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On the use of the FSAV/FSC characterization to monitor and guarantee the solar results of combisystems

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Abstract

The FSC method enables to characterize combisystems performances thanks to a simple quadratic curve. This characteristic curve could be used to guarantee annual performances of a system and to control its proper functioning. This would raise interest and trust of users in such systems. This paper introduces how to use measured data with the FSC method in order to monitor the combisystem, estimate its annual performance during the system operation, compare the guaranteed and estimated annual performances and finally check the actual performance realized. The proposed algorithm is tested using many detailed yearly simulations of a combisystem.

Key-words: Solar Combisystems, Guarantee of Solar Results, Monitoring

1. Introduction

Solar combisystems (SCS) are complex systems which use solar heat with an auxiliary heating system to provide energy for Space Heating (SH) and Domestic Hot Water (DHW) needs. So far, there is no automatic simple method to let the user monitor the proper functioning of his installation and to guarantee a precise level of performance. However this kind of service could be very attractive and could increase users' confidence in such systems.

The FSC method (Letz, 2009) is a method dedicated to SCS characterization. It is based on the Fractional Solar Consumption (FSC), a dimensionless quantity which takes into account boundary conditions (solar resource, SH and DHW needs) and sizing aspects of a SCS (collector area, storage size). The FSC criterion is independent from the proper SCS operations and the author showed that fractional energy savings (FSAV) of each SCS can be expressed as a quadratic function of FSC. This resulting curve must be estimated and set beforehand by the manufacturer who wants to guarantee the performances of its systems.

On the other hand, (Letz, 2010) has also shown that actual monthly performances of SCS are bound to solar resources through a precise function.

Thus, the combination of both ways of characterizing SCS performances could be very helpful to monitor and guarantee solar results of combisystems.

2. Nomenclature

This paper uses the nomenclature described in Tab. 1 hereunder in its different equations.

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Tab. 1: Variables used for monitoring the SCS

Variable	Unit	Description
a_{GRS}	-	Coefficient for the characterization of the system annual performances (guaranteed performances)
b_{GRS}	-	Coefficient for the characterization of the system annual performances (guaranteed performances)
c_{GRS}	-	Coefficient for the characterization of the system annual performances (guaranteed annual performances)
a_{oper}	-	Coefficient for the characterization of the system monthly operation
b_{oper}	-	Coefficient for the characterization of the system monthly operation
c_{oper}	-	Coefficient for the characterization of the system monthly operation
a_{SH}	$kW.K^{-1}$	Coefficient for the characterization of the monthly space heating needs of the building
b_{SH}	kWh	Coefficient for the characterization of the monthly space heating needs of the building
$FSAV_{th}$	-	Fractional energy savings
$FSAV_{th,GRS}$	-	Fractional energy savings guaranteed from the FSC curve
FSC	-	Fractional Solar Consumption
X	-	Characteristic ratio for the operation curve
DH	K.h	Degree Hours
Q_{Aux}	kWh	Energy consumed by the auxiliary boiler
$Q_{DHW,nd}$	kWh	Energy for the Domestic Hot Water needs
$Q_{Loss,ref}$	kWh	Energy losses of the storage tank of the reference system
$Q_{SH,nd}$	kWh	Energy for the Space Heating needs
$Q_{Solar,Usable}$	kWh	Usable solar energy
$Q_{Ref,th}$	kWh	Energy consumed by the reference system
Q_{Sol}	$kWh.m^{-2}$	Solar irradiation on the collector plane
S_{Coll}	m^2	Collector area
$\eta_{Aux,ref}$	-	Annual efficiency of the boiler of the reference system

An additional subscript "month" is used to indicate that the monthly value of the variable is considered. The symbol ~above the variable means that the variable is estimated.

3. Metrology and measurements

The case study of this work is a solar combisystem with auxiliary gas boiler (Fig. 1).

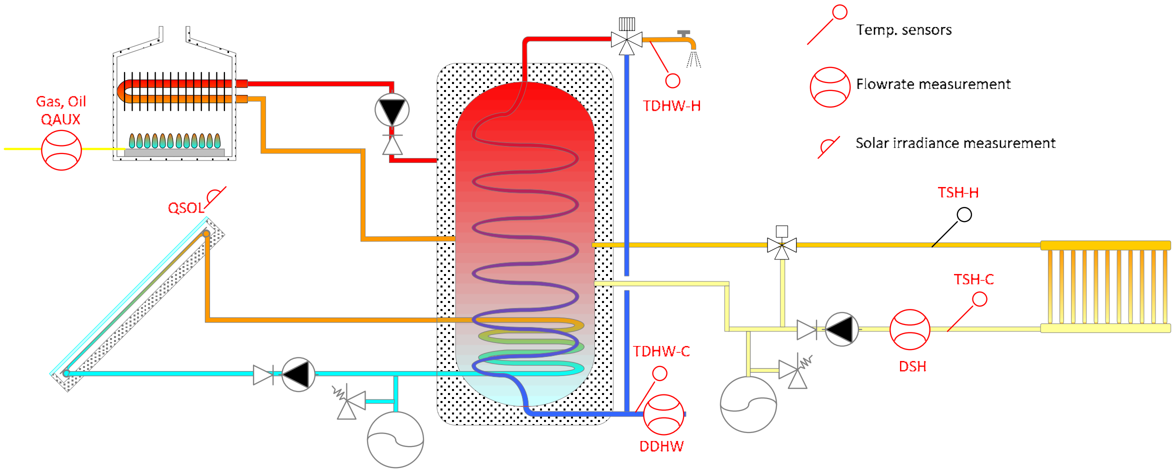

Fig. 1: Studied Solar Combisystem equipped with measuring instruments

The minimum metrology needed for monitoring such a system must enable the calculation of:

- Heat flows through fluid circulation at SH and DHW loops by means of temperature and flow rate measurements.
- The solar irradiation on the collector plane.
- The gas consumption.

The measuring instruments considered in this paper are described in Tab. 2.

Tab. 2: Variables used for monitoring the SCS

Variable	Unit	Description
DSH	$kg.h^{-1}$	Flowrate in the SH loop
DDHW	$kg.h^{-1}$	Flowrate in the DHW loop
TSH-H	°C	"Hot side" SH loop temperature
TSH-C	°C	"Cold side" SH loop temperature
TDHW-H	°C	"Hot side" DHW loop temperature
TDHW-C	°C	"Cold side" DHW loop temperature
QSOL	$kWh.m^{-2}$	Solar irradiation on the collector plane
QAUX	kWh	Auxiliary energy consumption
TROOM	°C	Room temperature
TAMB	°C	Ambient temperature

4. Estimation and guarantee of yearly performances

The yearly performance to be estimated and guaranteed with this methodology is the fractional energy savings $FSAV_{th}$ (eq. 1), which represent the auxiliary energy Q_{Aux} that is saved compared to a classical reference system (without solar loop) providing the same heat for DHW and SH needs ($Q_{DHW,nd}$ and $Q_{SH,nd}$ respectively). This reference energy $Q_{Ref,th}$ is calculated thanks to eq. 2, given a reference auxiliary efficiency $\eta_{Aux,ref}$ of 0.85 and reference storage losses $Q_{Loss,ref}$ of 644 kWh per year.

$$FSAV_{th} = 1 - \frac{Q_{Aux}}{Q_{Ref,th}} \qquad \text{(eq. 1)}$$

$$Q_{Ref,th} = \frac{Q_{SH,nd}+Q_{DHW,nd}+Q_{Loss,ref}}{\eta_{Aux,ref}} \qquad \text{(eq. 2)}$$

Letz (2009) has shown that fractional energy saving of a SCS can be represented as a simple curve according to the dimensionless quantity FSC (eq. 3), which is independent of the system and is proper to the working environment (climate, building, draw-offs). The annual performance of the SCS estimated this way is called $FSAV_{th,GRS}$ in this paper (eq. 5).

$$FSC = \frac{Q_{Solar,Usable}}{Q_{Ref,th}} \qquad \text{(eq. 3)}$$

$$Q_{Solar,Usable} = \sum_{i=1}^{12} min\left(S_{Coll}.\,Q_{Sol,month}(i);\; Q_{Ref,th,month}(i)\right) \qquad \text{(eq. 4)}$$

$$FSAV_{th,GRS} = a_{GRS} + b_{GRS}.FSC + c_{GRS}.FSC^2 \qquad \text{(eq. 5)}$$

The performance curve of the monitored SCS must be estimated before its installation. This could be done thanks to prior on site measurements campaign and/or several tests on semi-virtual test bench. Some tracks are currently being investigated in order to characterize SCS performances with short time tests (Leconte, 2012a, 2012b).The performance curve is then the guaranteed performance. The topic of this paper is not about how to get this performance curve but about how to use it for monitoring purpose. For this paper, it is assumed that the FSC curve of the studied system is already known. Its FSC curve is identified here by carrying out several TRNSYS annual simulations, with different building types, climates and collectors areas (Fig. 2). Building type SFH (Single Family House) refers to buildings defined in IEA SHC Task32 (Heimrath et Haller, 2007). The associated number represents the yearly SH needs in kWh.m^{-2} for the Zurich climate.

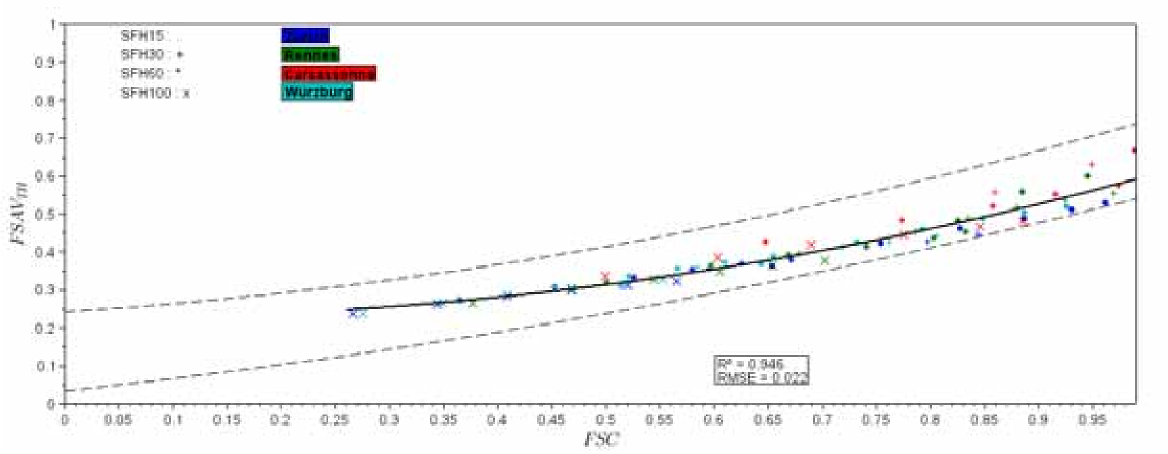

Fig. 2: FSAV-FSC curve of the studied SCS

Thus the yearly performance of any monitored SCS can be guaranteed. During the system operation, heat flows are calculated and integrated on a monthly basis. After one year of operation, those energies are used to calculate the FSC of the year and then the guaranteed solar result $FSAV_{th,GRS}$ from the performance curve. This guaranteed performance can then be compared to actual performance calculated thanks to the gas consumption measurements. This operation can only be done after a complete year of monitoring. Section 5 hereunder suggests another algorithm in order to be able to check the system performance from the first few months of monitoring.

5. Using the FSC procedure for monitoring and fault detection

Instead of waiting one year of SCS operation to check if the system will reach the expected performance, monitored data can be also smartly used to extrapolate the annual FSAV. The goal of the algorithm introduced below is to estimate each month the annual performance $\widetilde{FSAV}_{th}$ from actual system functioning and compare this estimation with the guaranteed performance based on the same hypothesis $\widetilde{FSAV}_{th,GRS}$ (thanks to the FSC curve). As expressed by equations 6 and 7, at the month m, the performance criterions are estimated by combining measured data of the former months (i from 1 to m) and energy estimations for the future next months (j from m+1 to 12).

$$\widetilde{FSAV}_{th}(m) = 1 - \frac{\sum_{i=1}^{m} Q_{Aux,month}(i) + \sum_{j=m+1}^{12} \tilde{Q}_{Aux,month}(j)}{\sum_{i=1}^{m} Q_{Ref,th,month}(i) + \sum_{j=m+1}^{12} \tilde{Q}_{Ref,th,month}(j)} \qquad \text{(eq. 6)}$$

$$\widetilde{FSAV}_{th,GRS}(m) = a_{GRS} + b_{GRS}.\widetilde{FSC}(m) + c_{GRS}.\widetilde{FSC}(m)^2 \qquad \text{(eq. 7)}$$

Thus, the algorithm steps are mainly dedicated to estimate the reference energy $\tilde{Q}_{Ref,th,month}$ and the auxiliary consumption $\tilde{Q}_{Aux,month}$ for the future months (m+1 to 12) from the available measures (1 to m).

The auxiliary consumption depends on the system functioning. It will be extrapolated thanks to an “operation curve” (eq. 7 and Fig. 4) that characterizes the on-going monthly performances of the system (Letz, 2010). Unlike the predetermined FSC curve that estimates theoretical guaranteed performances, this “operation curve” is identified on-line and represents the actual performances of the system.

The algorithm represented on Fig. 3 hereunder shows how to combine those two different characteristic curves.

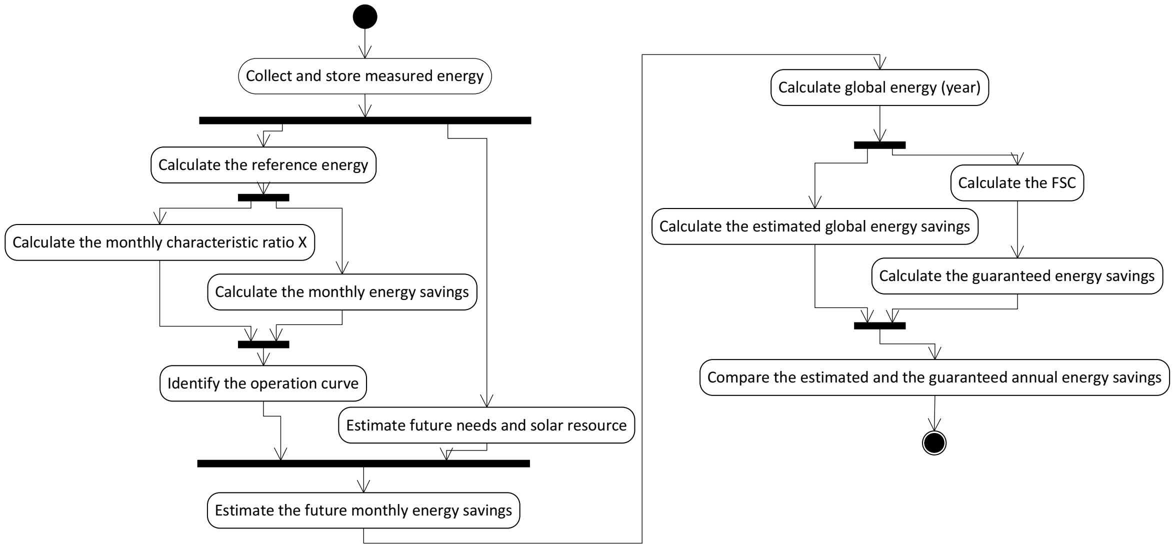

Fig. 3: Global diagram of the operations to be done monthly for the proposed monitoring procedure

Main steps are described below:

- Identification of the operation curve

Available monthly results of the on-going year are used to identify on-line the “operation curve”. The characteristic ratio X (eq. 8), based on measured solar irradiance and heating needs, is calculated for each month.

$$X_{month} = \frac{S_{Coll} \cdot Q_{Sol,month}}{Q_{Ref,th,month}} \quad \text{(eq. 8)}$$

The gas consumption measurements enable the calculation of the fractional energy savings on the same period ($FSAV_{th,month}$). Parameters a_{month}, b_{month} and c_{month} of the curve described by (eq. 9) are then identified in order to characterize the monthly performances of the system based on its actual operation (Fig. 4). The parameters are updated each month.

$$\widehat{FSAV}_{th,month}(X_{month}) = \frac{a_{month}(X_{month}-b_{month}) - [a_{month}(X_{month}-b_{month})]^{c_{month}}}{1-[a_{month}(X_{month}-b_{month})]^{c_{month}}} \quad \text{(eq. 9)}$$

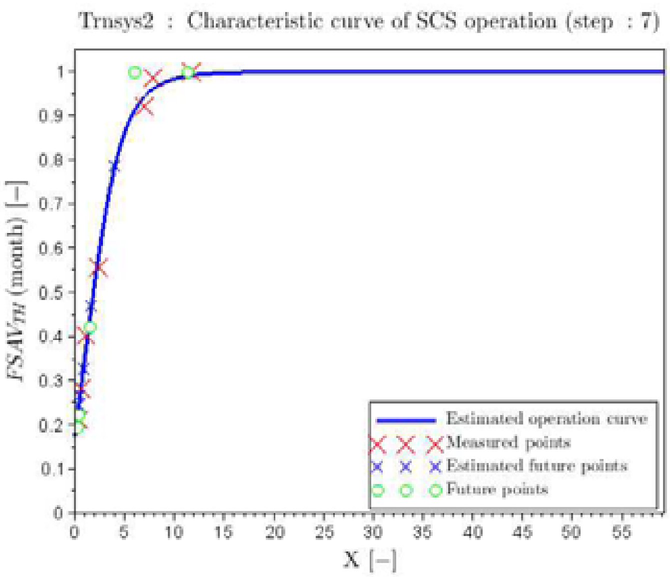

Fig. 4: Example of operation curve identification

- Estimation of future heating needs and solar resources

In order to estimate the annual performance of the system, the estimation of future energy savings for the next months $\widetilde{FSAV}_{th,month}$ is needed. To do so, future heating needs and solar resources must be roughly estimated beforehand and used to calculate future reference energy $\tilde{Q}_{Ref,th,month}$. Up to a certain limit, those estimations can be accurate; however there is no need for them to be precise as long as both methods are based on the same reference values.

The monthly solar irradiation is identified as a sinusoidal shape over the year using the already measured values (Fig. 5). Next months' values $\tilde{Q}_{Sol,month}(j)$ are then calculated according to this function.

For DHW needs, the mean monthly value is simply reproduced for the next months ($\tilde{Q}_{DHW,nd,month}(j)$).

For SH needs, the "energy signature" of the building is calculated thanks to a simple affine function as suggested by Fig. 5 and eq. 10 where a_{SH} and b_{SH} are the parameters to be identified with the already measured data. The heat needed for the next months $\tilde{Q}_{SH,nd,month}$ is evaluated using the "Degree-Hours" DH_{month} which in turn is extrapolated as a sinusoidal curve, in the same way as for solar irradiation.

$$\tilde{Q}_{SH,nd,month}(DH_{month}) = a_{SH}.DH_{month} + b_{SH} \qquad \text{(eq. 10)}$$

It is then possible to estimate the reference energy for the future months ($\tilde{Q}_{Ref,th,month}(j)$).

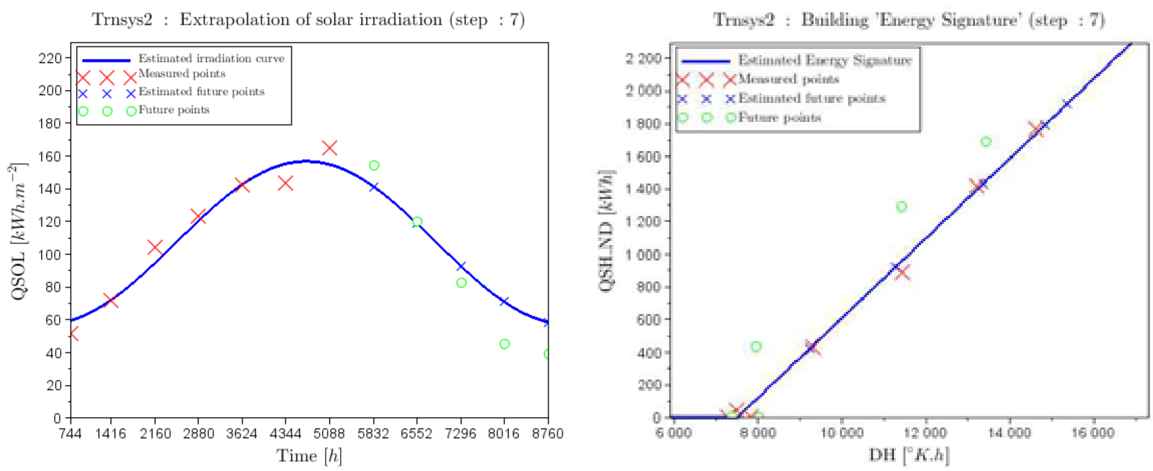

Fig. 5: Simple extrapolation of the solar resource and SH needs during the monitoring operation

- Estimation of the global energy savings

Estimations of the solar irradiance and the heating needs are used to calculate $\tilde{X}_{month}$ for the future months (with the same eq. 8 but with estimated values of $\tilde{Q}_{Sol,month}(j)$ and $\tilde{Q}_{Ref,th,month}(j)$). This estimated ratio is then used as input of the "operation curve" (eq. 9) to estimate the gas consumption over the future steps j of the algorithm (eq. 11).

$$\tilde{Q}_{Aux,month}(j) = \widehat{FSAV}_{th,month}\left(\tilde{X}_{month}(j)\right) \times \tilde{Q}_{Ref,th,month}(j) \qquad \text{(eq. 11)}$$

Then, a global expected annual $\widehat{FSAV}_{th}(m)$ is estimated as expressed by eq. 6.

- Calculation of the guaranteed energy savings

The same estimations of future heating needs and solar resources are also used to estimate the FSC of the complete year based on the same hypothesis (eq. 12).

$$\widetilde{FSC}(m) = \frac{\sum_{i=1}^{m} min(S_{Coll} \cdot Q_{Sol,month}(i); Q_{Ref,th,month}(i)) + \sum_{j=m+1}^{12} min(S_{Coll} \cdot \tilde{Q}_{Sol,month}(j); \tilde{Q}_{Ref,th,month}(j))}{\sum_{i=1}^{m} Q_{Ref,th,month}(i) + \sum_{j=m+1}^{12} \tilde{Q}_{Ref,th,month}(j)} \qquad \text{(eq. 12)}$$

Thanks to the guarantee FSC curve, the guaranteed $\widehat{FSAV}_{th,GRS}$ is calculated (eq. 7).

- Comparison of the estimated and the guaranteed annual performances

Finally, the guaranteed and the extrapolated energy savings are compared: if they are close, the system is working as expected and guaranteed by the manufacturer; if they are different, there may be a failure in the system and it should be checked. Further work is needed to define precisely to which extent this difference means an unsuitable system operation. For this paper, the significant absolute difference is arbitrarily set to 5%.

6. Results

The algorithm presented above has been developed and tested using numerous TRNSYS simulations of a SCS model validated with experimental data of a real system. The simulations presented in this paper treat two operating conditions of the same SCS with or without malfunction of the collector loop pump during the year, under two main boundary conditions (Tab. 2). The special event "Coll. Pump stops working" means that there is no flowrate in collector loop from the specified month, even if the conditions are favorable. The purpose is to check if the algorithm is able to detect at least this kind of obvious malfunction.

Tab. 2: Simulations used to test the proposed monitoring and global results

#	Climate	Building type	Collectors area	Special event	FSC	$FSAV_{TH,estim}$	$FSAV_{TH,GRS}$
TRNSYS2	Zurich	SFH60	16.1m²	-	0.59	0.36	0.35
TRNSYS3	Rennes	SFH100	10m²	-	0.39	0.27	0.28
TRNSYS5	Zurich	SFH60	16.1m²	Coll. Pump stops working from august	0.59	0.29	0.35
TRNSYS7	Rennes	SFH100	10m²	Coll. Pump stops working from may	0.39	0.19	0.28

For the properly working systems, estimated energy saving is very close to the guaranteed one whereas it is at least 0.05 below with collectors pump failure. Figures 6, 7, 8 and 9 below illustrate how those performances estimations evolve during the year with two different representations: the left plot compares estimated and guaranteed performances updated on a monthly basis; the right one plots the same points on the FSAV/FSC plan.

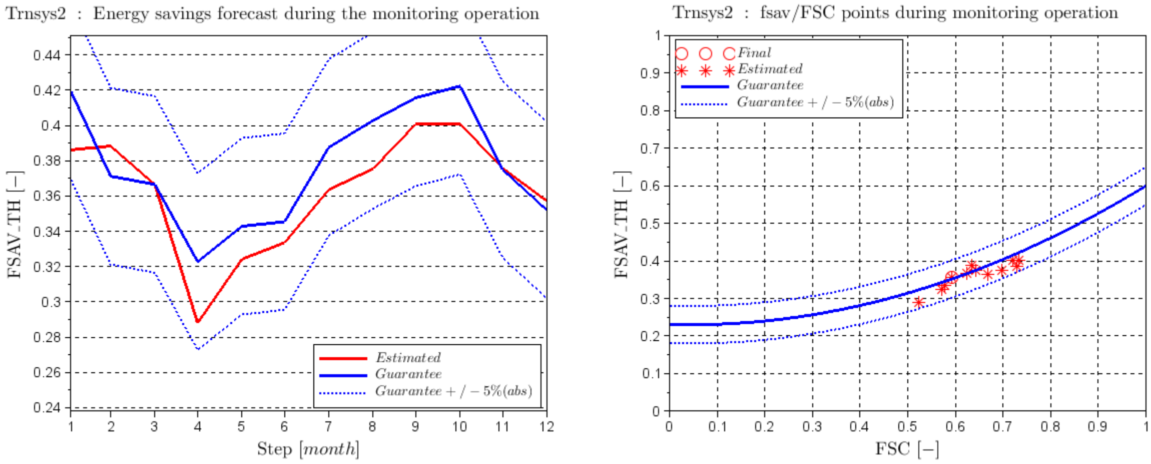

Fig. 6: Monthly estimated and guaranteed annual performances for the TRNSYS2 case study

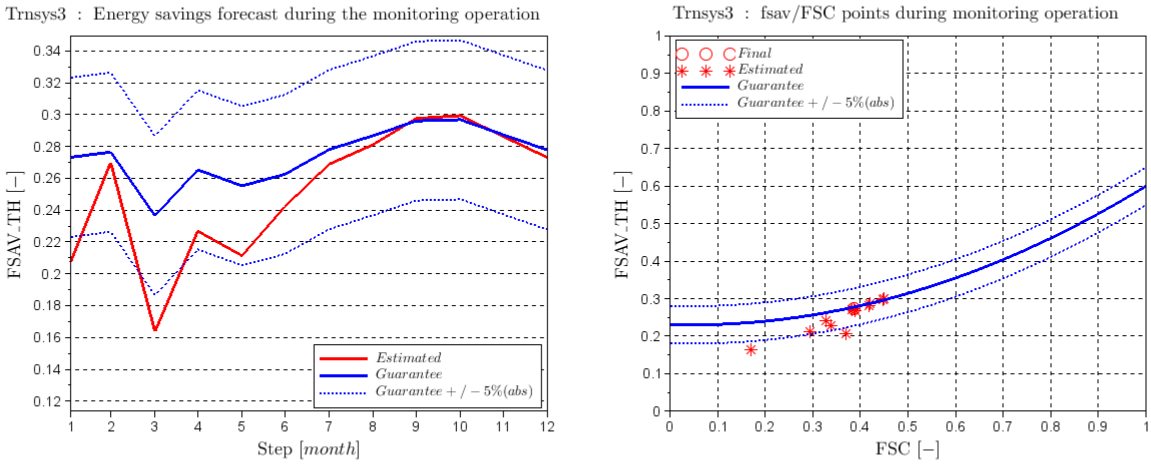

Fig. 7: Monthly estimated and guaranteed annual performances for the TRNSYS3 case study

Fig. 6 and Fig. 7 show that for properly working system, difference between estimated and guaranteed annual fractional energy savings doesn't exceed 0.05 except at the beginning of TRNSYS3 case: during the first 3 months of this simulation, there is not enough data to correctly identify the curves needed for this monitoring. However, after this "learning" period, results are very contained in the range of 5% around the guaranteed curve.

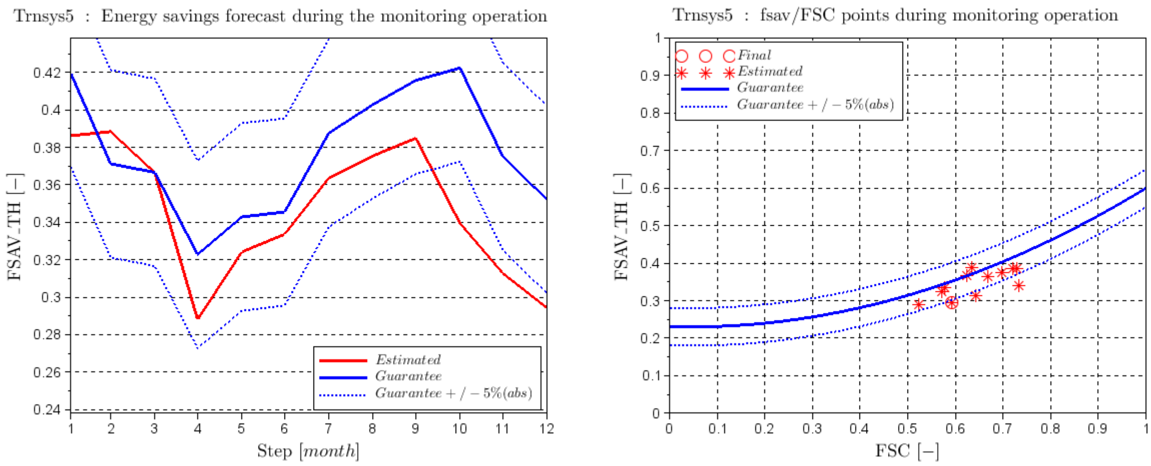

Fig. 8: Estimated and guaranteed annual performances at each month the TRNSYS5 simulation

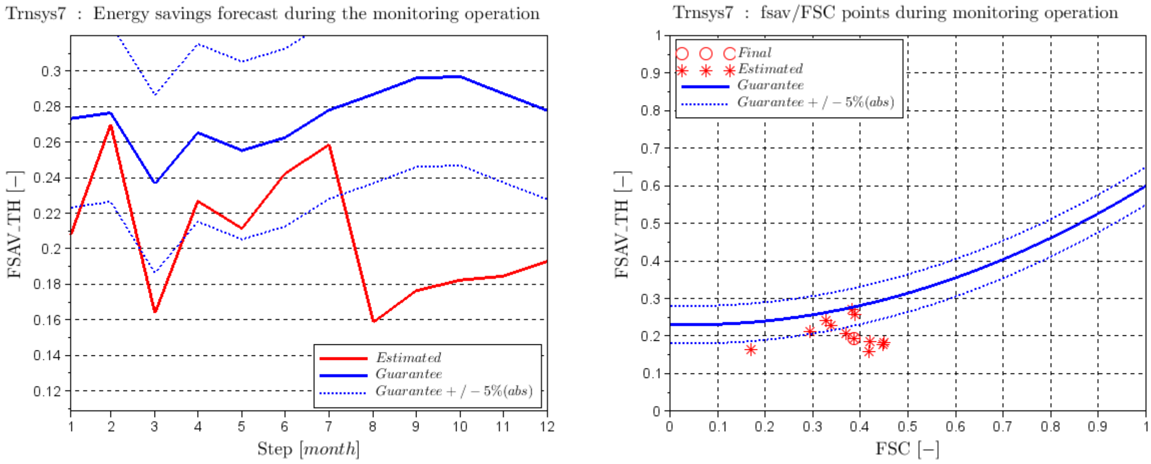

Fig. 9: Estimated and guaranteed annual performances at each month the TRNSYS7 simulation

Compared with the two previous figures (Fig. 6 and Fig. 7), Fig. 8 and Fig. 9 show that the monitoring algorithm is actually able to detect an improper SCS working by lowering the estimated annual performance before the end of the year. Starting from the time when a pump failure is simulated, $FSAV_{th,estim}$ drops below 0.05 lower than the guaranteed energy saving around two months later.

In TRNSYS5 simulation, the estimated performance goes down by 0.08 of $FSAV_{th,GRS}$ whereas the difference can even be larger than 0.12 in TRNSYS7 simulation. The time when the default happens has a significant impact on the failure detection (Fig. 10).

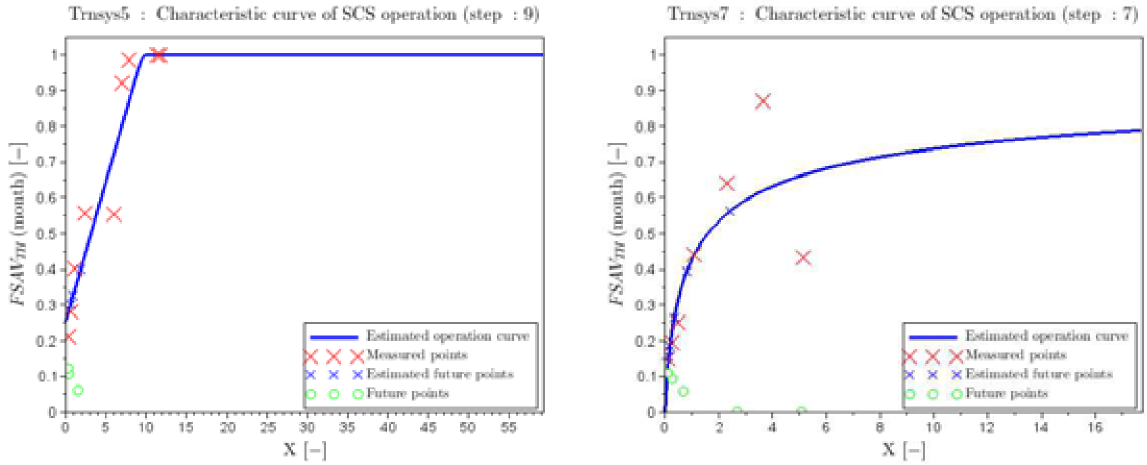

Fig. 10: Estimation of the "operation" curve during TRNSYS5 (left) and TRNSYS7 (right) simulations

A failure before or during summer introduces points with high scattering for the "operation curve" identification, leading to very low future performances estimation. On the other hand, a failure after summer brings points lower but that could be still close to the measured ones (low X values), without enough weight to introduce a large significant change in the "operation" curve. The estimated performance in this case is then actually lower but in a more moderate way.

7. Conclusion and outlooks

The monitoring algorithm introduced in this paper combines two different ways of characterizing SCS performances: one guarantee the annual fractional energy savings (FSC method) and the other links monthly actual performances with on-going working conditions ("operation curve"). Thus, by regular comparisons of their results, it is possible to check if the system is working as it is supposed to and if it would be able to reach the solar results guaranteed by the FSC curve.

The algorithm is tested with different TRNSYS simulations data. Results are promising since estimated and guaranteed performances are very close for well-working system. This proves that both characterizing methods are in accordance. Simulations with a collector's pump that stops working during the year show that this fault could be detected within 2 months (whereas this could be completely undetected for a SCS without monitoring).

This preliminary work reveals the relevancy of the approach described in this paper for automatic monitoring and fault detection of SCS. Additional investigations are suggested to further improve the algorithm:

- Test the algorithm with different failures at different time of the year, for long time operation;
- Reduce the number of points as low as possible for "operation" curve identification in order to make the algorithm more sensitive to failures happening after summer/during winter;
- Apply the monitoring algorithm with a weekly steps in order to reduce the time of failure detection;
- Tests on real plants to check the consistency of this algorithm with real measured data.

Such a monitoring procedure would enable manufacturers to guarantee the performance of their system, have the system checked in quite a short time if the actual performance doesn't match the guaranteed one, and so raise confidence of potential users in this kind of system. On the other hand, it still needs some more metrology on the system and the estimation of the FSC curve beforehand which is currently being investigated.

8. Acknowledgments

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