Towards Automated Continuous Performance Benchmarking of DHW and Combi Systems

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Abstract

Aiming at automated continuous performance benchmarking of domestic hot water (DHW) and combi systems, a performance control method based on FSC correlations is presented in this paper. The main influencing quantities on the scattering of the underlying FSC correlations are investigated, discussing the practicability of the method and evaluating possibilities to improve it.

Keywords: Solar heating, yield control, function control, monitoring

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1. Introduction

Solar thermal systems for single family houses are usually equipped with an auxiliary heating system which is able to cover the whole heat demand on its own. Hence, faulty design or operation of the solar part of the heating system often remains undetected by the end user, at least for a longer period. To avoid increased consumption of auxiliary heat and to enhance the trust of the users in solar thermal systems, an automated function and yield control is desirable. However, only measuring the solar yield is not sufficient, as design and operation faults outside the solar loop may affect the overall system performance. For example, a faulty installation or controller setting may lead to a situation where too much of the storage is heated by the auxiliary heater, significantly reducing the amount of energy the solar collector can contribute. Therefore, it makes sense to rate the overall system performance. But even if the actual heat demand is measured and the fractional auxiliary energy savings f_{save} are calculated (with an appropriate reference auxiliary heat), these values cannot be used directly to compare different systems with each other. Furthermore, one still misses the evaluation whether the yielded f_{save} values are in the expected range, since they also depend on the operating conditions like actual load and irradiance. Therefore, it is the goal to develop a performance benchmarking method, which can rate the system performance and allows the comparison between different systems.

2. Basic Method

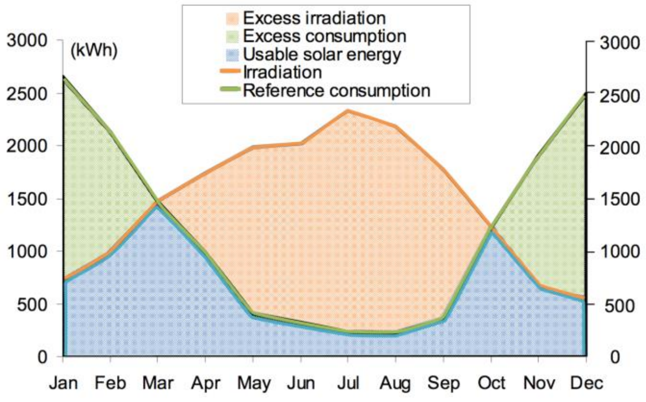

Fig. 1: Monthly energy consumption in contrast to usable and excess solar radiation for a specific building, dhw demand, collector area, slope and tilt (Letz, 2002)

Starting point for the performance benchmarking method is the Fractional Solar Consumption (FSC) method that was developed in IEA SHC task 26 to compare solar combi systems with different system designs and between different locations in Europe (Letz, 2002). Fig. 1 shows the underlying principle of the calculation. To define a usable solar energy ($E_{sol,use}$, blue area), the total irradiation on the collector area (orange area) is compared to the load (green area) on a monthly basis, hence taking into account that solar excess radiation in summer cannot be use.

FSC does not depend on any system design aspects except the collector area, but on the total irradiation on the collector area and the load. Therefore, it describes the energetic boundary conditions for the system. Effects of storage are not considered in FSC. For every system type, a correlation can be seen between f_{save} and FSC. This means that

doi:10.18086/eurosun2018.01.10 Available at http://proceedings.ises.org

the expected fractional energy savings $f_{save,expected}$ for a system can be derived in dependence of its actual irradiation (location) and actual load without an expensive individual simulation, allowing to compute a comparable performance indicator that relates the measured auxiliary energy savings to the expected values.

To calculate FSC, first the monthly energy sums are compared to each other, to determine the maximum usable solar energy:

$$E_{sol,use} = \sum_{i=1}^{12} \min\left[\left(A_{col} \cdot H_{t,i}\right), Q_{ref,i}\right] \qquad \text{(eq. 1)}$$

The heat demand $Q_{ref,i}$ is calculated as a fossil reference heating system considering domestic hot water demand (*dhw*), space heating (*sh*) and storage losses (*loss*) for each month (*i*):

$$Q_{ref} = \sum_{i=1}^{12} \frac{Q_{dhw,i}+Q_{sh,i}+Q_{loss,i}}{\eta_{boiler,ref}} \qquad \text{(eq. 2)}$$

Eventually, the Fractional Solar Consumption is calculated by dividing the useful solar energy by the reference energy demand:

$$FSC = \frac{Q_{sol,use}}{Q_{ref}} \qquad \text{(eq. 3)}$$

The FSC value therefore depends on collector area, location (e.g. solar radiation) and reference energy demand but is independent of system design, etc. It describes the energetic boundary conditions under which a system works.

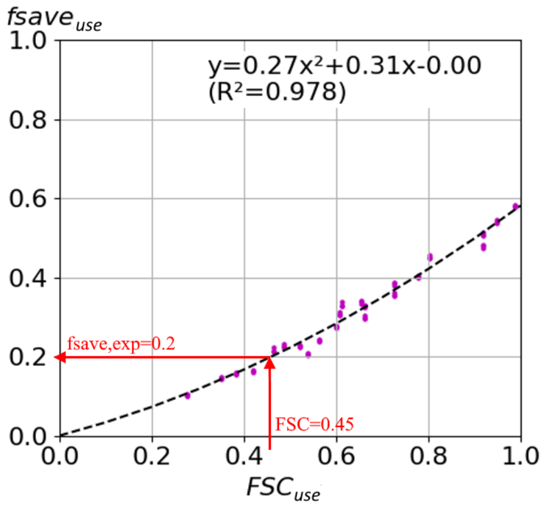

Fig. 2: FSC-fsave-correlation for a specific solar combi system (ext_{sol}+ext_{dhw}, see below), every dot represents an annual simulation with different boundary conditions

For every system type, a correlation is found between f_{save} and FSC. As fig. 2 shows, this relationship can be used to directly estimate the expected yearly f_{save} value for a given FSC value, without the need for dynamic system simulations.

To determine the FSC, the heat demand for space heating and domestic hot water and the solar radiation must be measured. Comparing the expected f_{save} to the measured one, the actual system performance can be benchmarked. By including the heat delivered by the (fossil) boiler and the heat demand into the calculations, the whole system is evaluated and not just the solar circuit.

It should be noted, that former publications concerning the FSC method always calculate their key figures using final energy, given as gas or oil consumption. The current approach for expanding the method for fault detection is based on usable energies, taking into consideration only the energies really delivered to or taken from the storage. In this way, no assumption concerning the boiler efficiency has to be made.

3. FSC correlations for solar combi systems

3.1 Modeling

Starting point for the simulation-based approach was the TRNSYS deck for solar combi systems developed in IEA task 32. This system, shown in fig. 3, was slightly adjusted and then used as starting point for every new hydraulic scheme, to ensure the comparability.

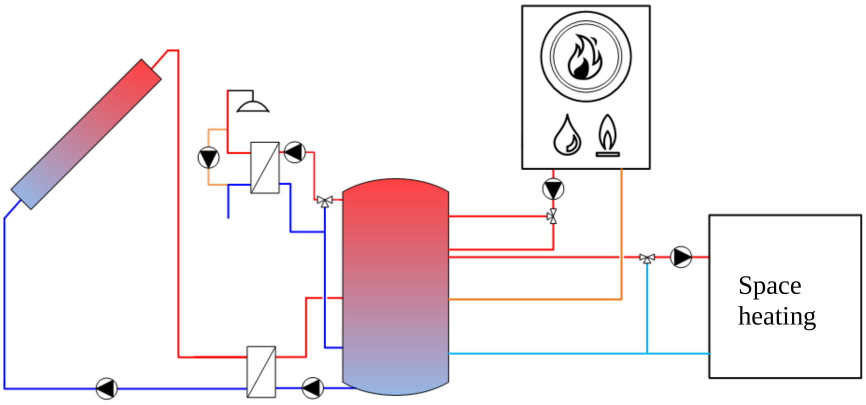

Fig. 3: Hydraulic scheme of system (ext$_{sol}$+ext$_{dhw}$)

System (ext$_{sol}$+ext$_{dhw}$) consists of a central buffer storage. The solar system provides energy via an external heat exchanger, while the boiler is directly connected to the storage. Domestic hot water preparation is implemented using a fresh water station, while the space heating loop is directly connected. More details especially concerning the control strategy for the different circuits can be found in (Heimrath & Haller, 2007).

The second standard combi system (ext$_{sol}$+ ext$_{dhw}$+RLA) uses the principle of return flow boosting. As shown in fig. 4, solar system and dhw preparation did not change, but the space heating circuit is not directly connected to the storage any more. If the space heating loop is in operation and the storage exceeds the return flow temperature (+hysteresis), the return flow is sent through the storage. Following, the auxiliary heater only needs to provide the additional heat demand to reach the desired flow temperature.

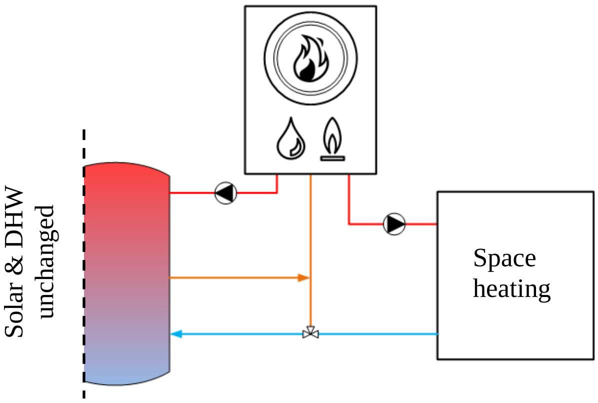

Fig. 4: Hydraulic scheme of system (ext$_{sol}$+ext$_{dhw}$+RLA)

The last standard combi system (int$_{sol}$+int$_{dhw}$) uses internal heat exchangers in the solar circuit and for domestic hot water preparation (fig. 5). The solar heat exchanger is located in the lower part of the storage while the dhw heat exchanger runs through the whole tank. In contrast to the other combi systems, system (int$_{sol}$+int$_{dhw}$) does not have a dhw circulation. This would cause a mixing of the thermal storage, reducing the solar gains (see below, application example).

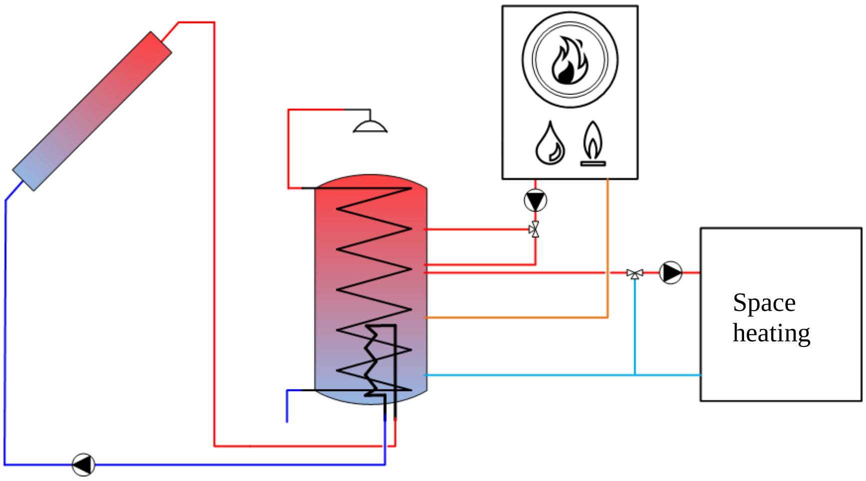

Fig. 5: Hydraulic scheme of system (int$_{sol}$+int$_{dhw}$)

3.2 Correlation and influencing factors (ext_{sol}+ext_{dhw})

On this basis, parametric studies were performed, varying important system and operation parameters like:

- Location: Stockholm (Sweden), Würzburg (Germany), Madrid (Spain)
- Space heating demand (building type): 30, 60, 100 kWh/(m²a) [calculated for Germany], special buildings for Spain
- Collector area: 5..50 m²
- Collector tilt: 30, 45, 70 °
- Specific mass flow rate in solar loop: 10..30 l/(m²hr)
- Boiler supply temperature: 63..75 °C
- Specific storage size: 40..100 l/m²$_{coll}$
- Domestic hot water profile and demand: 100..400 l/d
- Auxiliary heated storage volume: 50, 100, 150 l

This results in about 3.500 system simulations for each hydraulic scheme, producing > 10 k simulation outputs to be analyzed. This broad approach was chosen, to make sure, that the important and influential parameters are identified in the process.

Fig. 6 shows a selection of simulation results to illustrate the total scattering caused by the broad approach of the parametric study. As indicated by the dotted lines and the black arrows, a performance benchmarking is not reasonable on this basis. For a fixed FSC, there would be a bandwidth of expected energy savings of 18 to 30 %. Fortunately, many of the influencing parameters can be fixed. The boiler supply temperature can be easily measured while in operation and the dhw demand must be measured/calculated anyway. Moreover, the storage size should be one easy parameter to be known (e.g. given by the installer/plumber). If these parameters are fixed, the scattering decreases significantly, as shown in fig. 7. For the remaining points, correlation parameters for the quadratic regression can be found, that depict the relationship quite good.

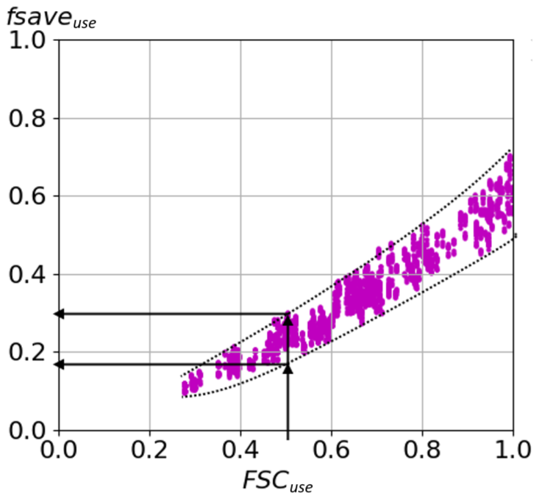

Fig. 6: FSC-fsave-correlations for system (ext_{sol}+ext_{dhw}), total scattering of parametric study

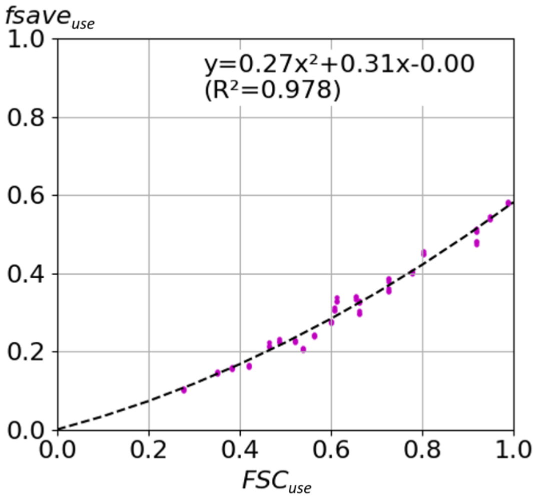

Fig. 7: FSC-fsave-correlations for system (ext_{sol}+ext_{dhw}), filtered by influencing factors

Unfortunately, it turned out, that the auxiliary heated storage volume and the storage heat loss rate also have a significant influence on the scattering, which are unlikely to be known. Other parameters, like location (weather), collector area, specific flowrate (solar), tilt and azimuth have proven to be unproblematic and only shift the points along the quadratic correlation curve.

3.3 Joint correlation for combi systems

Comparing the different combi systems to each other, the correlations turned out to be sensitive to the same parameters. If these influencing parameters remain fixed and key figures are calculated with the same reference heating system, the combi systems can be described by the same correlation as shown in fig. 8. The figure shows the expected f_{save} plotted against the FSC for each system simulation. It is to be mentioned, that the simulation results for system ($\text{int}_{sol}+\text{int}_{dhw}$) tend to be slightly higher. This is caused by the absence of dhw circulation. As the figure shows, there is only little scattering among the different combi system designs. In comparison to the scattering caused by variation of influencing parameters, e.g. the boiler supply temperature, the scattering caused by different system design is negligible.

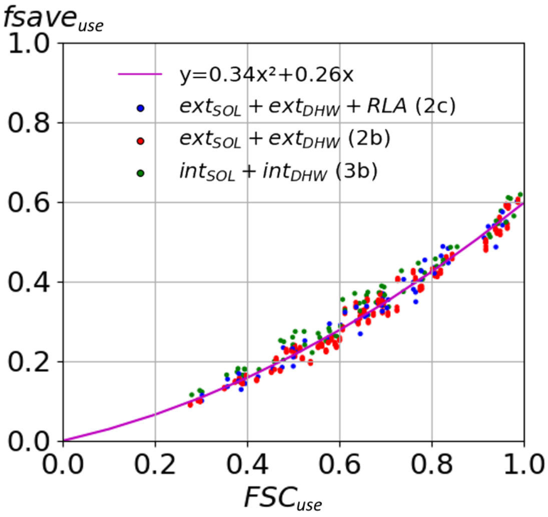

Fig. 8: Joint FSC-fsave-correlations for all investigated solar combi systems

4. Application for automated performance benchmarking

To illustrate the basic principle, fig. 9 shows the correlation for the combi system design ($\text{int}_{sol}+\text{int}_{dhw}$, see above): Solar heat is transferred to the heat storage by means of an internal heat exchanger, and domestic hot water (DHW) is also prepared via an internal heat exchanger that spreads over the whole storage height. Dots in fig. 9 show the system performance at different loads, collector areas and tilts and at different locations, where the storage size is adapted to the collector area. The blue dots represent normal operation and they are close to the expected performance described by a correlation curve (magenta line). The red triangles represent faulty systems with an installed domestic hot water circulation, so that the circulating hot water always heats the lower part of the storage, thereby decreasing the amount of energy the collectors can contribute. The red triangles lie well below the correlation curve and the FSC-based performance benchmarking method can identify these systems as faulty.

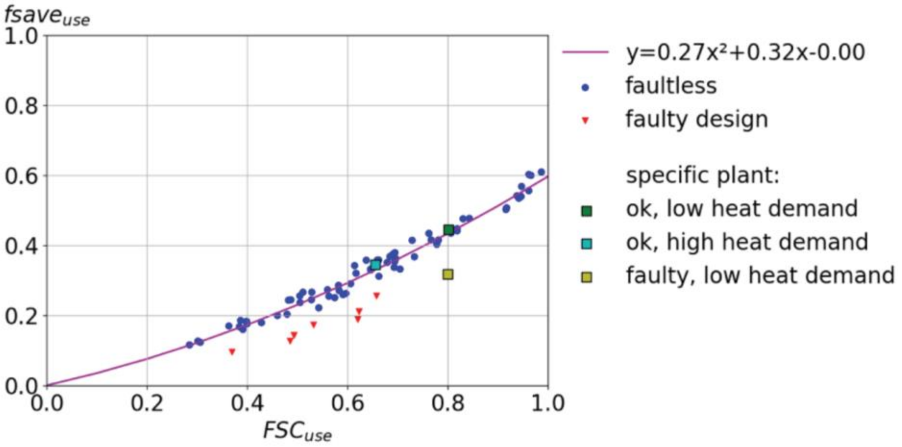

Fig. 9: Correlation for system with internal heat exchangers for solar input and DHW preparation (blue dots), and operating points for faulty designs that implement a DHW circulation that continuously heats the whole storage

To further illustrate the procedure, fig. 9 shows the performance of a certain combi system at three conditions. The green square represents a faultless combi system for a building with space heat demand of 30 kWh/m2. If the space heat demand is rather 60 kWh/m2, both fsave and FSC change, but the resulting point (cyan) still lies on the correlation. Otherwise, if the space heat demand actually is 30 kWh/m2, but a DHW circulation was installed (= overheated storage), a substantially lower fsave for the same FSC value is obtained (yellow square). The performance benchmarking method will recognize that there is no fault in the first case despite the reduced fsave and that there is a fault in the second case.

5. Applicability to solar system for dhw preparation (SDHW)

FSC was originally developed for solar combi systems. Looking at the market for solar thermal systems (in Germany), the majority of systems is installed in single family houses to support the dhw preparation and not for space heating. Thus, it had to be investigated whether the method is applicable for this SDHW systems as well.

Fig. 10 shows the standard SDHW system that was designed and modeled in TRNSYS. It consists of a small dhw storage with two internal heat exchangers for solar (bottom) and conventional boiler (top). The space heating loop is directly supplied by the boiler. Dhw preparation also includes a circulation pipe.

To ensure a common starting point for all systems this system was also developed using the modified task 32 deck.

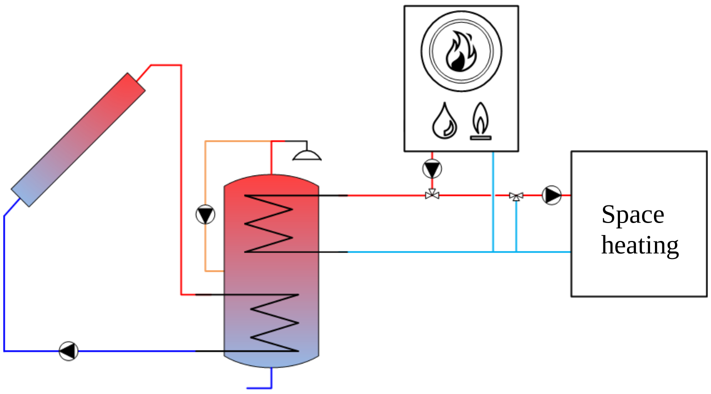

Fig. 10: Hydraulic scheme of SDHW system

To check applicability of the method and to identify influencing parameters, about 3.000 annual simulations were conducted in a first parametric study. Hereby the following parameters were varied:

- Location: Sweden, Germany, Spain
- Collector area: 2.8 m²
- Collector tilt: 30, 45, 60 °
- Boiler supply temperature: 55..75 °C
- Specific storage size: 35..60 l/m$^2_{coll}$
- Domestic hot water profile and demand: 100..400 l/d
- Auxiliary heated storage volume: 50, 100, 150 l

To illustrate the influences of the different parameters, the following four figures show the scattering of the annual simulations. For each figure, another influencing parameter is fixed to reduce the scattering.

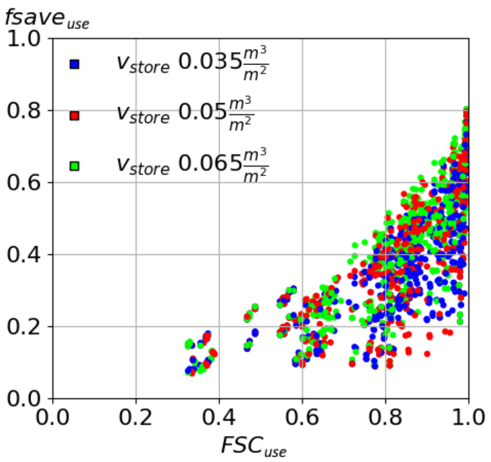

Fig. 11: FSC-fsave-correlations for SDHW system, total scattering of parametric study, UA$_{store}$ fixed

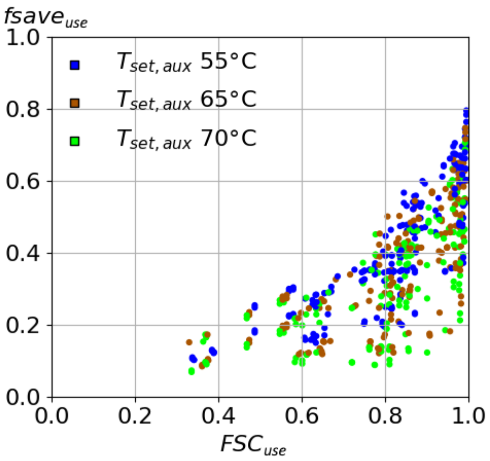

Fig. 12: FSC-fsave-correlations for SDHW system, fixed: UA$_{store}$, v$_{store}$=50 l/m$^2_{coll}$

Fig. 11 shows the initial bandwidth with all parameters varied. Directly compared to the total scattering for combi systems (fig. 6), the bandwidth here is much wider. This can be explained by the reduced total demand (only dhw instead of dhw and space heating). Even if the absolute effects of certain parameter changes are smaller compared to combi systems, the relative changes are significantly higher, causing a wider scattering. The storage size per m² collector area is marked with different colors to show the dependency. It can be seen that systems with higher storage capacities (50 and 65 l/m$^2_{coll}$) have a tendency towards higher energy savings. But still there are too many free parameters to build certain clusters. For fig. 12 the storage size was fixed to 50 l/m$^2_{coll}$ and the boiler supply temperature is marked in three different colors. As expected, systems with a higher boiler supply temperature show a lower fractional energy saving, at least for larger systems with FSC values > 0.5. For small systems this effect does not seem to be present, which could be explained with significantly undersized solar systems.

For fig. 13, the boiler supply temperature was fixed to 55 °C and with the daily dhw demand marked in different colors, there are three clusters to be seen. The highest dhw demand leads to higher energy savings and vice versa. The figure shows furthermore, that the scattering is greater if the demand is reduced. While the results for higher demand start at a FSC of about 0.3, the low heat demand only creates FSC of 0.7 and higher. This can be explained with the definition of FSC and the chosen collector areas (and storage sizes). For the systems with low dhw demand, the radiation on a collector plane of 2 m² already covers 70 % of the needed energy.

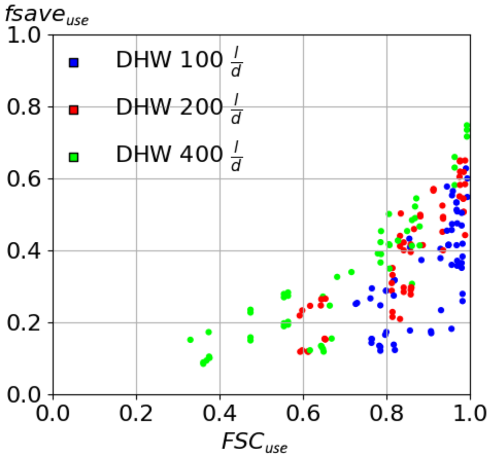

Fig. 13: FSC-fsave-correlations for SDHW system, fixed: UA_{store}, v_{store}=50 l/m$^2_{coll}$, $T_{set,aux}$=55 °C

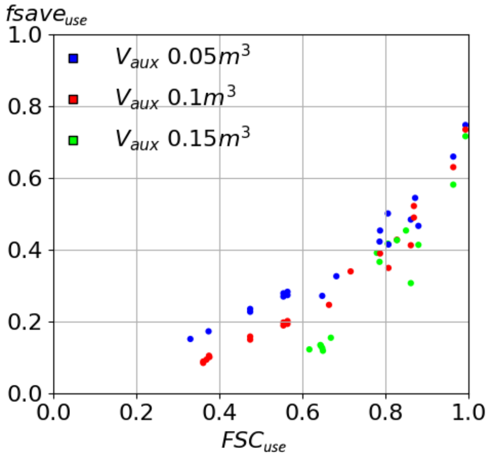

Fig. 14: FSC-fsave-correlations for SDHW system, fixed: UA_{store}, v_{store}=50 l/m$^2_{coll}$, $T_{set,aux}$=55 °C, dhw 400 l/d

Fig. 14 shows the remaining annual simulations if in the dhw demand is fixed to 400 l/d. The scattering has been reduced significantly, but still there are clusters visible for the different auxiliary heated storage volume. Smaller volumes lead to higher energy savings, because there is a larger part of the storage available for solar energy. In contrast to the tendency before, here the scattering seems to increase for lower FSC values, while the points to the upper right are close to each other. This can at least be partially caused by the overall storage volume. For the smaller systems to the left, the influence of the auxiliary heated volume is bigger, because it makes up a larger part of the storage itself. Towards higher FSC values the collector area and storage size increase and the proportion of auxiliary heated volume decreases, reducing the influence and therewith the scattering.

The overall tendency for SDHW systems, that a lower heat demand leads to more scattering, can be seen in fig. 15 as well. The figure shows a direct comparison of the simulated dhw demands, while the other influencing parameters are fixed.

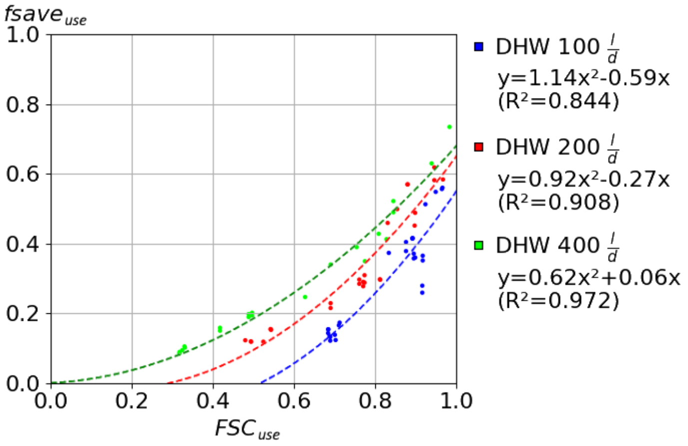

Fig. 15: Different FSC-fsave-correlations for SDHW system depending on the daily dhw demand, fixed: UA_{store}, v_{store}=50 l/m$^2_{coll}$, $T_{set,aux}$=55 °C, v_{aux}=0.1 m^3

6. Limitations and outlook

To benchmark a system performance using the describe method, measurement data of a whole year must be available. Since the FSC method compares energies monthly and the analyzed time period comprises 12 months, this is the starting point of every benchmarking. Subsequently the key figures can be calculated every month to detect decreasing performance, but still 12 months of data must be used. This means that even a total failure of a previously working solar loop has only slow effect on f_{save}, because over the whole evaluation period of a year, the fault-free operation times dominate initially. Since the idea of FSC is based on seasonal distribution of irradiation and heat demand, the evaluation period cannot be just shortened. Just choosing a shorter period of one month would for example lead to a constant FSC = 1 for the whole summer. Furthermore, the correlation with f_{save} was only shown for yearly evaluation periods. When aiming for shorter evaluation periods, it also has to be taken into account that the effects/state of the heat storage and also the amount of excess heat in summer become more important. To address this issue, new key figures have to be defined and tested.

Concerning the system correlations, it is planned to include the influencing parameters into the calculation via correction functions. Since the combi systems all react sensitive to the same parameters, it is reasonable to assume, that correction functions will affect their correlations in a similar way. If so, the combi systems can be described by just one correlation, which would simplify the necessary steps for performance benchmarking significantly and lead to an easily understandable, unified performance indicator.

For SDHW systems, while FSC correlations can be retrieved with some effort and the definitive need of correction functions, FSC might not be the best parameter to start with when estimating the expected f_{save}. The underlying reasons are that the proportions of the involved energy flows are quite different, and that the systems typically are not oversized with respect to the average summer demand. Therefore, methods to describe the performance in other parameter spaces are to be investigated.

7. Conclusion

The described approach for automated continuous performance benchmarking offers reasonable advantages over other state of the art methods. With the FSC-derived performance indicator a meaningful standalone key figure can be calculated. While other quantities like the saved kWh/a or f_{save} can only be interpreted by experts or with in depth knowledge of the according system, the performance indicator is self-explanatory. In contrary to the other key figures, it can be used to compare the performance of different systems to each other. Using the FSC-derived performance indicator, the (easy) question, whether a system works well or not can be answered with a simple yes or no. Thus, making the performance benchmarking more attractive to system operators. The FSC based approach offers the benefits of a dynamically calculated key figure, without the need for costly dynamic system simulations.

8. Acknowledgements

The research project “SolarCheck” (project number 0325870A) is funded by the Federal Ministry for Economic Affairs and Energy (BMWi). We want to thank the BMWi and the Project Management Jülich (PtJ) for their support. Also, we want to thank our project partners from industry and science: Bosch Solarthermie GmbH, Enertracting GmbH, SOLVIS GmbH, RESOL – Elektronische Regelungen GmbH, Vaillant GmbH, Viessmann Werke GmbH & Co. KG, WILO SE, Institute of Thermodynamics and Thermal Engineering (ITW) of the University of Stuttgart, INES (Institut National de l’Energie Solaire, France).

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