Task 55 Towards the Integration of Large SHC Systems into DHC Networks

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

B-D2 Collector fields – Check of performance

IEA SHC FACT SHEET 55.C.D.5.1.

Subject:	**Check of guaranteed 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.
Date:	15th December 2020
Authors:	Jan Erik Nielsen, PlanEnergi (jen@planenergi.dk
Download:	https://task55.iea-shc.org/fact-sheets

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Intro

This document defines simple procedures for guaranteeing and checking the power performance of solar thermal collector fields.

This fact sheet is an update of the IEA SHC Fact Sheet 45.A.3.1 "Guaranteed power output" (https://task55.iea-shc.org/fact-sheets) – and is based on the "simple check" of power output in the up-coming ISO TC180 standard "Collector fields - Check of performance". More detailed procedures are available in the standard.

Estimating collector field power performance

Simple procedures for guaranteeing 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:

$$P_{guarantee} = A_{GF} \cdot [\eta_{0,hem}\, G_{hem} - a_1\,(\theta_m - \theta_a) - a_2\,(\theta_m - \theta_a)^2 - a_5\,(d\theta_m\,/dt)] \cdot f_{safe} \qquad \text{(eq. 1)}$$

where:

$P_{guarantee}$:	Estimated power output	
A_{GF}:	Collector area corresponding to the collector module efficiency parameters: $\eta_{0,hem}$, a_1 , a_2 and a_5	[m²]
$\eta_{0,hem}$:	Optical efficiency	[-]
a_1:	1st order heat loss coefficient	[W/(K·m²)]
a_2:	2nd order heat loss coefficient	[W/(K²·m²)]
a_5:	Effective thermal capacity of collector incl. fluid	[J/(K·m²)]
G_{hem}:	Hemispherical solar irradiance on the plane of collector	[W/m²]
θ_a:	Ambient air temperature	[°C]
θ_m:	Mean temperature of solar collector fluid	[°C]
$d\theta_m\,/dt$:	Change in mean temperature in time	[K/s]

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:

$$\theta_m = (\theta_i + \theta_e) / 2 \qquad \text{(eq. 2)}$$

where:

[1] E.g.: Solar Keymark or similar.

θ_e: Hot side of collector field (= collector outlet temperature) [°C]

θ_i: Cold side of collector field (= collector inlet temperature) [°C]

f_{safe} Combined safety factor: $f_{safe} = f_P \cdot f_U \cdot f_O$

f_P: Safety factor taking into account heat losses from pipes etc. in the collector loop; if heat losses are estimated to be 3 %, f_P is 0.97

f_U: Safety factor taking into account measurement uncertainty; to be estimated, a factor of 0.9 - 0.95 could be recommended depending on accuracy level.

f_O: Safety factor for other uncertainties e.g. related to non-ideal conditions such as non-ideal flow distribution and unforeseen heat losses; if this uncertainty is considered insignificant, F_O can normally be put close to 1.

Restrictions on operating conditions

To limit uncertainties, it is important to give restrictions on the operation conditions for which the guarantee is valid. The restrictions given here means that only measurement points taken when the collector field is close to stable full power operation are valid.

Operation condition	Limits	Comments
Shadows	No shadows	
Incidence angle	≤ 30°	
Change in collector mean temperature	≤ 5 K	To avoid big change in collector temperature during one hour
Ambient temperature	≥ 5 °C	To avoid snow, ice, condensation on solar radiation sensors
Wind velocity	≤ 10 m/s	To be measured so it is representative for the wind velocity 1 - 3 m above highest point of collectors
G_{hem}	≥ 800 W/m²	

Table 1. Restrictions on operation conditions (power method). Measured and calculated power shall only be compared for data fulfilling restrictions above.

Example 1: Give a guarantee for a collector field performance

Collector data (from e.g. Solar Keymark data sheet):

Collector field area:

Module area (gross area): 13.2 m²
Number of collector modules: 1000
A_{GF} = 13 200 m²

Corresponding collector efficiency parameters (related to gross area):

$\eta_{0,hem} = 0.80$
$a_1 = 3.0$ W/(K·m²)
$a_2 = 0.01$ W/(K²·m²)
$a_5 = 10\,000$ J/(K·m²)

Other data (safety factors):

Estimated pipe heat losses: 3 % → $f_P = 0.97$
Estimated uncertainty on measurements: 10 % → $f_U = 0.9$
Safety factor other things, estimated: $f_O = 0.95$

=> $f_{safe} = 0.829$

Equation 1 for giving the guarantee is then:

$$P_{guarantee} = A_{GF} \cdot [\eta_{0,hem}\ G_{hem} - a_1\ (\theta_m - \theta_a) - a_2\ (\theta_m - \theta_a)^2 - a_5\ (d\theta_m\ /dt)] \cdot f_{safe} \qquad [W]$$

$$P_{guarantee} = 13\ 200 \cdot [0.80\ G_{hem} - 3.0\ (\theta_m - \theta_a) - 0.01\ (\theta_m - \theta_a)^2 - 10\ 000\ (d\theta_m\ /dt)] \cdot 0.829 \qquad [W]$$

$$\underline{P_{guarantee} = 10\ 947 \cdot [0.80\ G_{hem} - 3.0\ (\theta_m - \theta_a) - 0.01\ (\theta_m - \theta_a)^2 - 10\ 000\ (d\theta_m\ /dt)]} \qquad [W]$$

Give guarantee of 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 minimum ("min") 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]

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 [K]
$T_{prim,out,min} = T_{prim,out,full} - 10$ K [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.:

$$P_{hx} = P_{guarantee}(G) \qquad [W]$$

with

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

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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 significantly different then it should be calculated as $\Delta T_{mean} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\Delta T_1 / \Delta T_2\right)}$ [K] where $\Delta T_1 = T_{prim,in} - T_{sec,out}$ [K] and $\Delta T_2 = T_{prim,out} - T_{sec,in}$ [K].

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]
$d\theta_m$	< 5	[K]
dt	= 3600	[s]
G	= 900	[W/m²]
P_{hx}	= $P_G(G)$	[W]

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

Assuming same collector field as before:

$P_G(900)$	$= 10\,947 \cdot [0.8 \cdot 900 - 3.0 \cdot 55 - 0.01 \cdot 55^2 - 10\,000 \cdot (5/3600)]$	[W]
	$= 10\,947 \cdot [720 - 165 - 30 - 14]$	[W]
	$= 10\,947 \cdot 511$	[W]
	$= 5\,593\,917$	[W]
	≈ 5.6	[MW]

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

a) transfer 5.6 MW
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:

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[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.

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

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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 = 5.6 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.

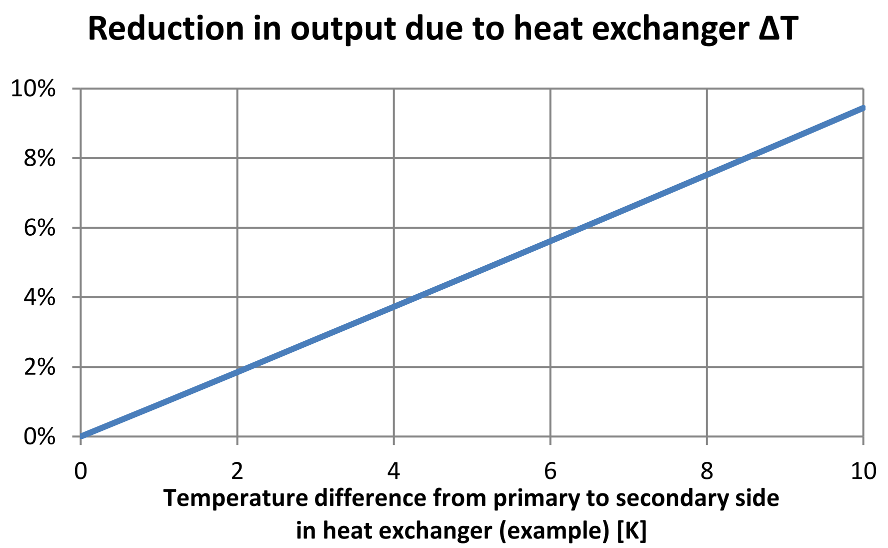

Figure 1. Example of the influence of the heat exchanger on the performance of the solar system. The higher the temperature difference across the heat exchanger (ΔT) the higher the temperature in the collector loop - and the lower the collector performance. The influence of the heat exchanger depends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

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]
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 (e.g. 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”).

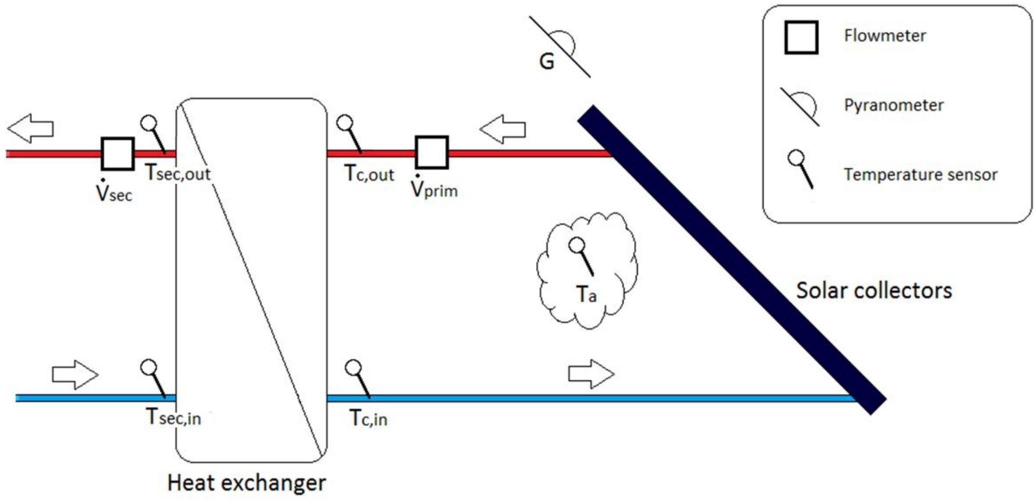

Fig. 2. Schematic drawing showing the measurement points. $T_{c,out} = T_{prim,in}$ and $T_{Cc,in} = T_{prim,out}$. (Source: PlanEnergi)

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	[m³/s] [5]
ρ_{prim}	Density of the collector fluid	[kg/m³]
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:

$G \geq 800$ W/m²
$T_a \geq 5$ °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 justified).

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:

$\sum Q_{hx,meas} \geq \sum Q_{guarantee}$ => Guarantee OK

Each $Q_{hx,meas}$ and $Q_{guarantee}$ is calculated as $P_{hx,meas}$ and $P_{guarantee}$ 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.

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

[5] Normally measured in m³/h and converted to m³/s by multiplying with 3600 s/h.

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

Guarantee is then OK.

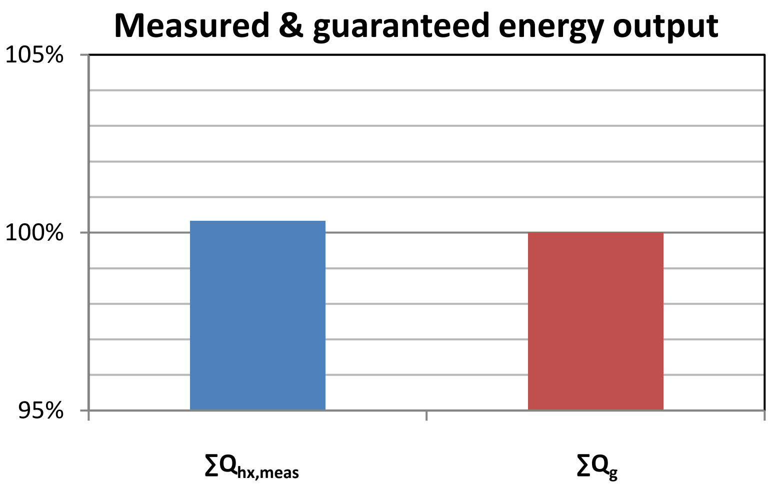

Fig.3. Plot of summarized measured energy and corresponding guaranteed energy. (Source: PlanEnergi)

Plotting the measured data points against the corresponding guaranteed ones shows that the variation of the data points looks reasonable - see fig. 4. Though there are points both above and below the red guarantee line" the sum of measurements in figure 3 shows that the guarantee indeed is fulfilled.

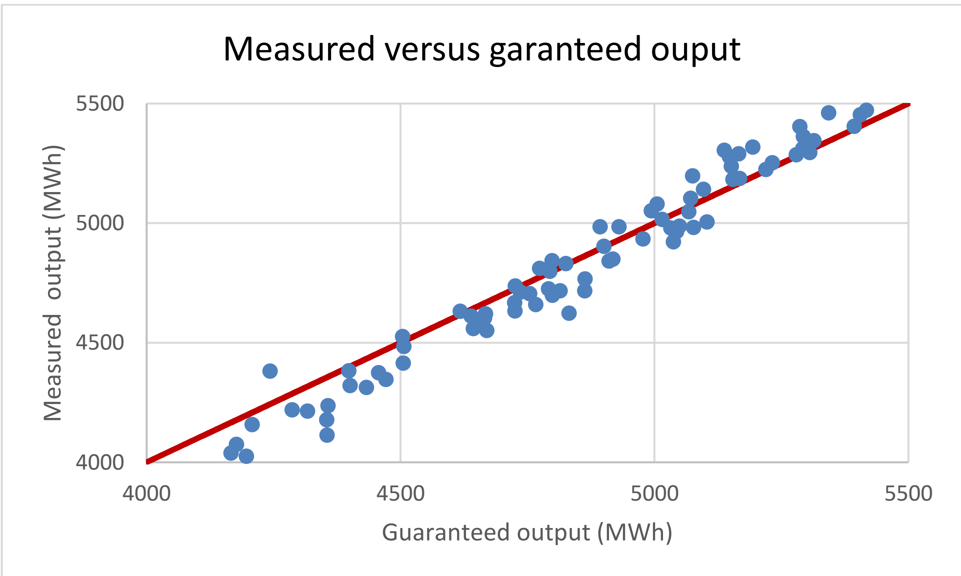

Fig.4. Plot of measured hourly energy against corresponding guaranteed hourly points. (Source: PlanEnergi).

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

$$\Delta T_{check} = f(P_{guarantee}) = c_1 \cdot P_{guarantee} + c_2 \qquad \text{[K]}$$

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

$$\Delta T_{check} = f(P_{guarantee}) \leq \Delta T_{guarantee,hx}$$

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 $\Delta T_{guarantee,hx}$ (in this case 5 K) for the given heat exchanger power $P_{guarantee}$ for which the guarantee is given (in this case 4.5 MW):

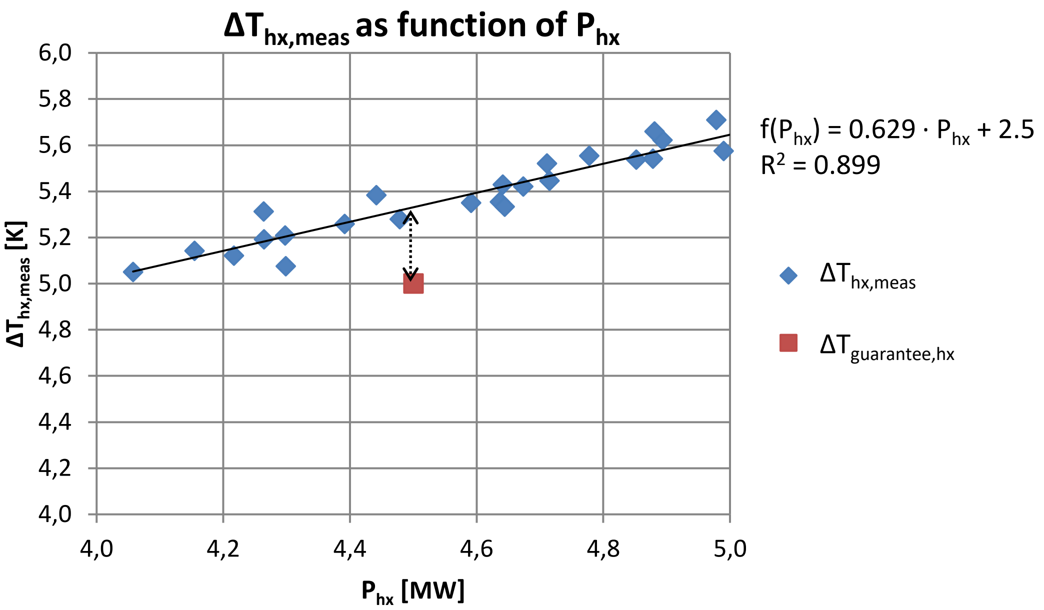

Fig.5. Logarithmic mean temperature difference across heat exchanger as function of the transferred power. Guarantee point indicated with red square at 4.5 MW; 5 K. It is seen that in this case the guarantee is NOT fulfilled! (Source: PlanEnergi)

Check of temperatures:

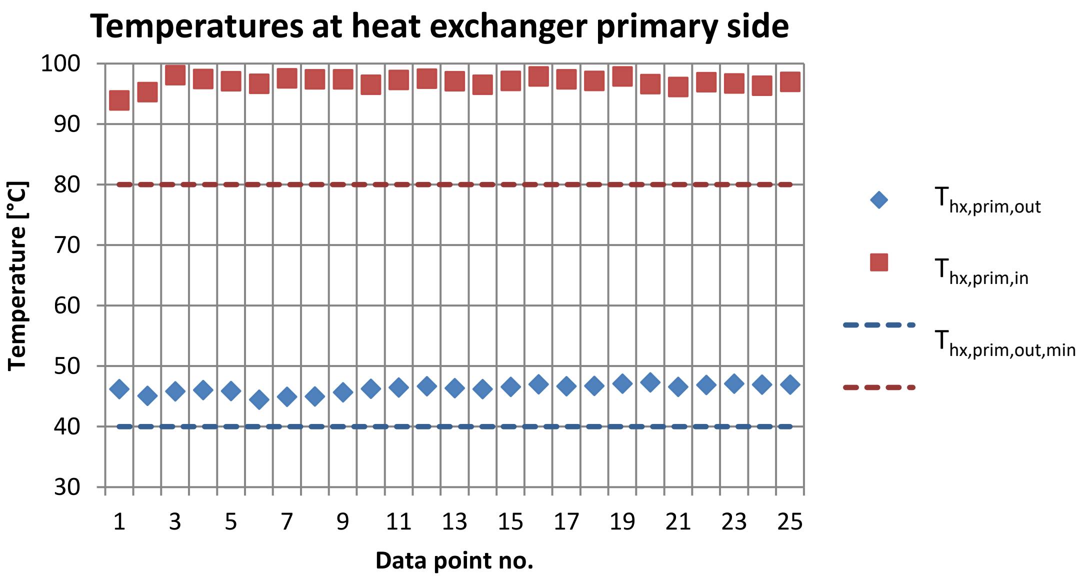

Fig.6. Temperature requirements fulfilled since $T_{hx,prim,out}$ is above $T_{hx,prim,out,min}$ (40 °C) and $T_{hx,prim,in}$ is above

Checking thermal capacity flow rate ratio:

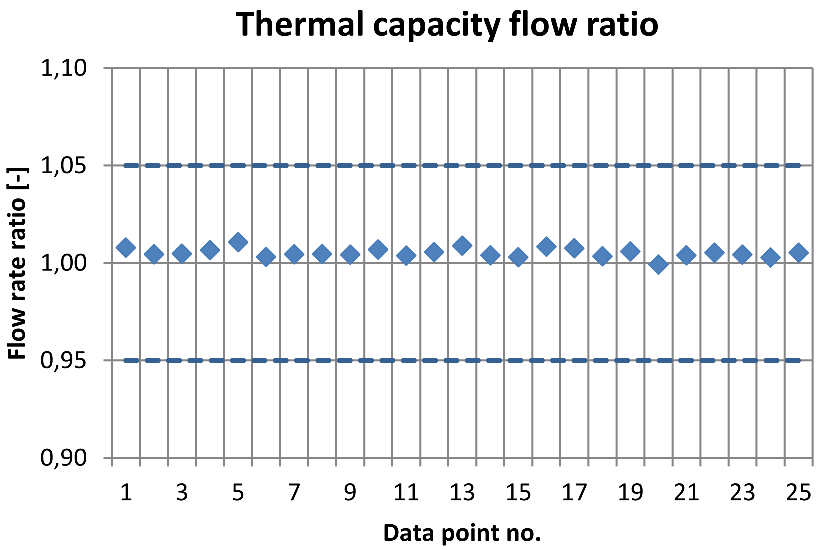

Fig.7. Capacity flow rate ratio requirement fulfilled since the measurement points are between 0.95 and 1.05 as required. (Source: PlanEnergi)

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.