Performance Evaluation of a High Solar Fraction CPC-Collector System

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Abstract

One of the most important goals on solar collector development is to increase the system's solar fraction. The studied collector is formed by a compound parabolic reflector which decreases the collector optical efficiency during the summer period. Hence, it is possible to increase the collector area and thus, the annual solar fraction, without increasing the overproduction. Collector measurements were fed into a validated TRNSYS model which estimates the solar fraction of the concentrating system and also that of a traditional flat plate collector, both for domestic hot water production. The system design approach aims to maximise the collector area until an annual overproduction limit is reached. Then, the highest solar fraction achieved by both systems was determined. The results show that, at 50° tilt, the concentrating system achieves 68% solar fraction using 17 m^2 of collector area compared to 66% solar fraction and 7 m^2 of a flat plate collector system. Thus, it is possible to install larger collector areas and achieve a higher solar fraction using the load adapted collector. However, the summer optical efficiency reduction was proved to be too abrupt. Consequently, the area increase is too big and the absorber surface of both systems becomes comparable making it difficult for the concentrating collector to compete with a conventional flat plate collector. However, if the reflector geometry is properly design, the load adapted collector can be a competitive solution in the market since it can be produced in a cheap way.

Keywords: Concentrating, Solar Thermal, Domestic Hot Water System, High Solar Fraction

Nomenclature

Monitored parameters:

P	Collector thermal power (W/m²)
G_b	Beam Irradiance (W/m²)
G_d	Diffuse Irradiance (W/m²)
T_{in}	Inlet temperature (°C)
T_{out}	Outlet temperature (°C)
T_f	Fluid mean temperature (°C)
T_{amb}	Ambient temperature (°C)
dV/dt	Flow (m^3/s)
C_p	Heat capacity (water) (J/(kg°C))
ρ	Density (water) (kg/m^3)
A_c	Collector area (m²)

Parameters in the collector model:

η_{od}	Diffuse efficiency (%)
η_{ob}	Beam thermal efficiency (%)
a_1	Heat loss factor (W/m^2 °C)
a_2	Temperature dependence of heat loss factor (W/m^2 °C^2)
K_{tab}	Incidence modifier for beam irradiance (-)
K_{tab_l}	Longitudinal incidence modifier for beam irradiance (-)
K_{tab_t}	Transversal incidence modifier for beam irradiance (-)
K_{tad}	Incidence modifier for diffuse irradiance (-)
$(mC)_e$	Collector effective thermal capacitance (J/(m^2°C))
θ	Angle of incidence onto the collector (°)

1. Introduction

One of the most important goals to be achieved by a solar thermal system is a high annual solar fraction (Mills and Morrison, 2003; Helgesson et al., 2002). While solar thermal systems can generally achieve a high annual fraction in areas near the equator, in regions where the annual solar irradiation is lower this can be difficult. In most such regions, the solar contribution profile peaks during the summer months and decreases during the winter period. On the contrary, the domestic hot water load is fairly constant during the whole year which means that these two factors do not match all year round. Thus, the annual net utilized solar energy is reduced.

It is common to design the system collector area so that the production over the summer period meets the thermal load (Helgesson A., 2004). The aim of these systems is to achieve a solar fraction close to 100% during this period and do not take into account the overproduction level. However, the solar production and consumption profiles are very different throughout the day. The solar production does not entirely take place at the same time as it is consumed by the users. Some of this extra energy can be stored in the solar tank, but not all of it. Hence, the system ends up with many hours where the collectors are in stagnation and many others where auxiliary energy is needed. Consequently, the real net utilized solar energy is much lower and the overproduction much higher than the system initially was thought to achieve. Furthermore, long stagnation periods influence long-term reliability and low maintenance operation of the collector system (Hausner R. and Fink C., 2000). Common problems are overheating and permanent damage on system components, regular loss of fluid, condensation pressure chocks, deterioration of the fluid that ends up clogging the system, fluid circulation noise (Hausner R. and Fink C., 2002). Hence, there is a need to define a deterioration factor taken into account when designing a new system. This factor limits the stagnation hours along the year and, consequently, minimizes the risk of system malfunctions along its lifetime. Also, there exists no validation model of the asymmetric compound parabolic collector (CPC) load adapted system. Related concepts to this collector have been reported by, for example, Tripanagnostopoulos et al. (2000), Norton et al. (1991), Chaves and Collares Pereira (2000), Mills and Morrison (2003).

This paper describes a collector design approach that increases the solar fraction by maximizing the energy contribution of the thermal collector system but also limiting the overproduction. This is accomplished by using the collector special design with optimal tilt, collector area and flow. As a result of these optimizations, the system is able to reduce the difference between the solar production and the domestic hot water load throughout the year and still avoid overproduction under a user-determined value. The collector parameters were determined based on a dynamic testing method and multi linear regression (Perers B., 1997). These parameters were then fed into a validated model in TRNSYS (Klein S., 1997) estimating the CPC collector system performance and comparing it with a flat plate collector system.

To increase the paper readability and to highlight its contributions to the field, the main objectives of the work are summarised below:

- To suggest a new design approach for solar thermal systems and apply it to a case study of a CPC load adapted collector system;
- To evaluate the performance of the CPC collector system and compare it with a conventional flat plate collector system.

2. Method

2.1. Experimental setup and collector design

A solar collector design in which relatively expensive selective absorber material is replaced by cheap reflectors was studied. The compound parabolic concentrator (CPC) collector with a geometrical concentration factor of 1.5 has been developed (Adsten M., 2004). The collector consists of a reflector, a bi-facial selective absorber and a support structure. The parabolic reflector has an optical axis normal to the collector glass which defines the irradiation acceptance interval of the reflector (Figure 1) (Helgesson et al., 2004). Once the incident radiation is outside this interval, the reflectors do not redirect the incoming beam radiation to the absorber, and the optical efficiency of the collector is reduced (Figure 1). Hence, the collector's optical efficiency changes throughout the year depending on the projected solar altitude. The tilt determines the amount of total annual irradiation kept within the acceptance interval. As a result, by varying the tilt, it is possible to increase the collector area without causing overproduction in the summer when the collector has lower optical efficiency. This type of collector is designated by irradiation balanced collector (Duffie and Beckman, 2006). The bifacial absorber used is a commercial product featuring a selective surface on both sides with high absorbance and low emission factors. Since the absorber is parallel to the glass in the upper part of the collector, a pocket of hot air is created decreasing convection heat losses. The support structure is made of light wood with empty spaces in between in order to reduce its weight, wind obstruction and material costs.

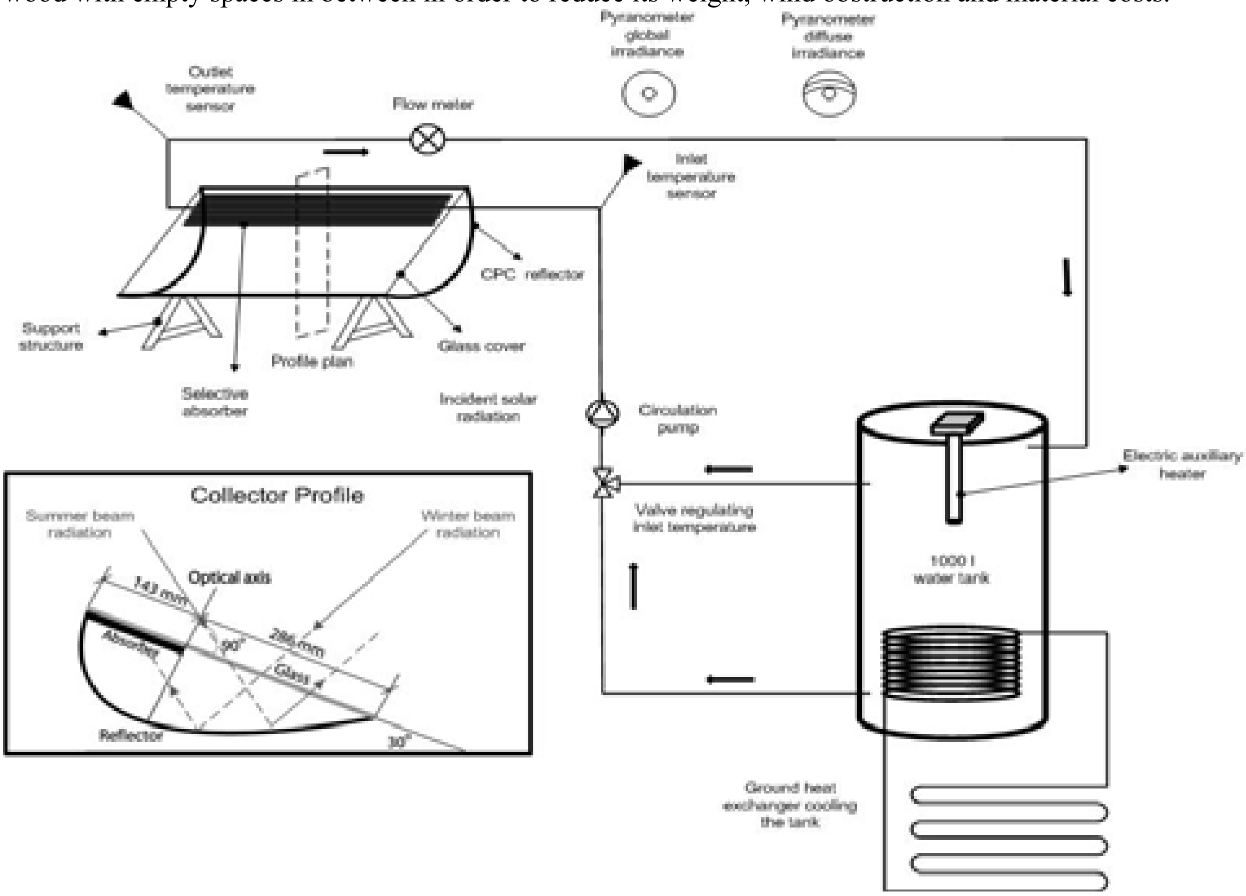

Figure 1. Experimental setup and CPC collector profile.

2.2. Testing and characterization method

Several measurements were carried out on the CPC collector in order to calculate the necessary parameters for the annual performance simulations. Measured average data was stored every 6 minutes between the 20th and the 29th of September, 2009. A simplified dynamic test method for determination of non-linear optical and thermal characteristics with multiple linear regretion was used (Perers, 1993; Perers, 1997; Duffie and Beckman, 2006):

$$P=\eta_{ob}\cdot K_{tab}(\theta)\cdot G_b + \eta_{od}\, K_{tad}\cdot G_d - a_1\cdot((T_{out}+T_{in})/2-T_{amb}) - a_2\cdot((T_{out}+T_{in})/2-T_{amb})^2-(mC)e\cdot dT_f/dt \quad (1)$$

where $K_{tab}(\theta)=K_{tab\_l}(\theta_l)\cdot K_{tab\_t}(\theta_t)$ (2)

$P=(\rho\ dV/dt \cdot C_p \cdot (T_{out}-T_{in})/A_c)$ (W/m²) (3)

In order to accurately determine the collector incidence angle modifiers, a special measurement procedure was performed. A biaxial method to model the incidence angle modifiers in the transversal and longitudinal plan was used. First, the influence of the glazing was measured in the longitudinal direction when the transversal incident angle is also constant. Secondly, the dependence of the reflector was measured on the transversal plane when the longitudinal incidence angle is constant. This was carried out by testing 2 identical CPC collectors during the autumn equinox, both tilted 55˚ from horizontal (Lund's latitude) but placing one of them horizontally and the other vertically like shown in Figure 2. This procedure is described in detail in (Helgesson, 2004). Typically, the measured curves are included in the collector model using a matrix made of singular incidence angle modifiers. The rest of them are linearly interpolated. In this study, the measured curves were included in the modelled using high grade polynomial equations. Hence, interpolations are avoided and the accuracy of the model increased.

2.3. Simulation model

A TRSNSYS model describing the whole solar collector system was created. Its main components are the CPC collector, radiation processor, circulation pump, domestic hot water load profile and storage tank with internal heat exchanger and auxiliary heater (Figure 3). The CPC collector model was created by Bengt Perers and further developed by Hellström, Bales, Fisher, Haller, Dalibard and Paavilainen (Perers and Bales, 2002). In this study, the biaxial incidence angle modifiers described by polynomial equations were added to the model. All the other components exist in the standard validated TRNSYS library. The storage tank volume is 300 litters and the auxiliary heater power is 3kW. The domestic hot water load profile were built based on the one described by (Lundh et al., 2009) but scaled to the latest data on Swedish total hot water consumption (Stengård 2009). 7 different water draw-offs were performed during the day. Furthermore, the annual hot water consumption variation effect was also introduced (Stengård 2009). The total annual consumption was set to 2050 kWh/year. The annual overproduction limit is 5000 ˚C.hour/year. This value takes into account not only the number of stagnation hours but also how much the temperature of the collector raised over 100 ˚C during that period. This value represents a reasonable maximum overproduction (100 hours of stagnation with 150˚C collector temperatur). This choice is further discussed on the "Performance analysis and discussion" section. Finally, by simulation iterations, the maximum collector area that corresponds to the maximum solar fraction but limiting the overproduction to 5000 ˚C.hour/year was determined. The collector flow was design to maximise the solar fraction for each collector area and tilt angle.

Figure 2 – CPC collector turned 90˚ during the autumn equinox.

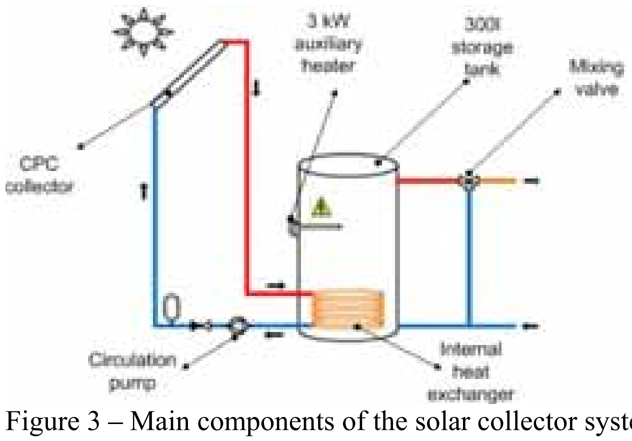

Figure 3 – Main components of the solar collector system model.

3. Measurement results

3.1. Thermal performance

The CPC collector parameters, estimated using multi linear regression on the measured data, and the parameters assumed to be typical for conventional flat plate collectors are presented in Table 1 and Table 2 respectivly.

Table 1. Measured CPC collector parameters.

Parameter	Value	Units
η_{ob}	0.64	(-)
η_{od}	0.31	(-)
a_1	2.8	W/m^2 °C
a_2	0.035	W/m^2 °C
$(mC)_e$	1923	J/m2 °C

Table 2. Typical flat plate collector parameters.

Parameter	Value	Units
η_{ob}	0.8	(-)
η_{od}	0.9	(-)
a_1	3.6	W/m^2 °C
a_2	0.014	W/m^2 °C
b_o	0.2	(-)
$(mC)_e$	8000	J/m2 °C

3.2. Incidence angle modifiers

The longitudinal and transversal incidence angle modifiers describing the glazed and reflector influence are shown in Figure 4. In order to obtain a symmetric curve for the longitudinal incidence angle modifier, and since this effect on glass has been often tested and documented, a theoretical equation was used to estimate these values.

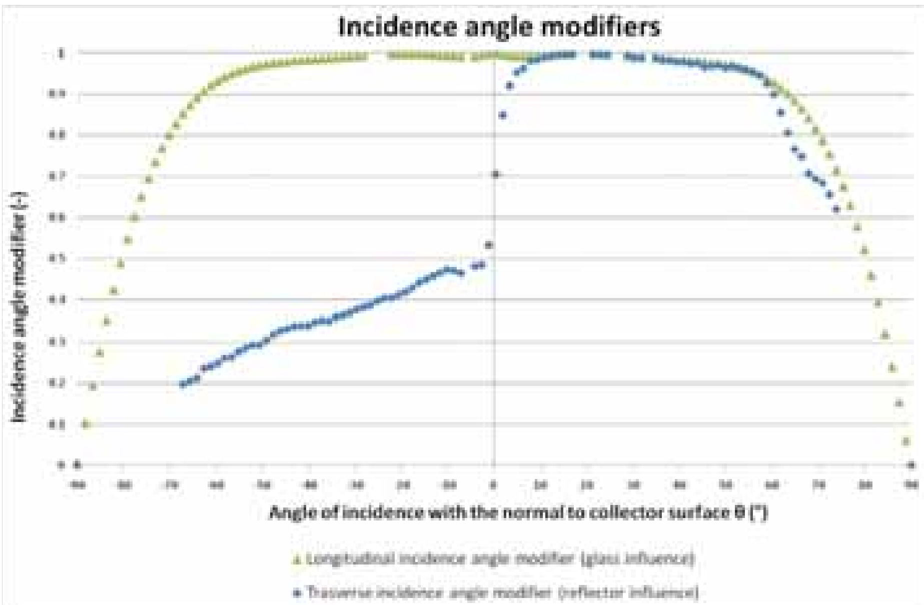

Figure 4 –Transverse and longitudinal incidence angle modifiers during autumn equinox

3.3. Model validation

In order to validate the CPC collector model, the measured and modelled power outputs were compared during the testing period (Figure 5). From the analysis of Figure 5, once can conclude that good agreement was found between the model and the measurements. In total, during that period the model underestimates the measured output by 8%. It was assumed that the CPC collector model is the only component that requires validation. The other components are standard and have been used with great reliability in the scientific community.

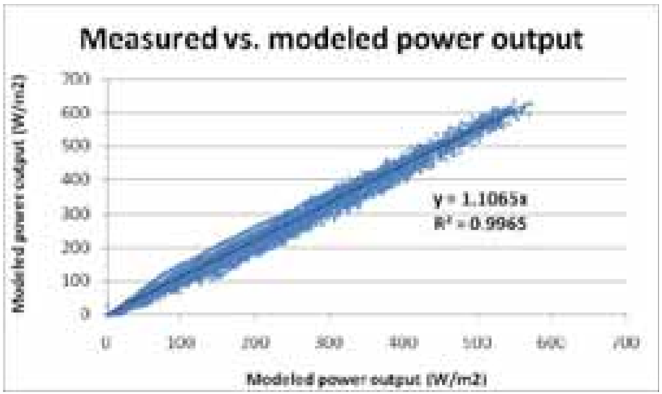

Figure 5 – Model and measured power output data during the testing period.

4. Performance analysis and discussion

Using the collector measured parameters, TRNSYS simulations were carried out for the concentrating collector and a traditional flat plate solar system situated in Lund, Sweden. The maximum solar fraction achieved by both systems, for several different tilts, is presented in the left axis on Figure 6. The correspondent maximum collector area that limits the annual overproduction under 5000˚C.hour/year is shown in the right axis of the same figure. Analysing this results one can understand that when the concentrating collector is set to low tilts the optical efficiency is high during the whole year and it behaves like a flat plate collector with peak production in the summer. On the other hand, when it is set to higher tilts, the optical efficiency is reduced along the year and overproduction only occurs for large collector areas. The balance between these two situations for Lund is somewhere around 50˚ tilt where the optical efficiency is only reduced during the summer resulting in a high annual solar fraction and still not using extremely large collector areas. For that tilt, the load adapted system achieves a solar fraction of 68% using 17 m2 of collector area compared to 66% and 7 m2 of a flat plate collector system. In Figure 7, the annual production profile of the 2 solar systems is presented for 50˚ tilt. One can notice the suppressed solar production during the summer in the CPC collector and the overproduction moved to the spring and autumn periods. When the CPC collector system achieves higher solar fractions than the flat plate collector system, it requires, at least, almost 3 times more collector area. Taking into account that the selective absorber surface of the CPC collector is 1/3 of its total glazed area (Figure 1), once can say that the absorber area in both systems is comparable. Since this component is considered to be the most expensive in the collector, it becomes very hard for the CPC collector system to compete with conventional flat plate collectors, for this particular design model. This is due to the exaggerated optical efficiency decrease which drops off to less than half of its highest value causing underproduction during the summer. However, if the reflector is design properly, the CPC collector can become a competitive solution since it can be produced in a cheap way.

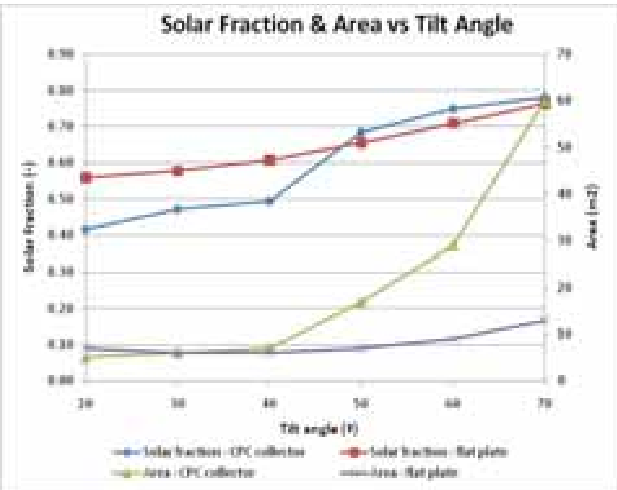

Figure 6 – Annual solar fraction and correspondent collector areas for both systems.

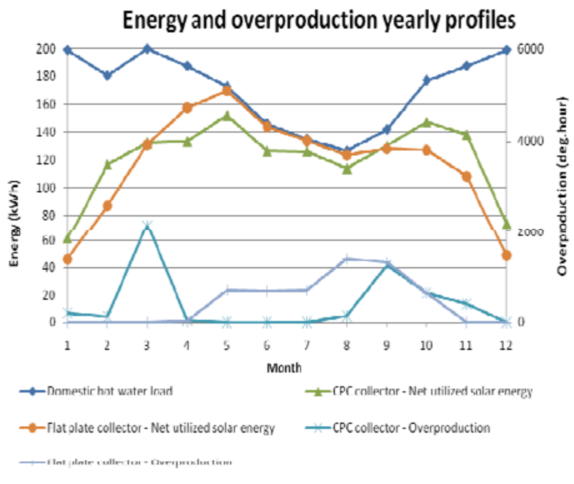

Figure 7 – Energy and overproduction profiles during the year for 50˚ tilt, 17m^2 of collector area and 0.12 l/min/m^2 of water flow.

It is also important to discuss the chosen value for the overproduction limit adjusting the system design. For larger overproduction limits, the CPC collector field is already covering the demand and the increase on collector area does not correspond to a proportional increase on the solar fraction. In fact, it will increase the overproduction instead. Thus, 5000 ˚C.hour/year was found to be a reasonable design limit for this system.

5. Conclusions

An evaluation of a load adapted CPC collector system was presented. The collector design aims to increase the solar fraction by adapting the solar production to the load. The evaluation includes a new design approach for the collector system that estimates the collector area based on an annual overproduction limit. A comparison with a standard flat plate collector system is also included.

The results show that, between 50˚ and 60˚ tilt, it is possible to install larger collector areas of the concentrating system and achieve higher solar fractions without increasing overproduction. For 50˚tilt, the concentrating system achieves 68% solar fraction using 17 m^2 of collector area compared to 66% solar fraction and 7 m^2 of a flat plate collector system. For the same glazed area, the absorber surface of the concentrating system is 1/3 that of the flat plate collector. Thus, from the result analysis, one can conclude that the collector area increase makes the total absorber area, in both systems, comparable. Hence, taking into account that the absorber area is the most expensive part of a collector, it becomes difficult for the concentrating system to compete with standard flat plate collectors. Nevertheless, this fact is valid for this particular collector design where the optical efficiency is reduced to less than half of its highest values during the summer. This exaggerated effect causes underproduction during this period reducing the annual solar fraction. If future models are developed with the appropriate reflector geometry, the collector can become a competitive solution in the market since it can be produced in a cheap way.

Acknowledgement

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References

Duffie, J.A., Beckman, W.A., 2006. Solar Engineering of Thermal Process. John Wiley & Sons.

Hausner, R. and Fink, C., 2000. Stagnation behavior of thermal solar systems. Download available at www.aee-intec.at/0uploads/dateien119.pdf.

Hausner, R. and Fink, C., 2002. Stagnation behavior of solar thermal systems. IEA SHC, task 26.

Tripanagnostopoulos, Y., Yianoulis, P., Papaefthimiou, S. and Zafeiratos, S., 2000. CPC solar collectors with flat bifacial absorbers. Solar Energy 69, 191-203.

Helgesson, A., Karlsson, B. and Nordlander, S., 2002. Evaluation of a Spring/Fall-MaReCo. In: proceedings of Eurosun Conference, Bologna.

Helgesson, A., 2004. Optical Characterization of Solar Collectors from Outdoor Measurements. Licentiate thesis, ISBN 91-85147-07-9, pp 293-294.

Klein, S. et al., 1999. TRNSYS, a Transient System Simulation. University of Wisconsin, Madison.

Adsten, M., Helgesson, A. and Karlsson, B., 2004. Evaluation of CPC-collector designs for stand-alone, roof- or wall installation. Solar Energy 79(6), 638-647.

Mills, D. and Morrison, G., 2003. Optimisation of minimum backup solar water heating system. Solar Energy 74(6), 505-511.

Perers, B., 1997. An improved dynamic solar collector test method for determination of non-linear optical and thermal characteristics with multiple regression. Solar Energy 59, 163-178.

Stengård, L., 2009. Energimyndigheten rapport 2009.

Widén, J., Lundh, M., Vassileva, I., Dahlquist, E., Ellegård, K. and Wäckelgård, E., 2009. Constructing load profiles for household electricity and hot water from time-use data—Modelling approach and validation. Energy and Buildings 41(7), pp 753-768.