Efficient Design of Solar Assisted Heating Systems for Multi-Family Houses

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Summary

Hydraulic concepts for solar heat appliances to support heating and domestic hot water in multi-family houses (solar combisystems) are investigated and compared by means of simulations and hardware-in-the-loop tests. The aim is to find best-practice solutions.

The standard for new constructions of multi-family housing is a central buffer storage system with fresh water station, but hot water storage systems are also used. Hydraulic concepts found in market research are compared concerning their efficiency, costs and complexity. Solar combisystems with fresh water stations are not very complex, offer high energy savings and the lowest heat generation cost: 0,19 €/kWh. This makes it the best practice concept for solar combisystems in multi-family houses.

Keywords: solar thermal system, hydraulic concept, multi-family houses, solar combisystems, fresh water station, solar assisted heating, hardware in the loop, simulations, domestic hot water, buffer storage

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2. Introduction

The market in Germany for solar thermal systems is almost completely (97%) restricted to detached and semi-detached houses, but 53% of all apartments are located in multi-family housing (IWU 2010). In order to supply more solar energy to multi-family housing and better penetrate this market, the different designs of solar assisted heating systems were evaluated - to help planners and installers identify the advantages and disadvantages of the hydraulic concepts and find the best concept.

The aim is to define best-practice solutions. The concept which offers the best compromise between lower overall costs, high energy savings and low equipment complexity is considered to be the best one. Methods used are market research, Hardware-in-the-loop-tests (HIL) and simulations (using TRNSYS and MATLAB)

3. Classification of concepts

The concepts are classified using 3 criteria: centrality (of the equipment), energy provision for domestic hot water (DHW) and energy provision for heating. The first criterion “centrality” in figure 1 refers to three functions of the concept: DHW- production, conventional heating and heat storage. How are these three carried out – separately (decentral) in each apartment or in one central place?

In figure 1, from left to right the concepts are getting more decentral: If the heating and hot water production is done centrally (concepts 1 to 7), a 4-pipe network is used distributing DHW and heating water in separate flow and return lines.

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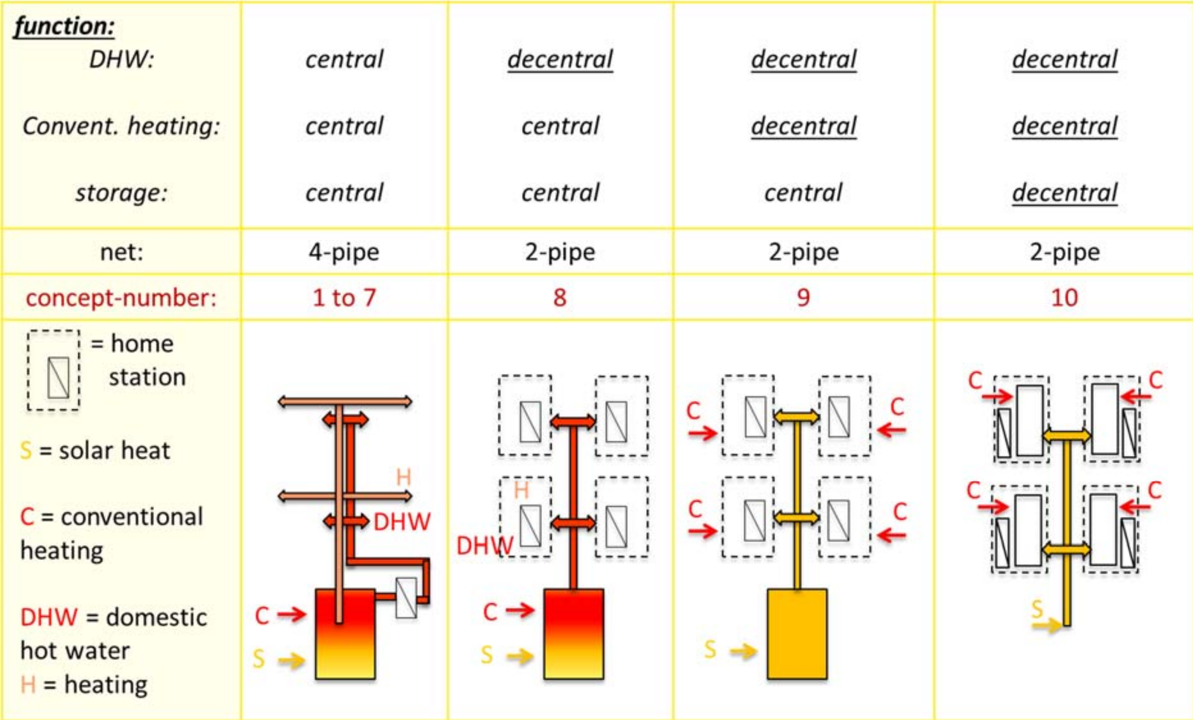

Fig. 1: Criterion Centrality: Solar-supported central and decentral concepts for heating and DHW in MFH

If the DHW is produced decentrally in the apartments (by a home station), only two pipes are needed (concept 8). If the hot water production and the conventional reheating takes place decentrally in the apartments, also a 2-pipe network is used and all network losses are solar losses (concept 9). If, additionally, heat is stored decentral, it is concept 10. (Wirth 2018)

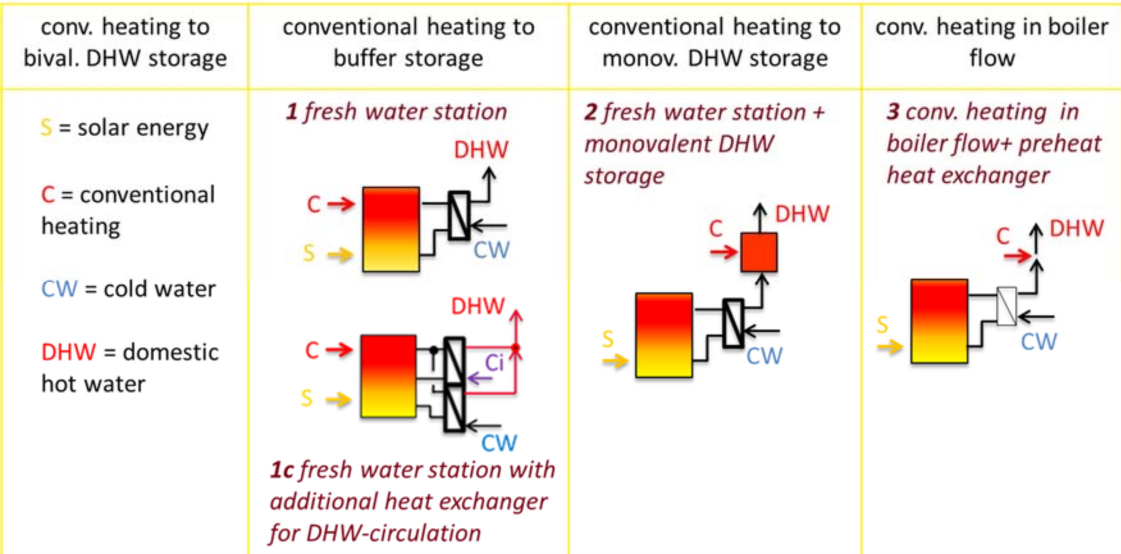

Fig. 2: the central concepts that transfer solar heat to DHW in the flow

The second criterion for classification is “energy provision for domestic hot water” and defines if the transition of solar heat to the hot water is “in the flow” (figure 2) or by charging a storage (figure 3). The four columns of both figures (2 and 3) separate different concepts and are defined by the different kind of storages the conventional heating is transferred to.

In the columns far right of figure 2 and 3 (concepts 3 and 7) it is not really a storage, but the conventional heating of DHW is in boiler flow. However, these concepts 3 and 7 will not be further investigated, because in reality they cannot be found in multi-family houses – among others for the reason that they require a very high thermal output of the conventional heating, only to cover the (maximum) DHW-demand.

Concepts 1, 1c and 2 in figure 2 are concepts with freshwater station. Concept 1 is the standard concept. Concept 1c uses an additional heat exchanger for heating up the DHW-circulation return flow separately – and not mixing warm circulation return with incoming cold water. This also prevents the lower part of the storage from being heated by the constant (24 hours) DHW-circulation.

With an additional monovalent DHW-storage (concept 2) higher DHW-comfort can be achieved and the buffer storage is only heated by solar energy.

This also applies to concept 4 and 6 in figure 3, concept 4 using a bivalent DHW-storage and concept 6 using two monovalent DHW storages. The first (cold) DHW storage is the solar preheat storage. Concepts 5 and 6 are used if the solar thermal system has to be integrated into an existing DHW-installation.

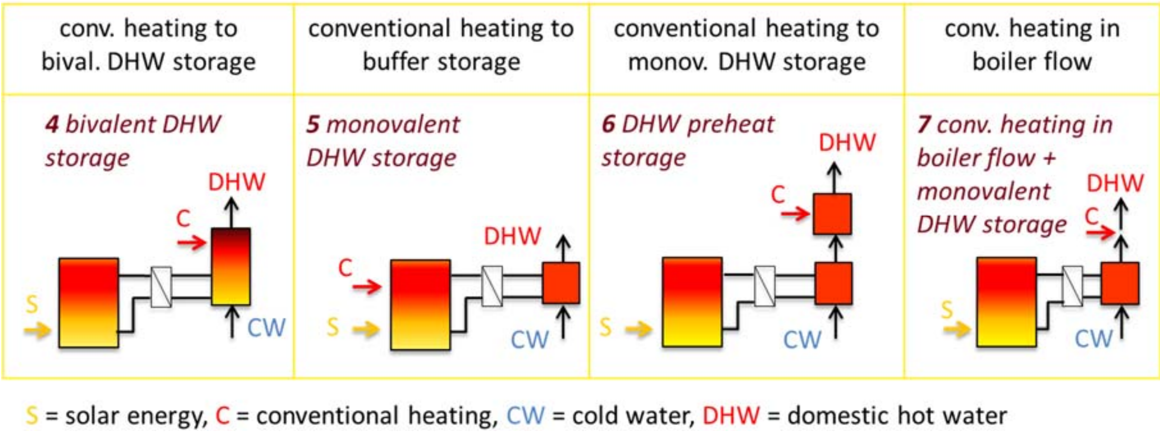

Fig. 3: the central concepts that transfer solar heat to DHW by charging a storage

4. Market research

For this market research 60 manufacturers were surveyed. They were asked for a system for a building with 8 apartments. Finally, 58 hydraulic systems of 28 manufacturers were taken into account. 13 of these are decentral hydraulic concepts in addition to 45 central concepts. Half of the central concepts included a fresh water station. A central buffer storage with fresh water station is standard in multi-family housing. For the future, manufacturers forecast more systems with home stations.

5. Concepts tested on the HIL test stand

As the market research suggests, a focus of the study is on systems with fresh water stations (concept 1), which are tested on the hardware-in-the-loop test bench in four variations:

a) Fresh water station (and a valve for stratified solar loading)

b) Fresh water station with „cold water preheating“,
(the incoming cold water is pre-heated by the circulation return flow)

c) Fresh water station with additional heat-exchanger for circulation (concept 1c in figure 2)

d) fresh water station with additional heat-exchanger for circulation and ultrafiltration module (ultrafiltration module provides a mechanical legionella treatment so that the hot water feed temperature can be lowered from 60°C to just above the desired tap temperature, for example 47°C)

Another focus of the study is on decentral concepts: concept 8 and concept 10 (figure 4) were also tested. Concept 10 is the most decentral one, with only the solar collectors left central.

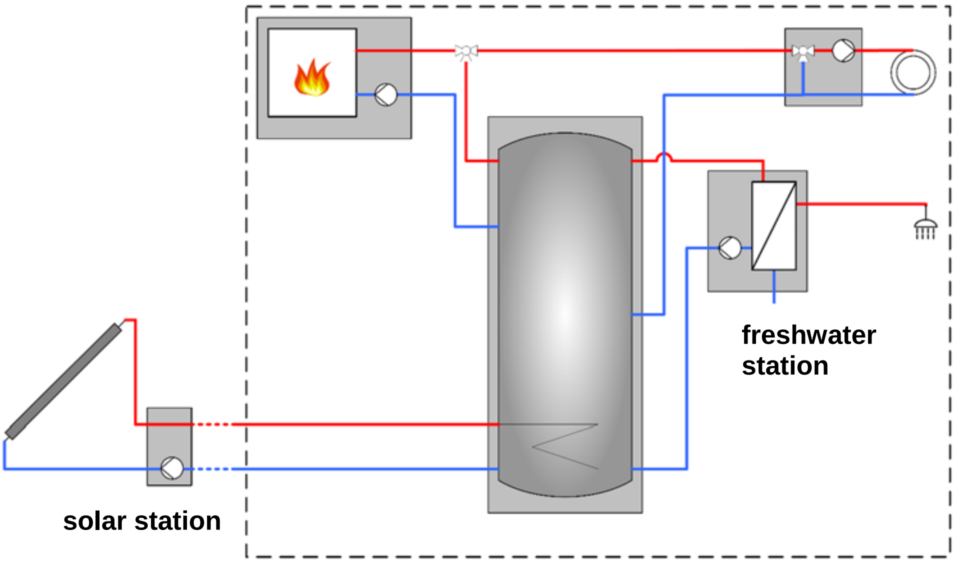

Fig. 4: decentral concept 10, all decentral facilities (in one apartment) in dotted lines

Concept 8 is tested first with a buffer storage with integrated boiler and second with decentral electrical reheating of DHW. The central concept 2 was also tested, the other concepts (4, 5, 6, 9) are only investigated by simulation.

The solar collectors, the weather and the building with its space heat demand, DHW-load and DHW-circulation do not exist in reality at the test bench, so they are simulated / emulated and parameterized as follows:

- Weather: Meteonorm (version 5), weather datasets from Zürich, Switzerland. Eight typical days were selected, so each measurement lasted 8 x 24 hours.
- Collector: aperture area 24 m², inclination 45°, orientated south, total pipe length 53.5 m
- DHW: 60°C, 55 liter per apartment and day, profile generated by the program DHWcalc (Jordan 2014)
- Circulation: 24 h DHW-circulation, maximum temperature difference of 5 K leading to a circulation volume flow of 150 l/h.
- Building: 4-storey multi-family house with 8 apartments each at a size of 65 m², heated by radiators.

6. Simulations

The HiL measurement data was used as the basis for the simulation models of all concepts, which are then run through annual simulations. All concepts from 1 to 10 (except 3 and 7) were simulated and compared - using one example system per concept. Then the following variations were simulated:

- solar plant aperture area: $A_{collector}$ = 14 m² to 33 m²,
- building from the 1960s not renovated - with a space heat demand of 173 kWh/m²a / building renovated according to German energy saving regulations "EnEV 2009" - with a space heat demand of 41 kWh/m²a

The system has to meet the loads of the DHW production, the DHW-circulation and the heating. Q_L is the sum of these loads. The load-related specific collector area a_{dsc} was used in the simulations:

$$a_{dsc} = \frac{A_{collector}}{Q_L} \; [m^2/MWh] \qquad \text{(eq. 1)}$$

7. Results

Solar combisystems (concepts 1, 2, 8 and 10) are measured on representative days and their functions are checked. All concepts from 1 to 10 (except 3 and 7) are simulated and their annual efficiencies are compared. Costs are added from real offers. Finally, the complexities of the concepts are assessed and compared.

Function

The real, (HiL-)tested systems are commercially available solar combisystems such as the systems for concept 1 and 2. The measured systems of concepts 8 and 10 are prototypes, system 10 in particular still has great optimization potential. Several discrepancies have been found in the functionality of the commercially available systems, concerning the system hydraulics, the selection of components and also the system control. One system has a mixing valve that is too slow. Another system is not optimally adapted to a 24-hour circulation period, whereby the correct integration of the circulation return (or the return flow of the fresh water station) is extremely important for an efficient system in a multi-family house (Adam 2017).

The solution approach of “cold water preheating” (concept 1b in chapter 5) could not yet be implemented profitably on the test stand. However, the simulation suggests energy savings of 2.2 % (for a variant of this pre-heating with a pipe heat exchanger for the cold water) compared to the standard concept 1.

Energy

In the following figures the final energy savings of all (solar) concepts are shown in comparison to a system without solar support, called reference system. The final energy saving fsav.EE is defined as follows:

$$f_{sav.EE} = 1 - \frac{E_{final}}{E_{final.ref}} \qquad \text{(eq. 2)}$$

where: E_{final} : final energy consumption [kWh]
$E_{final.ref}$: final energy consumption of the reference system [kWh]

For the definition of the reference system the DIN V 4701-10 "Energetische Bewertung heiz- und raumluft-technischer Anlagen" has been the guideline. This reference system is a central concept for DHW and heating generation with gas condensing boiler. Table 1 shows the boundary conditions:

Tab. 1: Definition and boundary conditions for the reference system (DIN V 4701-10)

General description	central generation of DHW- and heating: gas condensing boiler gas: 1,1 usable area of the building: 500 m² room heating requirements: 40 kWh/m²/a (renovated building), 170 kWh/m²/a (not renovated building) DHW requirement: 12,5 kWh/m²/a
Room heating	Transfer: free heating surfaces with 1 Kelvin spreading Distribution: horizontal distribution pipes outside the thermal envelope and all other pipes inside the thermal envelope. Heating design: 55/45 °C (renovated) and 70/55 °C (not renovated). Controlled heating circuit pump Storage: none Generation: Gas condensing boiler outside the thermal envelope
Domestic hot water	Distribution: 24-hour DHW circulation with distribution outside the thermal envelope Storage: indirectly heated storage with installation outside the thermal envelope Generation: Gas condensing boiler outside the thermal envelope
Ventilation	No consideration.
primary energy factor	natural gas: 1,1; electricity: 1,8

Figure 5 and 6 show the final energy savings of all concepts over the load-related specific collector area a_{dsc}.

The annual simulations show that concept 8 with decentral electrical DHW reheating and concept 10 have clear energy advantages, especially due to their low system and distribution losses. For a collector area of 1.1 m²/MWh, which corresponds to a collector area of 33 m² for the renovated building, there is a final energy saving of 42 % to 45 % for the concepts 8 and 10 in figure 5.

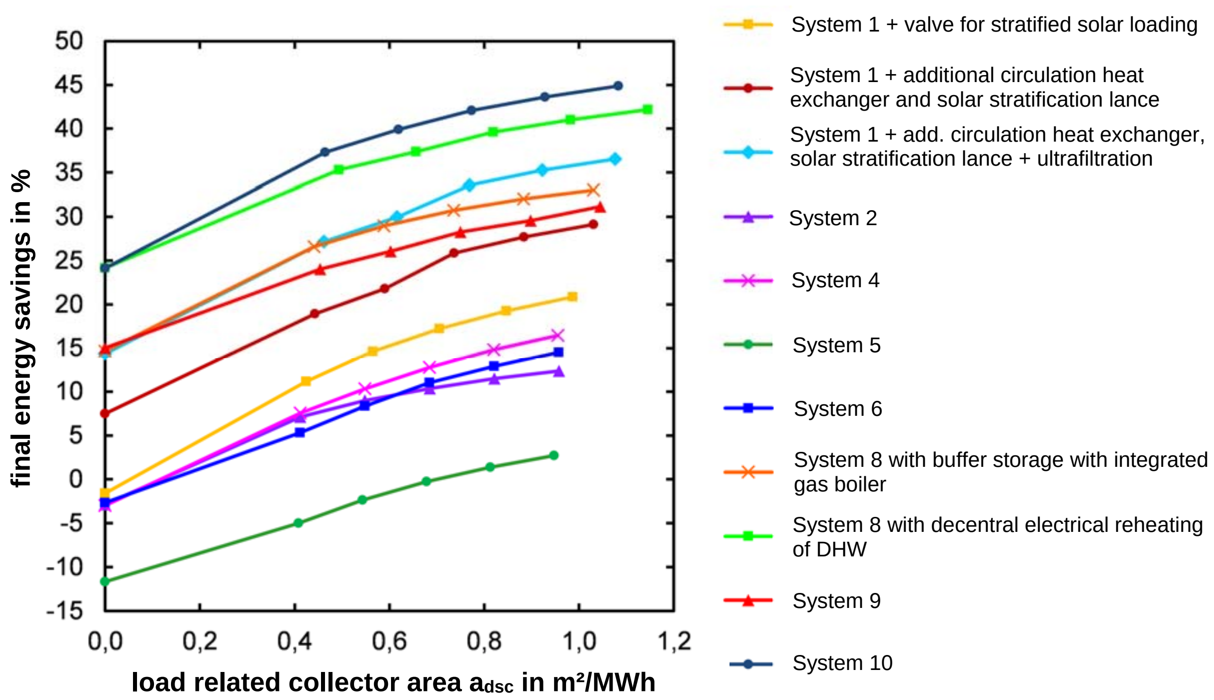

Figure 5: simulated final energy savings of all concepts for the <u>renovated</u> building

Within the central concepts, examples of concept 1 are the most energy-efficient.

A similar order of concepts applies to the non-renovated building in figure 6. But concept 8 with decentral electrical DHW reheating and concept 1 with ultrafiltration have a higher gradient than other concepts. So it becomes clear that both systems can make particularly effective use of solar heat because of (the higher heating loads of the non-renovated building and) the lower temperature level of the distribution lines - due to their concept. Therefore, for these concepts a larger design of the collector field is particularly noticeable.

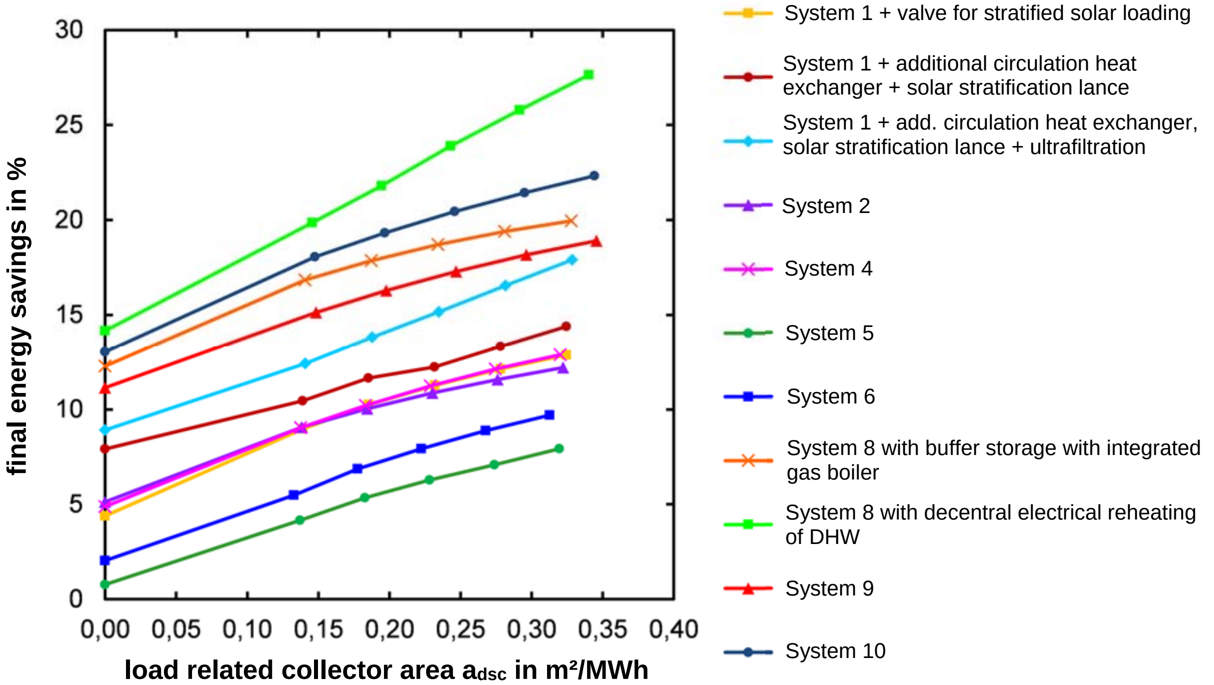

Figure 6: simulated final energy savings of all concepts for the <u>non-renovated</u> building

A benchmark procedure was developed to determine the potential of the concepts. Using simulations, individual causes of losses were analysed– in comparison to an ideal system. Efficiency is increased by keeping the temperature stratification in the storage, reducing heat distribution losses in the building and by compact installation.

Costs

Decentral concepts are energy-efficient, but their costs are high, especially for the concepts 9 and 10 (figure 7 and 8). So central concepts prove to be more economical: For the renovated building, the systems of concept 1 with fresh water station (without ultrafiltration) are the most cost-effective, often in the variant with separate circulation heat exchanger and lance for stratified loading. For the non-renovated building, concept 4 is also a cost-efficient system with low "levelized cost of heat" (LCOH, eq.3). The LCOH describes the cost for one heat unit in €/kWh.

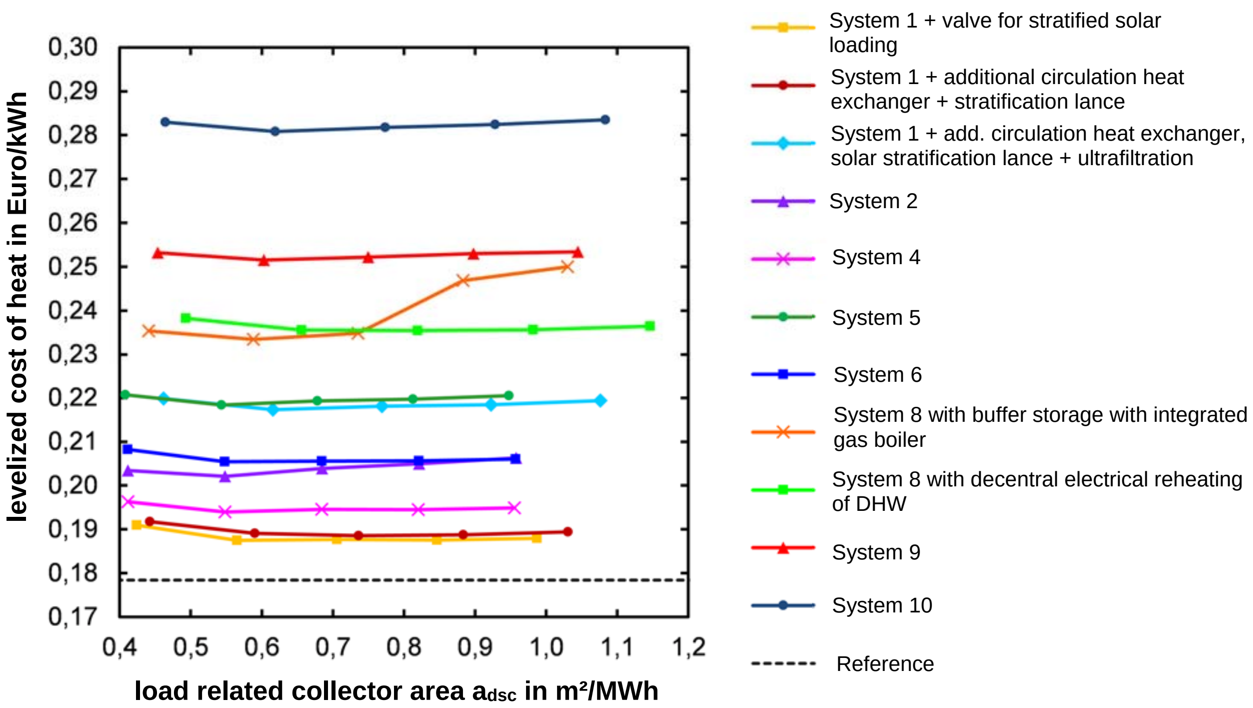

Figure 7: levelized cost of heat over the load-related specific collector area a_{dsc} for the renovated building

The LCOH is gained by dividing the equivalent annual costs EAC by the annual useful energy of the system Q_{use}:

$$LCOH = \frac{\text{EAC}}{Q_{use}} \left[\frac{€}{kWh}\right] \quad \text{(eq. 3)}$$

$$\text{EAC} = \text{AF} \cdot \text{NPV} = \frac{i}{1-(1+i)^{-T}} \cdot \sum_{t=0}^{T} \frac{R_t}{(1+i)^t} \left[\frac{€}{a}\right] \quad \text{(eq. 4)}$$

where:
- i: annual interest rate [-]
- T: observation period [a]
- t: year [a]
- R: net cash flow [€]
- NPV: net present value [€]
- AF: annuity factor [1/a]

Tab. 2: Applied boundary conditions for the economic efficiency analysis

annual interest rate	0,4 %
prices for energy	electricity: 29,7 €-Cent/kWh and natural gas: 6,1 Cent/kWh
price change factors	capital-related: 1,4 %/a and salary: 2,2 %/a electricity: 3,6 %/a and natural gas: 3,7%/a
observation period	20 years

In contrast to the variation of the collector area, the variation of the heat demand (building renovated / not renovated) has a noticeable effect on the costs. Generally, the costs are higher in the renovated building and the distances between the concepts are higher.

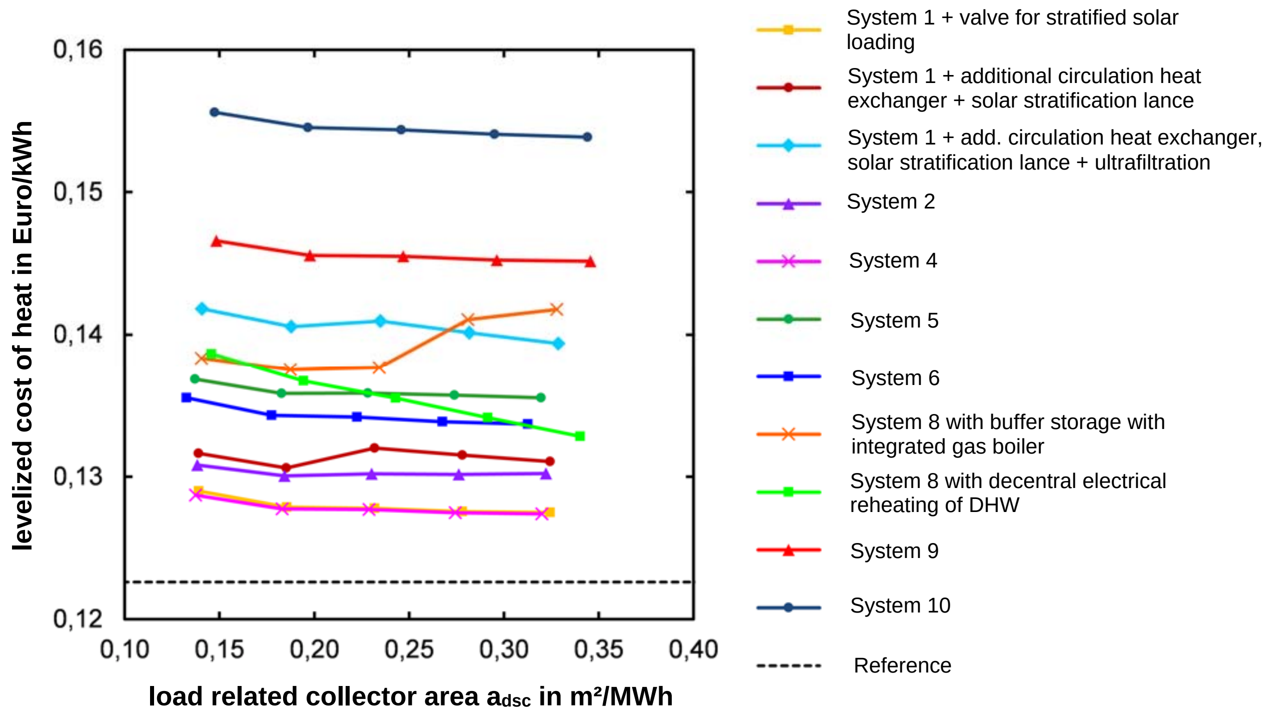

Figure 8: levelized cost of heat over the load-related specific collector area a_{dsc} for the non-renovated building

The LCOH of the most economical concepts, including the BAFA support, is still approx. 5 % higher than that of a conventional reference heating installation without solar part. This results in carbon abatement costs of less than 200 €/tCO_2 for concept 1 (Helbig Et al. 2017). With more realistic assumptions than in VDI 2067 for the maintenance costs of the storage tank and the lifetime of the collector and the storage, concept 1 is more cost-efficient than the reference.

The following optimizations of concept 1 are economical: a stratification valve in the return flow of the fresh water station with 2.4 % energy savings or a separate circulation heat exchanger with 4.0 % energy savings (Helbig et al 2018). In combination with a solar charging lance, both optimizations work better and yield energy savings of 3.9 and 6.0%, respectively.

To determine the costs of a concept, two offers were requested and the average costs were used as a basis. The cost differences between the individual offers are sometimes high and of the same scale as the cost differences between the concepts.

Complexity

The number of hydraulic components and the number of control sensors were counted to compare the degree of complexity of the concepts. There were no significant differences between the central concepts. Within the decentral concepts, concept 9 showed a very high level of complexity. The other concepts are simpler and therefore more reliable.

8. Conclusion

According to market research, hydraulics with fresh water station according to concept 1 are currently the most frequently offered in new constructions. The concept is not very complex, offers high energy savings and the lowest heat generation cost. This makes it the best practice concept for solar combisystems in multi-family houses.

Decentral concepts offer the highest energy savings. But the more decentral the concepts get, the more expensive they are. However, the investigated decentral concepts 8a, 8b and 10 are still in prototype condition and offer great potential for more compact design and cost reduction. In addition, the costs of the decentral conventional heating may not be attributed to the concept if they already exist or are mandatory for billing reasons.

9. References

Adam, M., Backes, K., Eggert, D., 2017. Symposium Thermische Solarenergie, Energetischer Vergleich verschiedener Zirkulationseinbindungen bei einer solaren Wärmezentrale mit Frischwasserstation.

DIN (Deutsches Institut für Normung e.V.): DIN V 18599-1, 2016 (Vornorm). Energetische Bewertung von Gebäuden – Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung, Teil 1: Allgemeine Bilanzierungsverfahren, Begriffe, Zonierung und Bewertung der Energieträger, Berlin.

Helbig, S., Steinweg, J., Eggert, D., Adam, M., 2017. Energetic and Economic Efficiency Evaluation of Solar Assisted Heating Systems for Multi-Family Houses. SHC, International Conference on Solar Heating and Cooling for Buildings and Industry, Conference proceedings, Abu Dhabi.

Helbig, S., Eggert, D., Adam, M., 2018. Einfluss von Speicheranschlusshöhen und geschichteter Speicherbe- und -entladung auf die Effizienz solarer Kombisysteme im Mehrfamilienhaus, Solarthermie-Symposium 2018.

IWU (Institut Wohnen und Umwelt), 2010. Datenbasis Gebäudebestand - Datenerhebung zur Energetischen Qualität und zu den Modernisierungstrends im deutschen Wohngebäudebestand, Darmstadt, http://www.datenbasis.iwu.de/dl/Endbericht_Datenbasis.pdf

Jordan, U., Vajen, K., 2014. Manual DHWcalc – Tool for the Generation of Domestic Hot Water (DHW) Profiles on a Statistical Basis, Version 1.20, Universität Kassel, Institut für thermische Energietechnik.

Wirth, H., Backes, K., Adam, M., Helbig, S., Eggert, D., 2018. Best-Practice-Lösungen für Mehrfamilienhäuser mit Solaranlage, Solarthermie-Symposium 2018.