Performance parameters of solar collectors - Validation and determination by a one-day measurement

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Abstract

The current version of ISO 9806 has merged the two test methods steady-state (SS) and quasi-dynamic (QD) in such a way, that now only one uniform formula is used to determine the collector performance. However, the individual methods remained almost unchanged. The various test methods often result in parameter sets being determined for the same collector that differ significantly from one another. With the help of a one-day validation measurement, the results can be made more precise and standardized. There is also the option of determining the complete parameter set with this single validation sequence under suitable conditions. On vice-versa, it is possible with validated parameters to predict or simulate daily yields in the complete temperature application range of a collector more precisely. Thus, solar thermal industry can make professional and reliable statements about yields, e.g. of large solar systems, beyond the mere determination of peak performance on the basis of a one-day yield check of performance.

Keywords: ISO 9806, steady-state, quasi-dynamic, one-day validation, yield check

1. Introduction

Since the early 1970s, solar thermal energy has been regarded as a basic technology for a 100% renewable energy supply. Since photovoltaics has developed rapidly, in particular due to feed-in tariffs, and prices per kWp have fallen steadily, heat generation with collectors has increasingly receded into the background. Although electricity plays a central role in our digital world, the actual share of energy consumption is low compared to the heat demand. For this reason, the efficient supply of CO_2-free heat from solar collectors is once again becoming more important in climate protection. In order for solar thermal energy to be able to fulfil this role, precise statements must be made about the energy yields that can be supplied. Due to the partially inaccurate determination of the collector parameters, manufacturers are reluctant to give reliable yield guarantees and often refer only to instantaneous performance data. This weakens the position of solar thermal compared to PV. The validation and improvement of collector parameters can close this gap. A major part of the work has been executed in the project ValiColl funded by the Solar Keymark Certification fund (SCF[1]), where a flat plate collector was examined by three experienced test labs. Together with results from industrial research and testing on evacuated tube collectors, the findings could be deepened and specified.

2. Advantages and disadvantages of the current test methods SS and QD in ISO 9806

The ISO 9806 standard for collector testing has been modified in recent years to express the thermal power delivered by different test methods by a common equation. Since the SS method works only with hemispheric irradiance and without an incidence angle modifier for diffuse solar radiation, the corresponding parameters are converted using predefined formulas, so that the heat output is represented at the end using the same formula as for the QD method. For typical flat plate and evacuated tube collectors, the general and quasi-dynamic equation is:

$$\dot{Q} = A_G \left(\eta_{0,b} K_b(\theta_L, \theta_T) G_b + \eta_{0,b} K_d G_d - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 - a_5 \frac{d\vartheta_m}{dt} \right) \quad \text{(eq.1)}$$

The steady-state test can only be performed under a blue sky and high irradiance. The power is determined for 4 temperature levels at normal incidence. With the given collector model from the standard, the optical efficiency and the loss factors can be determined, which are then used to approximate the power and efficiency curve. Using a tracker the incidence angle modifier can be determined in the longitudinal and transversal axis. The collector

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parameters are calculated by evaluating the energy balance of equation 2:

$$\dot{Q} = A_G\left(\eta_{0,hem}K_{hem}(\theta_L,\theta_T)G_{hem} - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2\right) \quad \text{(eq.2)}$$

The effective heat capacity C/A_G is calculated from the materials built in in the collector by using weighting factors and the incidence angle modifier for diffuse irradiance K_d is calculated using the table of the IAM for hemispherical irradiance.

Quasi-dynamic testing needs 4 or 5 days of different irradiation conditions. The collector is mounted on a fixed rack with fixed inclination. The inlet temperatures are kept on a constant level during a testing sequence. By variation of irradiance conditions and by using different inlet temperatures all performance parameters including the incidence angle modifier for beam and diffuse irradiance can be determined. The effective heat capacity is fitted as parameter a_5 and is used to adapt the thermal behavior of the collector to the measured power curve. All parameters are adjusted using the least squares method to achieve the best possible correlation.

The SS testing gives quite exact results for the 4 measured discrete points and the heat capacity. Whereas the transient behavior in between the points may contain inaccuracies. The assessment of diffuse irradiation is only theoretical as larger fractions of diffuse light are excluded. QD testing can adapt the measured power quite well and includes the assessment of diffuse irradiation more realistic. Due to the constant inlet temperature during the measurement, parameter a_5 is used more to represent the thermal response of the collector to variation of irradiance than the heat capacity. In fact, it is more of an adjustment parameter because it mostly overestimates the physical heat capacity of the collectors, especially if there is a larger temperature difference between the absorber and the fluid. Since the performance parameters are not independent of each other, these inaccuracies can lead to significantly different assessment of the same collector by the different testing methods, different test labs or different test personnel. The very fact that different parameter sets deliver almost identical results under the test conditions required by the standard, requires validation under more realistic operating conditions. In the past, the lack of validation in this respect has already led to unreasonable parameter values, huge deviations of yield simulations and irritations among the solar thermal industry.

3. Validation of test results

To check if the parameter set is realistic the collector can be tested in a validation sequence, which includes most of the typical operational condition. It consists of an increasing inlet/mean temperature curve up to a defined maximum at solar noon, which is kept until sunset. The maximum temperature must be selected in such a way that a useful power is still extracted at high incidence angles in order to evaluate the performance of the collector even at the limits of the operating range. Fig. 1 shows the principle characteristic of the mean collector temperature of a validation sequence for collectors with different heat loss factors a_1. Similar to the QD procedure the collector is mounted on a fixed rack with fixed inclination. It is advantageous, but not necessary, if the angle of incidence at noon is approximately perpendicular. The collector shall be oriented towards the equator.

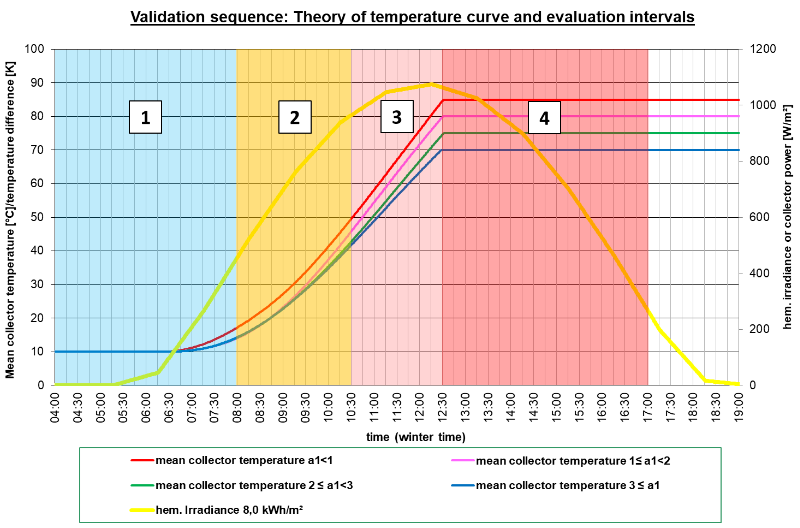
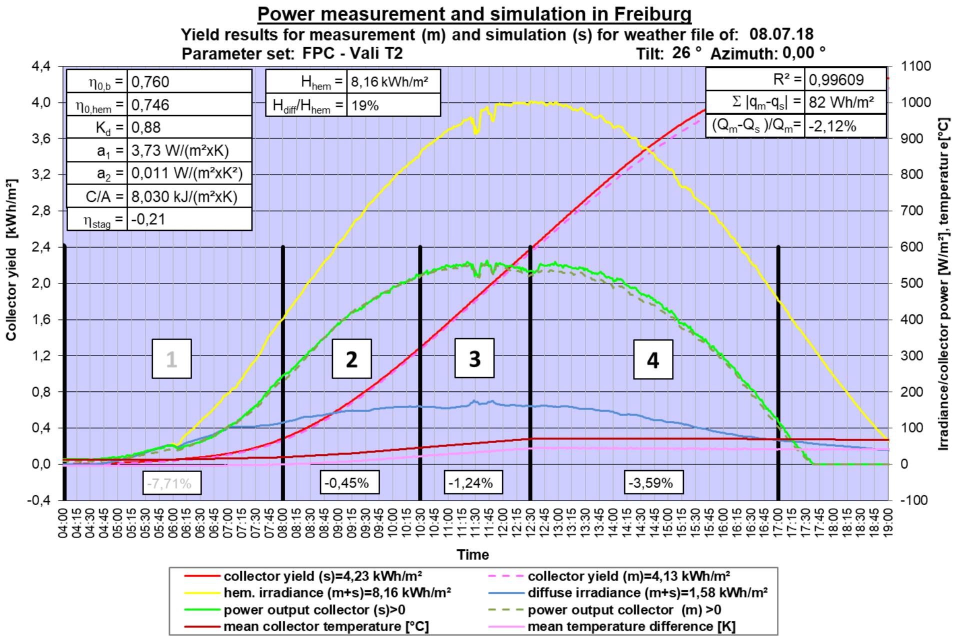


Fig. 1: Recommended temperature curves of a validation sequence for collectors with different heat losses

To check the precision of the performance parameters the energy balance from 08:00 to 17:00 has been evaluated and additionally four subintervals by simulation according to equation 1. For this purpose, it is important to use the physical parameter C/A_G instead of the fit parameter a_5 in order to represent the effective heat capacity in the calculation correctly. The example of a flat plate collector (FPC) in Fig. 2 using the parameter set (Vali – T2) derived from a SS test and applied to a validation measurement shows that within the energetic relevant intervals 2, 3 and 4 the consistency between measurement and simulation can be improved. The simulated power (continuous light green line) overestimates the measurement (dashed dark green line). Improving the parameter set like in the second diagram (Vali – optimized Fit 2-a) the difference in the energy balance can be close to zero for all 3 subintervals and the total balance for the day. In addition, the coefficient of determination R^2 is improved and the sum of the absolute deviation between the two curves is reduced significantly. Although the set Vali – T2 is already quite good the enhancement at higher temperatures is obvious and is highlighted by the good correspondence of the violet curves of the cumulated collector yield.



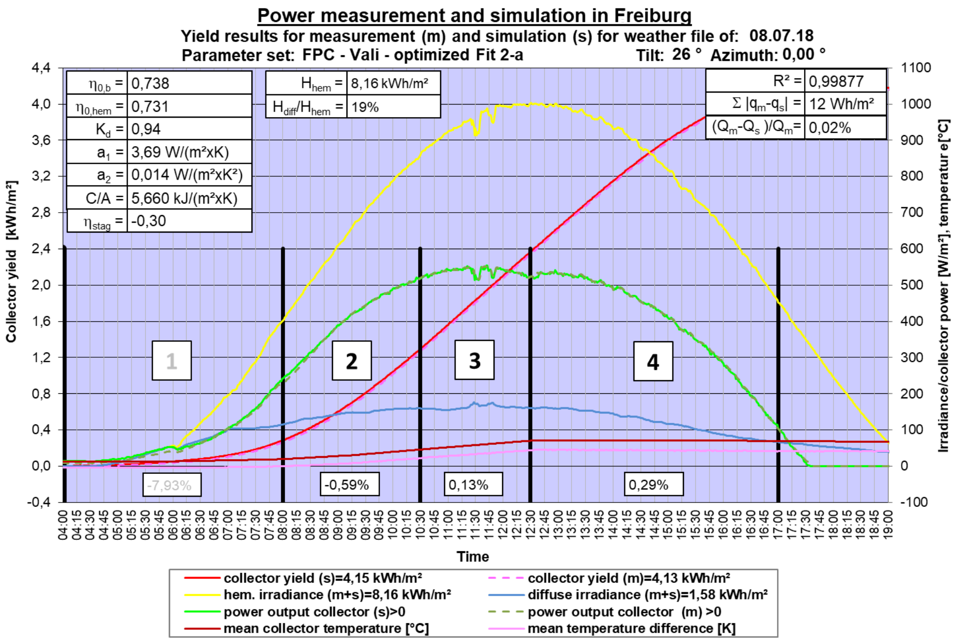


Fig. 2: Comparison of measurement (dashed lines) and simulation (continuous lines) for two different parameter sets of a FPC

The homogenous distribution of measurement points over the complete operational range of the collector during a high irradiation day (Fig. 3) enables to refine the parameter set to achieve reliable and reproducible results. The figure also shows the typical behavior of an FPC with strongly decreasing efficiency at higher temperatures and large angles of incidence later in the afternoon. The application limit is at a reduced temperature of 0.12 at low irradiance conditions.

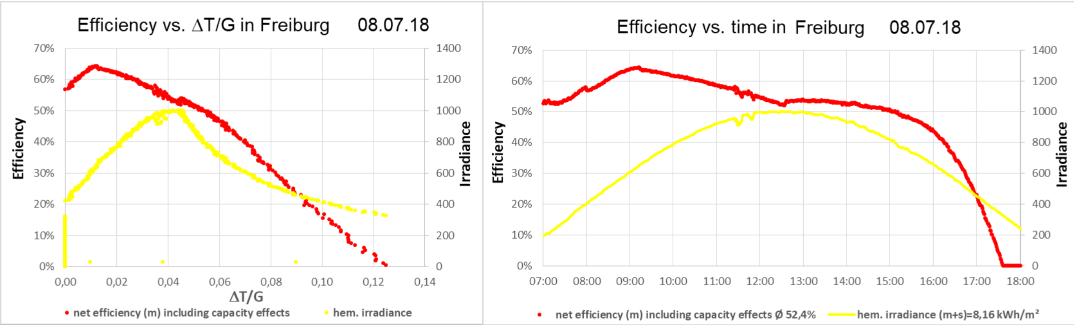


Fig. 3: Net efficiency vs. reduced temperature and vs. time on a sunny day of a FPC

A further investigation was carried out on an evacuated tube collector with CPC reflector (ETC+CPC). The collector was tested and certified with the QD procedure and additionally subjected to a validation measurement. Since the collector is also used in the temperature range 80 to 120 °C, an increase of the mean collector temperature up to 100 °C was tested. From component assessment like ray tracing of the CPC, testing of the evacuated tubes etc. there has been determined a theoretical set of parameters before executing the testing to find out the differences between theory and practice. The reddish lines in Fig. 4 represent the longitudinal IAM while the green ones show the transversal IAM. According to the permitted limits of the ISO 9806, the measurement of IAM (dashed lines) can be done only up to 70° in a reasonable way. The value for 80° is then interpolated. The validation values (continuous lines) are first derived from theoretic values (dotted lines) and then adapted with the validation sequence. It is obvious that the validation values had not to be changed very much from the theoretical ones to find a very good adaption. According to the standard, these values are given for each 10° and interpolated for the simulation. The longitudinal values of QD measurement show a quite low characteristic and at 60° incidence an atypical behavior.

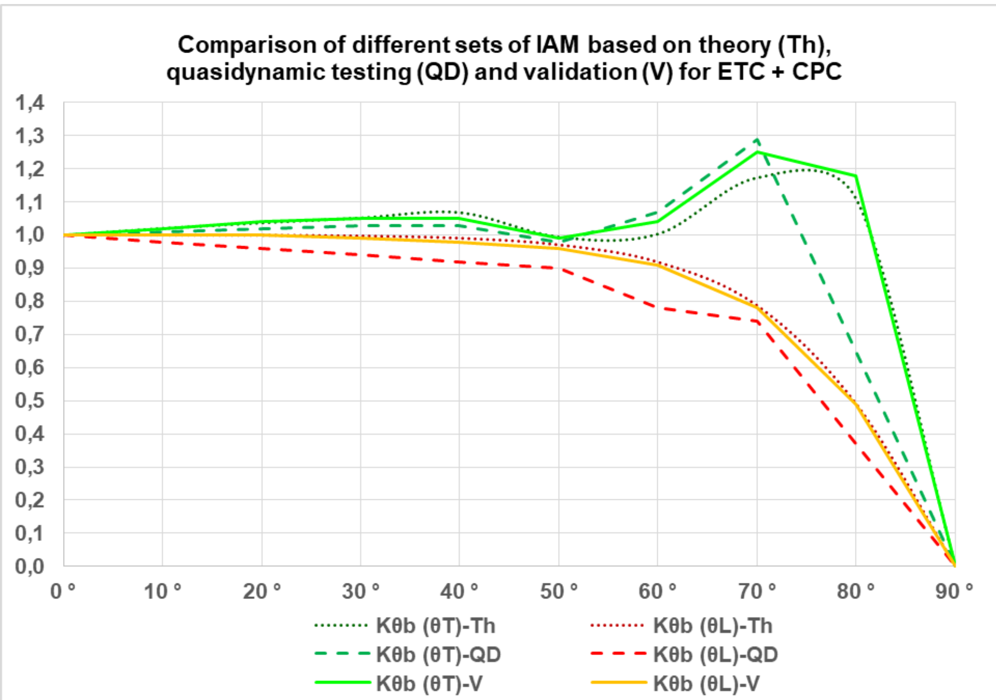
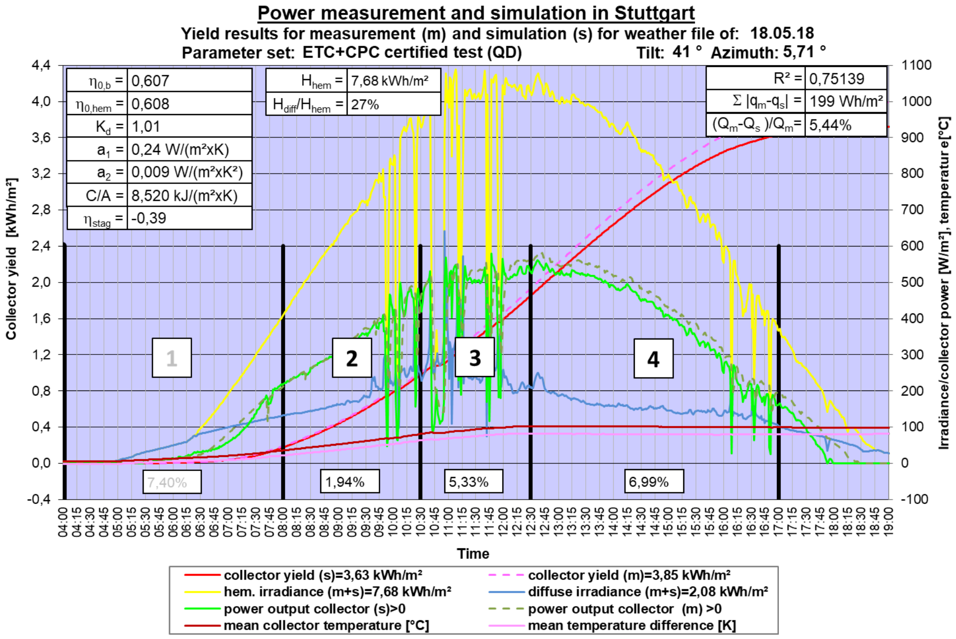


Fig. 4: Incidence Angle Modifier (IAM) of 3 different parameter sets

Comparing parameter sets of the "certified test (QD)" and the Validation called "adapted theory (V)" by simulating the validation sequence (Fig. 5) it can be seen, that until 10:00 and a mean collector temperature of 70°C (≈ mean collector temperature difference 50 K) the cumulated collector yield of the measurement and the simulation are very similar. With higher temperature, the QD set underestimates the measured values and results in more than 5% less daily yield than actually measured. On the other hand, the simulation of the Validation set follows the measured values quite exact and results in a total balance of 0 %. Due to the design of the collector with a significant temperature difference between the absorber and the fluid, the heat transfer in the shown 1-knot model simulation is delayed. Therefore, R^2 is not particularly good. If a second knot is added to the model (not presented here), the dynamics of the simulation curve and R^2 of the Validation set are much better too. The deviation in the energy balance for each subinterval then is below 1 %.



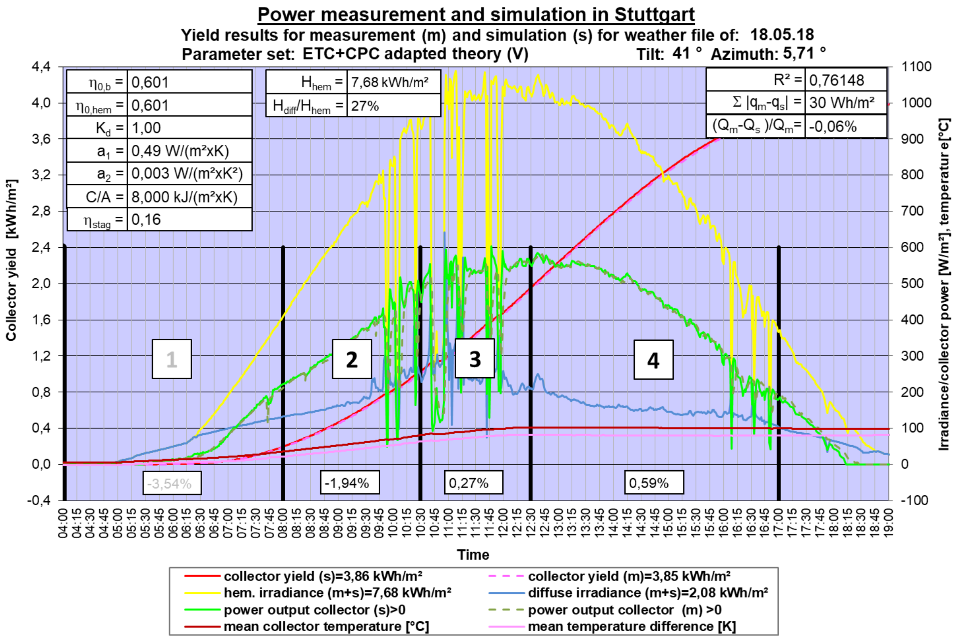


Fig. 5: Comparison of measurement (dashed lines) and simulation (continuous lines) for two different parameter sets of an ETC

In Fig. 6 the huge operational range of this ETC is displayed on a scale of the reduced temperature until 0.6. The net efficiency measured at the flow and return line of the collector remains almost constantly above 50 % during the typical operation time between 8:00 and 17:00. This is due to the low losses of this collector type and its special IAM caused by the CPC reflector and the tubular absorber. The fact of the high efficiencies would allow testing of the collector even at even higher temperature levels.

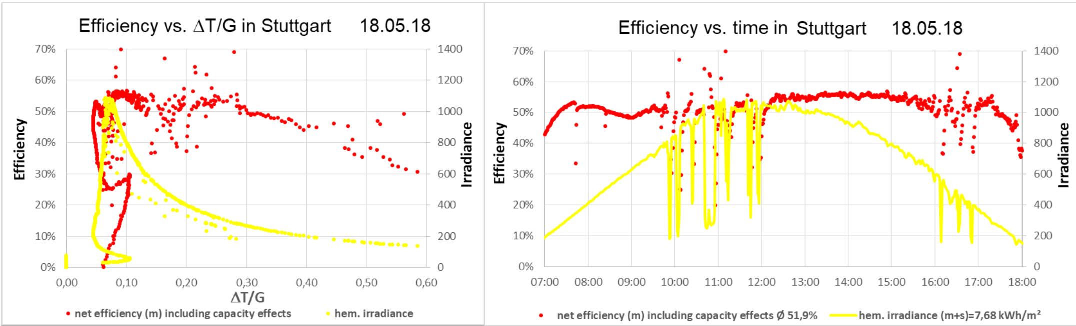


Fig. 6: Net efficiency of an ETC vs. reduced temperature and vs. time on a sunny day

4. Application and summary

The one-day measurement was validated for flat plate and evacuated tube collectors. It is currently applicable for non-tracking collectors and collectors with low concentration < 2 only. Further investigations are needed to determine whether it can also be used for tracking- and/or higher-concentration collectors. The validation sequence can be added to both test methods SS and QD. It is the link to achieve similar and reproducible parameter sets no matter which method you choose. It provides security for manufacturers concerning the yield of their products over the entire temperature application range and enhances the trust in solar thermal energy. The validation sequence provides the option to determine the whole parameter set by a cheap one-day measurements if the values are roughly known by theory or former testing. The method can be applied also to in-situ[2] measurements e.g. of large-scale application where it is difficult or impossible to provide constant and low temperature inlet temperatures. In practice days with high irradiation sum > 6.5 kWh/m^2 should be used to validate or determine the complete parameter set, while it is not necessary to have blue-sky conditions. Days with high diffuse irradiation are perfect to determine K_d more precisely. The detailed investigation shows that a good validation mostly needs significantly higher K_d values than calculated according ISO 9806 or a higher K_b characteristic more close to theoretical values, which then also result in a higher value for the calculated K_d. For the examined FPC the best fitting value is about 6 percent points higher than calculated. The reason for this is that the 1-knot model is only a rough physical model so that η_b, K_d, a_1 and a_2 are not independent from each other but linked. For the ETC collector the significant higher K_b characteristic resulted in a K_d =1.00. The possibility to reduce the deficits of the 1-knot model by adjusting K_d, as it is already practiced in the QD method, and as it should also be possible for the SS test, makes a more precise, but also more complicated 2-knot model obsolete. Furthermore, a parameter set, which has been refined that way, reduces unreasonable deviations and values for a_1 and a_2 and thus show typically a better physical relation to the stagnation temperature. The validation sequence is the key to this improvement. The results of the study can be used for further development of ISO 9806 and reducing costs for testing.

Furthermore, several one-day tests with different temperature profiles, lower irradiation, different azimuth and inclination were performed. General result is that a parameter set validated with a high irradiation sum can be used to simulate the results of days at different conditions within the range of the validation sequence quite well. This opens the possibility to check and evaluate the energy yields of large-scale applications by one-day measurements. This can be done for typical days with different irradiation sums in addition to the pure peak efficiency evaluation.

5. Acknowledgments

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6. References

[1] http://www.estif.org/solarkeymarknew/projects/scf

[2] http://proceedings.ises.org/paper/eurosun2018/eurosun2018-0167-Fahr.pdf

Appendix: Units and Symbols

Quantity	Symbol	Unit
Gross area of collector = Reference area	A_G	m^2
Heat loss coefficient	a_1	$Wm^{-2}K^{-1}$
Temperature dependence of the heat loss coefficient	a_2	$Wm^{-2}K^{-2}$
Fitted effective thermal capacity per m^2	a_5	$kJm^{-2}K^{-1}$
Calculated effective thermal capacity per m^2	C/A_G	$kJm^{-2}K^{-1}$
Hemispherical solar irradiance	G_{hem}	Wm^{-2}
Direct solar irradiance	G_b	Wm^{-2}
Diffuse solar irradiance	G_d	Wm^{-2}
Hemispherical irradiation	H_{hem}	$kWhm^{-2}$
Diffuse irradiation	H_{diff}	$kWhm^{-2}$
Incidence angle modifier for hemispherical solar radiation	$K_{hem}(\theta_L, \theta_T)$	-
Incidence angle modifier for direct solar radiation	$K_b(\theta_L, \theta_T)$	-
Incidence angle modifier for diffuse solar radiation	K_d	-
Useful power extracted from the collector	$\dot{Q}$	W
Measured energy extracted from the collector per m^2	Q_m	$kWhm^{-2}$
Simulated energy extracted from the collector per m^2	Q_s	$kWhm^{-2}$
Absolute difference between measured and simulated energy per time step	$\lvert q_m - q_s \rvert$	Whm^{-2}
Coefficient of determination	R^2	-
Ambient air temperature	ϑ_a	°C
Mean temperature of heat transfer fluid	ϑ_m	°C
Peak collector efficiency collector based on hemispherical irradiance	$\eta_{0,hem}$	-
Peak collector efficiency collector based on direct irradiance	$\eta_{0,b}$	-
Calculated collector efficiency at (estimated) stagnation temperature	η_{stag}	-