Energetic and Economic Efficiency Evaluation of Solar Assisted Heating Systems for Multi-Family Houses

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Abstract

For holistic efficiency evaluation of solar-assisted heating systems in multi-family houses common system designs are tested with hardware-in-the-loop measurements. The experimental results provide the basis for the subsequent energetic and economic efficiency analysis. A previously introduced efficiency measure called "central performance factor of the heating facility" (CPF) is used to evaluate energetic efficiency of the overall heating system. Using this measure it can be explained, how system designs comprising low heat distribution losses (e.g. 2-pipe heat distribution networks or an ultrafiltration module in the DHW circulation return flow) feature the highest CPF. Cost analysis show, however, that such designs incorporate elevated levelized cost of heat compared to the other systems under investigation. Carbon abatement cost are combining the energetic and economic evaluation into one parameter. The results show that concepts with a bivalent heat storage tank and a fresh water unit connected to a 4-pipe heat distribution network, are leading to the lowest carbon abatement cost, at a minimum value of 46 €/tCO_2.

Keywords: solar combisystems, whole system testing, levelized cost of heat, carbon abatement cost

1. Introduction

There are various hydraulic design concepts for the integration of solar thermal energy into the heat supply of multi-family houses. Additionally, the control algorithms and the type of heat distribution network may vary. The variety of technical solutions therefor are hardly comparable for planners and installers due a lack of comprehensive system evaluation. This establishes a general obstacle for the application of solar thermal systems, especially in Germany, where solar thermal systems are used almost exclusively (97 %) for the heat supply of houses with one to three residential units (BSW, 2007), although more than 50 % of the apartments are situated in multi-family houses (IWU, 2010). In this paper selected solar-assisted heat supply concepts are evaluated in an energetic and cost-effective manner, in order to identify or derive optimal system concepts.

1.1 Evaluation method

Functional system evaluations (Helbig et.al, 2016) are carried out using a hardware-in-the-loop (HIL) test procedure (see Figure 1). For this purpose, the central components of the heat supply system (referred to "central heating facility" in the sequel) are implemented according to manufacturer´s instructions and tested under emulated, real operation conditions. Weather data and solar thermal collectors as well as the building with the heat distribution system are part of a dynamic simulation model in TRNSYS to ensure standardized and reproducible boundary conditions for system tests. The central heating facility is connected to thermostatic emulators during the tests, which supply the simulated heat gain or remove the required heat. The behavior of the emulators is calculated by means of real-time simulations in TRNSYS. With a time interval of one minute measured values are passed as input data to the simulation environment. Thus the HIL system can react dynamically to the behavior of the central heating facility. The test device allows the emulation of heating capacities sufficient for 20 residential units under central-European climate conditions and a solar thermal collector power of up to 60 kW.

doi:10.18086/swc.2017.29.04 Available at http://proceedings.ises.org

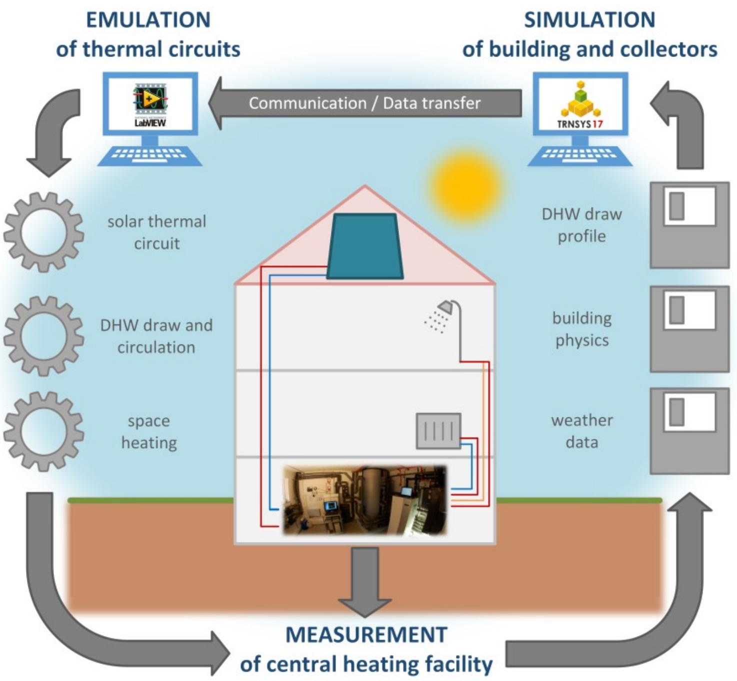

Fig. 1: Hardware-in-the-loop (HIL) test procedure for central heating facilities

The subsequent energetic evaluation is based on the results of high-resolution annual simulations of the solar-assisted heat supply systems under investigation. The simulation models are derived from the TRNSYS models of the HIL tests. Thereby, the performed measurements provide the data basis for model validations which allows a very precisely parametrization of the components of the central heating. While the HIL measurements are carried out for up to eight selected days, which generate all typical operation conditions within a year, the system simulations cover a complete year.

Finally, an economic analysis of the systems under investigation has been done. The economic evaluation is based on the results of the energetic system evaluation and a cost analysis of the single components of the central heating facility. Thereby two different evaluation parameter are used: levelized cost of heat (LCOH) and carbon abatement cost (AC_{CO2}).

1.2 Tested systems and applied boundary conditions

The tested solar-assisted heating systems for multi-family houses can be distinguished according to the type of heat distribution system, their solar heat storage and the hot water and boiler connection. In figure 2 the distinguishing features of the tested systems for the DHW preparation is shown. Additionally, all systems have solar support for space heating. The reference case has no solar support and is characterized by a domestic hot water storage and a 4-pipe distribution network.

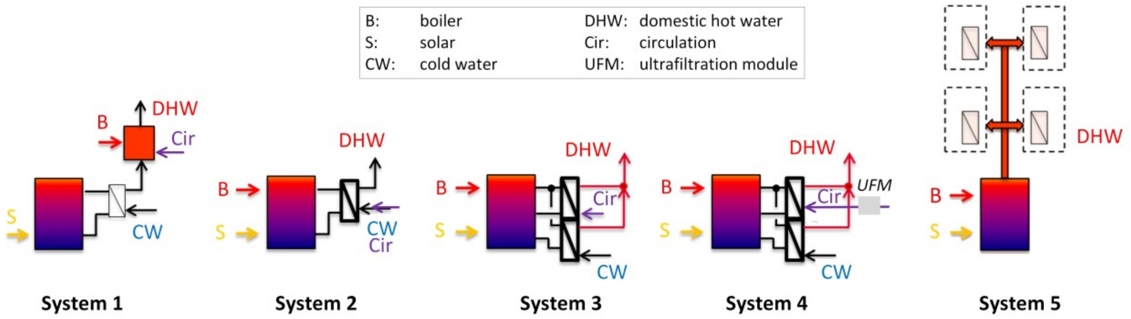

Fig. 2: Simplified hydraulic schemata for the DHW preparation of the tested systems (Adam et.al, 2016)

System 1 to System 4 are characterized by a 4-pipe distribution network, while System 5 has a 2-pipe distribution network. In system 1, solar heat is transferred exclusively to the monovalent solar heat storage tank.

The solar storage is used to preheat domestic hot water via a fresh water unit. Systems 2 to 4 differ in the number of heat exchangers in the fresh water unit. While system 2 has a common heat exchanger for heating both the domestic hot water (DHW) and the circulation return, the systems 3 and 4 have two separate heat exchangers for these tasks. System 4 is furthermore characterized by an ultrafiltration module in the circulation return. This provides a mechanical legionella treatment whereby the DHW flow line temperature can be lowered to little above the desired tap temperature (e.g., 47°C). System 5 has a bivalent heat storage tank from where the heat is distributed to the decentralized apartment transfer stations. The flow line temperature in the 2-pipe heat distribution network is constant at 50°C.

Tab.1: Boundary conditions for hardware-in-the-loop measurements and dynamic system simulation

	Description	Values
weather data	Meteonorm (version 5), location: Zurich, Switzerland	• days for HIL measurements: 38, 71, 99, 112, 175, (230), 250, (356)
solar thermal circuit	flat plate collectors as well as pipes between roof and central heating facility	• aperture area: between 14 m² and 33 m² • inclination: 45°, orientation: south • total pipe length: 53.5 m
space heating and distribution	multi-family house in Germany with a construction year between 1958 and 1968 and an energy-focused refurbishment according to the standards of EnEV 2009	• multi-zone simulation model (52 thermal zones) • number of apartments: 8 • detailed heat distribution network with more than 100 pipe sections • size of an apartment: 65 m² • heating system: radiators
domestic hot water draw	draw profile generated with DHWcalc (Jordan, Vajen, 2014)	• 55 litre per apartment and day (assumption of 1.8 inhabitants per flat)
domestic hot water circulation	constant circulation 24 hours a day	• 19 litre per hour and apartment (according to a maximum temperature difference in the flow line of 5 K)

2. Energetic efficiency evaluation

2.1. System boundaries and evaluation parameter

Figure 3 shows the system boundaries employed for balancing the energy fluxes of a solar assisted heat supply system for a multi-family house. Of particular interest is the boundary around the central heating facility with its energetic inputs and outputs. The central heat demand of the building ($Q_{central}$) combines the space heat demand and distribution losses as well as the heat demand for DHW and circulation. An efficiency measure previously introduced (Helbig et.al, 2016) is employed for the energetic evaluation of the investigated central heating facilities: the central performance factor of the heating facility (CPF). It represents the ratio of the central heat demand of the building as energetic benefit to final energy demand (E_{final}) as energetic expenditure:

$$CPF = \frac{Q_{central}}{E_{final}} \; [-] \qquad \text{(eq. 1)}$$

For an overall evaluation of the energy conversion chain, the central performance factor of the heat supply chain (CPF_{plus}) is additionally introduced as an assessment parameter. In this case, the useful energy (Q_{use}) is set in relation to the primary energy (E_{prim}). The CPF_{plus} thus represents the reciprocal value of the plant effort (e_P) according to DIN V 4701:

$$CPF_{plus} = \frac{1}{e_P} = \frac{Q_{use}}{E_{prim}} \; [-] \qquad \text{(eq. 2)}$$

In contrast to the CPF, the CPF_{plus} also allows the comparison of systems with different fossil energy sources and thus different primary energy factors. In addition, effects for reducing distribution heat losses can be assessed. However, a disadvantage of the CPF_{plus} is that both the useful energy and the primary energy are not measurable variables.

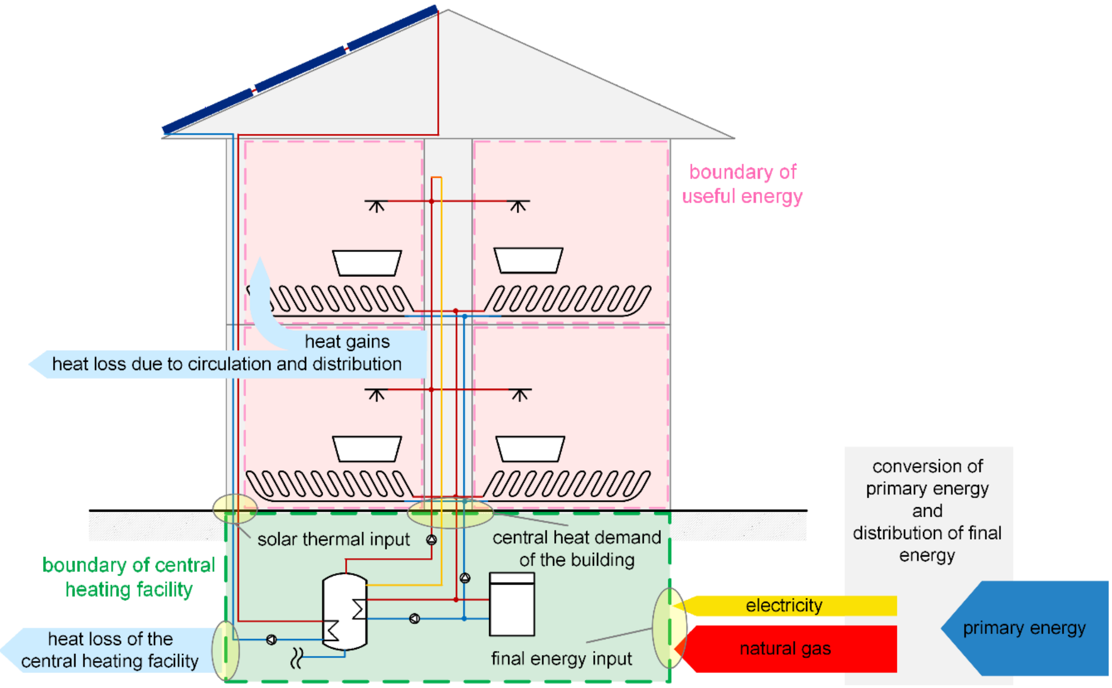

Fig. 3. **Definition of system boundaries for the energetic efficiency evaluation (Helbig et.al, 2016)**

Both the CPF and the CPF_{plus} are strongly dependent on the chosen boundary conditions (solar thermal collectors, weather and building characteristics, see Table 1). Accordingly, the demand-specific collector area (a_{dsc}) is selected as the reference parameter. It forms the quotient from the collector area (aperture) to the central heat demand of the building:

$$a_{dsc} = \frac{A_{col}}{Q_{central}} \left[\frac{m^2}{MWh}\right] \qquad \text{(eq. 3)}$$

The benchmark procedure according to (Steinweg et.al, 2016) is used to calculate the maximum possible CPF or CPF_{plus} of an idealized central heating facility. For this purpose, the maximum collector circuit yield is determined by taking into account the temperature levels of the heat sinks in the monthly balance method. The central heating facility has no conversion losses from final energy to building energy. A comparison between the investigated systems and the benchmark makes it possible to determine the theoretical optimization potential of the individual systems (Helbig et.al, 2016).

2.2 Results

Figure 4 shows the CPF over the demand specific collector area for the systems 1 to 5, as well as for the reference system without solar support and the benchmark. It can clearly be seen that the central heating facilities 1 and 2 without solar support ($a_{dsc} = 0.0$) have identical energy efficiency (CPF) as the reference system. Systems 3 to 5, on the other hand, show an efficiency increase compared to the reference system without any solar support. The second heat exchanger in the fresh water unit (system 3 and 4) is leading to a better stratification of the heat storage tank whereas the ultrafiltration module in the circulation return (system 4) as well as the 2-pipe heat distribution network (system 5) are lowering the heat distribution losses. An increasing demand-specific collector area always leads to an increase in efficiency of the central heating facilities. For example, a solar support due to a demand specific collector area of 1.0 m^2 / MWh is leading to an efficiency increase of the central heating facilities of 15 to 37 %-points compared to the reference system. It can be seen that this increase in efficiency between the tested systems with solar support can differ by up to 22 %-points. However, system 5 as the most efficient of the systems under investigation still has a theoretical optimization potential of the CPF of a further 45 %-points (difference to the benchmark) with a demand-specific collector area of 1.0 m^2/MWh. The theoretical optimization potential is made up of technical optimization measures and system idealization (Helbig et.al, 2016).

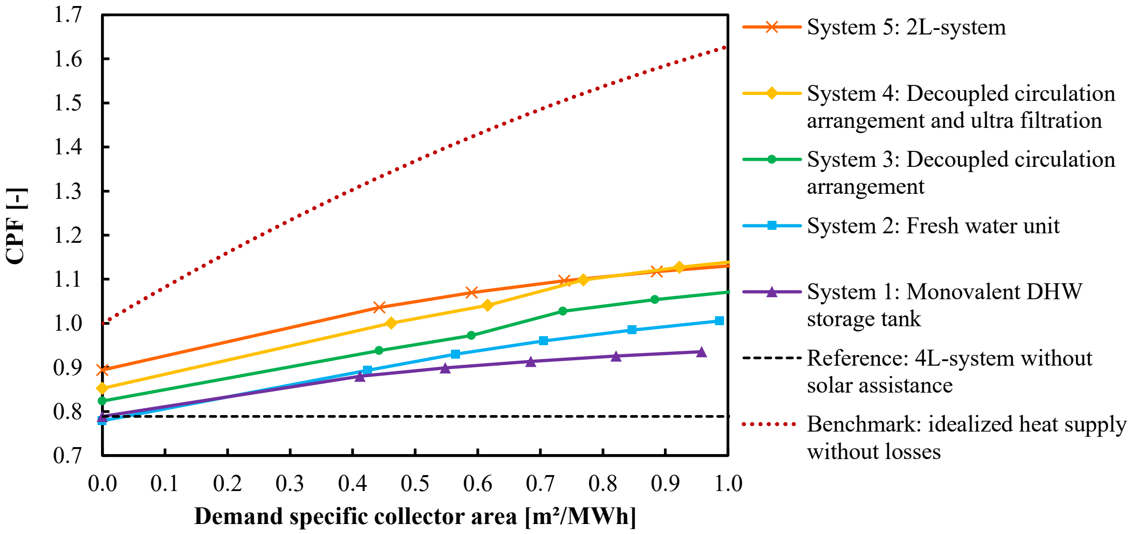

Fig. 4: Central performance factor of the heating facility over the demand specific collector area

Figure 5 shows the CPF_{plus} as a function of the demand-specific collector area. Since the CPF_{plus} evaluates a larger section of the energy conversion chain, its values always lie below those of the CPF.

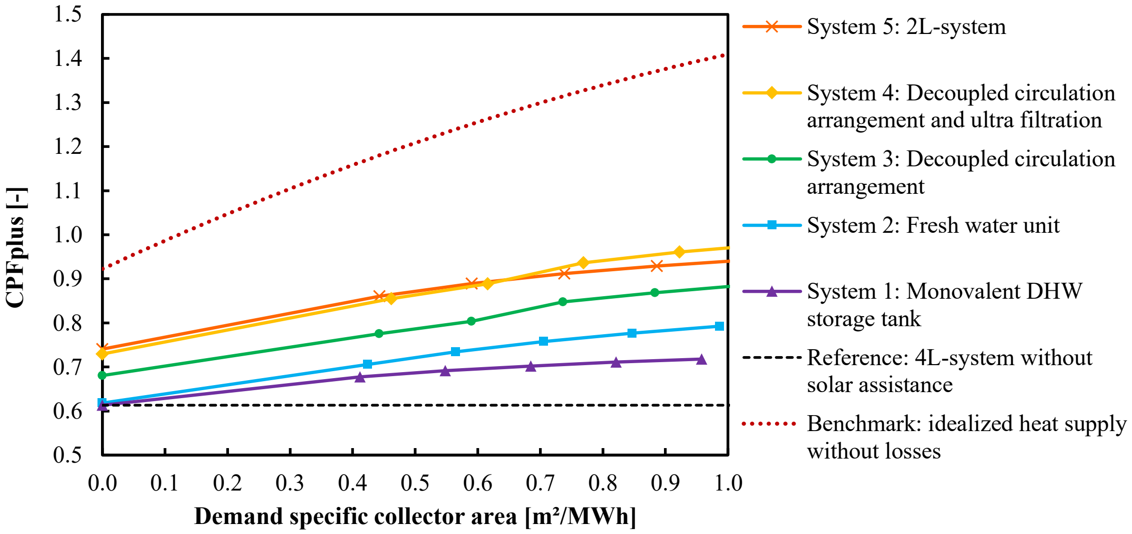

Fig. 5: Central performance factor of the heat supply chain over the demand specific collector area

A comparison between the CPF_{plus} in figure 5 and the CPF in figure 4 shows that both evaluation variables lead to a similar result in the efficiency assessment of the investigated systems. However, it can be seen in detail that the systems 4 and 5, compared to systems 1 to 3, have a relative efficiency increase in the heat supply which is attributable to lower heat distribution losses. In system 4 the reduction of those losses are a result of reduced DHW flow line temperatures because of the ultrafiltration module. The reduced heat distribution losses in system 5 are due to the application of a 2-pipe heat distribution network instead of a 4-pipe system. But it appears that the relative efficiency increase due to the ultrafiltration module is higher than the one due to the 2-pipe heat distribution network.

3. Economic efficiency evaluation

3.1 Evaluation parameter

In order to assess the economic efficiency of solar-assisted heating systems, levelized cost of heat (LCOH, see equation 5) as well as carbon abatement cost (AC_{CO2} see equation 6) are calculated and compared for the systems under investigation. Both evaluation parameter rely on the calculation of the equivalent annual cost (EAC) which is determined by multiplying the annuity factor (a) with the net present value (NPV) (see VDI 2067):

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

where: i: annual interest rate [-]
T: observation period [a]
t: year [a]
R: net cash flow [€]

In the net cash flow (R) different types of costs (capital-related costs, demand-related costs, operation-related costs) as well as price change factors are considered. The investment costs as part of the capital-related costs come from real offers of an installation company for heating technology. The offers distinguish between component, delivery and assembly costs. Disbursements for replacements, which correspond to the depreciation period of the single components (VDI 2067), are also part of the capital-related costs as well as the possible payments by a residual value and incentives for thermal solar collectors of the German Federal Office of Economics and Export Control (BAFA, 2017a). The demand-related costs include the costs for electricity and natural gas. The operation-related costs are composed of the costs for maintenance, which were also selected according to the VDI 2067, as well as the costs for maintenance and inspection. The latter are from the offerings of the installation company, which contains a maintenance contract.

In addition to the offers for the systems under investigation, alternative offers were also made which have a quite similar hydraulic specification compared to the systems under investigation, but originate from another manufacturer. The alternative offers serve to assess the cost differences between the systems as well as between the manufacturers. The evaluation is done anonymously. It should be considered that to calculate the levelized cost of heat for the alternative manufacturers' systems, the respective energy efficiency of the systems under investigation is assumed. Accordingly, the levelized cost of heat of the alternative manufacturers are associated with additional uncertainty, which must be taken into account when interpreting and evaluating the results. Further boundary conditions for the economic efficiency calculation are summarized in table 2.

The levelized cost of heat describe the monetary expenditure for one heat unit. Therefor the equivalent annual cost are divided by the annual useful energy of the system:

$$LCOH = \frac{\mathrm{EAC}}{Q_{use}} \left[\frac{€}{kWh}\right] \qquad \text{(eq. 5)}$$

Carbon abatement cost describe the additional cost for the carbon saving measure per unit CO_2 avoided. Consequently, for the calculation of abatement costs a reference system (ref) needs to be defined (see section 1.2). The annual CO_2 emissions caused by each system are determined by adding up the product of the carbon intensity per kilowatt-hour (CIPK) and the final energy demand for all energy sources used (n):

$$AC_{CO2} = \frac{\mathrm{EAC}_{Sys} - EAC_{ref}}{\left(\sum_{j=1}^{n} CIPK_j \cdot E_{final,j}\right)_{Sys} - \left(\sum_{j=1}^{n} CIPK_j \cdot E_{final,j}\right)_{ref}} \left[\frac{€}{tCO_2}\right] \qquad \text{(eq. 6)}$$

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
CIPK	electricity: 526 gCO_2/kWh and natural gas: 202 gCO_2/kWh

3.1 Results

Figure 6 shows the LCOH and figure 7 the AC_{CO2} for the systems 1 to 5 and the reference system. The LCOH and AC_{CO2} for the benchmark are not shown, since this is not a real system. While the solid lines in figure 6 and 7 indicate the results for the systems tested in the HIL test, the dotted lines represent the results for systems with similar hydraulic specification, but from alternative manufacturers. In both figures the unsteady steps in the graphs of system 5 and system 1 (alternative offer) result from a nonfulfillment of a requirement for the incentives of solar thermal collectors from the German Federal Office of Economics and Export Control. The critical requirement states that the collector specific volume of the heat storage tank has to be larger than 40 l/m² (BAFA, 2017a). If it is clearly shown that a system has a solar support also for space heating and not just for the DHW preparation the limit of 40 l/m² can be undercut by 10 % (BAFA, 2017b). Nevertheless the systems 5 and 1 (alternative offer) do not fulfill the incentive requirement for all demand specific collector areas under investigation although the storage tanks have been replaced by similar models of the manufacturer with a larger volume as the collector surface area increases. However, a storage volume of 1500 liters was assumed as the upper limit, since the installation of even larger individual storage units in multi-family buildings is regarded as unrealistic and a possible storage cascading has so far not been used in the investigated systems.

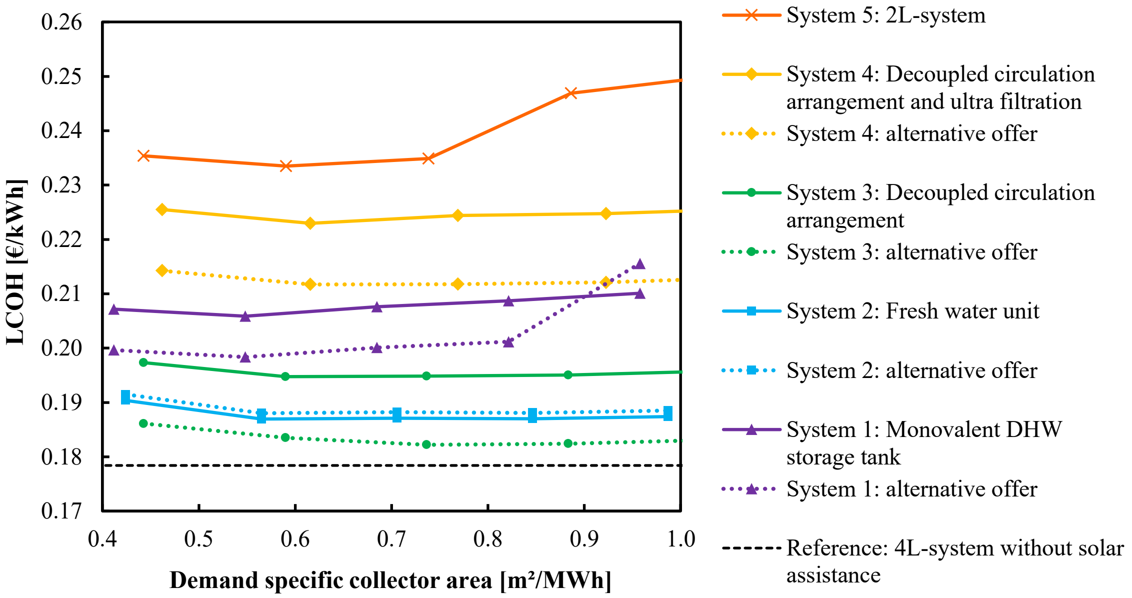

Fig. 6: **Levelized cost of heat over the demand specific collector area for the investigated systems and alternative offers with a similar hydraulic specifications**

It can be seen in figure 6 that all solar-assisted systems have higher levelized cost of heat than the reference system. When comparing the solar-assisted systems with each other, it appears that systems 2 and 3 have the lowest LCOH, with system 3 showing a greater difference between the considered manufacturers. In system 1, the large number of components and the low energy efficiency lead to high LCOH. The two most energy efficient systems under investigation are at the same time the ones with the highest LCOH. While for system 4 that is a result of the high costs for the ultrafiltration module, for system 5 the high costs for eight decentralized apartment transfer stations and their installation are leading to LCOH of more than 0.23 €/kWh.

Looking at figure 7 it appears that the systems with the lowest LCOH (systems 2 and 3) also feature the lowest AC_{CO2}. The alternative offer of system 3 is reaching 46 €/tCO_2 at its lowest point (at 0.74 m²/MWh). In contrast to that, system 1 shows to have the highest AC_{CO2} with over 1000 €/tCO_2 (at 0.4 m²/MWh). Although the AC_{CO2} is an economical parameter it is combining the energy efficiency analysis (CPF) and the economic efficiency assessment (LCOH). As a result, system 5 with the highest LCOH but also the highest CPF features lower AC_{CO2} than system 1 which is representing the most inefficient solar-assisted system under investigation.

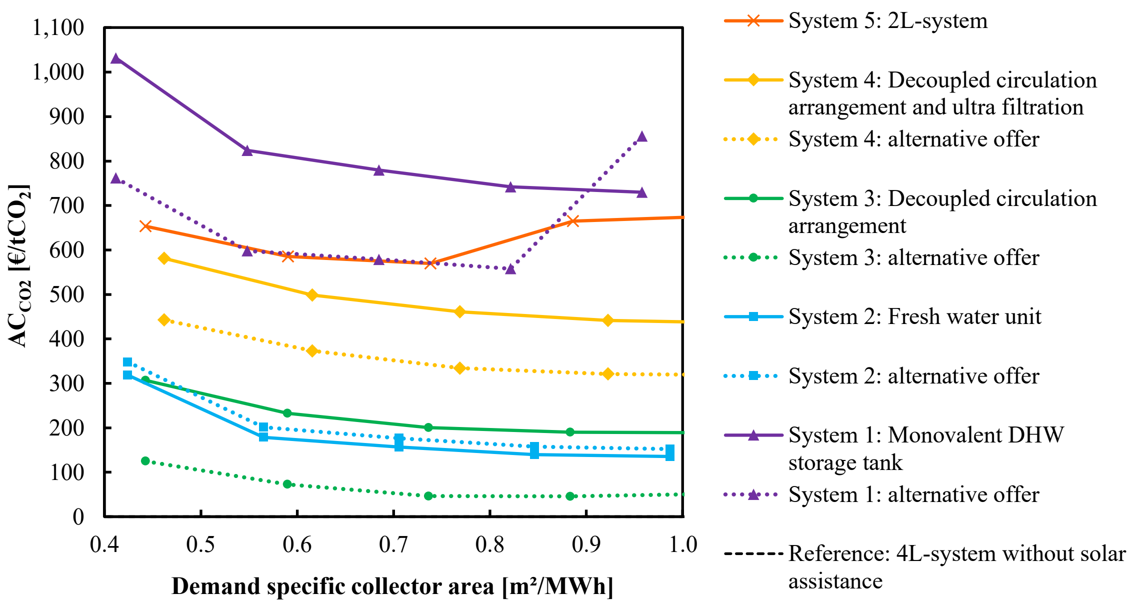

Fig. 7: Carbon abatement cost over the demand specific collector area for the investigated systems and alternative offers with similar hydraulic specifications

4. Conclusion

The overall assessment of solar-assisted heat supply concepts requires not only single component tests, but also tests of the entire system. The investigation shows that a significant increase in efficiency and utilization of the available solar heat can be achieved through compact installation (small number of components or short piping between components), the maintenance of the temperature layering in the heat storage tanks (e.g. stratified charging devices or circulation decoupling) and reduction heat distribution losses (e.g. 2-pipe heat distribution network or ultrafiltration module). The latter is not just reducing distribution heat losses within the building but also conversion losses within the central heating facility. Accordingly, systems that aim for reduced system temperatures show also a higher efficiency in the CPF and not just in the CPF_{plus}, which is explicitly considering distribution heat losses due to the chosen evaluation boundaries. In contrast to the CPF_{plus} the CPF can be easily determined in almost every building, since the input variables end energy and central heat demand of the building can be recorded without much effort with standard measuring technology.

The economic efficiency analysis shows that solar-assisted heat supply systems under investigation have higher levelized cost of heat than the reference system without solar support. A clear economic assessment of the systems is only possible to a limited extent, since the differences in the levelized cost of heat between the systems are roughly the same as the differences between the manufacturers. However, the increase in the number of components and therefore the complexity of the system also means that the levelized cost of heat are increasing.

The carbon abatement cost allows a combined energetic and economic evaluation of the systems and should therefore be the parameter used for the overall assessment of solar-assisted heat supply concepts. Moreover the carbon abatement cost offer the possibility to compare solar-assisted heat supply concepts with other activities where CO_2 emissions are avoided, like electricity production from photovoltaics or wind. The investigation presented in this paper disclosed large differences between the carbon abatement costs of the different solar-assisted heat supply concepts in multi-family houses. The carbon abatement cost moved in a span between 46 and over 1000 €/tCO_2. The most efficient systems in the meaning of a combined energetic and economic efficiency showed to be the systems 2 and 3 where the carbon abatement cost varied between 46 and 300 €/tCO_2 depending on the manufacturer and the demand specific collector area.

5. Acknowledgement

The project SUW-MFH presented in this paper is funded by the German Federal Ministry for Economic Affairs and Energy based on a decision of the German Federal Parliament (reference number: 03ET1212B). The project is carried out in cooperation with the University of Applied Sciences Düsseldorf. The authors are grateful for the financial support and responsible for the content.

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7. Appendix

Nomenclature		
A_{col}	collector area	[m²]
AC_{CO2}	carbon abatement cost	[€/tCO$_2$]
a	annuity factor	[a^{-1}]
a_{dsc}	demand-specific collector area	[m²/MWh]
CIPK	carbon intensity per kilowatt-hour	[gCO$_2$/kWh]
CPF	central performance factor of the heating facility	[-]
CPF_{plus}	central performance factor of the heat supply chain	[-]
EAC	equivalent annual cost	[€/a]
E_{final}	final energy demand	[kWh]
E_{prim}	primary energy demand	[kWh]
e_P	plant effort	[-]
i	annual interest rate	[%]
LCOH	levelized cost of heat	[€/kWh]
NPV	net present value	[€]
$Q_{central}$	central heat demand of the building	[kWh]
Q_{use}	useful energy	[kWh]
R	net cash flow	[€]
T	observation period	[a]