Quasi-Dynamic Testing of a Novel Concentrating Photovoltaic Solar Collector According to ISO 9806:2013

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Abstract

Testing and certification of solar thermal collectors has been widely researched and improved over the years, however, many of the developments in the test standards has been focused primarily on generic flat plate collectors. In this study, the focus was on depicting the applicability of the current standard in characterizing the performance of a novel concentrating solar collector of design.

The applicability of the Quasi-Dynamic Testing (QDT) method for collector certification, by the ISO 9806:2013, is studied to be used in characterizing the novel concentrating PVT collector, and to point out the weaknesses observed, and essential additions required.

Keywords: Concentrating Photovoltaic Thermal Collector, C-PVT, Quasi-Dynamic Testing, QDT

1. Introduction

Testing and characterizing performance is an essential task when developing any new technology. Regarding solar collectors, their thermal performance must be tested and characterized. To achieve this, the two methods listed by ISO 9806:2013 are Steady State testing and Quasi-Dynamic Testing (QDT). Though testing under steady state conditions can yield useful results, testing under dynamic conditions using the Quasi-Dynamic methodology offers some advantages:

- It allows for the characterization of a wider range of collectors
- Testing can be conducted under a wider range of operating and ambient conditions
- It yields a more complete and complex characterization

The process to achieve the goals of this study is as follows: identifying the key parameters in the QDT equation, setting up the test sequence according to the QDT methodology, verifying the usability of the test system for conducting QDT by testing a generic flat plat collector, testing and characterizing a novel concentrating PVT collector, and finally comparing and analyzing the results to draw conclusions.

Looking at the thermal collector model under the QDT procedure, the Quasi-Dynamic thermal collector model equation as adapted by the ISO 9806:2013 can be identified as:

$$\frac{\dot{Q}}{A} = F'(\tau\alpha)K_{\theta b}(\theta_L,\theta_T)G_b + F'(\tau\alpha)K_{\theta d}G_d - c_1(t_m - t_a) - c_2(t_m - t_a)^2 \quad \text{(eq. 1)}$$

$$-c_3u(t_m - t_a) + c_4(E_L - \sigma T_a^4) - c_5\frac{dt_m}{dt} - C_6uG$$

Running the parametric characterization for this equation typically yields an accurate representation of the expected operational performance of a solar thermal collector. However, this does not fully cover PVT collectors or collectors with a unique geometry due to three main reasons:

- Obtaining enough data points for the transversal Incident Angle Modifier (IAM) for a non-symmetrical collector geometry can be difficult.

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- In practice, the averaging period used to obtain a single data entry point for the QDT is maximally 10 minutes, which might not necessarily be enough for a collector with a special geometry.
- The standard permits neglecting the long wave radiation if the collector to be tested is glazed, which is not always negligible for concentrating collectors operating at elevated temperatures under different sky conditions.

2. Methodology

The Quasi-Dynamic Testing (QDT) method for thermal solar collectors was implemented to characterize the thermal performance of a generic flat plate collector (FPC). This was done so that the test rig utilized could be validated. Subsequently, the QDT methodology was implemented to characterize the Solarus PowerCollector™ (PC).

2.1. Solarus PowerCollector™

Figure 1 illustrates an exploded view of the the Solarus PowerCollector™ (PC). It is a concentrating, hybrid solar photovoltaic and solar thermal panel (C-PVT). Concentrating (C) means that it has a curved mirror to collect and reflect more sunlight throughout the day. Hybrid means that it combines solar photovoltaic (PV) generation of electricity with solar thermal (T) generation heat.

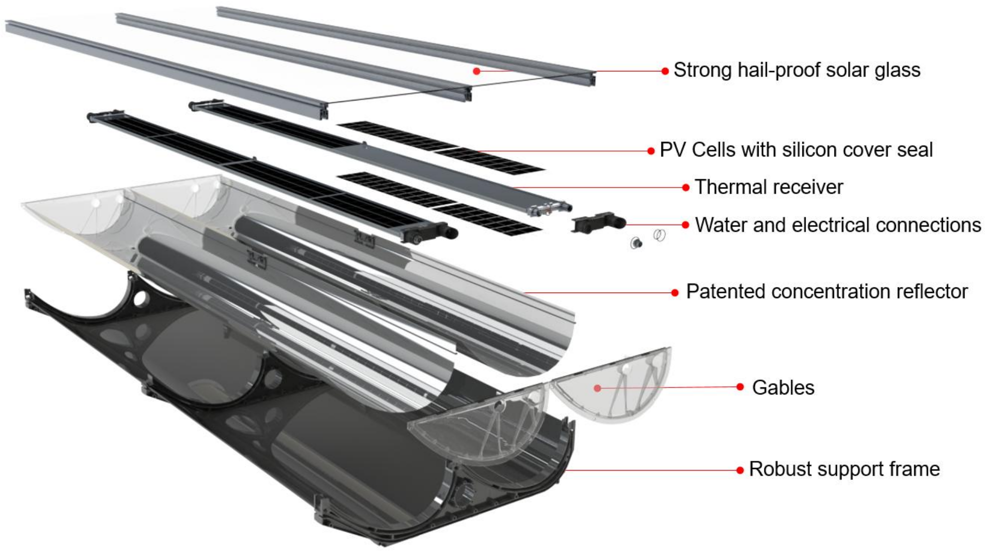

Fig. 1: Solarus PowerCollector™ (PC).

The PC consists of two major components: the collector box and the receiver core.

The collector box can be sub divided into 4 components:

- A black plastic solid frame that provides structural support to the reflector.
- A gable with a reported transparency of 90 % and that is made from Polymethylmethacrylate (PPMA) that seals the collector sides.
- A 4mm tempered solar glass with anti-reflective treatment (on both sides) to reach an absorptance of 1.5 % and a reflectance of 2 % per side.
- A 0.4 mm aluminium reflector with a concentration factor of 1.7 and a reflectance of 92 % reflectance at an air mass of 1.5, according to the standard.

The receiver core is the heart of the Solarus C-PVT. It is 2321 mm long, 165 mm wide and 14.5 mm thick. As shown in Figure 2, there are solar cells on both sides of the aluminum receiver. These solar cells are encapsulated by highly transparent silicone with a reported transparency of 97 %.

Figure 2: Receiver core.

The receiver consists on an aluminum receiver with 8 elliptical channels as shown Figure 3. The cooling fluid flows through the 8 channels in order to extract heat from the collector. The core is made of extruded aluminum.

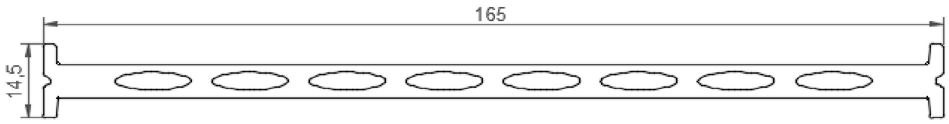

Figure 3: Elliptical channels in receiver

The collector uses standard monocrystalline solar silicon cells with an efficiency of 19.7 %. The cell string layout consists in 4 cells strings in the bottom and 4 in the top side of the receiver. This is shown in Figure 4:

Figure 4: Receiver, showing 4 cell strings and its distribution in the receiver.

2.2. Test Rig

A solar thermal collector test rig was set up on a rooftop according to the European standard EN 12975-2:2006, the predecessor to the current ISO standard, to run tests according to the SST method. Furthermore, on the roof, a rotatable mounting platform is available for mounting and testing of thermal collectors as shown in Figure 5.

Figure 5: Rooftop collector mounting stand.

The test rig possesses an advanced hydraulic circuit that is capable of sustaining testing conditions for two separate collectors and is schematically compatible with the recommended circuit layout as provided by the ISO 9806:2013 standard.

All test measurements are obtained using a data acquisition device, and this data acquisition device is connected to a computer that logs the measurements every 10 seconds. Figure 6 shows a schematic of the data measurement and logging system.

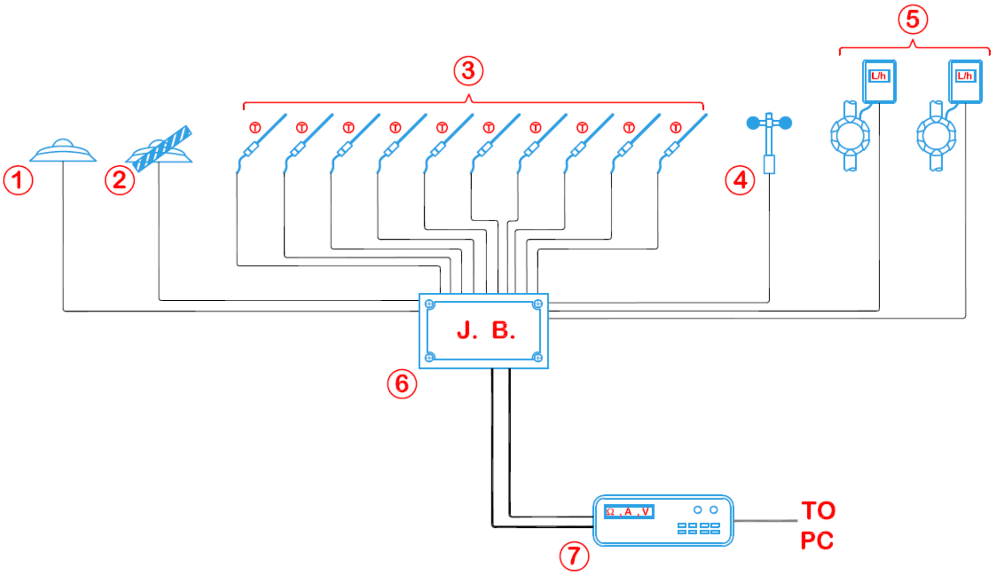

Figure 6: Data measurement and logging system.

Table 1 lists the details of the temperature and flow regulation system:

Table 1: Details of temperature and flow regulation system.

Item No.	Description	Manufacturer	Model	Relevant Info
1	Pyranometer	Kipp & Zonen	CM11	Industry standard for monitoring and logging solar irradiance. Sensitivity 7 $\mu V \cdot W^{-1} \cdot m^{-2}$ – 14 $\mu V \cdot W^{-1} \cdot m^{-2}$ Non-linearity <0.2 %.
2	Pyranometer with shading ring	Kipp & Zonen	CM11	
3	Temperature sensors	Unknown	PT100	4 wire RTD sensor, individually calibrated
4	Wind Speed sensor	Thies Clima	N/A	Accuracy ±0.5 $m \cdot s^{-1}$ Resolution <0.1 $m \cdot s^{-1}$ Range 0.5 $m \cdot s^{-1}$ – 50 $m \cdot s^{-1}$
5	Flow Sensors	Krohne	IFC 300	Electromagnetic flow sensor Accuracy ±0.3 % of mean value
6	Junction Box	--	--	--
7	Data logging device	Agilent Technologies	34972A	Highly sophisticated programmable data measurement and export device capable of high-resolution voltage, current, and resistance measurements simultaneously with PC interface for logging

A dedicated temperature and flow regulation control panel is used to regulate the operational set-values as shown in Figure 7. It offers the possibility to control the pump speed, and the heating and cooling elements, in order to achieve the required test boundaries dictated by the standard.

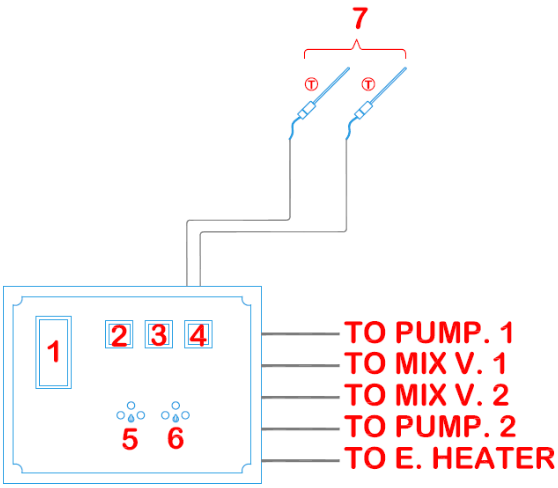

Figure 7: Temperature and flow regulation system.

Table 2 lists the details of the temperature and flow regulation system:

Table 2: Details of temperature and flow regulation system.

Item No.	Description	Manufacturer	Model	Relevant Info
1	Pump control panel	Danfoss	2216e	Frequency drive pump controller regulating the primary pump (Pump. 1) flow rate
2	Heater control unit	Eurotherm	2216e	PID controller regulating operation of the system's electrical heating elements based on a temperature set point, temperature signal is taken from an RTD sensor located in line after the heating element.
3	Control unit – cooling circuit 1	Eurotherm	2216e	PID controller regulating operation of the system's borehole cooling pump (Pump. 2) and mixing valve (Mix V. 1) based on a temperature set point, temperature signal is taken from an RTD sensor located in line after the cooling circuit heat exchanger.
4	Control unit – cooling circuit 2	Eurotherm	2216e	Unused heat pump cooling circuit controller
5	Mixing valve – cooling circuit 1	--	--	Electrically actuated mixing valve controlled by the borehole cooling control unit to regulate the coolant fluid flow from the borehole.
6	Mixing valve – cooling circuit 2	--	--	Unused heat pump cooling circuit mixer
7	Temperature sensors	Unknown	PT100	2 RTD sensor, one after the heating element, and one after cooling circuit 1

2.3. Testing Procedure

The testing procedure for the FPC and the PC are almost identical and consisted of the following steps:

- Full day tests including all day type sequences were conducted. This lasted 7 days for the FPC and 17 days for the PC. Data was logged at 100 second intervals.
- The raw data was filtered so that unusable data points could be removed. Input values were averaged over

a period of 10 minutes to characterize the thermal capacitance.

- The data was validated via visual inspection to check for compliance with the required criteria for QDT. Four visual inspections of data are conducted. First, the reduced temperature vs total irradiance is plotted. It is checked to make sure that all the inlet temperatures tested can be identified. Second, diffuse irradiance vs total irradiance is plotted. From this it is ensured that the diffuse irradiance fraction is within acceptable limits. Third, wind speed vs total irradiance is plotted. From this it is ensured the wind distribution is diverse over a range of irradiance as required by the standard. Finally, incidence angle vs beam and diffuse irradiance is plotted. It is ensured that a diverse distribution of beam and diffuse irradiance is achieved for the full range of incidence angles.
- Multiple Linear Regression (MLS) is used to determine the required coefficients.

3. Results

3.1 Test results for the flat plat collector under QDT conditions

An outdoor test was conducted under QDT conditions to characterize the FPC.

Latitude: 60.48°

Longitude: 15.44°

Collector azimuth: 0°

Collector tilt: 35°

Orientation of absorber tubes during testing: Horizontal

Peak Power, $\dot{Q_p}$ $(G = 1000\ W/m^2)$ per collector unit: 1490 W

Table 3 shows the power output for the FPC:

Table 3: Power output in W/m^2 (FPC).

Irradiance			
t_m-t_a [K]	**400 W·m^{-2} (G_b=200 W·m^{-2}, G_d=200 W·m^{-2})**	**700 W·m^{-2} (G_b=440 W·m^{-2}, G_d=260 W·m^{-2})**	**1000 W·m^{-2} (G_b=850 W·m^{-2}, G_d=150 W·m^{-2})**
0	570	1,020	1,490
10	470	910	1,380
30	260	710	1,180
50	50	500	970
70	0	290	760
89	0	100	570

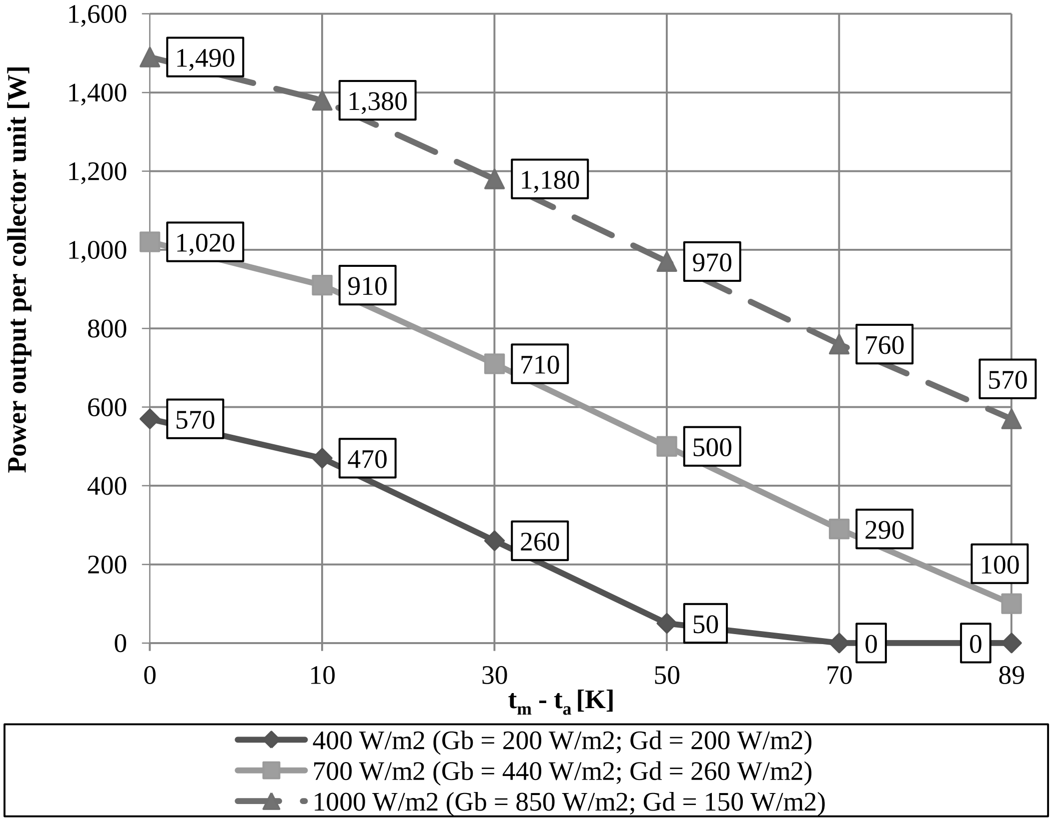

Figure 8: Power output per collector unit (FPC).

Thermal performance based on gross area and mean temperature of heat transfer fluid.

Gross area used for curve: 2.00 m^2

Fluid flow rate used for the test: 0.04 kg/s

Table 4 lists the thermal performance formula (equation 1) coefficients for the FPC:

Table 4: Thermal performance formula coefficients

Gross Area: 2.00 m^2		
Coefficient	**Value**	**Standard deviation**
$\eta_{0,b}$	75.5%	2%
$K_{\theta d}$	0.90	1%
b_0	0.136	2%
C_1	4.352	-2%
C_2	0	-
C_3	0.28	-22%
C_4	0	-
C_5	-6,779	11%
C_6	0	-

Table 5 lists the incidence angle modifier for the Solarus PC:

Table 5: Incidence angle modifier

θ	10	20	30	40	50	60	70	80
$K_{\theta b}$	0.98	0.98	0.97	0.95	0.92	0.90	0.80	0.72

3.2 Test results for Solarus PowerCollector™ under QDT conditions

An outdoor test was conducted under QDT conditions to characterize the Solarus PC.

Outdoor test.

Latitude: 60.48°

Longitude: 15.44°

Collector azimuth: 0°

Collector tilt: 35°

Orientation of absorber tubes during testing: Horizontal

Table 6 shows the power output for the FPC:

Table 6: Power Output (PC)

	Irradiance		
t_m-t_a [K]	**400 W/m^2 (G_b=200 W/m^2, G_d=200 W/m^2)**	**700 W/m^2 (G_b=440 W/m^2, G_d=260 W/m^2)**	**1000 W/m^2 (G_b=850 W/m^2, G_d=150 W/m^2)**
0	350	680	1,140
10	290	620	1,090
30	150	480	940
50	0	290	750
70	0	50	510
105	0	0	0

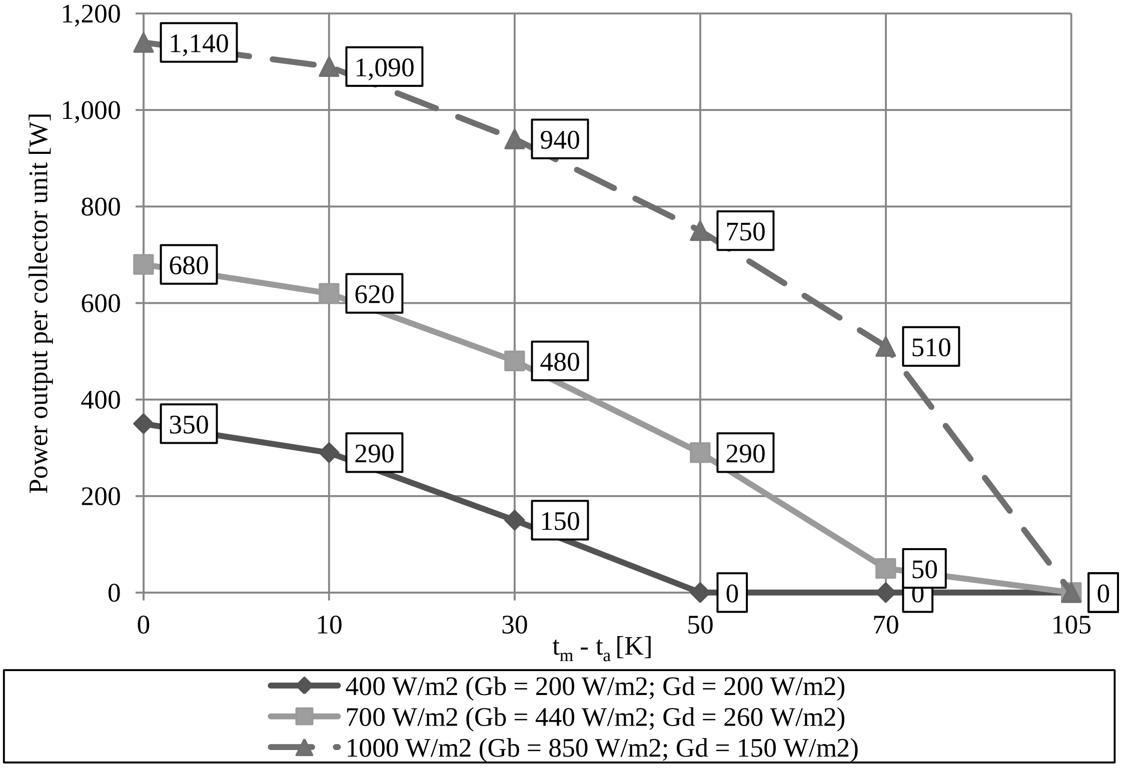

Figure 9: Power output per collector unit (FPC).

Thermal performance Based on gross area and mean temperature of heat transfer fluid.

Gross area used for curve: 2.57 m^2

Fluid flow rate used for the test: 0.04 kg/s

Table 7 lists the thermal performance formula (equation 1) coefficients for the Solarus PC:

Table 7: Thermal performance formula coefficients (PC)

Gross Area: 2.57 m^2		
Coefficient	**Value**	**Standard deviation**
$\boldsymbol{\eta_{0,b}}$	48.9%	3%
$\boldsymbol{K_{\theta d}}$	0.38	9%
$\mathbf{b_0}$	0.192	3%
$\mathbf{C_1}$	1.294	-20%
$\mathbf{C_2}$	0.023	-14%
$\mathbf{C_3}$	0.2	-74%
$\mathbf{C_4}$	0	-
$\mathbf{C_5}$	-5929	38%
$\mathbf{C_6}$	0	-

Table 8 lists the incidence angle modifier for the Solarus PC:

Table 8: Incidence angle modifier (PC)

θ	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
$\boldsymbol{K_{\theta b}}$	0.96	0.94	0.96	0.95	0.89	0.78	0.71	0.46

4. Discussion and Conclusions

4.1 Flat Plate Collector

To test the parameter characterization of the FPC, actual power generated is plotted against the power calculated from the formulated model. The results of both are in harmony indicating the success in the parameter characterization. These results were as expected and also validate the test rig. This was confirmed and illustrated in Figure 10.

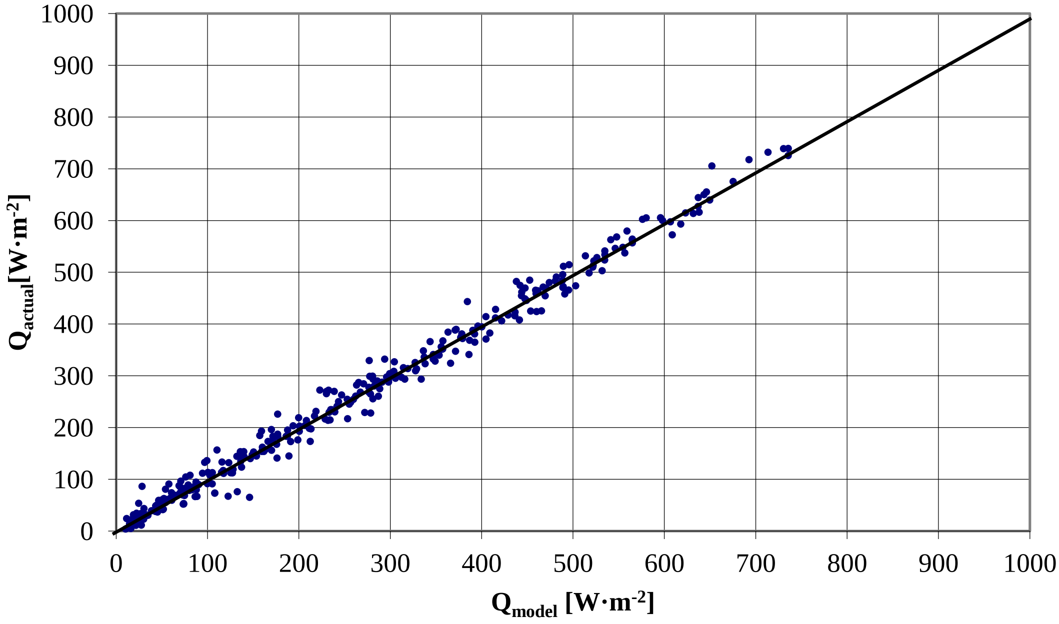

Figure 10: Actual measured production to model predicted production (FPC).

Coefficients C_4 and C_6, where omitted as per the recommendation of the standard or glazed collectors. On the other hand, coefficient C_2 (the temperature dependence of heat losses) is usually essential in the model unless it comes out as statistically insignificant even with enough data points at elevated testing temperature, in that case the standard permits omitting it and the MLR is repeated without including its data.

However, coefficient C_3 could have been omitted initially, but it was attempted to include its data points, and they proved to be statistically significant to be include in the model even though it possesses a relatively high standard deviation.

4.2 Solarus PowerCollector™

Although with a higher standard deviation, the power output from both the formulated model and measured the values were congruent. Hence, it can be concluded that the parameter characterization was successful. This was confirmed and illustrated in Figure 11.

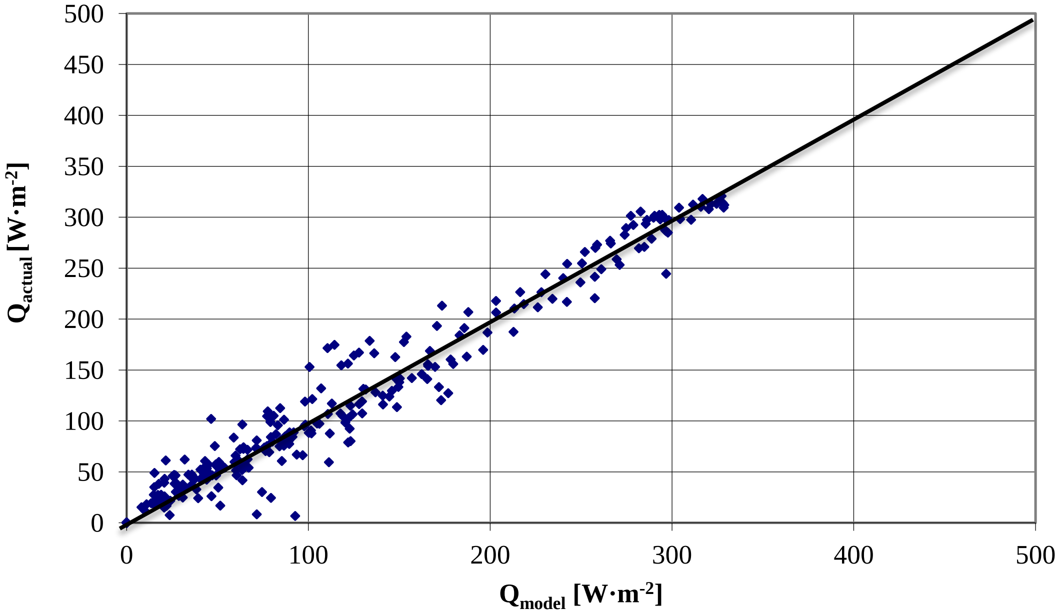

Figure 11: Actual measured production to model predicted production (PC).

Furthermore, the power production using the obtained parameters of QDT and the parameters obtained from the AEL test lab (η=0.496, a_1=3.155W/m^{2}K, a_2=0.022W/m^{2}K^2) is shown in Figure 12. Comparison conditions assumed at 1000W/m^2 hemispherical irradiance, no diffuse, 3m/s wind speed, and normal incidence angle. The results in this comparison are also in congruence.

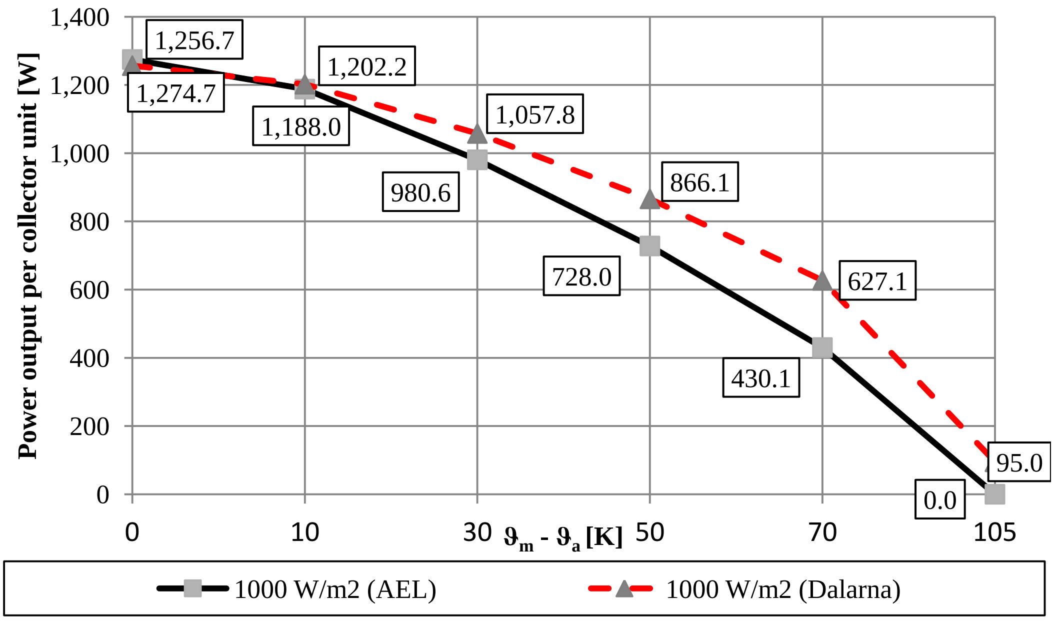

Figure 12: Actual measured production to model predicted production (PC).

5. References

Fischer, S., Heidemanna, W., Müller-Steinhagena, H., Perersb, B., Bergquistc, P., Hellströmd, B., Collector test method under quasi-dynamic conditions according to the European Standard EN 12975-2, Solar Energy, Vol. 76, Issues 1-3, 117-123.

International Organization for Standards, 2013, ISO/FDIS 9806: Solar energy — Solar thermal collectors — Test methods.

Osório, T., Carvalho, M.J., Testing of solar thermal collectors under transient conditions, Solar Energy, Vol. 104, 71-81

Seené, G., Ollas, P., Optimization of the Quasi Dynamic Method for Solar Collector Testing.