribution system is crucial for Solar-Active-Houses, in particular when flat plate collectors are utilized. Furthermore, the strongest enhancement of the solar thermal fraction with the highly effective evacuated tubular collectors compared to the flat plate collector is reached for high temperature heating systems.

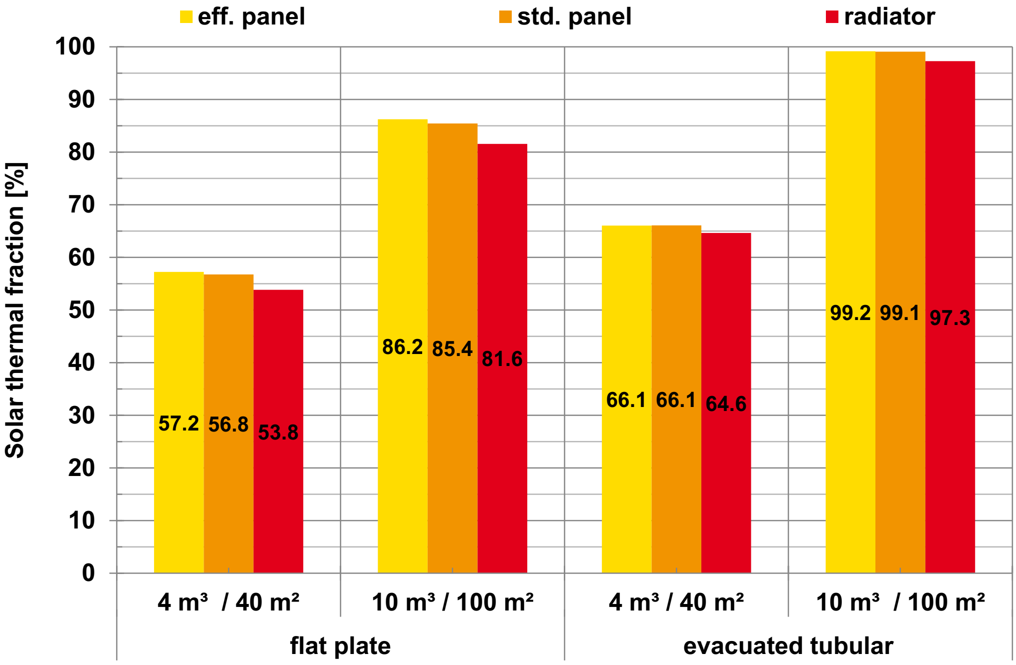

Fig. 6: Dependency of the solar thermal fraction on the space heat distribution system for different collector types and different combinations of store volume and collector area (simulation results)

4. Conclusion and outlook

In the research project HeizSolar the Solar-Active-House concept for solar thermal fractions between 50 % and 100 % of the total heat demand of buildings has been scientifically evaluated in detail for the first time. Based on an extensive simulation study, the findings from the in-situ monitoring of nine existing buildings regarding the functionality and feasibility of the concept could be confirmed. Additionally, optimisation potentials regarding the design, dimensions, characteristics and operation conditions of such systems could be identified. Within this contribution, some major aspects concerning the Solar-Active-House concept were exemplarily assessed at hand of a moderately well insulated single family house at the location of Passau, Germany. First of all, the dynamic interaction between heat supply system and building was found to have a profound influence on the thermal performance of Solar-Active-Houses. With the thermal store integrated into the thermal zone of the building, the heat losses cover between 5 % and 15 % of the space heating demand for all considered system configurations.

Regarding a certain climate and the corresponding heat demand of a building, the dimensions of both the store and the solar thermal collector are most decisive for the achievable solar thermal fractions. With the standard flat plate collector a solar thermal fraction of 50 % is reached for instance with a store volume of 2 m^3 in combination with 45 m^2 collector aperture area whereas with a store volume of 4 m^3 a collector area of only 30 m^2 is required. It was found that for the considered building, a desired solar thermal fraction can be reached most efficiently with a specific store volume of around 100 l/m^2. With the high end evacuated tubular collector, 50 % solar thermal fraction can be reached either with a 2 m^3 store volume in combination with a collector area of 26 m^2 or with a 4 m^3 store and a collector area of 22 m^2. Furthermore, the solar thermal fraction enhancement achieved with the evacuated tubular collector compared to the standard flat plate collector was found to be maximal for high temperature heating systems such as radiator heating. It was stated, that the stagnation times during the summer period significantly increase with the tubular collector, which may require precautionary measures. Consequently, a facade installation may be beneficial for the utilization of high performance collectors. Though the solar thermal fraction is slightly decreased, the stagnation times in the summer period are minimized. With the standard flat plate collector, the usage of a low temperature heating system is highly recommendable.

As a next step, further parameter variations will be carried out, particularly regarding the insulation standard of the building as well as the climate conditions. Additionally, system configurations with different auxiliary heating systems as well as with hot water stores located outside the thermal zone of the building will be assessed. Furthermore, the evaluation will be extended with regard to the demand of parasitic electric energy for the system operation. With respect to the optimal dimensions of the collector field and the thermal store, an economic and ecologic evaluation will be done.

5. References

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Nomenclature

symbol	unit	quantity
A_{col}	[m²]	solar thermal collector aperture area
$f_{sol,th}$	[-]	solar thermal fraction
Q_{aux}	[kWh]	useful heat delivered by the auxiliary heating system
Q_{DHW}	[kWh]	useful heat demand for domestic hot water preparation
$Q_{loss,amb}$	[kWh]	non-useful heat losses of the heat supply system
$Q_{loss,use}$	[kWh]	useful heat losses of the heat supply system covering a fraction of the space heating demand of the building
$Q_{\mathrm{SH,aux}}$	[kWh]	useful heat for space heating covered by auxiliary heat and solar thermal heat ("preheating")
$Q_{SH,sol}$	[kWh]	useful heat for space heating covered by solar thermal heat only

symbol	**unit**	**quantity**
$Q_{\mathrm{SH,load}}$	[kWh]	gross space heating load of the building without incorporation of any heat losses by the supply system
$T_{\mathrm{DHW,ret}}$	[°C]	return temperature from the hot water circuit to the store
$T_{\mathrm{SH,ret}}$	[°C]	return temperature from the space heating circuit to the store
$T_{\mathrm{sol,ret}}$	[°C]	return temperature from the store to the solar circuit
$T_{\mathrm{sto,bot}}$	[°C]	bottom temperature of the hot water store
$T_{\mathrm{sto,mean}}$	[°C]	mean temperature of the hot water store
$T_{\mathrm{sto,top}}$	[°C]	top temperature of the hot water store
V_{sto}	[m³]	effective volume of hot water store