IEA SHC Task 49

SolarPACES Annex IV

Solar Process Heat for Production and Advanced Applications

Comparison of process heat collectors with respect to technical and economic conditions

Technical Report A.2.1

Authors:
Federico Giovannetti, ISFH
Pedro Horta, FhG ISE

With contributions by:
Heinz Marthy and Mercedes Hannelore Rittmann-Frank, SPF
Sven Fahr and Korbinian Kramer, FhG ISE
Julian Hertel and Victor Martinez, UIB
Marco Scarpellino and Vittorio Palmieri, TVP Solar

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1 Introduction

Whereas the optimal design of Solar systems in the scope of Solar Heat for Industrial Processes (SHIP) is a matter of detailed system simulation, a preliminary analysis on the technical-economic feasibility of such investment must rely on a simplified methodology enabling an assessment of system design boundary conditions: heat load, suitable technologies, estimated yield and economic analysis.

Process temperatures found in industrial processes are manifold, ranging from low (T<100ºC), medium (100ºC < T < 250ºC) to high (T > 250ºC) operating temperatures: low and medium temperature processes presenting a high share of heat demands on the mining, food & beverage, tobacco, pulp & paper, machinery and transport equipment manufacturing sectors; high temperatures presenting a high share of heat demand on the chemical, non-metallic minerals and basic metals production sectors (Ecoheat 2006)

As thermal losses (thus efficiency) in a solar collector are directly related to the operating temperature and different solar collector technological concepts are based on different strategies aiming the minimization of heat losses at increasingly higher operating temperatures, the range of solar collector technologies suiting process heat applications is also wide: stationary, tracking, air-filled, evacuated – all of them presenting optical and thermal specificities and falling into different technology cost ranges, determining their technical and economic performance under prescribed operating conditions.

In view of assuring the means of comparing different technological possibilities, technology independent yield assessment methodologies are required. The available solar collector standard ISO 9806 (2013) provides already a solar collector model enabling such a common framework for technology inter-comparison. Setting the backbone for such a technology independent approach, such model is able to deliver detailed simulation results in the framework of detailed system design.

Considering the importance of the pre-design stage in the investment decision process, the present report focuses on simplified calculation methods enabling an efficient and effortless approach to the technical-economic feasibility of Solar Process Heat investments, while holding the ability to generate reliable and inter-comparable results enabling the establishment of the technological and economic boundary conditions required to proceed to a deeper investment analysis / system design stage.

Considering the inter-relation of technological, methodological and economic aspects involved in the preliminary technical-economic analysis stage, the report provides an overview of the most relevant topics therein included:

- Solar collector technologies, providing an insight to the different available technologies, operating temperature range and operation requirements;
- Solar yield calculation methods and tools, providing simplified yield estimate approaches and the production of key figures enabling a due technical assessment;
- Economic analysis, highlighting the most relevant aspects to be considered in the investment analysis and providing methodologies enabling the production of key figures enabling a due economic assessment;
- Decision factors, gathering technical and economic assessment results into the establishment of the boundary conditions for investment viability.

2 Symbols and abbreviated terms

Symbol	Description	Unit
A	Area	m²
a_1	Heat loss coefficient at $(\theta_m - \theta_a) = 0$	W/(m²K)
a_2	Temperature dependence of the heat loss coefficient	W/(m²K²)
C	Concentration	-
c_1	Heat loss coefficient at $(\theta_m - \theta_a) = 0$	W/(m²K)
c_2	Temperature dependence of the heat loss coefficient	W/(m²K²)
c_3	Wind speed dependence of the heat loss coefficient	J/(m³K)
c_4	Sky temperature dependence of the heat loss coefficient	-
c_5	Effective thermal capacity	J/(m²K)
c_6	Wind dependence in the zero loss efficiency	s/m
E_L	Long wave irradiance	W/m²
f_{beam}	Fraction of beam radiation	-
G	Irradiance	W/m²
G_b	Beam irradiance	W/m²
G_d	Diffuse irradiance	W/m²
G_{fld}	Modified irradiance on collector field	W/m²
G_{hem}	Hemispherical irradiance	W/m²
K_b	Incidence angle modifier for beam radiation	-
K_d	Incidence angle modifier for diffuse radiation	-
K_{fld}	Incidence angle modifier for collector field	-
K_{hem}	Incidence angle modifier for hemispherical radiation	-
L	Latitude	degrees
n_{col}	Number of collectors in a field	-
Q	Annual energy output	kWh/a
Q_{col}	Annual specific collector energy output	kWh/m²a
Q_{fld}	Annual collector field energy output	kWh
$\dot{Q}$	Instantaneous power	W
T	Temperature	°C
t	Time	s
u	Wind speed	m/s
α	Solar absorptance	-
ε	Thermal emittance	-

η	Collector efficiency	-
η_0	Zero-loss efficiency	-
θ_a	Ambient temperature	°C
θ_i	Incidence angle	degrees
θ_L	Longitudinal incidence angle	degrees
θ_m	Mean collector fluid temperature	°C
θ_T	Transversal incidence angle	degrees
τ	Solar transmittance	-

Term	**Description**	
CCost	Collector costs	€/m²
CPC	Compound parabolic concentrator	
DHW	Domestic hot water	
ETC	Evacuated tubular collector	
FPC	Flat plate collector	
HTF	Heat transfer fluid	
IAM	Incidence angle modifier	
LFR	Linear Fresnel Reflector	
PTC	Parabolic through collector	
SCOH	Simplified cost of solar heat	€/kWh
SH	Space heating	

3 Solar collector technologies

In the present SHIP applications are suited by well-established technologies covering the range of process temperatures found in different industrial sectors: low (T < 100ºC), medium (100ºC < T < 250ºC) or high temperature (250ºC < T < 400ºC).
Considering that solar collectors suiting industrial processes might also suit non-industrial applications (e.g. hot water production on the Residential sector or high pressure steam for power generation purposes) it is important to establish the scope of a Solar Process Heat Collector definition in terms of:

- their modularity: such collectors must be prone to medium (10^2 m^2) or large (10^3 m^2) solar fields and present easy/fast collector installation and repair/replacement procedures as well as the potential for hydraulic field layouts with low costs for connecting parts and low pressure drop;
- their robustness and safety: such collectors must present material properties and design features suitable for a reliable and safe operation under the conditions of an industrial environment, including special regard to overheating and stagnation conditions (Frank et al, 2014);
- their operation and maintenance requirements: the operation and maintenance procedures (basic, excluding repair/replacement) must be accessible to end-user technical personnel without special training in solar technologies (besides the basic training required for the use and operation of any new equipment);
- their integration into running processes: at either heat supply (e.g. steam network) or heat demand (industrial process) levels, by their compatibility with pre-existing (hydraulic) circuits, interference with production processes and by the use of common and standard components or heat transfer fluids (HTFs), not requiring additional efforts on safety or procurement procedures to the end-user.

The latter links directly to the operating temperatures of such collectors. Even if present line-focus concentrator technologies enable heat delivery at temperatures up to 400ºC (and the current developments related to thermal power generation drive maximum temperatures to the range of 550ºC, with molten salt HTFs), such temperatures stand for stepping up in costs, complexity and safety parameters which might not be common to a wide range of industrial processes and sectors.
Thus, considering the requirements of ease-of-use, no added efforts and technical resources to a wide range of end-users, process heat applications here considered are those suitable to provide heat, at a reasonable efficiency, in the low and medium temperature ranges, i.e., T < 250ºC.
This chapter presents the most prominent technological concepts underlying market available collector technologies, their relation to operating temperature and operation requirements, as well as the background for their performance assessment under prescribed operating conditions. For more information about radiation and heat transfer in process heat collector as well as about available products it is referred to the TASK Report A.1.3. (Horta 2015)

3.1 Introduction

The installed capacity of solar thermal collectors has been driven by well-established solar collector technologies suitable to low temperature applications, such as glazed or unglazed flat plate or evacuated tube collectors.
Different solar collector technologies emerge from adoption of different thermal performance strategies and optical designs, suiting improved performances in different

temperature ranges. Availability of new materials and adoption of new optical designs lead to a flourishing landscape of technologies.
Regardless of the performance enhancement strategies adopted, collector technologies might be divided into two different categories, related to the use of concentration and thus to the use of tracking systems:

- stationary collectors: technologies without concentration or with very moderate concentration factor (typically $C < 2$) suitable for a fixed positioning;
- tracking collectors: solar concentrators (typically $C > 10$) requiring the use of tracking systems enabling incidence conditions within the collector acceptance, thus following the Sun along its trajectory throughout the day.

3.1.1 Stationary collectors

Not neglecting concepts such as evacuated flat-plate collectors, the most common technologies currently available as marketed products are:

- flat-plate collectors (FPC): (selective) flat absorber with back and side thermal insulation and with/without single or multiple flat glazing cover; hydraulic circuit attached to the back of the absorber surface; stationary collector suitable to the low temperature range (T < 100ºC);
- evacuated tube collectors (ETC): selective absorber layer coating the outer surface of the inner glass wall of a Dewar evacuated tube; hydraulic circuit based on a U-pipe or on heat pipes, mounted inside the evacuated tube sleeve; stationary collector suitable to the low and lower boundary of medium temperature ranges (T < 120ºC);
- Compound Parabolic Concentrator (CPC) collectors: stationary line-focus concentrator (with low concentration factor) designed after non-imaging optics concepts for ideal concentrators; might be combined with evacuated tubes (with external concentrator reflectors) or with flat (or flat-type) absorbers with external glazing; depending on the absorber and on the effective concentration factor is suitable to the low and medium temperature ranges (T < 100ºC – 150ºC).

3.1.2 Tracking collectors

The development of solar concentration technologies, driven from the early 1980's by Solar Thermal Electricity (STE) established the technological ground for R&D and product development activities. Such developments were led by Parabolic Trough Collector (PTC) technology and more recently by derivate line-focus concepts, such as the Linear Fresnel Reflector (LFR) technology, to mention the most prominent.

- Parabolic Trough Concentrator (PTC): tracking line-focus concentrator designed after the parabola geometrical feature of reflecting any ray incident on its aperture parallel to its axis to the parabola focus; one-axis tracking around the longitudinal (absorber) axis; coupled with evacuated or non-evacuated (single-pass) absorber tubes; depending on the absorber and on the effective concentration factor is suitable to the medium temperature ranges (100ºC < T < 250ºC);
- Linear Fresnel Reflector (LFR) Concentrator: tracking line-focus concentrator designed after the Fresnel principle of dividing a parabola into segments displaced in (or close to) a horizontal plane; individual mirror one-axis tracking around the longitudinal axis; coupled with evacuated or non-evacuated (single-pass) absorber tubes located at a vertical displacement related to its focal length; used with a secondary concentrator located around the absorber to enhance its optical behavior;

depending on the absorber and on the effective concentration factor is suitable to the medium temperature ranges (100ºC < T < 250ºC).

3.1.3 Temperature levels

In view of the operating temperature dependence of solar collector thermal losses (see 3.3.1), the selection of the most suitable solar collector technology is directly related to the heat demand temperature (in turn related with the solar integration strategy adopted in the definition of the system layout: process or supply level (Muster et al. 2015)).
Considering both the range of process temperature in different industrial sectors (Lauterbach et al. 2012; IRENA 2015b) and the most suitable range of operating temperatures of the different collector technologies, the scheme presented in Fig.3.1summarizes this information and can be regarded as a preliminary step into defining the most suitable technologies for the operating conditions found on a prescribed project.

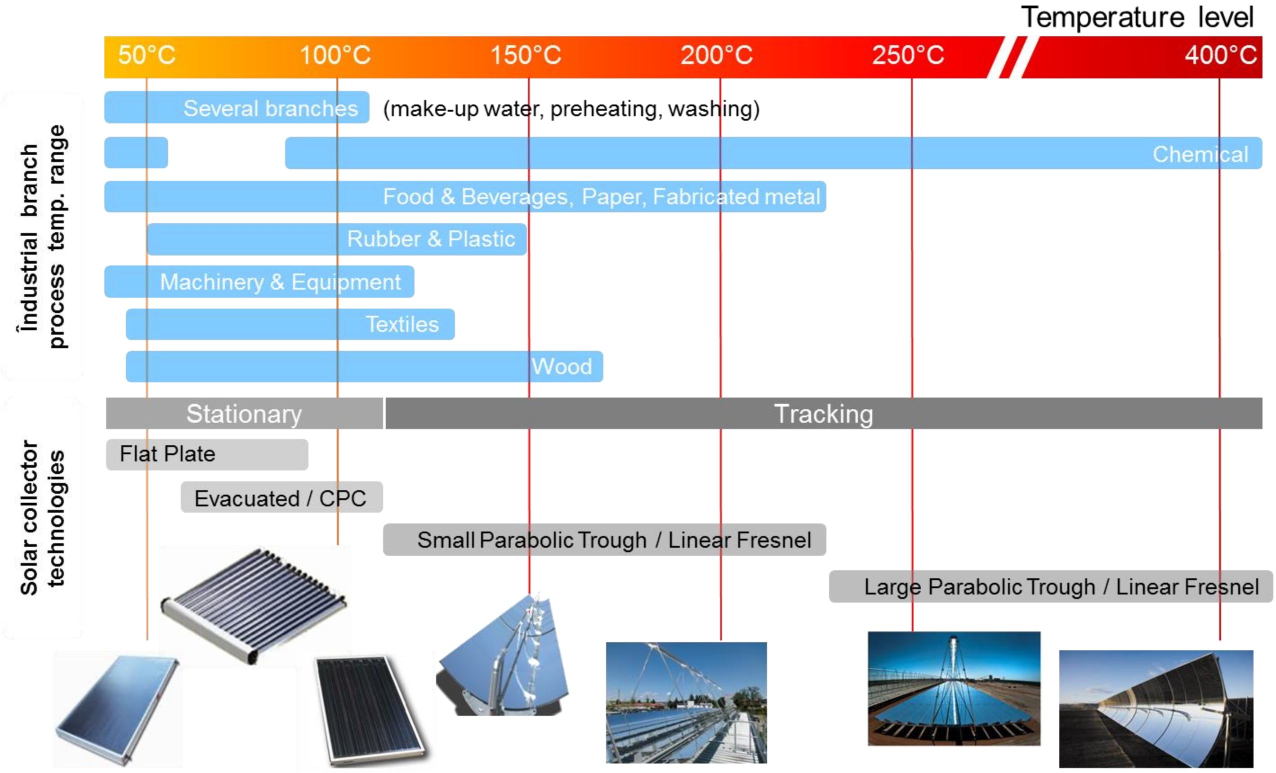

Fig.3.1 – Stationary and tracking solar collector technologies related to operation temperature and process temperature range in different industrial branches

3.2 Collector characterization

The performance of a solar collector depends not only on its thermal behavior, determining how much heat is lost to the surroundings when its temperature raises, but also on its optical behavior, determining the amount of irradiation which effectively hits the absorber and its transformed in heat on the HTF. As so, solar collector efficiency is not a fixed value, as it depends on the collector operating temperature, but is rather represented by a curve - the efficiency curve.
In spite of the specificity of the different technological concepts underlying the wide scope of available solar collector technologies, a technology independent method for determining

collector efficiency enabling an even comparison of results is required. The solar collector testing standard ISO 9806 (ISO 9806 2013) provides such a method. According to this standard, solar collector optical and thermal characterization parameters can be experimentally determined after one of two different solar collector models. Use of such collector characterization parameters with prescribed climate and operation conditions data enables, according to the corresponding collector model, the calculation of collector instantaneous power and, thus, calculation of collector thermal energy output over a prescribed period and under prescribed operating conditions.

3.2.1 Collector model

The measurement of solar collector optical and thermal performance parameters is experimentally achieved by means of standardized procedures, based on the measurement of instantaneous power values. The international standard available for this purpose (ISO 9806 2013), defines testing procedures and collector characterization parameters following one of two collector models: steady-state or quasi-dynamic.

A specific instantaneous collector power equation (referred to collector gross area[1]) is given, according to the steady-state model, as:

$$\frac{\dot{Q}}{A} = G\eta_{0,hem}K_{hem}(\theta_L, \theta_T) - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 \qquad \text{(Eq.4)}$$

According to this model, the collector is characterized optically according to:

- an optical (or zero-loss) efficiency, $\eta_{0,hem}$, accounting for the optical losses between the collector aperture area and the absorber (under normal incidence conditions);
- an incidence angle dependent Incidence Angle Modifier, K_{hem}, accounting for the impact of incidence conditions (both on the Longitudinal and Transversal directions) over the optical performance of the collector,

and thermally according to a thermal loss coefficient, a_1, and its dependence of temperature expressed in a coefficient a_2, accounting for thermal losses under prescribed operation and ambient temperature conditions.

According to the quasi-dynamic model, this equation turns into:

$$\frac{\dot{Q}}{A} = \eta_{0,b}K_b(\theta_L, \theta_T)G_b + \eta_{0,b}K_dG_d - c_6uG - c_1(\vartheta_m - \vartheta_a) - c_2(\vartheta_m - \vartheta_a)^2 - c_3u(\vartheta_m - \vartheta_a) + \qquad \text{(Eq.5)}$$
$$+ c_4\left(E_L - \sigma T_a^4\right) - c_5\frac{d\vartheta_m}{dt}$$

According to this model, the collector is characterized optically according to:

- an optical (or zero-loss) efficiency, $\eta_{0,b}$, accounting for the optical losses between the collector aperture area and the absorber (under normal incidence conditions) and referred to beam irradiation;
- an incidence angle dependent Incidence Angle Modifier, K_b, accounting for the impact of incidence conditions (both on the Longitudinal and Transversal directions) over the optical performance of the collector and referred to beam irradiation;

1 Reference to collector Gross Area rather than to Aperture Area was introduced in the most recent version of the standards. Collector characterization parameters obtained after previous standards versions might be referred to collector Aperture Area. This should be checked when dealing with a specific collector.

- an incidence angle dependent Incidence Angle Modifier, K_d, accounting for the impact of incidence conditions (both on the Longitudinal and Transversal directions) over the optical performance of the collector and referred to diffuse irradiation;
- a coefficient, c_6, related to the zero-loss efficiency dependence on wind speed, *u*;

and thermally according to:

- a thermal loss coefficient, c_1, and its dependence of temperature expressed in a coefficient c_2, accounting for thermal losses under prescribed operation and ambient temperature conditions;
- a coefficient, c_3, related to thermal losses dependence on wind speed, *u*;
- a coefficient, c_4, related to thermal losses dependence on long wave irradiance;
- a coefficient, c_5, expressing the thermal capacitance of the collector (rendering the model dynamic, i.e., time dependent).

Besides introducing a dynamic parameter, dependent on the solar collector thermal capacity, the quasi-dynamic model presents a major difference to the steady-state model in terms of the decoupling of radiation components (direct and diffuse radiation) on the determination of optic performance parameters. Considering the aspects related to diffuse radiation acceptance in solar concentrators, this model was thus adopted as the one to be used when testing solar concentrators.

3.2.2 Efficiency curve

Both the steady-state and the quasi-dynamic solar collector models are built upon the separation of optical and thermal losses, following inherently the different dependencies of both phenomena. As so, it may be stated that from a threshold (maximum) temperature independent efficiency (accounting only for optical losses), collector instantaneous efficiency is decreased with increased operating temperature levels due to the temperature dependence of thermal losses.

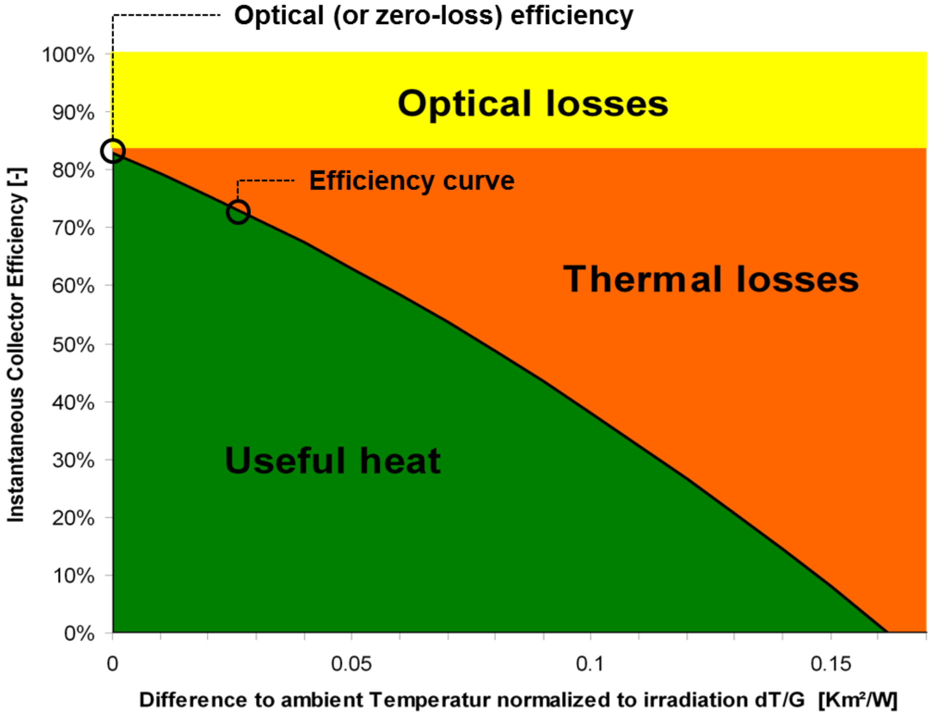

Fig.3.2 – Solar collector efficiency curve

The efficiency curve is thus a representation of collector instantaneous efficiency with

increasing temperature differential between collector (or mean heat transfer fluid) and ambient temperatures.
As represented in Fig.3.2, the efficiency curve starts with the optical (or zero-loss) efficiency value and presents a downward evolution with increasing temperature differential (to ambient temperature), standing for increasing thermal losses and thus reduced instantaneous efficiency values. The slope of the efficiency curve is directly related to the thermal loss coefficients obtained as thermal characterization parameters as result of the solar collector testing procedures.
According to the specific instantaneous power equations provided by each of the collector models, solar collector performance can thus be represented after power output curves obtained for (reference) solar irradiation and ambient temperature conditions, as presented in Fig.3.3 for some representative technologies (the power curves presented are based in typical collector characterization parameters and do not represent any particular available product).

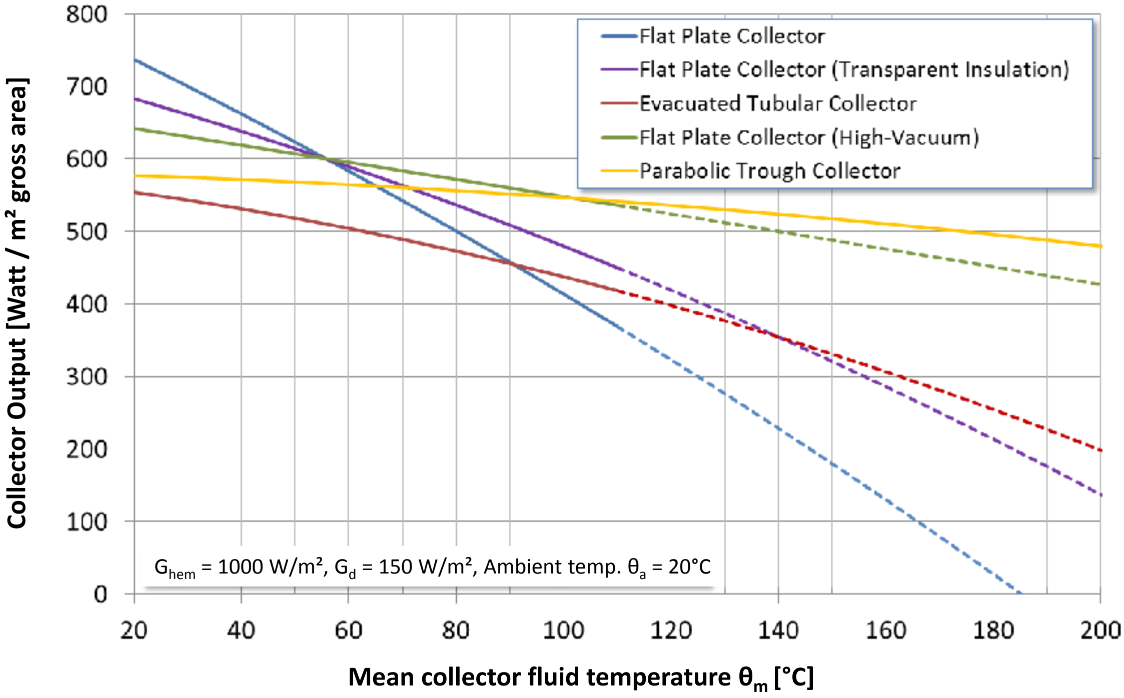

Fig.3.3 - Examples representing power curves of different solar collector technologies

3.2.3 Incidence Angle modifier (IAM)

The Incidence Angle Modifier (IAM) reflects the impact of incidence dependent optical and geometrical properties of the solar collector on its absorber surface irradiance. In view of the varying incidence conditions to which (one-axis tracking and stationary) solar collectors are subjected, it is thus essential for long term energy calculation.
The IAM, accounting for incidence angle dependent variation of optical effects, is defined as the ratio of optical efficiencies at a prescribed and at normal incidence:

$$K(\theta)=\frac{\eta_0(\theta)}{\eta_0} \qquad \text{(Eq.6)}$$

and includes effects such as:

- angular variation of optical properties of reflectors (ρ), glazing (τ) and absorber (α);
- angular variation of optical path (average number of reflections <n>, transmissivity effects);
- End of line effects;
- Angular variation of the effective aperture area;
- Tracking inaccuracies.

Incidence Angle Modifier values are also obtained experimentally after the standardized testing procedures, which include instantaneous power measurements at different incidence conditions along the two geometrical axes defining most of the solar collector technologies described in 3.1: the longitudinal (including the absorber axis) and transversal planes (Flat Plate collectors collectors do not present a bi-axial geometry, thus requiring Incidence Angle Modifier measurements at different incidence angles, along any prescribed plane normal to the aperture plane).

3.2.4 Availability of collector characterization parameters

Optical and thermal characterization parameters obtained after one (or both) of the solar collector models presented in ISO 9806 are available, for certified solar collectors, at the Solar Keymark database (Solar Keymark 2015). Promoted by ESTIF – European Solar Thermal Industry Federation, Solar Keymark is a voluntary third-party certification mark for solar thermal products, demonstrating to end-users that a product conforms to the relevant European standards and fulfils additional requirements. The Solar Keymark is used in Europe and increasingly recognized worldwide.
Besides ISO 9806, directly linked to the Solar Keymark database, other solar collector standards are available: For example ASHRAE 93-2003, applicable to non-tracking collectors or ASTM E 905-87 applicable to tracking collectors (Hofer A. et al. 2015). Additional collector databases are available as well at other national or international certification entities such as the American Solar Rating and Certification Corporation (SRCC).

4 Collector performance rating

Energy performance represents the most important technical criterion for comparison of different collector products and technologies. Collector performance rating can provide useful information for a preliminary feasibility study at a pre-design stage of solar process heat installations. This Chapter focuses on the concept of collector thermal energy output and presents simplified calculation methodologies and tools, discussing current restrictions or shortcomings as well as suggesting possible improvements.

4.1 Introduction

The efficiency or instantaneous power curves presented in Chapter 3 must be regarded as a graphical representation of the optical and thermal performance of the collector under a very specific set of boundary conditions: one collector module under normal incidence conditions and reference irradiance. As so, the use of these curves alone to the comparison of different collectors would fall short of the more complex framework of real operation conditions, including varying incidence angle, inlet temperature, climate or load profile.

Realistic and reliable information about the collector performance can be only provided by detailed system simulations, taking not only the collector but also all the components of the system as well as weather data and load profiles into considerations. Such calculations presuppose a detailed knowledge of the system and the availability of data about the processes under investigation, which is usually not the case in a preliminary feasibility study. The development of a suitable methodology to assess the system performance for solar process heating in an advanced design stage was addressed by Subtask C in the framework of TASK 49. The results are documented in the corresponding Technical Report (Platzer et al. 2015a).

A common evaluation practice in solar thermal applications, before starting more complex system simulations is to calculate the collector yield, which represents the thermal energy output of the collector per collector area (kWh/m²). It results from a time integration of the instantaneous power over a defined period of time *Δt*, as shown by the following equation with regard to the steady-state collector model presented in Section 3.2.1:

$$\int_{\Delta t} \frac{\dot{Q}}{A} dt = \int_{\Delta t} G\eta_{0,hem} K_{hem}(\theta_L, \theta_T) - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 dt \qquad \text{(Eq.7)}$$

Collector yield calculations are based not only on collector performance data but also on many other different factors, the most important of them being:

- Collector tilt angle, orientation and tracking options
- Load profiles (operating temperature)
- Weather data (ambient temperature and irradiance)

Simplified or more detailed yield calculation models can hence be implemented depending on the accuracy of the algorithms and inputs used. As already pointed out, collector output calculations represent a very useful but approximate performance assessment approach. The main aspects to be taken into consideration when using a simplified approach, compared to that based on system based calculations, are:

Heat transfer medium: Collector performance parameters used for energy output calculation are determined according to ISO 9806 under defined test conditions, i.e. with a specific heat transfer medium (in most cases water) and at a specific flow rate (in most cases turbulent flow regime). Real solar plants for process heating are usually operated with other media (water-glycol or thermal oils) and with lower flow rates, which might lead to lower performance levels (this is especially the case when laminar flow regimes occur).

Collector field losses: Collector field losses can include different contributions, such as heat losses due to the piping (depending on the pipe length, on the connections and on to the quality of the thermal insulation used) self-shading effects (depending on the field geometry chosen) and collector end losses, relevant for line-focus concentrating technologies and to be considered with regard to the information contained in the IAM results (depending on the collector testing conditions).

System losses and configuration: Beside collector field losses, significant losses can also occur at storage, heat exchangers, distribution pipes as well as at all other system components, which are neglected in the collector yield calculation (s. Chapter 5).

Load profiles: As a consequence of neglecting system design and operation, collector energy output calculations assume in most cases and also in the methodologies presented in this report a constant load during the considered period of time as well as a constant collector average temperature. The collector output is generally overestimated.

Others: Among additional factors affecting the performance of the collector in real operation shading from surroundings and weathering have to be mentioned. These aspects are strongly depending on the location and on the sensitivity of the specific collector technology used and are very difficult to quantify even in the case of detailed system simulations.

The impact of these different aspects depends on the specific application and on the methodology chosen for rating the collector performance. Some examples for process heating are reported in Sections 4.2.1 as well as in Platzer et al. (2015a).

4.2 Methodologies

Instantaneous power can be integrated over different periods of time to get information about the thermal energy output of the collector under specific conditions. The present Section features two different simplified methodologies already adopted for performance rating of solar collectors for domestic hot water production or space heating (T < 100 °C) and discusses their suitability for the use in process heat applications.

4.2.1 Annual collector energy output

The annual approach calculates the collector thermal energy output over the course of one year and represents the most comprehensive method to assess and compare the collector performance in a simplified way. It considers weather occurrences (irradiance and ambient temperature) on the basis of detailed data sets and can on that account more accurately reproduce the energy gain and loss of the collector.

Figure 4.1 clarifies this basic aspect by comparing the performance of two different collectors by means of instantaneous power and annual energy output at various mean fluid temperatures. The graphs show that the critical temperature T_{cr} resulting from the intersection of the performance curves and defining the more suitable operating range for each collector is shifted to the higher temperatures, if the calculation is assessed according to the annual approach. Furthermore the relative performance difference between the two collectors at a specific temperature significantly increases (for example 50% instead of 15% at a fluid temperature of 100°C), which can strongly affect the overall evaluation. These differences vary depending on the boundary conditions chosen for both calculations.

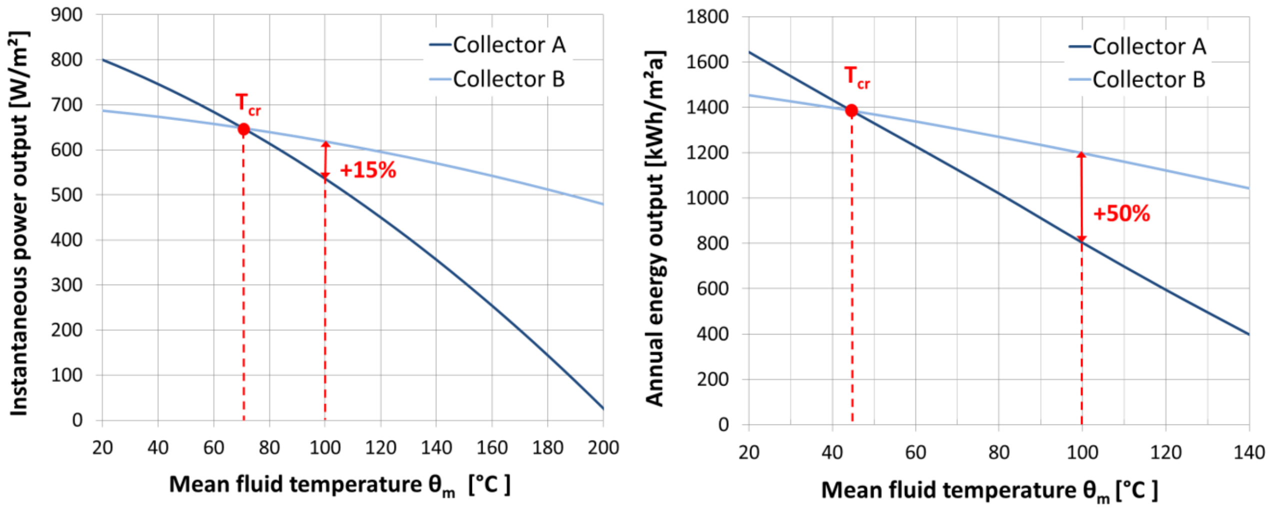

Fig. 4.1 - Performance comparison of two different collectors based on instantaneous power (left) and annual energy (right) output. The instantaneous power curve refers to an irradiance of 1000 W/m² and to an ambient temperature of 20 °C. The annual output is calculated for 45° tilt angle, south orientation and weather data of Seville (dataset from Meteonorm).

This methodology has been used since 2011 within Solar Keymark, the CEN/CENELEC European mark scheme (already mentioned in Section 3.2.4) dedicated to solar thermal collectors and factory made solar thermal systems based on the international Standard series ISO 9806. The calculations are in this case carried out on the basis of certified collector performance data for reference locations with different weather conditions and reference operating temperatures, representative for solar thermal systems for domestic hot water DHW and space heating SH (25°C, 50°C and 75°C). The results are generally intended for collector comparison but in some countries (i.e. Germany) are also used as criterion to get public subsidies for the installation of solar thermal systems.
The calculations are carried out with the software ScenoCalc, specifically developed for Solar Keymark within a European Project. Detailed information about this as well as about other suitable tools and procedures for annual energy output calculation is given in Section 4.4.
The annual approach can be implemented independently of the targeted application area and has to be regarded as the best suitable simplified methodology also for performance rating of process heat collectors. Compared to its common use for DHW and SH, the use of such approach for process heat related applications implies a much wider temperature range and an accurate reproduction of the optical behavior of concentrating and tracking technologies.
As already pointed out, collector energy output is a useful assessment criterion for preliminary feasibility analysis, but cannot and shall not replace detailed system

simulations. Figure 4.2 exemplarily compares calculations based on different methodologies for solar process heat case studies investigated in the framework of TASK 49 (Platzer et al. 2015a), emphasizing the impact of relevant aspects like system design and load profiles.

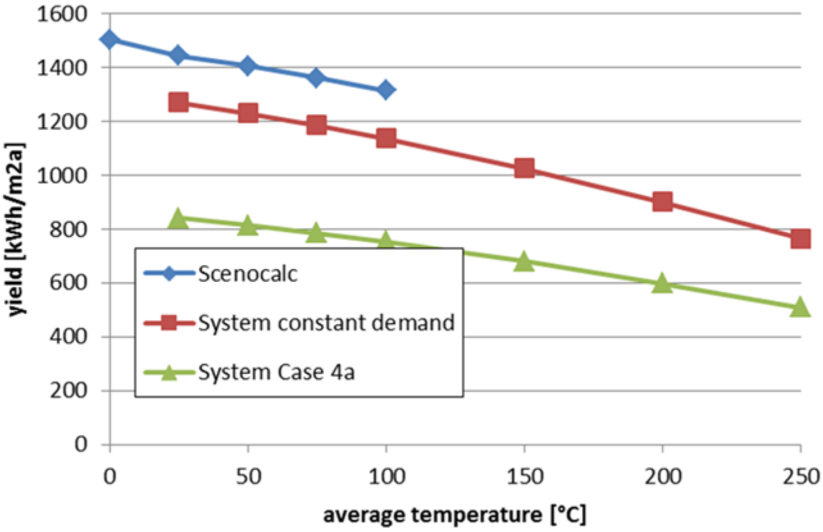

Fig. 4.2 - Comparison between energy output based of simplified collector output calculations (ScenoCalc) and detailed simulations considering the impact of the whole system as well as of the real heat demand.

4.2.2 Daily collector energy output

The daily methodology was introduced by the American Solar Rating and Certification Corporation (SRCC 2011) and is currently in use both for collector and system performance rating. It features a thermal performance rating for solar collector at specified rating conditions in a specified rating environment: the simplified calculation is based on certified collector data and carried out for three reference days with representative weather conditions (high, medium and low irradiation) and for 5 different temperature differentials (difference between collector and ambient temperature) which are held constant throughout the day.
This methodology is originally applicable to all non-tracking collectors whose instantaneous thermal performance can be adequately established by the appropriate Standard test procedures. As for the annual approach, aim of the performance rating is to provide both the manufacturer and the consumer with a tool for making comparison between collector and collector concepts over a broad range of operating temperatures.

The calculation is carried out on hourly basis by using a predefined table (s. Table 4.1) and relies on the following assumptions:

- The irradiation data are derived from the computation procedure derived by Liu and Jordan as modified by Rabl (Collares-Pereira and Rabl 1979). Diffuse irradiation is thus assumed to be distributed isotropically throughout the field of view of the collector.
- Latitude L is 40°N and declination angle is 0° (correspond to equinox) for all three reference days.
- The collector is assumed to be facing south and to be tilted from the horizontal at an angle equal to the latitude.

Table 4.1 - Reference table used for the calculation of daily output of solar collectors according to the SRCC methodology for high irradiation ((the calculation is exemplarily carried out for an evacuated tubular collector).

Solar Time	I_{BP} W/m²	I_{dP} W/m²	I_{TP} W/m²	θ	Ω	Ψ	K_d ($K_{\theta d}$)	$K_{\alpha\tau}(\theta)$ [$K_{\theta b}(\theta)$]	Modifier irradation W/m²
7	116.72	47.32	164.03	75	75	0	0.974	0.55	110.28
8	268.13	91.48	359.61	60	60	0	0.974	0.84	314.33
9	435.32	126.18	561.50	45	45	0	0.974	0.93	527.75
10	589.89	157.73	747.62	30	30	0	0.974	0.98	731.72
11	693.99	173.50	867.49	15	15	0	0.974	0.99	856.04
12	728.69	179.81	908.50	0	0	0	0.974	1	903.82
13	693.99	173.50	867.49	15	15	0	0.974	0.99	856.04
14	589.89	157.73	747.62	30	30	0	0.974	0.98	731.72
15	435.32	126.18	561.50	45	45	0	0.974	0.93	527.75
16	268.13	91.48	359.61	60	60	0	0.974	0.84	314.33
17	116.72	47.32	164.03	75	75	0	0.974	0.55	110.28

The daily collector energy gain results from the hourly contributions calculated by means of the collector model, using incidence angles, direct and diffuse irradiation as inputs. The rating itself is an analytically derived set of numbers representing the characteristic all-day-energy output of the solar collector. The results for an evacuated tubular collector are exemplarily shown in Table 4.2.

Table 4.2 - Reference table used for the thermal performance rating of solar collectors according to the SRCC daily methodology (the calculation is exemplarily carried out for an evacuated tubular collector).

COLLECTOR THERMAL PERFORMANCE RATING			
kWh$_{th}$ per panel per day			
Climate --> Category (Ti-Ta)	High Radiation (6.3 kWh/m²d)	Medium Radiation (4.7 kWh/m²d)	Low Radiation (3.1 kWh/m²d)
A (-5 °C)	8.7	6.6	4.4
B (5°C)	8.3	6.2	4.0
C (20°C)	7.7	5.5	3.4
D (50°C)	6.5	4.3	2.2
E (80°C)	5.1	3.0	1.1

The comparison of rating numbers for different collectors provides finally the basis for the choice of the more suitable product for the specific application (operating temperature and irradiation level).

Suitability for the use with process heat collectors: The daily methodology represents the most simple and straightforward approach based on the concept of energy output to rate the performance of a solar collector. The calculation can be easily carried out with an Excel-Sheet and without the use of dedicated and more complex simulation tools by using the collector performance parameters. The most significant restriction is the very low flexibility of the method, which can be summed up as follows:

- The temperature differentials suggested / used in the current version are intended for domestic hot water, space heating and cooling applications and need to be extended to the typical temperature ranges for process heating. Which temperatures have to be chosen for the evaluation depends on the specific case under investigation. As a general rule the rating shall not be performed for temperatures above 210 °C, which is the maximum currently supported by the testing standards.

- The collector orientation is predefined. To extend the method, further predefined scenarios (i.e. other incidence angles) have to be calculated and included in the original rating table, whereas the number of options should be limited.
- The rating works with three predefined irradiation conditions. Comparative calculations for evacuated flat plate and tubular collectors within TASK 49 have shown that the daily approach generally leads to similar results to those achieved by annual simulations on hourly basis carried out for three different locations featuring respectively low (Freiburg, DE), medium (Seville, FR) and high (Riyadh, SA) irradiation levels, as displayed in Table 4.3. For some combinations of climate categories and locations/irradiation levels, however, the deviation between the two methodologies is very high.

Table 4.3 - Performance comparison between an evacuated flat plate collector and an evacuated tubular collector based on the daily (upper table) and the annual (lower table) approach. The tables report the energy output difference in percent. The annual calculations are carried out with the simulation tool TRNSYS and weather datasets from Meteonorm.

COLLECTOR OUTPUT COMPARISON - DAILY APPROACH			
Output difference in %			
Climate -->	High Radiation	Medium Radiation	Low Radiation
Category (Ti-Ta)	6.3 kWh/m²d	4.7 kWh/m²d	3.1 kWh/m²d
A (-5 °C)	36%	36%	35%
B (5°C)	39%	40%	42%
C (20°C)	45%	49%	55%
D (50°C)	59%	69%	95%
E (80°C)	82%	116%	233%

COLLECTOR OUTPUT COMPARISON - ANNUAL APPROACH			
Output difference in %			
Climate -->	High Radiation	Medium Radiation	Low Radiation
Category (Ti-Ta)	2216 kWh/m²a	1752 kWh/m²a	1113 kWh/m²a
A (-5 °C)	46%	42%	39%
B (5°C)	49%	45%	45%
C (20°C)	55%	52%	54%
D (50°C)	71%	72%	81%
E (80°C)	102%	110%	135%

The comparison hasn’t been extended to other collector types and the validity of the results for more complex IAM has to be further investigated. If the irradiation level of the location considered for the process heat installation differs from the predefined irradiation conditions, higher deviations are expected.

- The rating methodology doesn’t account for the irradiation transformations necessary for tracking collectors. As for the definition of new collector orientations, the existing deficit could be overcome by pre-calculating incidence angles for typical collectors used for process heating like one-axis-tracking LFR or PTC to be introduced into the reference table.

Summing up, the daily approach represents a more realistic method to compare collector technologies than the simple instantaneous efficiency or power curve. Even for similar boundary conditions it still achieves different results if compared to the more detailed annual simulation and the present status shows significant shortcomings with regards to process heat collectors. Its use can therefore be suggested only for non-tracking collectors if no suitable tools for annual output calculation are available at a pre-design stage.

4.3 Calculation inputs and parameters

For simplified collector output calculations three different kind of information are needed, independently of the methodology or tool adopted: the collector data (efficiency parameters, IAM, area), the location and the corresponding weather data (basically temperature, solar geometry and irradiance, if wind and infrared irradiance are not considered), the operating conditions (collector orientation and mean fluid temperature). This section provides the reader with basic information about the requirements to be fulfilled and suggestions for the choice of suitable inputs and parameters.

4.3.1 Collector data

The collector data set consists of efficiency parameters, including IAM, and the collector area. It is recommended to use data from certified measurements according to the test standard ISO 9806. As already mentioned in Section 3.2.4, this information is available on the websites of certification associations such as Solar Keymark for Europe or SRCC for USA.
An important aspect to be taken into consideration is the reference collector area used for determining the efficiency parameters, which is given in the correspondent collector data sheet: ISO 9806 prescribes the use of the gross area (area defined by the outer dimensions of the collector), but most of the measurements carried out in the past years refer to the aperture or to the absorber area (area in which the solar radiation enters the collector and area of the solar absorber respectively). The discrepancy between these reference areas varies from collector to collector and can significantly affect the results of energy output calculation. It’s therefore recommended to check the consistency of the inputs data.

4.3.2 Climatic data

The choice of suitable climatic data is crucial for the planning of solar energy systems even at a pre-design stage and in case of simplified collector output calculations. Climatic data, especially irradiation, exhibit a high spatial and temporal variability as displayed in Figures 4.3 with regards to the worldwide distribution of horizontal global irradiation. This basic topic has been intensively investigated in the past and many useful suggestions can be found in the literature. Our report specifically refers to the work of the IEA TASK 36 “Solar Research Knowledge Management”, which among its activities also developed an online guide to help non-expert users to make an educated decision about which data sets are appropriate depending on the type of application and on the location (UNEP 2015). Relevant aspects to take into account and requirements to fulfill for our task can be summed up as follows:

Time resolution: Hourly data are generally considered the minimum resolution in order to achieve enough accurate results for every solar thermal application.

Time coverage: As a general rule a period equal to or longer than 10 years is recommended to stay within the limit of 5% of the long term variability expected over the lifetime of the system.

Spatial resolution: Depending on the accuracy level required by the feasibility study, the simulation has to be carried out with weather data of locations with a distance between 10 and 100 km from the site selected for the installation of the solar plant.

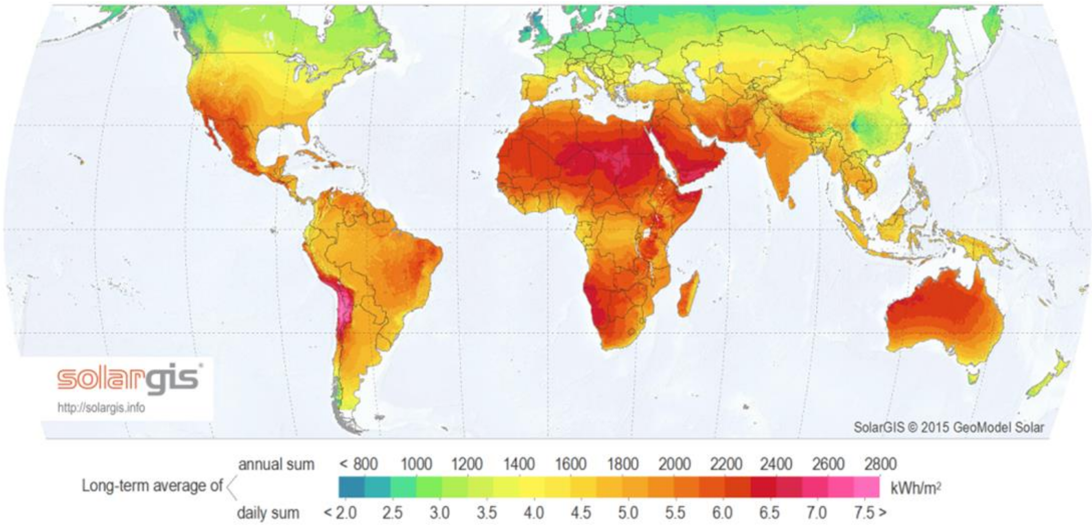

Fig. 4.3 - World map of horizontal global irradiation (SolarGIS 2015).

Reliable climatic data sets (both irradiation and temperature) are generally available at the National Meteorological Institutes. As exemplary source offering bench marked data worldwide Meteonorm can at this point be mentioned (Meteonorm 2015). This commercial software is widespread in the solar thermal community and was also used for the simulations within TASK 49.

4.3.3 Operating conditions

The last aspects to be considered in the output calculation are the conditions at which the collector is expected to operate, i.e. the reference mean fluid temperature and the collector orientation.
The calculation has to be carried out for a mean temperature which refers to the temperature(s) of the process(es) to be assisted. For specific projects or installations these data are usually provided by the company. For more general studies aiming at investigating the potential and/or the application area of a collector or a collector technology, useful information can be found in the literature (Lauterbach et al. 2012; IRENA 2015b). It is recommended to use slightly higher values (+10K) than the process temperatures in the simulation to take heat losses occurring in a real system into account.
For the collector orientation, azimuth and tilt angle as well as tracking mode and axis have to be defined.

4.4 Simulation tools

The report focuses on two simulation tools specifically developed for annual collector energy output calculation, ScenoCalc and Gain Buddy, and also presents an overview of more general programs, which are intended for detailed system simulations but can also be implemented for simplified calculations. A detailed description of the system simulation tools used in the TASK can be found in the Technical Report C2 (Platzer et al. 2016b).

4.4.1 ScenoCalc

ScenoCalc is a MS Excel based tool for the calculation of annual energy outputs of solar collectors which was developed within the EU-project QAiST (Qualitiy Assurance in Solar Thermal Heating and Cooling Technologies) by the SP Technical Research Institute in Sweden (SP 2014).

Main goal of the development was to enable test institutes and certification bodies to convert collector model parameters determined through standardized efficiency tests into energy performance figures. This is done in order to give end-users the opportunity to compare different type of solar collectors under different weather conditions. ScenoCalc is currently used as the basis for the Solar Keymark (SK) certification of solar collectors. It was primarily designed for the use on domestic hot water systems, which mostly use standard flat plate (FPC) and evacuated tubular collectors (ETC) as heat source, but takes also concentrating and tracking collectors into consideration.

The program computes the monthly and annual energy gains for different temperature levels. It is exclusively focused on the collector output and does not take into account any system configuration or load profile. It assumes a continuous load for all energy collected and constant mean fluid temperatures. The calculation can either be performed for SK-Certificate evaluations or for more general evaluations. In the following the main features of the general evaluation option, which offer more flexibility in the definition of the input parameters, are briefly presented. For a detailed description of the program and of the calculation procedures it is referred to the official document, which can be freely downloaded on the website of the SP technical Research Institute (SP 2014).

Weather data: In the standard configuration the calculation can be carried out for 4 predefined locations with different representative European climates: Stockholm (SE), Würzburg (DE), Davos (CH) and Athens (GR). The user can also upload specific weather data in order to more correctly simulate the behavior of the collector on the site chosen for the solar plant installation. The hourly data set consists of ambient temperature, horizontal irradiance, direct normal irradiance, wind speed u and long wave irradiance E_L (these last two are optional inputs used for uncovered collectors). Diffuse and hemispherical irradiance on the collector plane are then calculated on the basis of the Hay-Davies model (Hay and Davies 1980).

Collector performance data: The calculation is based on the collector models featured by ISO 9806 and described in Section 3.2.1. The parameters are to be chosen according to the correspondent steady-state or quasi-dynamic approach, which are both supported.

Incidence angle modifier (IAM): The collector behavior under non-normal incident radiation can be described in two different ways. Choosing the simplest option, the user enters the IAM-value at θ_i = 50° and the program calculates the angular distribution according to the approximate b_0-formula (Souka and Safwat 1966), assuming rotational symmetry. Choosing the more detailed option, the user can enter the transversal and longitudinal IAM between 0° and 90° with a 10° step. With specific regards to the IAM definition for concentrating collectors the program shows some shortcomings: It doesn't allow entering values > 0 for incident angle of 90°, the calculation procedure is inaccurate for Linear Fresnel Collectors (Morin et al. 2012) and it doesn't provide a separate representation of row end losses, which could enable to scale the tests results to arbitrary row lengths.

Collector orientation: The orientation of the collector is defined by entering tilt and azimuth angle. Different tracking options can furthermore be chosen: vertical axis tracking (collector azimuth angle = sun azimuth angle), two axis tracking (collector azimuth angle = sun azimuth angle and collector tilt = solar zenith angle), horizontal North-South tracking and horizontal East-West tracking. The only restriction for process heat collectors is the missing possibility to describe Linear Fresnel Reflector or tracking collectors with other directions of the tracking axis.

Temperature range: Even if reliable collector efficiency data from certified measurements are available up to 185 °C and extrapolations up to 210 °C are supported by the standard, the calculation can be carried out only for mean fluid temperatures between 0 °C and 100 °C. This represents the most significant limitation of the current version of ScenoCalc for the use with process heat collectors.

Summing up, ScenoCalc can calculate annual energy output only for low temperature collectors and is not a suitable tool for higher performing products like concentrating and tracking. To comply with process heat collectors the necessary improvements have to be implemented in an updated version of the program.

4.4.2 GainBuddy

GainBuddy is an executable stand-alone-software for windows, which was developed at the Institute of Solar Technology SPF and financed by the Swiss Federal Office of Energy (SFOE). The program can be downloaded from the SPF-Website and be used as a registered user for free (SPF 2015).
The main development idea was to provide the end-user for a tool able to calculate the thermal energy output of solar collector fields with fixed mounted or tracked collectors. Differently from ScenoCalc or other available tools, GainBuddy can take field geometry and correspondent shading effects, which can play an important role in large solar thermal plants, as well as row end losses into consideration. The energy output of the collector field Q_{fld} is then calculating according to the formula:

$$Q_{fld} = A_G \cdot n_{col} \int_{\Delta t} G_{fld}\eta_{0,hem} - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 dt \qquad \text{(Eq.8)}$$

where n_{col} represents the number of collectors in the field and G_{fld} a modified irradiance on the collector plane, taking the effect of the radiation incidence angle on both the collector and the collector field into consideration.

$$G_{fld} = G_{hem}(\theta_i) \cdot K_{hem}(\theta_i) \cdot K_{fld}(\theta_i) \qquad \text{(Eq.9)}$$

with K_{fld} = incidence angle modifier for the collector field.

The software can be used from a small graphical user interface (GUI) or from the command shell. For the calculation, three different sets of parameters are defined by the

user and transferred in form of text files to the main algorithm. The result is saved as a text file as well, reporting the monthly and yearly based energy output values and the available irradiation on the collector field for heat production. As other simplified tools it assumes a constant load and a constant mean fluid temperature over the year.
The main features of the program as well as the relevant aspects with regards to process heat collectors are described in the following.

Collector performance data: The collector is defined by the efficiency parameters according to the steady-state model featured by ISO 9806 and by the collector dimensions (width and height). Differently from ScenoCalc, the quasi-dynamic model is not supported.

Incidence angle modifier (IAM): The program offers more options than ScenoCalc to describe the behavior of the collector under non-normal incident radiation. The IAM can be defined by using the Ambrosetti formula (Ambrosetti and Keller 1985), by entering longitudinal K_L and/or transversal K_T values between 0° and 90° or by entering an array for modifiers deviant from longitudinal or transversal direction. For concentrating collectors, the acceptance angle can be additionally defined and the possibility to neglect diffuse radiation is given. The angle resolution of the input values can be chosen between 1 and 10 degrees. This allows a more precise definition of the collector performance even in case of complex IAM.

Collector field: The collector field is defined by the orientation of the collector installation axis, by the amount of collectors in a row, by the amount and the distance of collector rows and by the type of the mounting system (fix-oriented or tracked). Only one-axis tracking is supported, which allows the simulation of linear concentrating collectors like PTC or LFR.

Weather data: The program is supplied with several predefined locations, whose weather data are based on the Meteonorm database. The user can upload its own location, which is defined by the correspondent weather data (ambient temperature, global horizontal irradiation, diffuse horizontal irradiation - more properties are optional -), by the location position (longitude, latitude and altitude) and by the unit of the time value (UTC-Value). Differently from ScenoCalc, diffuse and hemispherical irradiance in the collector plane are calculated according to the Perez model (Perez et. al. 1987).

Summing up, GainBuddy represents a suitable simplified tool for the calculation of collector or collector field energy output. With the exception of the missing possibility to support the quasi-dynamic model, it exhibits no limitation for the use in solar process heating applications.

4.4.3 System simulation tools

System simulation tools are intended for more complex and comprehensive calculations taking system design and detailed load profiles into consideration. Their use is therefore restricted to expert users. These tools generally exhibit a similar modular and more or less flexible structure, consisting of different units representing real or virtual components of the solar energy system, which can be adapted. Some programs allow to freely programming new components. On this account they generally do not present any limitation for the calculation of energy output of process heat collectors. This Section just proposes a list of the tools, which were implemented within TASK 49, briefly featuring relevant information about climatic and collector data. A detailed description can be found in the Technical Report C2 (Platzer et al. 2015b).

TRNSYS: This commercial software was originally developed at the University of Wisconsin and is now supplied by the American company Tess (TRNSYS 2015).
- Climatic data/models: Large database, which can be extended with custom datasets.
- Collector data/models: Standard Library with 18 different collector models which can be adapted and extended with custom models

T*SOL®: T*SOL® is developed and supplied by the German company Valentin Software GmbH (TSOL 2015)
- Climatic data: Large database, which can be extended with custom datasets
- Collector data/model: The current version supports only liquid based flat plate and evacuated tube collectors. A new release implementing Linear Fresnel and Parabolic through collectors is scheduled for 2016.

POLYSUN: Polysun® is a simulation program originally developed at the Institute of Solar Technology SPF in Switzerland and now supplied by the company Vela Solaris AG (Vela Solaris 2015)
- Climatic data: Large database, which can be extended with custom datasets
- Collector data/model: Large database, which ca be extended with custom products. The calculation for the heat gains in the collector field does not consider row shading or end losses.

COLSIM: ColSim is a in-house simulation software (not publicly available) initially designed and further developed at Fraunhofer ISE (COLSIM 2015).
- Climatic data: Custom data can be uploaded
- Collector data/model: Flat plate and evacuated tube collectors are calculated on the basis of the steady-state efficiency equation. For line focusing collectors the energy gain is calculating on the basis of a simplified equation considering only zero-efficiency, direct irradiation and IAM, and taking end losses into consideration.

INSEL: INSEL (INtegrated Simulation Environment Language) provides an integrated environment and a graphical programming language for the creation of simulation applications. INSEL was originally developed for modeling of renewable energy systems at the former Renewable Energy Group at the Faculty of Physics of Oldenburg University, Germany (INSEL 2015).
- Climatic data: Custom data can be uploaded
- Collector data/model: The collector model used in the simulation is based on the test method under quasi-dynamic conditions. The influence of the angle of incidence on the optical performance of the collector (IAM) is taken into account.

GREENIUS: Greenius is a simulation environment for the performance estimation of generic renewable energy projects. Greenius was originally developed at the German Aerospace Centre (DLR) for internal use. Thanks to funding within the FreeGreenius project it is now available free of charge (Greenius 2015).
- Climatic data: Custom data can be uploaded
- Collector data/model: Greenius offers a steady-state model and an additional model for line focusing solar technologies.

4.5 Calculation examples

This section presents exemplarily collector output calculations based on the annual methodology, covering the main topics discussed in the Chapter.

Figures 4.4 and 4.5 display the output of different collector technologies (based on generic collector data) for representative European climates, in order to give a general idea of the performance range of these technologies as well as of their sensitivity to temperature levels and weather data.

This basic approach can be extended to perform more complex potential analysis, as shown by Martinez et al. (2012). The researchers carried out a comprehensive simulation study on three concentrating collectors, featuring different tracking and receiver concepts (a fixed mirror solar concentrator, a small sized parabolic through and a linear Fresnel reflector) for 995 locations worldwide, from latitude 53°S to 65°N. Aim of their work was to identify a dependence between the collector energy output and weather data commonly available such as global irradiation or ambient temperature.

The calculation was conducted with the software TRNSYS and using the Energy Plus public weather database as inputs (Energy Plus 2015). By implementing a multiple linear regression analysis, they found a strong correlation between output, latitude, operating temperature and fraction of beam radiation f_{beam} (R^2 about 0.975 in most cases under investigation). For quick assessment purpose, useful two-dimensional iso-energy contours chart were developed, as displayed in Figure 4.6. Similar promising approaches can be implemented even for low-concentrating or non-concentrating collectors

Figures 4.7 to 4.9 compare simulations carried out with the tools ScenoCalc and GainBuddy for different collector technologies at a mean fluid temperature of 100 °C, which is currently the maximum input allowed by ScenoCalc. The results show a very good agreement for the flat plate collector (Figure 4.7) and for the evacuated tubular collector with compound parabolic concentrator (Figure 4.8), with monthly deviations below 5% and yearly deviations below 1.5%. For the higher concentrating parabolic through collector the difference increases up to 8% and 4% respectively, which is supposed to depend on the different radiation models adopted by the programs or on their calculation routine (Figure 4.9). Similar results were achieved for other fluid temperatures and locations, thus proving the comparability of the two softwares within the specific temperature range. To enable the comparison for PTC end losses, which are by default considered in GainBuddy, were separately calculated and added to the monthly yields (for this specific case an additional gain of 3-4%).

Figure 4.10 presents the influence of self-shading effects on a field of parabolic through collectors at a mean fluid temperature of 150 °C. The simulated field consists of 24 collectors with an aperture of 1.8 m, disposed in 12 rows with a distance of 3 m. The calculation shows that the reduction of annual energy gain taking self-shading into consideration, which is distributed over the year in dependence of the incidence angle of the solar radiation, amounts to 10%. The results attest on the one side the relevance of this effect, on the other one the utility of the new feature introduced by the simulation tool GainBuddy.

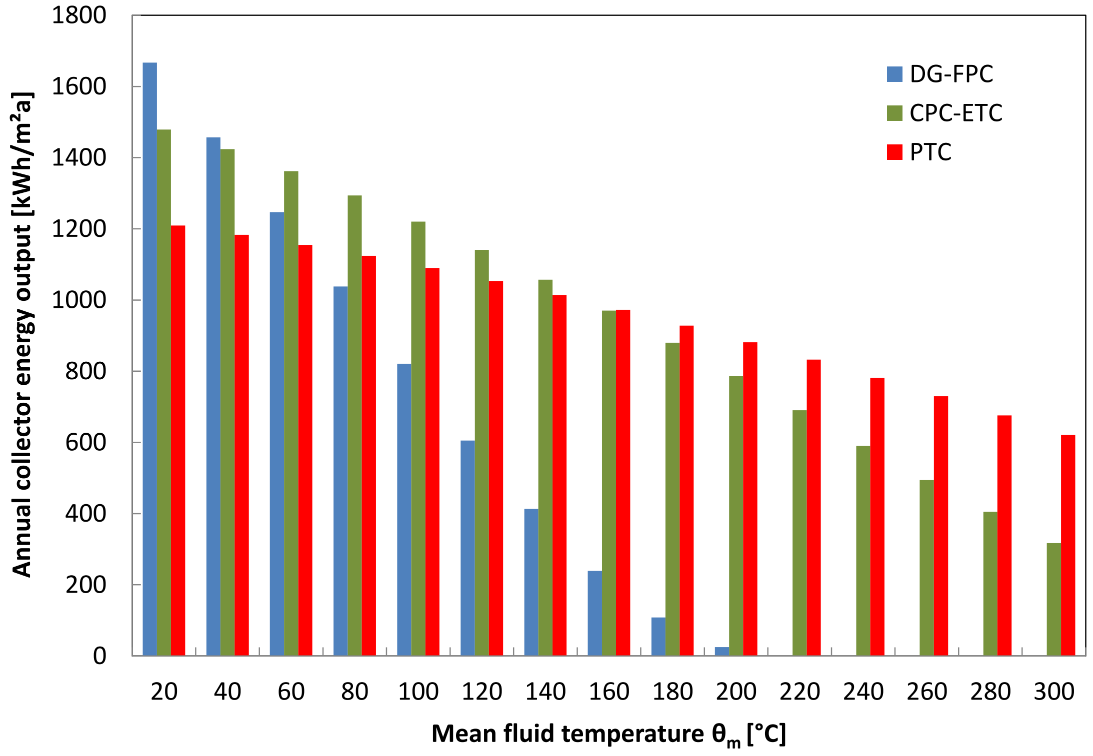

Fig. 4.4 - Annual energy output of different collector technologies in dependence of their mean fluid temperature calculated with GainBuddy (location: Seville; weather dataset: Meteonorm; orientation stationary collectors: south, 30° tilt angle; orientation tracking PTC: north-south axis).

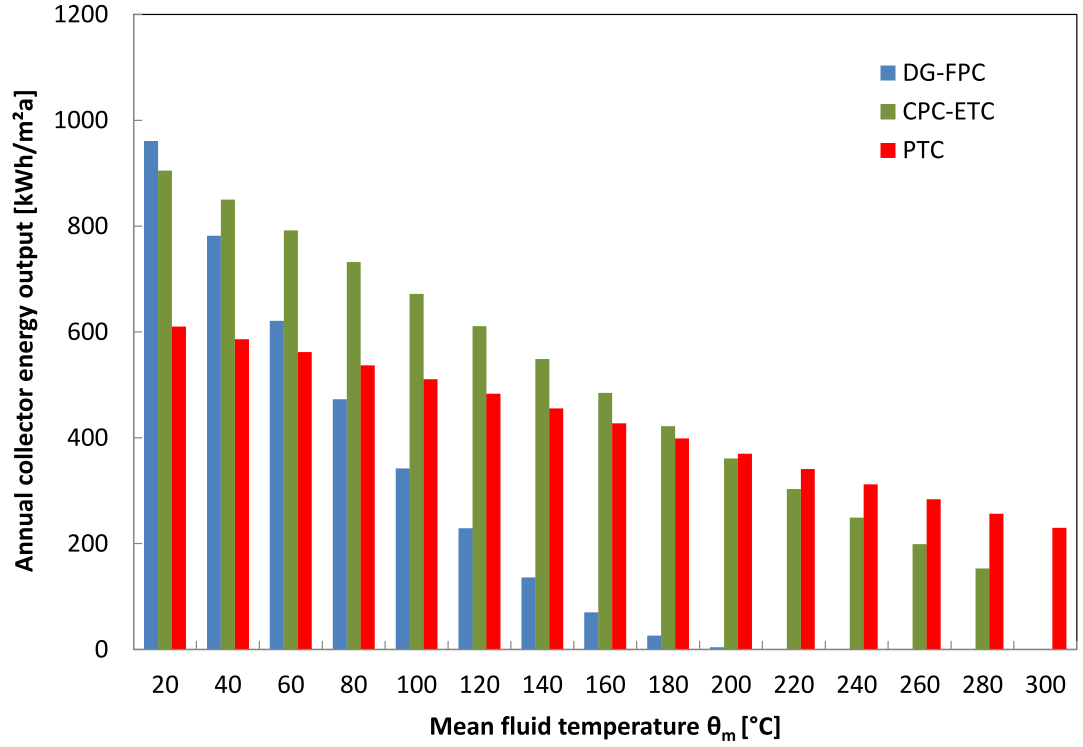

Fig. 4.5 - Annual energy output of different collector technologies in dependence of the mean fluid temperature calculated with GainBuddy (location: Graz; weather dataset: Meteonorm; orientation stationary collectors: south, 40° tilt angle; orientation tracking PTC: north-south axis).

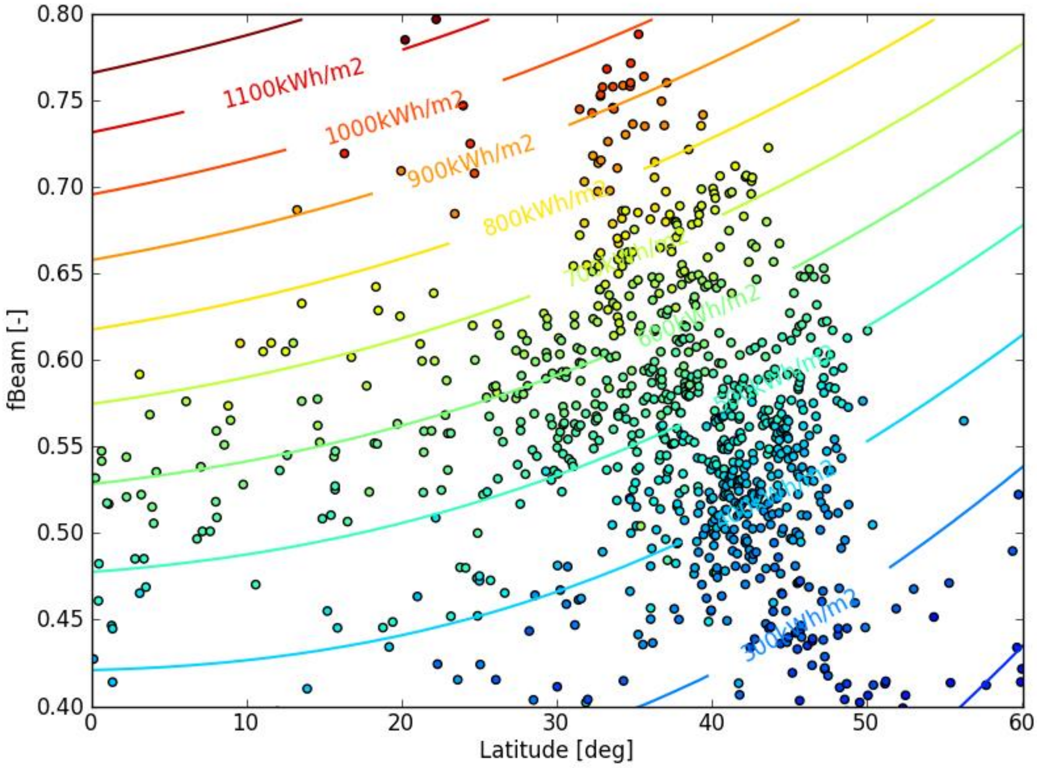

Fig. 4.6 – Iso-energy contour chart for the quick performance assessment of a parabolic through collector, as calculated by Martinez et al. (2012). The colored dots represent the locations used for the calculation. (weather dataset : Energy Plus; collector orientation: north-south tracking axis).

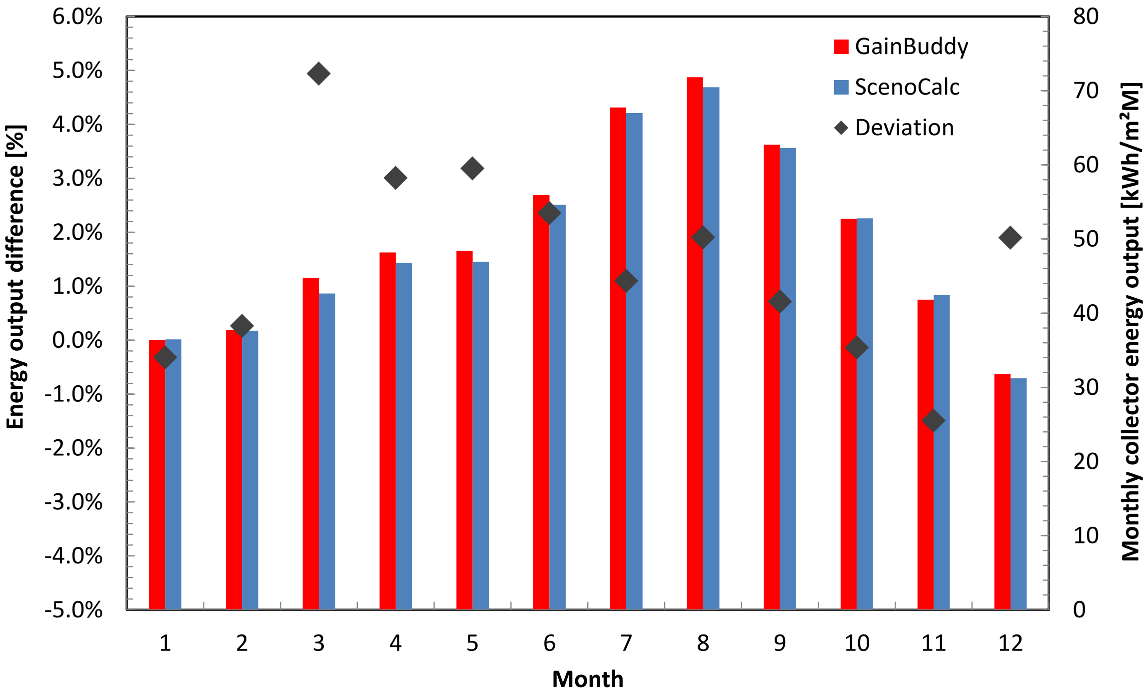

Fig. 4.7 - Monthly energy output of a generic flat plate collector: comparison between the simplified calculation tools ScenoCalc and GainBuddy (location: Seville; weather dataset: Meteonorm; collector orientation: south, 45° tilt angle)

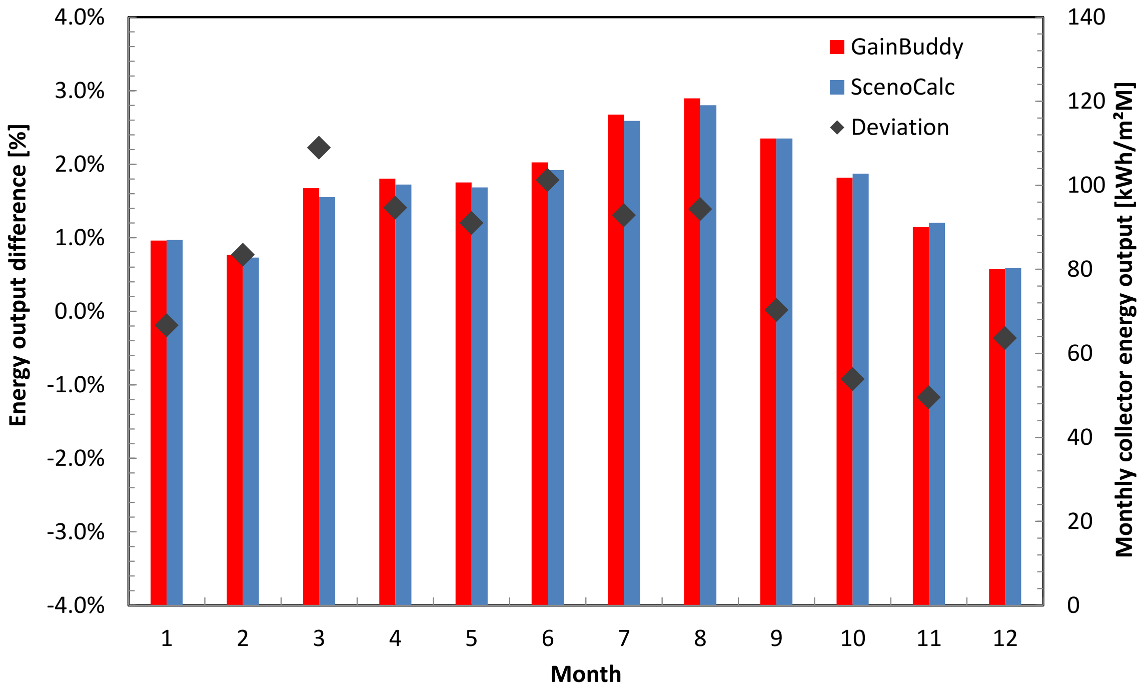

Fig. 4.8 - Monthly and annual energy output of a generic evacuated tubular collector with compound parabolic concentrator: comparison between the simplified calculation tools ScenoCalc and GainBuddy (location: Seville; weather dataset: Meteonorm; collector orientation: south, 45° tilt angle).

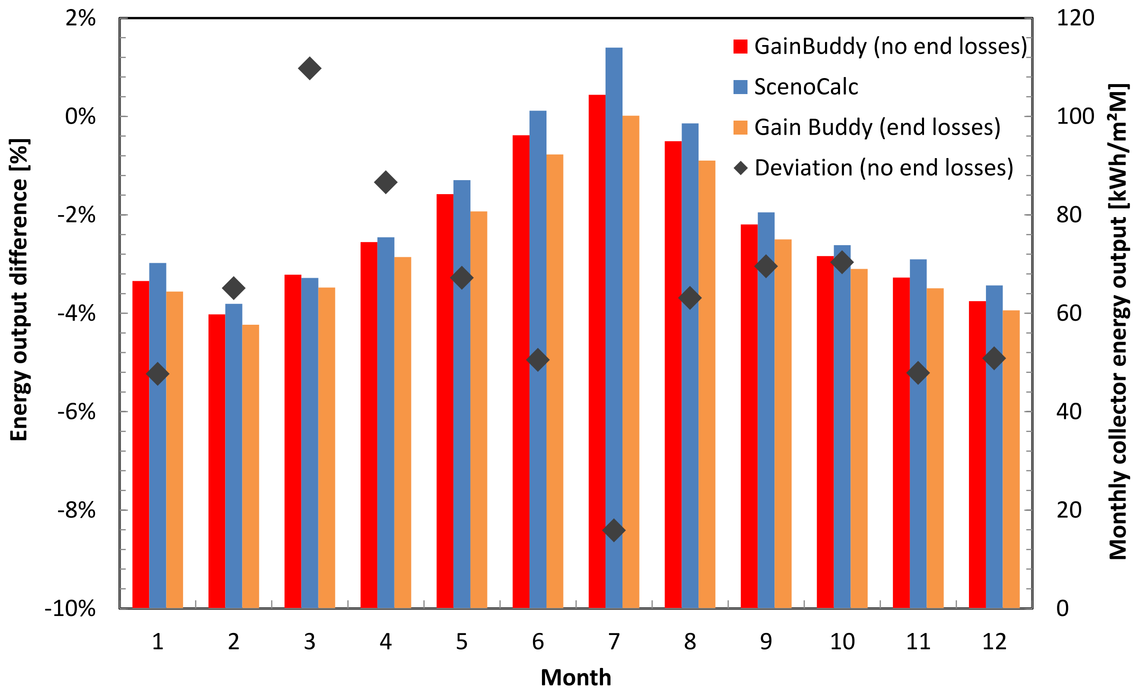

Fig. 4.9 - Monthly and annual energy output of a generic parabolic through collector: comparison between the simplified calculation tools ScenoCalc and GainBuddy (location: Seville; weather dataset: Meteonorm; collector orientation: east-west tracking axis). For GainBuddy both results with and without considering collector end losses are reported.

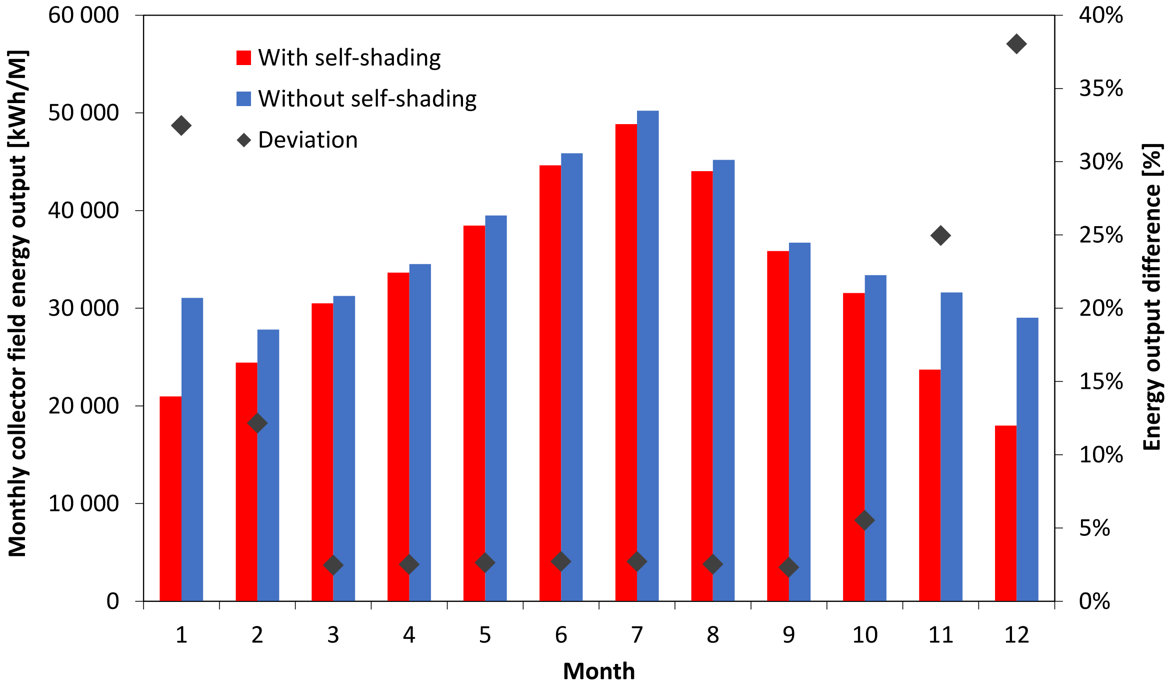

Fig. 4.10 - Monthly energy output of a generic parabolic through collector field at a mean fluid temperature of 150°, with/without consideration of self-shading effects, calculated with GainBuddy (location: Seville; weather dataset: Meteonorm; collector orientation: east-west tracking axis; collector field geometry: 24 collectors with an aperture of 1.8 m, 12 rows with a distance of 3 m).

5 Economic comparison

The economic comparison of different collectors relies on the balance between the investment and operation costs and the economic revenues obtained from the investment: the energy yield valued according to the heat production costs from alternative (conventional) sources.
At a pre-feasibility stage, yield calculations based on the simplified methodologies presented in Section 4.2 stand only for the performance of the solar collector being operated at a prescribed temperature under prescribed incidence and climate conditions. Whereas such simplified approach enables a comparison of collector yield results, it does not capture the dynamics of a full system operation, namely the impact of using a thermal storage, varying heat loads or system control strategies and constrains leading to variable collector inlet temperatures or dumped energy conditions, e.g.
Such impacts, captured only on the results of system simulations as those provided by system simulation tools discussed in Section 4.4, are illustrated in Figures 5.1 and 5.2, namely the impacts of solar field and TES volume dimensioning on solar system gains and solar fraction:

- an increase on the solar field size for the same load profile (translating into a lower utilization ratio, in liters of heater water per m^2 of collector aperture) stands for a high solar fraction, on one hand, but for a lower solar gain on the other, i.e., the specific solar collector yield decreases (which is explained by an higher average operating temperature and, thus, by an average lower solar field efficiency);
- an increase on the TES volume for the same load profile stands for a high solar fraction and high solar gain (which is explained by a lower average operating temperature and, thus, by an average higher solar field efficiency).

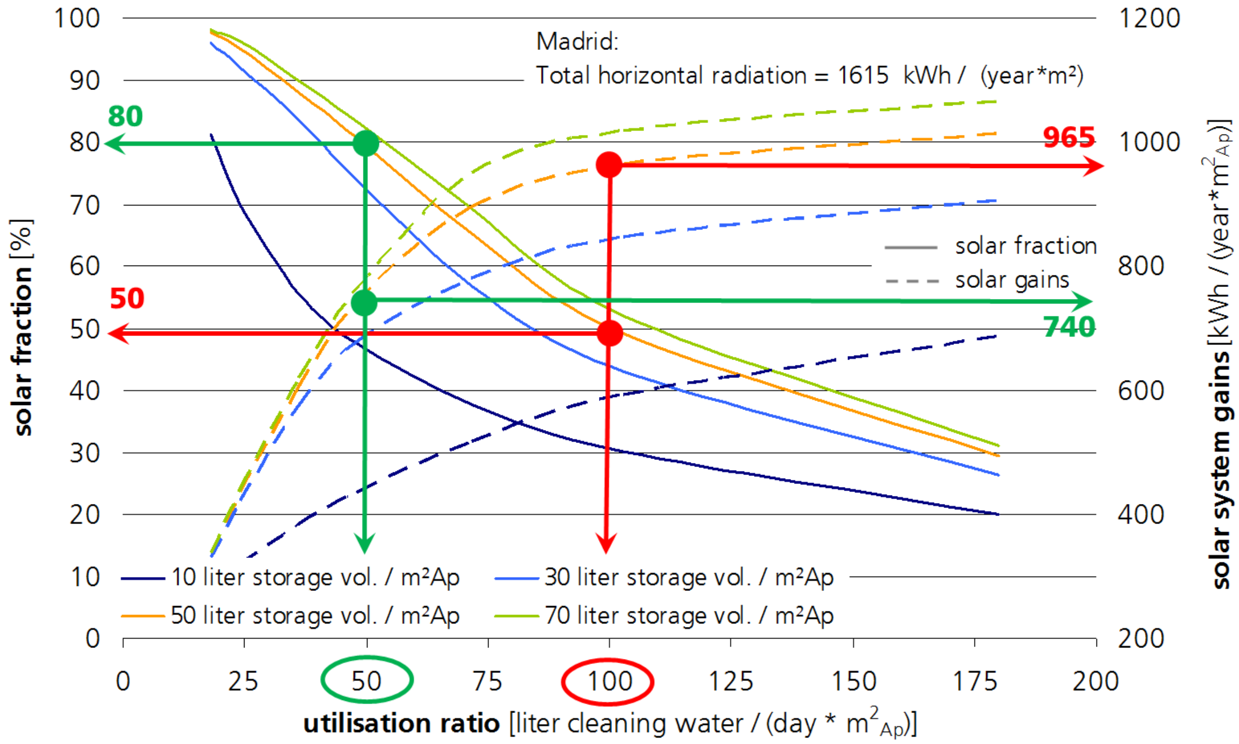

Fig.5.1 – Impact of solar field dimensioning on solar fraction and solar system gains, adapted from (Heß and Oliva 2011)

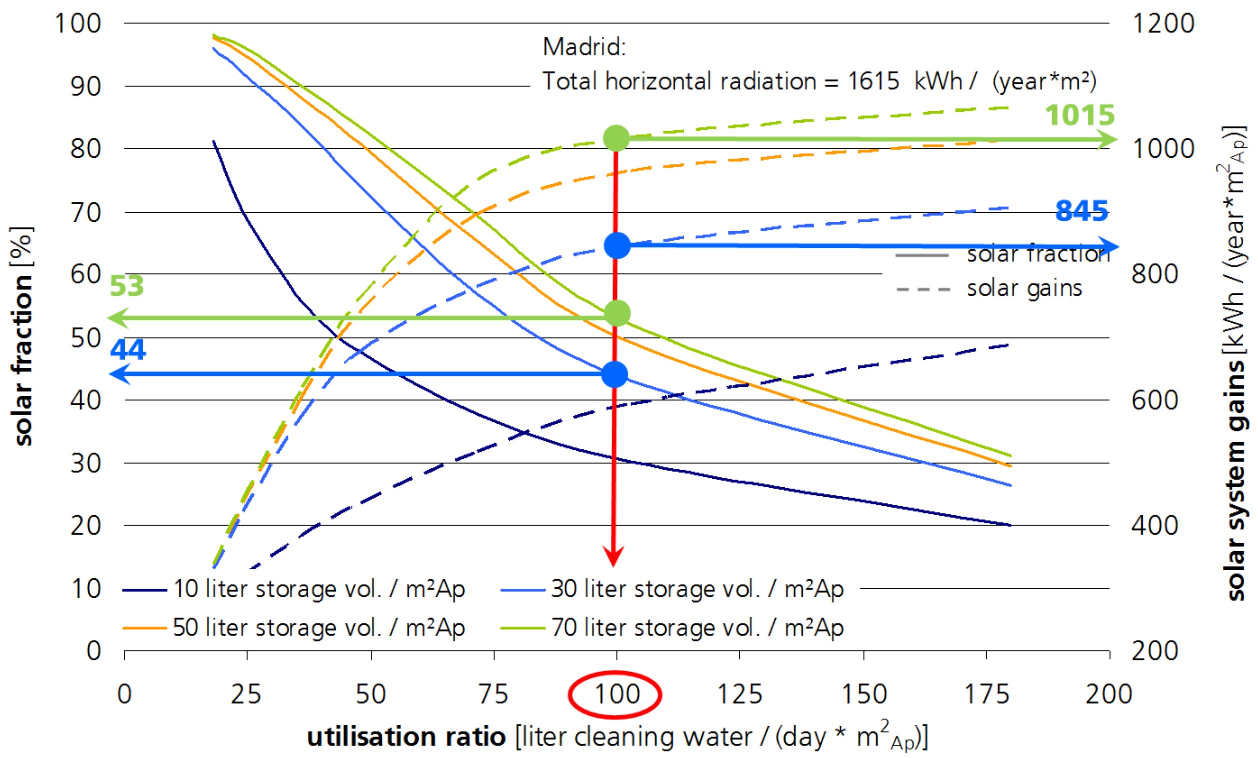

Fig.5.2 – Impact of TES volume on solar fraction and solar system gains, adapted from (Heß and Oliva 2011)

As so, an economic comparison of solar collectors at a pre-feasibility stage relies on a specific cost of heat produced by the collector under the operation conditions defined on the simplified yield assessment, considering only the costs of the collector, the estimated annual yield and an estimated collector lifetime, according to:

SCOH = CCost / (Qcol x lifetime) [€/kWh]

where:

- CCost is the collector cost [€/m^2]
- Qcol is the collector annual yield obtained from the simplified calculation [kWh/(m^2.year)]
- lifetime is the estimated collector lifetime [years]

Depending on the information available in the preliminary design stage, specific cost and yield can also be referred to the collector field, in order to produce a more comprehensive key-figure.

A deeper approach to system economic performance must rely on the results of more detailed system simulation and on the results of a conventional investment analysis:

- Internal rate of return (IRR);
- Net Present Value (NPV);
- Payback Period;
- Levelized Cost of Heat (LCOH)

For an exhaustive performance assessment environmental aspects like CO_2 emissions should also be considered, separately or by using a combined indicator. For more information about this topic it is referred to the already mentioned Report C3 of TASK 49 (Platzer et. al. 2015a).

6 Conclusion and recommendations

A comparative performance assessment of collector technologies represents a useful approach in a preliminary design stage of solar installations for process heating. Previous experiences with SHIP projects show that basic information about the processes of the manufacturing company under investigation (set-up of the heating system, load and load profiles, etc.) and, then, about the possible solar thermal integration (integration point, system configuration and rough dimensioning, etc.) are not available or not easily accessible at the very beginning. Due to the higher time investment, a more detailed and reliable system analysis can therefore be carried out only in an advanced design stage. Such an assessment can also be valuable for collector manufacturers interested in analyzing the potential of their own products for specific industrial applications. Aim of the report is, thus, to provide decision-makers, planners, end-users and manufacturers with a simple and reliable procedure defining a key-figure which sums up relevant technical as well as economic aspects and takes the peculiarities of process heating into account.

The technical analysis presented focuses on the energy performance of the collector. With regards to the methodology, the annual energy output at a defined operating temperature, well-established in Europe for DHW and SH applications and already adopted by Solar Keymark, is identified as the best suitable approach. This calculation relies on few and easily available inputs like the collector data, the weather data for a location next to the installation site and the process temperature(s). Compared to the SRCC procedure, it provides more realistic results and is flexible enough to be adapted for process heating. As to the calculation tools, the report mainly analyses programs for not-expert users. ScenoCalc, official Solar Keymark output calculator and directly linked to the correspondent collector database, exhibits severe shortcomings which at the present state impair its use for SHIP applications. An update is strongly recommended. The software GainBuddy, specifically developed at SPF for solar process heating, proved on the contrary to fulfill most of the requirements and can therefore be suggested for this use. First comparisons between these two simplified tools within the validity range of ScenoCalc (temperatures below 100°C, not or low concentrating collectors) show a good agreement. More extensive investigations with highly concentrating collectors like line-focusing PTC or LFR are still necessary and planned. It has to be mentioned, that the measurement and characterization itself of this kind of collectors is a current research topic (Fahr and Kramer 2016).

Another technical aspect, which may have a significant impact on the final decision but was not taken into consideration in the report, is the collector installation. Especially in case of roof-mounted solar plants, dimension, geometry and maximum bearing load of the roof can represent a practical restriction or even prevent the installation of a solar thermal system. The collector weight mainly depends on the specific technology and typically ranges between 15 kg/m² (single-glazed FPC or ETC) and 30 kg/m² (double-glazed FPC or line-focusing collector). Mounting systems on the contrary depend more on the mechanical load on the collector (wind, snow, etc.) than on the collector itself and their weight can vary from 1-2 kg/m² (simple substructure on sloped roof) up to 100 kg/m² or higher (substructure with sinkers on flat roof). The calculation of mechanical loads and the design/choice of correspondently suitable mounting systems are complex, site (climate, height and type of the building) specific issues, which cannot be generally linked to collector technologies.

For the economic assessment end-user costs in €/m² are to be considered. Depending on the degree of information available, specific costs for the simple collector or of the installed field (including mounting system) can be used.
Specific cost of heat (SCOH, in €/kWh) produced by the collector (or by the collector field) over its lifetime is finally suggested as the key-figure to adopt for the comparison of different products.
This simplified technical-economic assessment deliberately neglects operating and maintenance costs, which are strongly dependent on the system configuration. Special collectors with technical features affecting the cost of the solar plant over its lifetime (i.e. collectors preventing overheating) are therefore penalized. It is recommended to take these additional aspects into consideration even in an early stage of the feasibility analysis.

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IEA Solar Heating and Cooling Programme

The Solar Heating and Cooling Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is

*To enhance **collective knowledge** and **application** of solar heating and cooling through **international collaboration.***

The members of the Programme collaborate on projects (referred to as "Tasks") in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

A total of 53 such projects have been initiated to-date, 39 of which have been completed. Research topics include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44)
- Solar Cooling (Tasks 25, 38, 48, 53)
- Solar Heat or Industrial or Agricultural Processes (Tasks 29, 33, 49)
- Solar District Heating (Tasks 7, 45)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52)
- Solar Thermal & PV (Tasks 16, 35)
- Daylighting/Lighting (Tasks 21, 31, 50)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- Storage of Solar Heat (Tasks 7, 32, 42)

In addition to the project work, there are a number of special activities:

- SHC International Conference on Solar Heating and Cooling for Buildings and Industry
- Solar Heat Worldwide – annual statistics publication
- Memorandum of Understanding with solar thermal trade organizations

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