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Performance Testing and Optimization of Solar Assisted Heating Systems for Multi-Family Houses

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Abstract

The variety of designs for solar assisted heating systems (also called solar combisystems) in multi-family houses is wide and has not been evaluated systematically. Functional insufficiencies, resulting from unfavorable device combinations as well as improper control design place significant market barriers for the application of this technology. Using hardware-in-the-loop tests, functional aspects of the most common system designs are investigated and evaluated. Further dynamic system simulations on an annual basis allow an energetic evaluation and later a comparison of the different design options. In this contribution we present the results for the first tested solar assisted heating system. Furthermore, the study suggests the introduction of a novel evaluation parameter referred to as the *performance factor of the central heating facility,* and a novel reference parameter referred to as the *demand-specific collector area*. A newly developed benchmark procedure is comparing the central heat demand of the building to the maximum solar thermal gain of the solar circuit in order to calculate the maximum performance factor possible for an idealized central heating facility. Using this benchmark procedure, optimization potentials are exemplarily disclosed for the tested solar combisystem. The results highlight a high optimization potential of the system control and the process layout of central heating facilities, achievable with low cost at the same time.

Keywords: *solar combisystem, hardware-in-the-loop, whole system testing, system simulation, benchmark*

1. Introduction

The high theoretical potential for the reduction of final energy demand through the use of solar assisted heating systems was pointed out in earlier studies (e.g. Papillon, 2010). But there is a difference between theoretical potential and real final energy savings. One reason for the divergence are significant insufficiencies of the yield and the efficiency of solar assisted heating systems as result of inadequate hydraulic installation (Letz et al., 2010). Moreover, there is a wide and largely un-evaluated variety of available hydraulic designs for solar combisystems, especially for multi-family houses (MFH). Such systems combine the components solar thermal collectors, thermal storage tank(s), heat source(s) and distribution circuits. The research project "solar assisted heating systems for multi-family houses" (SUW-MFH) intends to identify the most efficient system design based on a functional, energetic and economic evaluation of these systems.

Selected common designs of large central solar combisystems are tested as integrated systems by hardware-in-the-loop (HIL) measurements to identify insufficient controller, valves, hydraulic connections and interaction between components. Besides functional evaluation of the investigated systems, the results of HIL measurements serve as data base for the validation of dynamic simulation models. Based on simulation results an energetic evaluation is performed by comparing the results to a newly developed benchmark procedure. An economic evaluation and comparison of the diverse system designs will be performed at a later stage of the project and respective results will be reported in future communications.

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Nomenclature		
A_{col}	collector area	[m²]
a_{dsc}	demand-specific collector area	[m²/MWh]
CPF	performance factor of the central heating facility	[-]
E_{final}	final energy demand	[kWh]
n_{HS}	number of heat sinks	[-]
$Q_{central}$	central heat demand of the building	[kWh]
Q_{circ}	heat losses due to domestic hot water circulation	[kWh]
Q_{DHW}	heat demand for domestic hot water draw	[kWh]
Q_{dist}	heat losses due to distribution of heat within the building	[kWh]
Q_{SH}	heat demand for space heating	[kWh]
$Q_{sol,eff}$	effective solar thermal gain	[kWh]
$Q_{sol,max}$	maximum solar thermal gain	[kWh]
$Q_{sol,pot}$	potential solar thermal gain	[kWh]
T_m	mean temperature	[°C]

2. Methodology of performance testing and evaluation

2.1. Hardware-in-the-loop measurements and dynamic system simulation

In order to standardize boundary conditions for performance tests of solar combisystems, only the central components of these systems (in the following referred to as *central heating facility*) are integrated into HIL tests. These central components may be thermal storage tank(s), a solar heat transfer station, an auxiliary heater, central fresh water station(s) and respective hydraulic connections. The components are implemented factory-set and connected to several emulators which serve as solar heat source and building heat sink (space heating, domestic hot water draw and circulation). The behavior of the emulators and their interaction with the central heating facility is calculated by real-time simulations in TRNSYS. Employing a time discretization of one minute, measured data of the HIL test is given as an input to the simulation environment which then adjusts the present set-values of the emulators. Therefore, the emulators are allowed to react to the instant behavior of the central heating facility rather than just follow a predetermined load profile. Weather conditions and solar thermal collectors as well as the building are part of the dynamic simulation model to ensure equal conditions for all solar combisystems under consideration in this work (see Table 1).

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

	Description	**Values**
weather data	Meteonorm, location: Zurich, Switzerland	• days for HIL measurements: 38, 71, 99, 112, 175, 230, 250, 356
solar thermal circuit	solar thermal collectors as well as pipes between roof and central heating facility	• collector area: variable between 0 m² and 32 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 flats: 8 or 16 (depends on the size of the tested system) • detailed distribution network with more than 100 pipe sections (for a house with 8 flats) • size of a flat: 65 m² • heating system: radiators
domestic hot water draw	draw profile generated with DHWcalc (Jordan, Vajen, 2014)	• 55 litre per flat and day (assumption of 1.8 inhabitants per flat)
domestic hot water circulation	constant circulation 24 hours a day	• 19 litre per hour and flat (according to a maximum temperature difference in the flow line of 5 K)

HIL measurements are performed for eight individual days capable of representing typical meteorological patterns during the course of a year. The days are selected in order to cover all possible load situations of the systems which can occur over a year. Related approaches exist on the literature, e.g. a good prediction of the annual thermal performance (Haller et al., 2013), but have turned out to be inadequate for the HIL method employed in this work. The chosen day sequences include sunny and cloudy days in all seasons as well as extreme climate settings for winter and summer. The respective HIL tests are measured separately, always regarding both pre- and post-conditioning of the system and the related simulation model to ensure defined start conditions for devices and model and to allow the calculation of thermal capacity changes.

A new HIL test facility has been developed and implemented at the ISFH, capable of emulating up to 20 flats in a MFH. Figure 1 provides an overview of this test facility. It shows the first tested solar combisystem during operation.

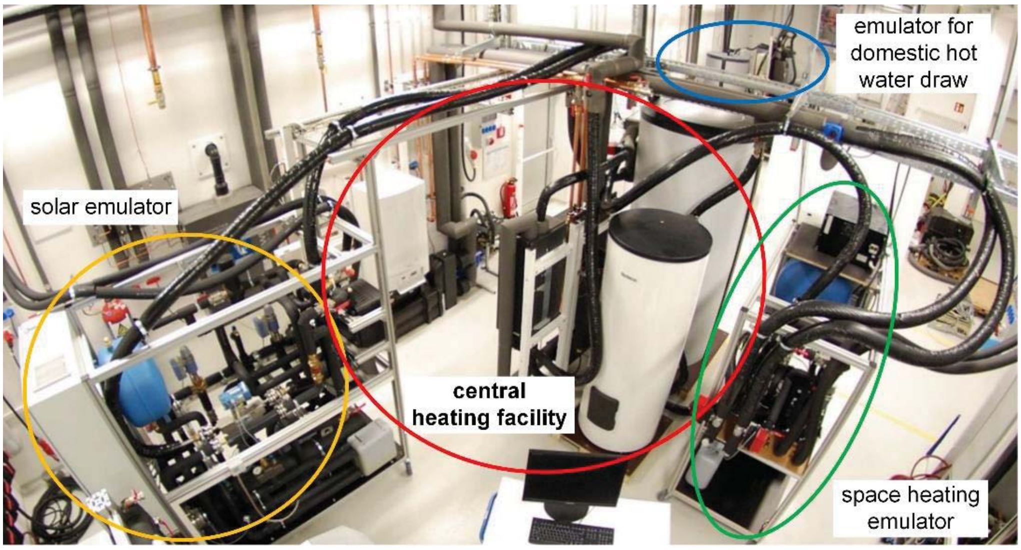

Fig. 1: Hardware-in-the-loop test facility developed for the emulation of up to 20 flats in a MFH and 60 kW solar thermal collector power, equipped with a central heating facility (red encircled), space heating emulator (green), solar emulator (yellow) and emulator for domestic hot water draw (blue)

For simulations of the complete solar assisted heating systems, the dynamic simulation model is extended by the components of the central heating facility. The added components of the model are parametrized and validated by using datasets from the HIL tests. Firstly, by qualitative comparison of measured and simulated temperature and mass flow curves, respectively, to ensure adequate implementation of control strategies and control hysteresis. Secondly, by quantitative comparisons of the energy balances of both individual components and the overall system, to guarantee the eligibility of the simulation model for further energetic evaluations of the solar assisted heating system. Therefore, the validation procedure can ensure high quality of simulated values on the one hand while allowing fast variations and optimizations of the control system, hydraulic connections or components on the other hand. The performed system simulations are covering a complete annual period, discretized by minutes, thus allowing to assess the specific system dynamics.

2.2. Energetic evaluation of solar assisted heating systems

Figure 2 shows the system boundaries employed for balancing a solar assisted heat supply for MFH. Of particular interest are the boundaries of the central heating facility comprising the solar thermal and final energy inputs and the heat loss and central heat demand as output. The final energy input covers fossil fuel and electricity whereas the central heat demand of the building ($Q_{central}$, see Equation 1) considers the heat demand for space heating (Q_{SH}) and distribution heat losses (Q_{dist}) as well as the heat demand for domestic hot water draw (Q_{DHW}) and circulation (Q_{circ}). Distribution heat losses as well as heat losses caused by domestic hot water circulation address heat demands to the central heating facility such that, the central heat demand of the building must not be equalized with useful energy.

$$Q_{central} = Q_{SH} + Q_{DHW} + Q_{dist} + Q_{circ} \quad \text{(eq. 1)}$$

A part of distribution and circulation heat losses can be credited as heat gains if they are localized inside the boundary of useful energy in Figure 2. By occurring outside of the boundary of a central heating facility it is not of further interest for an energetic evaluation of a central heating facility. For an overall evaluation of the heat supply of a MFH, which is not part of this paper, heat gains have to be taken into account.

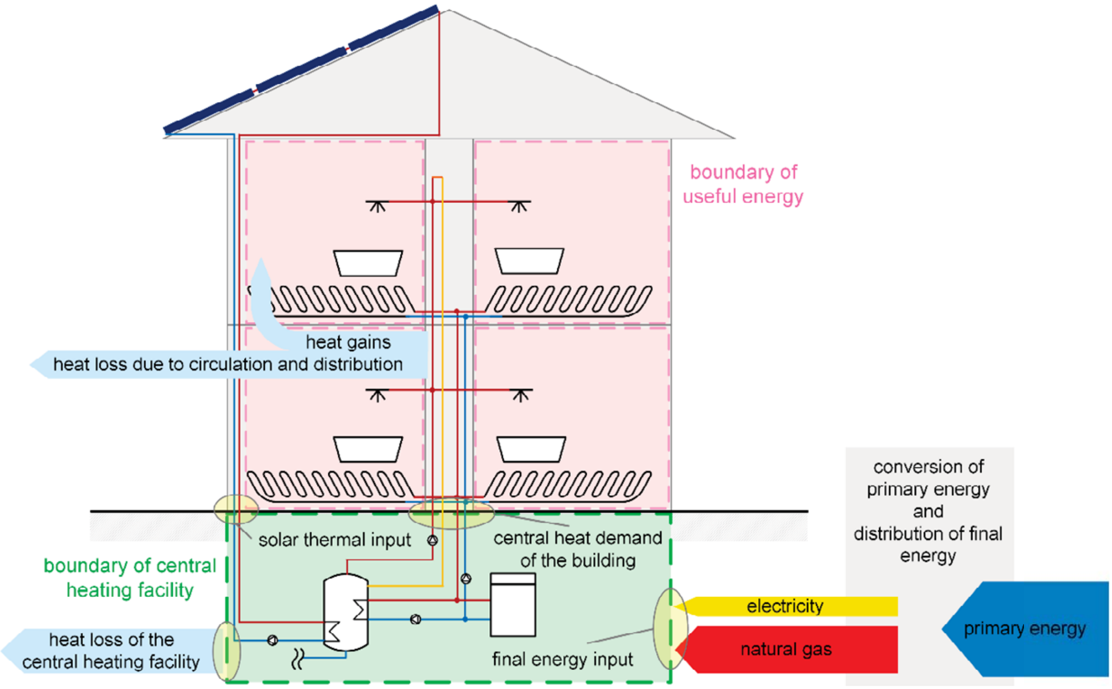

Fig. 2: Definition of system boundaries for the energetic evaluation of central heating facilities as part of solar combisystems in multi-family houses

To evaluate and compare different designs of solar assisted heating systems a novel evaluation parameter is introduced, referred to as the *performance factor of the central heating facility* (CPF, see equation 2). It is defined by the ratio between the central heat demand of the building as energetic benefit and the final energy input (E_{final}) as energetic effort.

$$CPF = \frac{Q_{central}}{E_{final}} \quad \text{(eq. 2)}$$

The interpretation of the CPF is comparable to the seasonal performance factor (SPF) of solar heat pump systems as of IEA SHC TASK 44 (Malenković et al., 2013). In extension to this, the CPF is applicable to all central heating facilities of solar assisted heating systems owing to proper definition of system boundaries. Note that in the specific case of a solar combisystem without a central heating facility, or 100 % solar fraction, it is not advisable to use the CPF as evaluation parameter.

The CPF if highly dependent on the defined boundary conditions of performance testing (solar thermal circuit, weather and building properties). In consideration of this, and to ensure a wide comparability of systems, we also suggest a novel reference parameter, referred to as *demand-specific collector area* (a_{dsc}). It is defined as the ratio between collector area and central heat demand of the building:

$$a_{dsc} = \frac{A_{col}}{Q_{central}} \quad \text{(eq. 3)}$$

2.3 Benchmark procedure

A benchmark procedure has been developed to estimate the effective solar thermal gain ($Q_{sol,eff}$) which can be utilized by an idealized central heating facility. The procedure extends an approach by Steinweg et al. (Steinweg et al., 2016) and employs the calculation of a maximum possible CPF. The method is comparable to the FSC procedure of IEA SHC TASK 26 (Letz, 2002). In contrast to the FSC method the benchmark procedure used here matches the central heat demand of the building with the maximum solar thermal gain of the solar circuit ($Q_{sol,max}$) rather than the solar thermal potential. Both approaches rely on monthly energy data. However, it turned out that taking into account the efficiency of the solar thermal collectors and heat losses between collectors and central heating facility yields to a more realistic estimation of the CPF. Central assumptions and boundary conditions of the benchmark procedure are:

- monthly correlation of maximum solar thermal gain and central heat demand of the building (idealized thermal storage tank)
- no heat losses and no parasitic energy (electricity) consumption of the central heating facility
- conversion of final energy without losses
- characteristics of solar thermal collector, weather conditions and central heat demand of the building are boundary conditions

Main part of the benchmark calculation is the determination of the effective solar thermal gain which represents the solar thermal input to the central heating facility. Basis of this is on the one hand the calculation of the maximum solar thermal gain for different mean temperatures (T_m) of the collector fluid with the chosen collector specification (see Figure 3). On the other hand the central heat demand of the building needs to be separated into different heat sinks with their mean temperatures (see Figure 4).

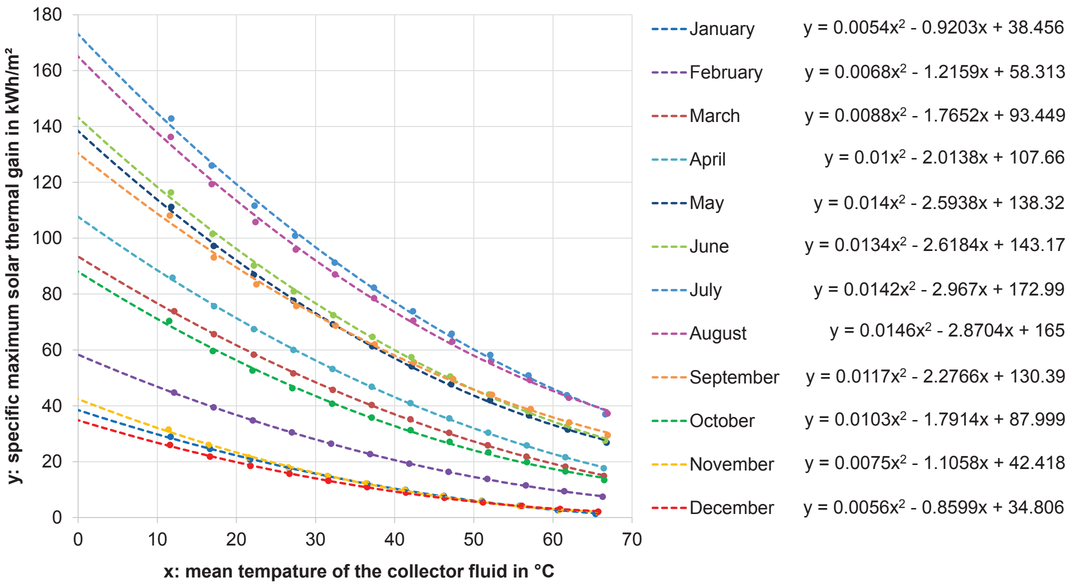

Fig. 3: Specific maximum thermal gain of the solar circuit over the mean temperature of the collector fluid on a monthly base accompanied by formulas of the trend lines (weather: Zurich)

Figure 3 shows the area specific maximum gain of the solar thermal circuit as function of the mean temperature of the collector fluid. The functions are correlated for every month in the year based on dynamic system simulations performed with TRNSYS, regarding an area specific mass flow rate of 50 kg/(h·m²) and Meteonorm climate data for the city of Zurich. The correlated functions (second degree polynomial) are provided in the figure. The functions allow the direct calculation of the maximum solar thermal gain for each month, once the collector area and the mean temperature of the individual heat sinks are set.

Figure 4 exemplifies for a selected month (March), how the central heat demand of the building may be split up into different heat sinks. The same procedure is used for the other months of a year. The figure regards three heat sinks: space heating (SH: red), domestic hot water draw (DHW: green) and domestic hot water circulation (circ: blue). For these heat sinks the specific heat demand and the temperature interval at which the demand occurs are indicated. Inspection shows that the respective temperature intervals for space heating and DHW circulation are quite small (7 K and 4 K, respectively), but the one for DHW draw is much higher (56 K: from 10°C to 66°C), than a standard solar thermal collector could possibly provide. Standard solar devices are typically capable of temperature shifts of about 15 K (with some degree of type- and operation-strategyspecific variety). To adjust a system to this interval, heat sinks comprising larger temperature intervals may be subdivided accordingly. For example in Figure 4, the domestic hot water demand is subdivided into four separate heat sinks which sum up to the same total demand, while the temperature intervals of the individual sink is adjusted to a level of about 14 K, maintaining the following temperature level order:

- $T_{m,i} < T_{m,(i+1)}$: $T_{m,DHW,1} < T_{m,SH} < T_{m,DHW,2} < T_{m,DHW,3} < T_{m,DHW,4} < T_{m,circ}$

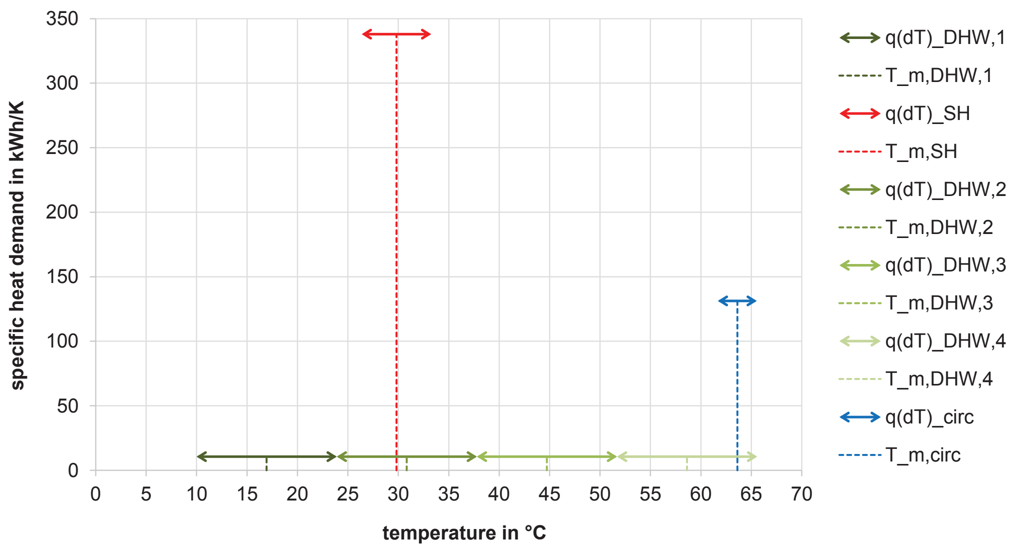

Fig. 4: Specific heat demand (q) over the corresponding temperature intervals (dT) and the resulting mean temperature (T_m), exemplified for the month March and for different heat sinks considered: hot water circulation (circ), space heating (SH) and domestic hot water draw (DHW,1-4: divided into four heat sinks)

The effective solar thermal gain is calculated on monthly basis ($Q_{sol,eff,k}$) by the following procedure: Firstly, the heat demand of the heat sink ($Q_{hs,i}$), which appears at the lowest temperature level is matched with the maximum solar thermal gain at this temperature ($Q_{sol,max}(T_{m,i})$). If the heat demand of the first heat sink is lower than the maximum solar thermal gain, the remaining solar gain is offered to the next heat sink in the temperature range. This procedure may be repeated until the maximum number of heat sinks (n_{hs}) is reached, or the maximum solar thermal gain is exploited. The potential solar thermal gain ($Q_{sol,pot}$) is an auxiliary quantity and not subject of further reflection:

$$Q_{sol,eff,k} = \sum_{i=1}^{n_{hs}} Q_{sol,eff,k,i} \qquad \text{(eq. 4)}$$

with: $\quad Q_{sol,eff,k,i} = min\left(Q_{sol,pot,k,i}, Q_{hs,k,i}\right)$

$i = 1$: $\quad Q_{sol,pot,k,i} = Q_{sol,max,k}\left(T_{m,i}\right)$

$i > 1$: $\quad Q_{sol,pot,k,i} = Q_{sol,max,k}\left(T_{m,i}\right) \cdot \left(1 - \frac{Q_{sol,eff,k,(i-1)}}{Q_{sol,pot,k(i-1)}}\right)$

month: $\quad 1 \leq k \leq 12$

heat sinks: $\quad 1 \leq i \leq n_{hs}$ with $\quad T_{m,i} < T_{m,(i+1)}$

The maximum possible CPF (benchmark) can be derived from the sums of the monthly central heat demand and effective solar thermal gain under consideration of the assumptions mentioned above:

$$CPF_{benchmark} = \frac{\sum_{k=1}^{12} Q_{central,k}}{\sum_{k=1}^{12}(Q_{central,k} - Q_{sol,eff,k})} \qquad \text{(eq. 5)}$$

3. Evaluation and optimization potential of the first tested solar assisted heating system

3.1. Description of the system and validation of the simulation model

The tested solar combisystem represents a conventional central heating facility upgraded by a solar thermal unit. A simplified hydraulic layout is sketched in Figure 5. Solar complemented parts (besides the solar thermal circuit) are a solar thermal storage tank, a solar station and a fresh water economizer. Solar thermal heat is fed into the system only through the solar thermal storage tank, from where the heat is distributed for preheating of cold freshwater and for shifting the temperature of the return flow to the boiler. The boiler is providing heat either for space heating or for the domestic hot water tank with priority for the latter. Both thermal storage tanks are equipped with internal heat exchangers without stratified charging devices. The emulated hydraulic circuits of the system are indicated by yellow background color in Figure 5. Beside the hydraulic circuits two temperature sensors are emulated by electrical resistor cascades. These are the ambient temperature sensor, used by the boiler for calculating the heating curve and the collector temperature sensor which is important for the operation of the solar station.

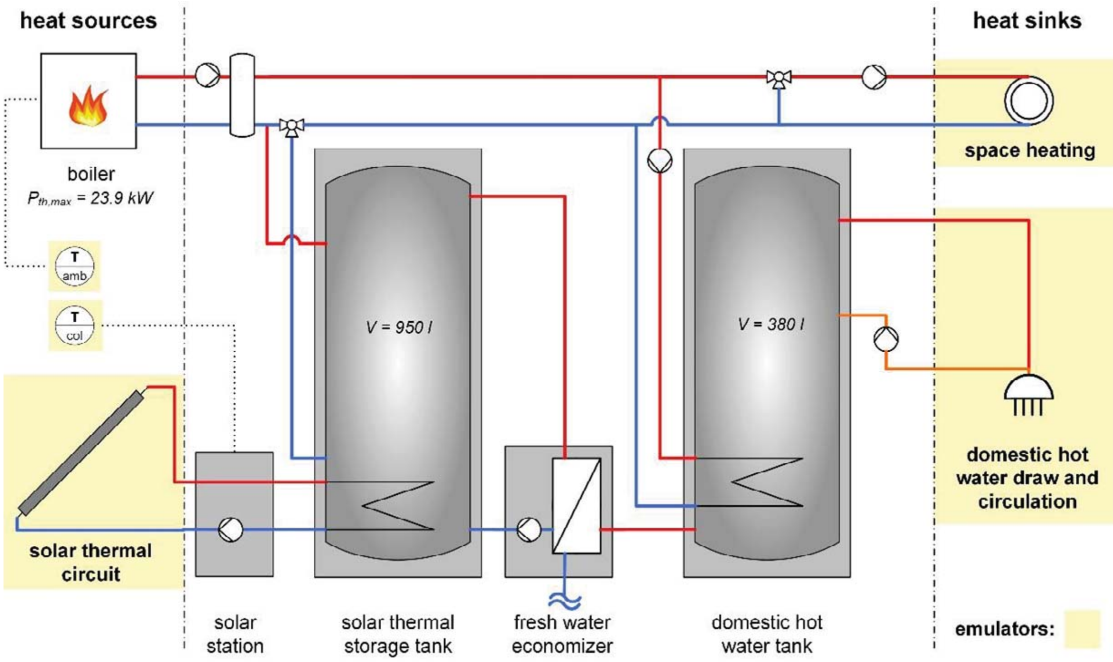

Fig. 5: Simplified hydraulic layout of the tested central heating facility with attached emulators (yellow)

The tested solar assisted heating system is dynamically simulated in TRNSYS. The validation of the model shows good results in the qualitative as well as in the quantitative comparison, see Table 2. These results have been calculated using the system boundary of the central heating facility indicated in Figure 2. The calculation considers the sequence of eight representative days during the course of the year, as explained earlier. As it turned out, for the day which represents an extreme, hot summer day, the allowed operation temperature of the solar thermal emulator was exceeded and therefore, this specific day had to be excluded from the results. Electricity as parasitic energy for the operation of electric devices like pumps and system control has not been measured and is therefore not part of the comparison in Table 2. But being a simulation result, the electricity consumption will be considered for the energetic evaluation based on the annual simulation results.

Tab. 2: Comparison of energy balances between HIL measurement and simulation of the first tested central heating facility as cumulated values of seven analyzed days (without extreme summer day)

			HIL measurement [kWh]	**simulation** [kWh]	**difference** [%]
input	final energy input	natural gas	2893	2894	0
	solar thermal input		173	169	-3
output	central heat demand of the building	SH + dist	-2408	-2428	1
		DHW	-95	-97	2
		circ	-113	-115	1
	heat losses		-65	-45	-30

The differences between simulated and measured cumulated energy amounts are lower than 4 % (relative value). There is one exception of this: the heat losses of the central heating facility exhibit a deviation of -30 %, which, however, results from the heat loss measurement and not from the simulation. The heat losses represent not a directly measured quantity but is calculated from the energy balance of the individual components of the central heating facility. In this situation, related measurement errors are superimposed as heat loss which leads to overestimation of the true value. Despite of this, the absolute divergence between simulated and measured heat losses amounts to 20 kWh. Compared to the total central heat demand of the building of 2617 kWh (measured), the heat loss deviation between HIL measurement and simulation can be tolerated.

3.2. Functional analysis

HIL measurements of the tested solar assisted heating system disclose two functional insufficiencies of the control system:

- The boiler controller is not working properly.
- A restricted interaction between the boiler controller and the controller of the solar thermal storage tank leads to a limited usage of solar thermal heat.

The boiler comprises a modulating burner with a nominal heat output between 4.8 kW and 23.9 kW (in condensing mode). As long as heat is solely produced for space heating, the burner is modulating perfectly within this power range. However, when supplying heat for the domestic hot water tank, the boiler is operating like having a single stage burner at maximum heat output. Due to a limited heat transfer capacity of the internal heat exchanger in the domestic hot water tank, the burner displays a high number of start-stop-cycles. Although this behavior does not entail efficiency loss, reduced durability of the burner device must be expected.

Another insufficiency of the tested system is the limited usage of solar thermal energy. As it is shown in Figure 5, there is a hydraulic connection (via the hydraulic separator) for using solar heat from the solar thermal storage tank to heat up the domestic hot water tank (under consideration of temperature levels). But the control system is not allowing an exclusive usage of solar thermal energy for charging the domestic hot water tank. Instead, the boiler is running the whole year, providing heat which could also be taken partly from the solar thermal storage tank without using any fossil fuel.

3.3. Identification of optimization potential by means of the benchmark procedure

The energetic analysis is based on dynamic system simulations covering a complete annual period. Among other possible parameters the evaluation is focused on the performance factor of the central heating facility as a function of the demand-specific collector area (see Figure 6). Therefore, several simulations with a variable collector area (between 0 m² and 32 m²) and a constant central heat demand of the building were performed. A comparison between the tested system installed factory-set and the benchmark allows to assess the optimization potential. A detailed analysis with a simulative approach identifies thereby single limitation sources.

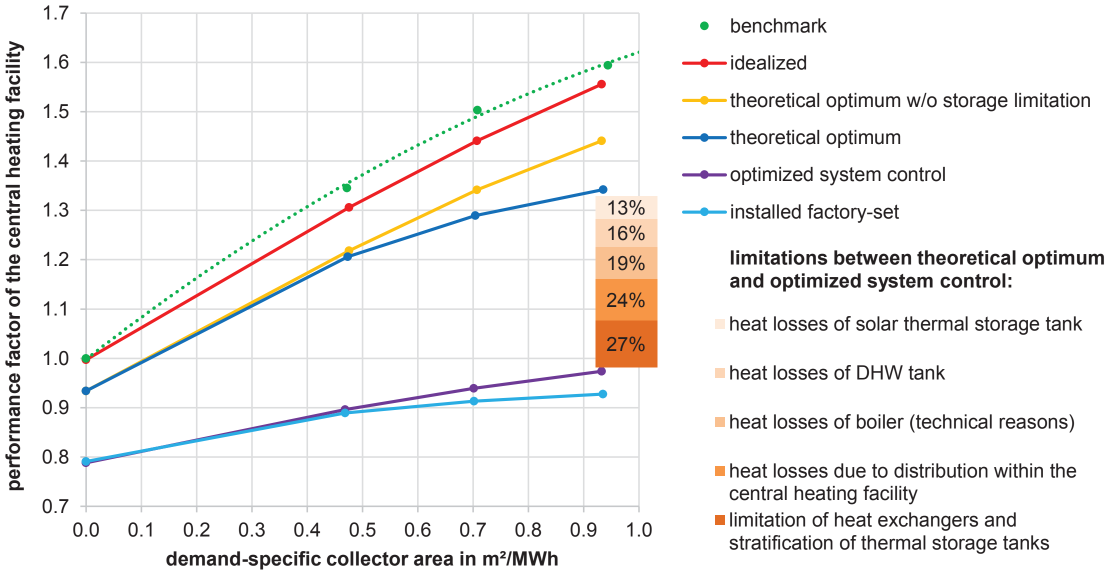

Fig. 6: Comparison between the benchmark and the CPF of the tested central heating facility (installed factory-set) by analyzing the different limitation sources

In the first place, the control system is optimized by eliminating the functional insufficiencies of the system which have been described earlier. This optimization can be done without any financial or material effort. The larger the demand specific area, the higher the optimization potential of the CPF by an improved usage of solar thermal energy. A second optimization series has been simulated, called "theoretical optimum". Therefore, different technical and chemical possible optimizations have been done, without changing any system components. The single limitation sources between "optimized system control" and "theoretical optimum" and their percentage influence for the improvement of the CPF are shown in Figure 6. The limitation of heat exchangers and a limited stratification of the thermal storage tanks have the largest influence on the CPF. Whereas the heat losses of the thermal storage tanks show the lowest limitation, the heat losses due to distribution within the central heating facility comes up to be the second highest deficit. Heat losses of the boiler only consider technical limitations caused by radiation losses and combustion inefficiency. Another limitation of the analyzed system, compared to the benchmark, is the limited storage capacity of the solar thermal storage tank. The impact of an increased solar thermal storage tank from ca. 1 m³ to 10 m³ is shown with the yellow curve. Thereby the improvement of the CPF is getting bigger, as the demand specific collector area increases. It has to be considered that all optimizations done before are maintained, like no heat losses of the storage tanks and an idealized stratification.

After optimizing the system it is idealized in a final step. For this purpose the parasitic energy demand of electric devices (e.g. pumps) is neglected and a complete utilization of the higher calorific value of fossil fuel is assumed. Both approaches are neither technical nor chemical possible. The simulation results of the idealized version of the tested solar heating system are almost approaching the benchmark. The remaining difference between these two curves can be explained with the fundamental limitation of the hydraulic connection of the analyzed system. Heat from the solar thermal circuit can only be fed into one heat sink: the solar thermal storage tank. In contrast, in the benchmark procedure the single heat sources are supplied with solar heat in sequence of their temperature level.

4. Conclusion and prospect

HIL measurements offer the possibility of functional evaluations of solar assisted central heating systems under standardized test conditions. The HIL results of the first tested central heating facility showed major insufficiencies concerning the control system causing a restricted usage of solar thermal energy. First results of the second evaluated system disclose also functional deficits in the control system. Managing the interaction of the different system components is one of the most important tasks and offers a lot of possibilities for the improvement of system performance with low financial or material effort. Functional evaluations of further systems will show, if this result can be confirmed and therefore be generalized.

The results of the HIL measurements provide also the basis for further investigations concerning the energetic efficiency of systems. With validated dynamic simulation models a high quality of simulation results can be assured. For the analysis of annual simulation results a new parameter - *performance factor of the central heating facility* - is introduced. The parameter is applicable to all central heating facilities due to the clear definition of system boundaries. Together with the new reference parameter - *demand specific collector area* - they allow an objective comparison of different analyzed solar combisystems, which will be done in the course of the project in order to identify the most efficient system design under consideration of functional, energetic and financial aspects.

A newly developed benchmark procedure is matching the central heat demand of the building with the maximum solar thermal gain of the solar circuit to determine the maximum performance factor possible of an idealized central heating facility. For a detailed analysis of the single systems a comparison to the benchmark and an itemization of single limitation sources showed to be a good procedure for the identification of optimization potential. This approach disclosed the limitation of heat exchanger and a limited stratification of thermal storage tanks to be the largest limitation factor besides the heat loss due to distribution within the central heating facility. Furthermore the restriction of efficiency due to insufficiencies in the control system is numbered and compared to the impact of the remaining limitation sources.

5. Acknowledgement

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