Guaranteed power output

Subject:	**Guarantee power output** of large collector fields
Description:	Procedures to **give power output guarantees** for large collector fields and heat exchangers Procedures to **check power output guarantees** for large collector fields and heat exchangers.
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Download:	http://task45.iea-shc.org/fact-sheets

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Intro

The performance guarantees described here relate to the power performance of a collector field and a heat exchanger under some restricted ("full load") operating conditions. The procedures described here do not pretend to give and check a guarantee on the annual output of the system. For annual output guarantee, see IEA-SHC Fact Sheet 45.A.3.2 "Guaranteed annual output" (http://task45.iea-shc.org/fact-sheets).

Giving guarantees

The procedures for giving guarantee for the collector field power and heat exchanger performance are given below.

Give solar collector field guarantee

Guarantee for the collector field performance can be given in the form of a guarantee equation:

$$P_g = A_c \cdot [\eta_0 \cdot G - a_1 \cdot (T_m - T_a) - a_2 \cdot (T_m - T_a)^2] \cdot f_P \cdot f_U \cdot f_O \quad \text{(eq. 1)}$$

where:

P_g: Guaranteed performance (thermal power output) [W]
A_c: Collector area corresponding to the collector module efficiency parameters: η_0, a_1 and a_2
η_0: Optical efficiency [-]
a_1: 1st order heat loss coefficient [W/(K·m²)]
a_2: 2nd order heat loss coefficient [W/(K²·m²)]
G: Solar irradiance on collector plane [W/m²]
T_a: Ambient air temperature [°C]

The collector module efficiency parameters should be based on certified[1] test results.
The mean collector fluid temperature is taken as simple average of in and outlet temperatures:

$$T_m = (T_{c,in} + T_{c,out}) / 2 \quad \text{(eq. 2)}$$

where:

T_m: Mean temperature of solar collector fluid [°C]
$T_{c,out}$: Hot side of collector field (= collector outlet temperature) [°C]
$T_{c,in}$: Cold side of collector field (= collector inlet temperature) [°C]
f_P: Safety factor taking into account the pipe heat losses in the collector field and transmission lines; f_P = 1 – pipe heat loss ratio. So if the pipe losses are estimated to be 3 % f_P should be 0.97
f_U: Safety factor taking into account measurement uncertainty; f_U = 1 – measurement uncertainty. If the total measurement uncertainty is estimated to be ±10 %, f_U will be 0.9
f_O: Safety factor for other things. Could typically be 0.95 to take into account non-ideal flow distribution and unforeseen heat losses

Restrictions on operating conditions – data points only valid if:
- $G \geq 850$ W/m²
- No shadows on collectors
- No snow/ice/condensation on solar radiation sensors
- $T_a > 10$ °C

[1] E.g.: Solar Keymark, SRCC, Global Solar Certification, or similar.

No significant change (< 2 K) in collector mean operating temperature during an hour

Example 1: Give a guarantee for a collector field performance

Collector data (from Solar Keymark data sheet):
Module area:

$A = 13.2\ m^2$

Corresponding collector efficiency parameters

$\eta_0 = 0.8$

$a_1 = 3.0\ \ W/(K\cdot m^2)$

$a_2 = 0.01\ \ W/(K^2\cdot m^2)$

Other data:

Estimated pipe heat losses: 3 %
Estimated uncertainty on measurements: 10 %
Safety factor other things 0.95
Number of collector modules: 1000

Guarantee equation 1 with the values inserted is then:

$$P_g = 13200 \cdot [0.8\cdot G - 3.0 \cdot (T_m - T_a) - 0.01\cdot (T_m - T_a)^2] \cdot 0.97 \cdot 0.90 \cdot 0.95 \qquad [W]$$

$$= 10947 \cdot [0.8\cdot G - 3.0 \cdot (T_m - T_a) - 0.01\cdot (T_m - T_a)^2] \qquad [W]$$

Give guarantee for heat exchanger performance

The performance guarantee for the heat exchanger ("hx") in the solar collector loop can be given as a maximum logarithmic[2] mean temperature difference between the primary ("prim") and secondary ("sec") side of the heat exchanger:

$\Delta T_{g,hx}$ = guaranteed value [K]

for a given set of requirements on in- and outlet temperatures on primary side:

$T_{prim,in,min}$ ≥ *given value 1* (e.g. 80 °C) [°C]

$T_{prim,out,min}$ ≥ *given value 2* (e.g. 40 °C) [°C]

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[2] If the capacity rates on both sides of the heat exchanger are approx. equal (they should be!), then the logarithmic mean temperature difference is approx. equal to the arithmetic mean. If the capacity flows are significant different then it should be calculated from:

$$\Delta T_{mean} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

where

ΔT_1: $T_{prim,in} - T_{sec,out}$

ΔT_2: $T_{prim,out} - T_{sec,in}$

It is recommended to set these minimum temperature values 10 K below the typical full load situation in order to be sure to have valid data points for checking the guaranty, i.e.

$T_{prim,in,min} = T_{prim,in,full} – 10$ K
$T_{prim,out,min} = T_{prim,out,full} – 10$ K

Power value:
The guarantee should be given for a certain value of the power transferred through the heat exchanger; a natural choice would be the power corresponding to a typical full load situation, e.g.:

$P_{hx} = P_g$ [W]

with

G: chosen to 900 [W/m²]
T_m: chosen to be the mean collector temperature at full load[3]
T_a: chosen to 15 °C.

It is recommended to include some safety margin on $\Delta T_{g,hx}$ e.g. 0.5 K.

It is important to specify the fluid (*brand name, type name, glycol percentage*) and to give maximum allowed tolerance on the capacity flows (w) on primary and secondary side of the heat exchanger (e.g. $0.95 \leq w_{prim} / w_{sec} \leq 1.05$).

Example 2: Give a guarantee for a heat exchanger performance

The typical full load situation is defined as:

$T_{prim,in,full}$	= 90	[°C]
$T_{prim,in,min}$	= 80 (10 K lower as recommended)	[°C]
$T_{prim,out,full}$	= 50	[°C]
$T_{prim,out,min}$	= 40 (10 K lower as recommended)	[°C]
T_a	= 15	[°C]
$T_m – T_a$	= (90 + 50) / 2 –15 = 55	[K]
G	= 900	[W/m²]
P_{hx}	= P_g	[W]

$0.95 \leq w_{prim} / w_{sec} \leq 1.05$

Assuming same collector field as before:

P_g	$= 11060 \cdot [0.8 \cdot 900 – 3.0 \cdot 55 – 0.01 \cdot 55^2]$	[W]
	$= 11060 \cdot 525$	[W]
	= 5.80	[MW]

Choosing a heat exchanger specified (with the actual glycol mixture) to

[3] If the temperature decrease between $T_{c,out}$ and $T_{hx,prim,in}$ is negligible, these values can be assumed equal here. The same thing accounts for $T_{hx,prim,out}$ and $T_{c,in}$. Equation 2 can then be used to determine T_m. These assumptions depend on the physical distance between the measurement points, i.e. whether or not they are placed close to each other.

a) transfer 5.8 MW at primary side
b) run with temperatures in and out of primary side at 80 °C and 40 °C respectively
c) have a mean temperature difference across the heat exchanger of 3 K

it should then be safe[4] to give a guarantee of:

$\Delta T_{g,hx}$ = 3.5 [K] (including a safety interval of 0.5 K).

The guarantee could look like the following text box:

The logarithmic mean temperature difference *across the heat exchanger (from primary side to secondary side)* ***is maximum 3.5 K*** *under the following conditions:* • *Fluid: Primary side: Tyforop Chemie GmbH type "Tyfocor HTL", 30 % wt; secondary side: water* • *Power transferred = 5.8 MW* • *Temperatures: Primary side: Inlet temperature ≥ 80 °; outlet temperature ≥ 40 °C* • *Tolerance on the capacity flows on primary and secondary side of the heat exchanger: 0.95≤ w_{prim} / w_{sec} ≤ 1.05)*

For the example given (example no. 2) the influence of the heat exchanger ΔT on the instant performance is seen in fig.1. The figure shows the reduction in collector performance for the collector described in example no. 1, running at the given "full load situation". It is seen that the reduction in performance in this case approximately equals the ΔT.

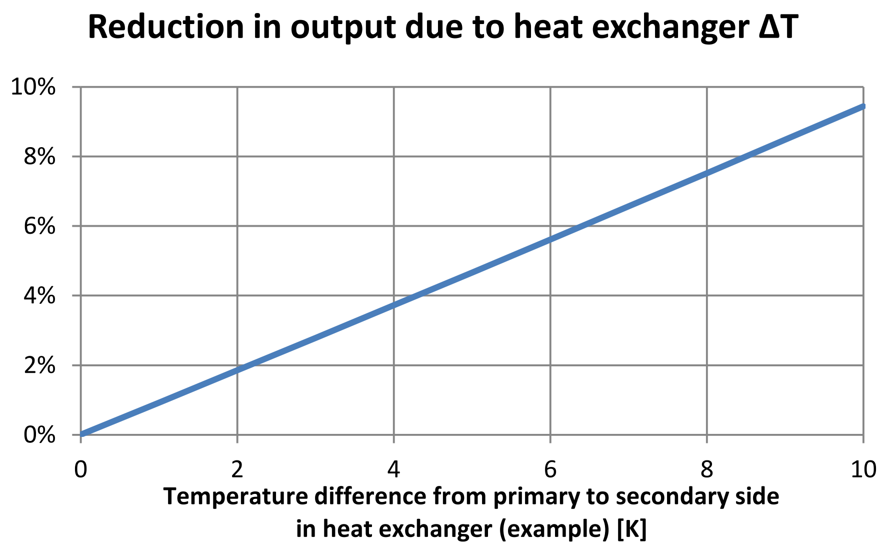

Figure 1. Example of the influence of the heat exchanger on the performance of the solar system. The higher the temperature difference across the heat exchanger (ΔT) the higher the temperature in the collector loop - and the lower the collector performance. The influence of the heat exchanger depends on the heat loss coefficient of the solar collector: The higher the collector heat loss coefficient - the larger the influence of the heat exchanger. (Source: PlanEnergi)

[4] Note: It might be wise to have the provider/manufacturer of the heat exchanger involved in this guarantee.

Checking performance guarantees

In the following procedures are given to check the guarantees described above.

Measurements needed for checking guarantees

To check the solar collector field performance guarantee it is necessary (at least) to measure the following data points (see figure 2 below):

$T_{c,out}$:	Outlet temperature from collector field (measured at heat exchanger inlet)	[°C]
$T_{c,in}$:	Inlet temperature to collector field (measured at heat exchanger outlet)	[°C]
P_{hx}:	Thermal power supplied to (or from) heat exchanger	[W or kW]
G:	Solar irradiance on collector plane	[W/m²]
T_a:	Ambient air temperature (shadowed and ventilated)	[°C]

To check also the guarantee on the heat exchanger the following additional points shall be measured:

w_{prim}	Capacity flow in collector loop primary side (glycol mixture side)	[W/K]
$T_{hx,sec,out}$	Outlet temperature from heat exchanger secondary side (water side)	[°C]
$T_{hx,sec,in}$	Inlet temperature to heat exchanger secondary side (water side)	[°C]
w_{sec}	Capacity flow in heat exchanger secondary side (water side)	[W/K]

Requirements:

Logging time ≤ 2 minutes

Recording time = 1 hour

Time and date for all recorded data are needed. The values in the record shall represent the average values over the last hour. (ex.: data in the record saved 2011:04:31:12:00 represent the average values in the hour from 11:00 to 12:00 on April 31st 2011). Time indication shall always be "standard time" (not daylight saving time or "summer time").

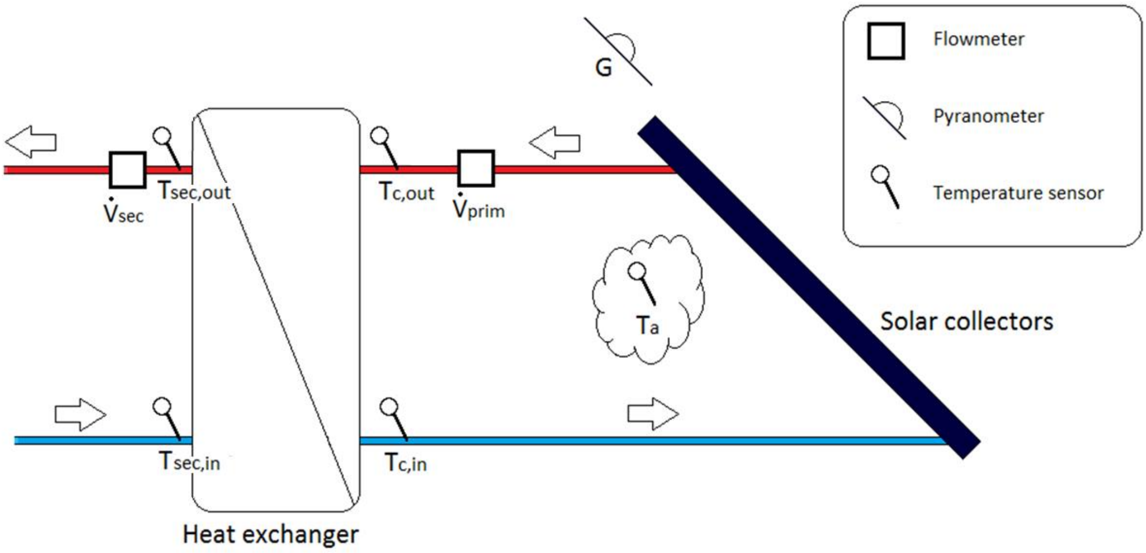

Fig. 2. Schematic drawing showing the measurement points. $T_{c,out} = T_{prim,in}$ and $T_{Cc,in} = T_{prim,out}$.
(Source: PlanEnergi)

Referring to figure 2 the heat exchanger power is calculated either for the primary or the secondary side, e.g. for the primary side as:

$$P_{hx} = \dot{V}_{prim} \cdot \rho_{prim} \cdot c_p \cdot (T_{prim,in} - T_{prim,out}) \qquad \text{(eq. 3)}$$

where

P_{hx}:	Thermal power supplied to (or from) heat exchanger	[W]
$\dot{V}_{prim}$	Flow rate in primary loop	$[m^3/s]$[5]
ρ_{prim}	Density of the collector fluid	$[kg/m^3]$
c_p	Heat capacity of solar collector fluid	[J/(kg·K)]
$T_{prim,in}$	Inlet temperature on the primary side of the heat exchanger	[°C]
$T_{prim,out}$	Outlet temperature on the primary side of the heat exchanger	[°C]

The calculation is the same for the secondary side except for the fact that the inlet and outlet temperatures are switched in the formula.

Valid data points

Only data points (hourly average values) fulfilling the following requirements are valid:

- $G \geq 850\ W/m^2$
- $T_a \geq 10\ °C$
- No snow or ice or condensing on/in collectors and solar radiation sensor
- No shadows on any collector in the field
- Incidence angle of direct solar radiation ≤ 30°

For checking the collector performance, the measuring period shall have at least 20 data records. All valid data records in the period shall be used unless it is obvious that errors in data or very atypical operating conditions occur (omitting valid data points shall be reported and explained).

Checking collector field performance guarantee

The summarized measured (“meas”) energy output for all valid data point are compared with the corresponding energy calculated according to the guarantee formula (eq.1), using the measured weather data and temperatures in collector loop. If this measured energy is equal to or greater than the energy corresponding to the guarantee calculation, then the guarantee is fulfilled:

$$\sum Q_{hx,meas} \geq \sum Q_g \Rightarrow \text{Guarantee OK}$$

Each $Q_{hx,meas}$ and Q_g is calculated as $P_{hx,meas}$ and P_g multiplied by time (3600 s) respectively [J].
Plot of corresponding data points for measured and calculated thermal power should be made to check for deviations. See example below in figure 4.

[5] Normally measured in m^3/h and converted to m^3/s by multiplying with 3600 s/h.

Example 3: Checking collector field performance guarantee

Data points from a performance check of a Danish system are used to illustrate the checking and plotting. 28 valid data points were recorded. Summing up hourly measured energy output and comparing with the sum of guaranteed energy output shows that

$$\sum Q_{hx,meas} \geq \sum Q_g.$$

Guarantee is then OK.

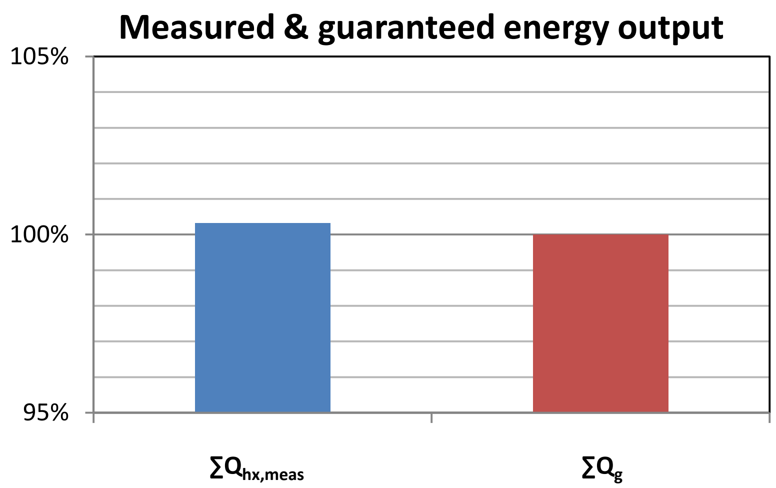

Fig.3. Plot of summarized measured energy and corresponding guaranteed energy. (Source: PlanEnergi)

Plotting the measured data points against the corresponding guaranteed ones shows that the variation of the data points looks reasonable - see fig. 4.

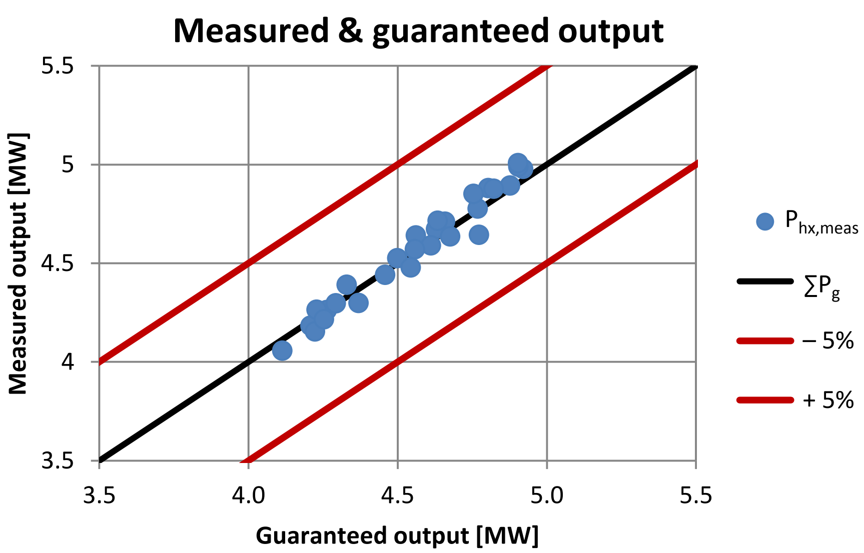

Fig.4. Plot of measured thermal power point against corresponding guaranteed thermal power points. (Source: PlanEnergi)

Checking heat exchanger performance guarantee

The performance guarantee of the heat exchanger can be checked by plotting the measured logarithmic mean temperature difference across the heat exchanger against the transferred thermal power. A linear regression based on these measurements has the expression

$$f(P_{hx,meas}) = c_1 \cdot P_{hx,meas} + c_2 \qquad \text{(eq. 4)}$$

where

$f(P_{hx,meas}) = \Delta T_{hx,meas}$ [K]

c_1 and c_2 are constants determined by the linear regression.

When the power for which the guarantee was made (P_g) is inserted in equation 4, it is revealed whether or not the temperature difference is too large since the calculated value

$\Delta T_{check} = f(P_g) = c_1 \cdot P_g + c_2$ [K]

must be lower than or equal to the guaranteed maximum temperature difference $\Delta T_{g,hx}$. Hence the guarantee is fulfilled if

$\Delta T_{check} = f(P_g) \leq \Delta T_{g,hx}$

It shall be documented that the temperature and capacity flow requirements are fulfilled.

The example below illustrates this checking.

Example 4: Checking heat exchanger temperature difference:

The guarantee:

The temperature difference across the heat exchanger is maximum **5 K** under the following conditions:

- Fluid: Primary side: <*fluid specification*>; secondary side: water
- Power transferred = 4.5 MW
- Temperatures: Primary side: Inlet temperature ≥ 80 °; outlet temperature ≥ 40 °C
- Tolerance on the capacity flows on primary and secondary side of the heat exchanger: $0.95 \leq w_{prim} / w_{sec} \leq 1.05$)

The plot in figure 5 shows

- measured temperature difference points $\Delta T_{hx,meas}$
- a linear regression based on the measurement points
- the guaranteed maximum temperature difference $\Delta T_{g,hx}$ (in this case 5 K) for the given heat exchanger power P_g for which the guarantee is given (in this case 4.5 MW):

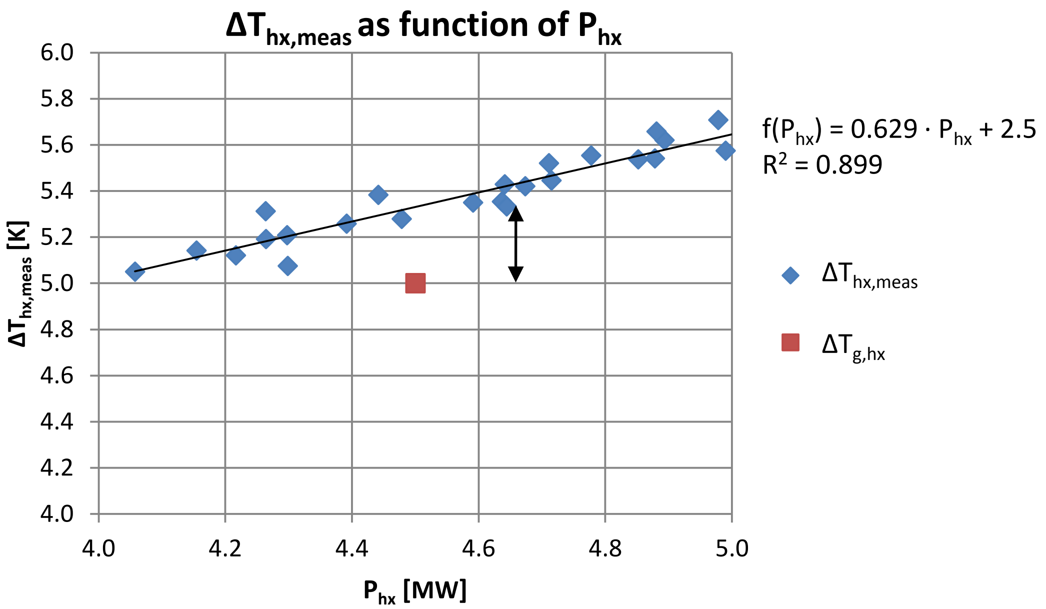

Fig.5. Logarithmic mean temperature difference across heat exchanger as function of the transferred power. Guarantee point indicated with red square at 4.5 MW; 5 K. It is seen that in this case the guarantee is NOT fulfilled! (Source: PlanEnergi)

Check of temperatures:

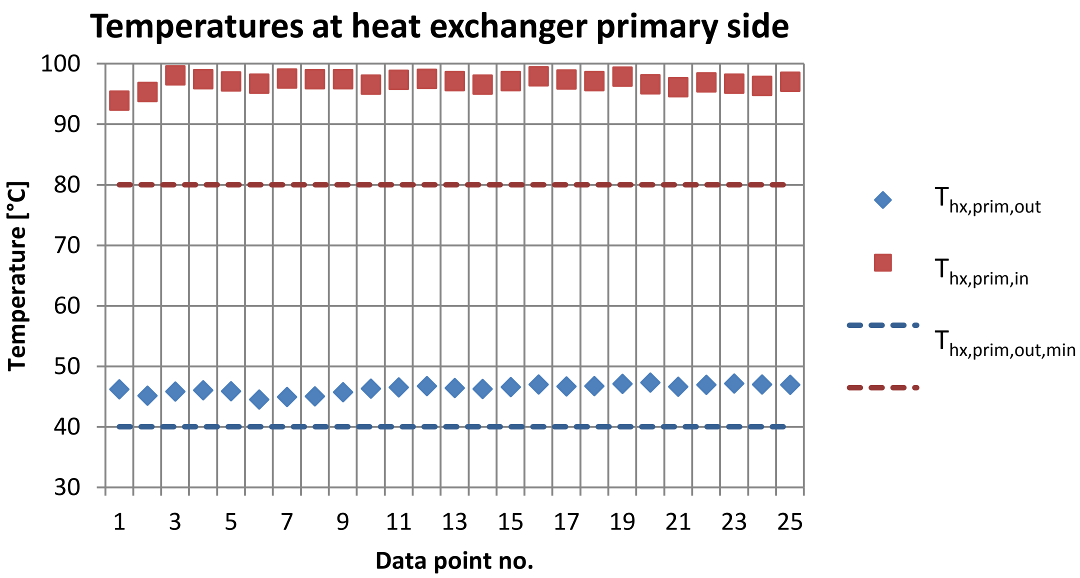

Fig.6. Temperature requirements fulfilled since $T_{hx,prim,out}$ is above $T_{hx,prim,out,min}$ (40 °C) and $T_{hx,prim,in}$ is above

Checking thermal capacity flow rate ratio:

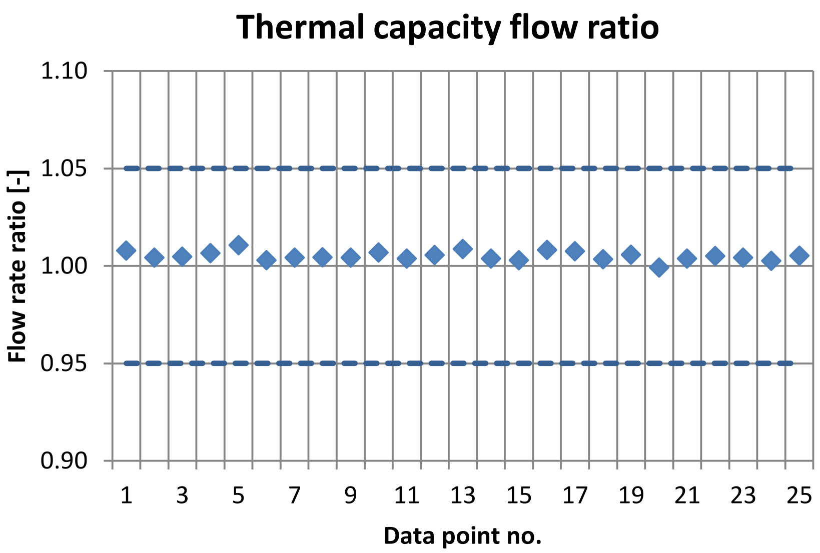

Fig.7. Capacity flow rate ratio requirement fulfilled since the measurement points are between 0.95 and 1.05 as required. (Source: PlanEnergi)

It is seen that the requirements given in the heat exchanger performance guarantee is fulfilled (as seen in figure 6 and 7) BUT the guarantee is in this case NOT fulfilled (as seen in figure 5). Only if the red, square marker in figure 5 is above the regression line the guarantee is fulfilled - and this is not the case here.

In the next page is seen a template which can be used to check that all necessary component details are noted as well as the collector fluid properties.

Annex: Templates

Template for the equipment used for data logging

Equipment type	Name of manufacturer and component	Placement and orientation	Measurement range	Uncertainty +/- [%]
Solar radiation sensor			[W/m^2]	
Flowmeter 1			[m^3/h]	
Flowmeter 2			[m^3/h]	
Temperature sensors			[°C]	

Table A.1. Properties of the equipment used for measuring the collector and heat exchanger efficiency.

Template for the solar collector fluid properties

Name of manufacturer		[-]
Product name		[-]
Concentration		[wt %]
Heat capacity (40 °C)		[J/(kg·K)]
Heat capacity (80 °C)		[J/(kg·K)]
Density (40 °C)		[kg/m^3]
Density (80 °C)		[kg/m^3]

Table A.2. Solar collector fluid properties of the fluid used in the tests.