Solar district heating guidelines

Solar collectors

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Efficiency expression

General terms

The efficiency of a solar collector depends on the ability to absorb heat and the reluctance to "lose it" once absorbed. Figure 7.1.1 illustrates the principles of energy flows in a solar collector.
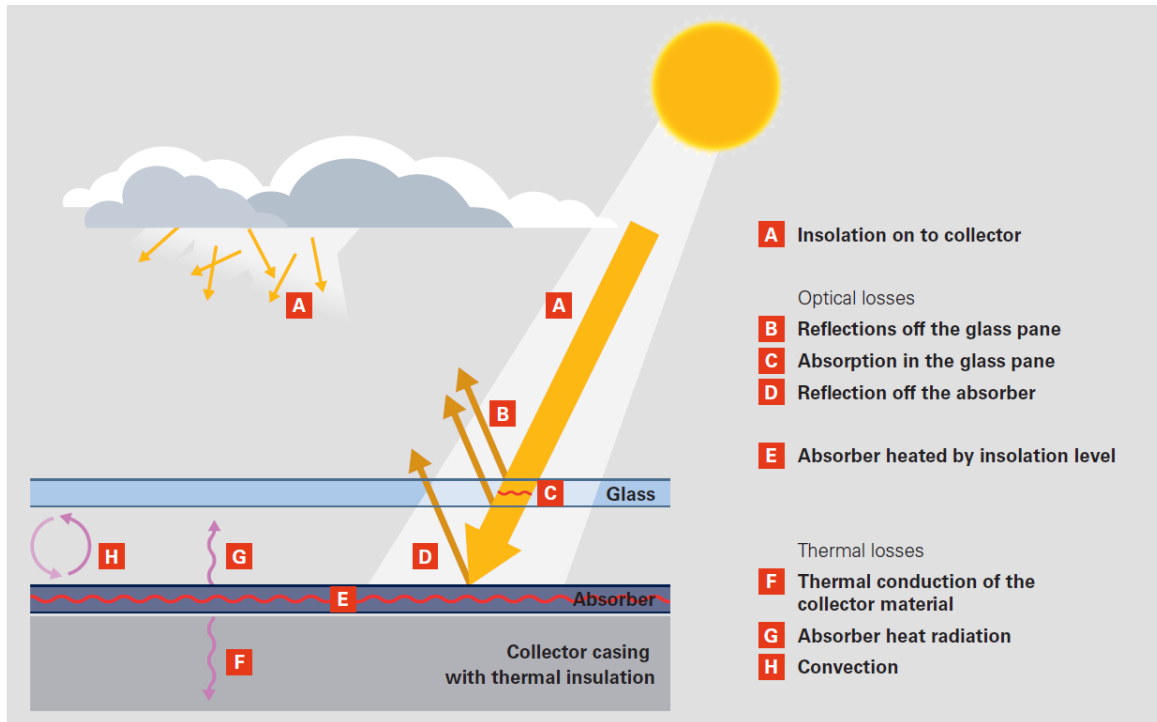

Fig. 7.1.1. Principle of energy flows in a solar collector [1].

A simple way to calculate the efficiency is to use equation 7.1.1 below and the parameters found on the data sheet of the collector:

η_0:	Maximum efficiency if there is no heat loss*	[-]
a_1	1st order heat loss coefficient	[W/(K·m²)]
a_2:	2nd order heat loss coefficient	[W/(K²·m²)]

These parameters should be determined according to the European standard EN12975 and provide the basic information to determine the efficiency:

$$\eta_c = \eta_0 - a_1 \frac{(T_m - T_a)}{G} - a_2 \frac{(T_m - T_a)^2}{G} \qquad \text{(eq. 7.1.1)}$$

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* *Also referred to as the "optical efficiency".*

where

η_c:	Collector efficiency	[-]
G:	Total (global) irradiance on the collector surface	[W/m^2]
T_m:	Mean collector fluid temperature	[°C]
T_a:	Temperature of the ambient air.	[°C]

The efficiency parameters of a wide range of collectors can be found at www.solarkeymark.org. This website list only collectors which have been tested according to the standard EN12975 by an impartial test institute.

The optical losses are constant regardless of the temperature. To minimize these losses some manufacturers use anti reflective (AR) treated glass which increases the amount of radiation transmitted through the cover glass by reducing the reflection. The AR treatment can be made in different ways. It can consist of an etching of the glass surface by subjecting the glass into a pool with certain chemicals (before the collector assembly)[†] or it can be made as a coating, i.e. a layer on the glass. Glass with low iron content, which helps to minimize the optical losses, is standard.
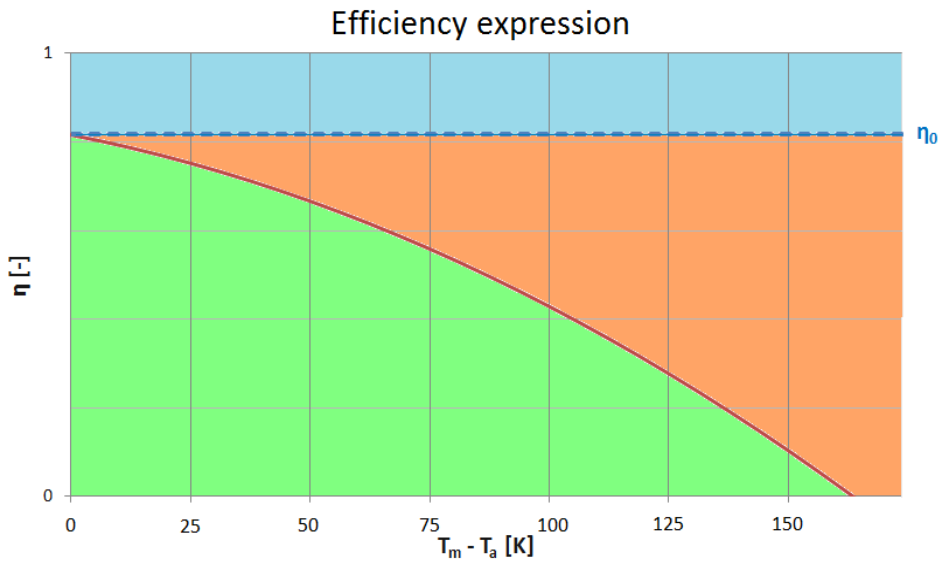

Fig. 7.1.2. Example of the efficiency expression from equation 7.1.1 (red line) illustrating the losses and useful energy for a given irradiation level (e.g. 1000 W/m^2). The efficiency is plotted as function of the temperature difference between the mean collector temperature and the ambient temperature. The colours indicate the ratio between the optical losses (blue), the heat losses (orange) and the useful energy (green) which can be compared to the total amount of energy from the irradiation (equal to 100 % on the secondary axis).

[†] *Further info on AR treatment by etching can be found at www.sunarc.net.*

The collector power output can then be calculated as:

$$P_c = A_c \cdot \eta_c \cdot G \tag{eq. 7.1.2}$$

where

P_c:	Power output from the collectors	[W]
A_c:	Collector area	[m^2]

It is very important that the efficiency parameters are based on the same area as used in equation 7.1.2 e.g. collector *aperture* area.

Incidence angle modifier

The part of the irradiation reflected at the glass and absorber surface is not constant. It depends on the incidence angle of the solar irradiation. To account for this, an incident angle modifier (IAM) is multiplied by the maximum collector efficiency η_0 in equation 7.1.1.

Figure 7.1.3 shows an example of the IAM as function of incident angle for a flat plate collector. In the test report of the collector the IAM is generally given for the incident angles of 10°, 20°, 30°, 40°, 50°, 60° and 70°, but it can also be given as one of the following expressions:

$$K_\theta = 1 - b_0 \cdot \left(\frac{1}{\cos(\theta)} - 1 \right) \tag{eq. 7.1.3}$$

where

K_θ:	IAM	[-]
b_0:	Constant stated in data sheet provided by manufacturer and/or test institute	[-]
θ:	Incidence angle on collector plane	[°]

or

$$K_\theta = 1 - \tan^p \left(\frac{\theta}{2} \right) \tag{eq. 7.1.4}$$

where

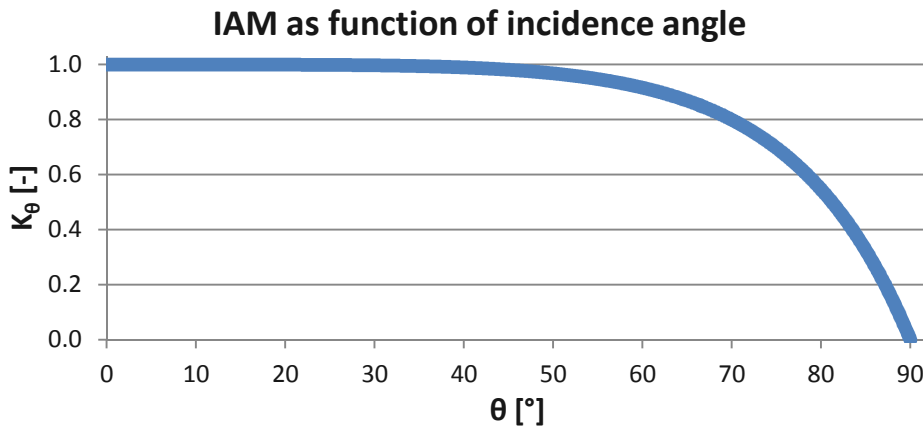|		
p:	Constant stated in data sheet provided by manufacturer and/or test institute	[-]

IAM as function of incidence angle

Fig. 7.1.3. Example of IAM as function of incidence angle for a flat plate collector type used for SDH (based on eq. 7.1.4).

The radiation going directly from the sun onto the collectors is called *beam* radiation or *direct* radiation. Some of the solar radiation is scattered by the molecules in the atmosphere. A part of this radiation is again reflected in clouds or small particles in the air and onto the collectors. This is referred to as diffuse irradiation. Even on a sunny day with clear blue sky, not all of the irradiation comes directly from the sun – some comes from the rest of the hemisphere though the percentage in this case is small. Reflectance from the ground and nearby obstacles may be calculated as a separate part, but is sometimes included in the calculation as part of the diffuse radiation.

For very detailed calculations equation 7.1.1 and 7.1.2 are split in two using

- the direct and diffuse irradiation instead of the global irradiation and
- the IAM for direct and diffuse irradiation separately.

Equation 7.1.2 then becomes:

$$P_c = A_c \cdot \left(\eta_0 \cdot \left(G_b \cdot K_\theta + G_d \cdot K_{60} \right) - a_1 \cdot \left(T_m - T_a \right) - a_2 \cdot \left(T_m - T_a \right)^2 \right) \qquad \text{(eq. 7.1.5)}$$

where

G_b:	Beam radiation (direct) on collector plane	[W/m^2]
G_d:	Diffuse radiation	[W/m^2]
K_θ:	IAM for the incidence angle at the given time step	[-]
K_{60}:	IAM for diffuse radiation	[-]

Diffuse radiation is coming from all incidence angles between 0° and 90°, therefore an average value of IAM at θ = 60° is used.

Often an approximated average IAM can be multiplied by η_0 in equation 7.1.1 thus including the IAM in the calculations without having to use the more complex equation 7.1.5.

Flow rate

Though the efficiency of the *collectors* is high if the flow is maximized (thereby minimizing the operating temperature thus lowering the collector heat loss), it is often not optimal for the overall plant efficiency since high flow requires more pump power and/or larger pipe diameter. Besides, there is a maximum limit for the flow rate, to avoid erosion corrosion. However a flow high enough to be turbulent, ensures good thermal conductivity between the absorber pipes and the fluid.

The pressure loss of the collectors as well as the pipe system is of high importance when it comes to calculating the collector array design. The more collectors connected in series, the less total system pipe length and the less heat loss from these pipes. This requires a high flow rate to avoid the temperature to be too high at the outlet and a high flow rate will result in a high pressure loss over the row. As for all parts of a SDH plants, the design of collector array and the associated pipe system requires an optimization which provides the lowest heat price.

The efficiency expression in the data sheet from the certified test institutes is based on a certain flow level (typically 0.02 kg/s per m^2 collector). In some collectors the flow rate should be at a certain minimum level to ensure a uniform flow distribution in the absorber. As indicated in figure 7.1.4 the buoyancy effect may in some cases be significant enough to result in a lower flow in the top absorber strips if the flow is at a certain lower level (specific for the given collector type and operating conditions). If the flow is non-uniform the temperature distribution will be uneven which will lead to a decreased efficiency and it may even lead to boiling locally in some absorber strips without showing it at the measured (mixed) outlet temperature. Theoretical and experimental testing [2] of a 12.5 m^2 flat plate collector resulted in a recommendation of not using a flow rate lower than 6 liters/min for the given collector model. However the flow rate distribution is dependent on several things such as manifold diameter, riser pipe diameter, exact geometry of inlet and outlet, T-junctions between manifold and riser pipes, fluid temperature and viscosity. This means that whether the buoyancy effect may be significant or not depend on the specific collector model.
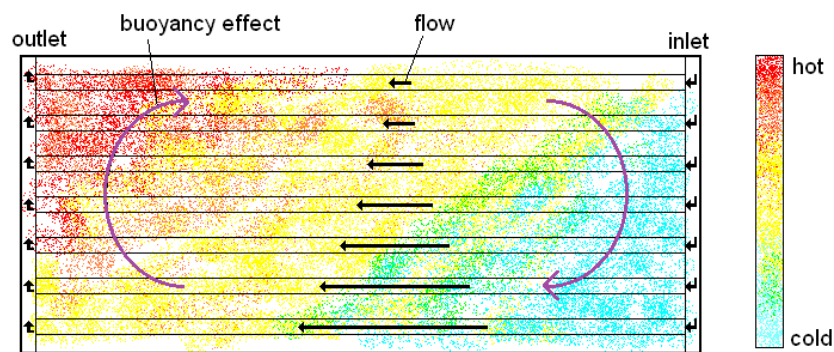
Fig. 7.1.4. Principle sketch of a FPC with too low flow leading to a non-uniform flow distribution. (Based on [2].)

Different solar collector types

The most common collector types are evacuated tubular collectors (ETC) and flat plate collectors (FPC) without vacuum. Different types of these collectors are described below. Concentrating collectors (Parabolic trough, Fresnel etc.) may also be used, but since a large part of the annual irradiation is diffuse – especially in the northern part of Europe – and these types do not utilize the diffuse part, they are not described further in this fact sheet.

Flat plate collectors

FPCs can be made with or without a convection barrier between the absorber and the cover glass. Often the convection barrier consists of a thin plastic foil (e.g. made of EFTE or FEP[‡]) stretched out between the absorber and the glass cover or an extra layer of glass. Just as the distance between absorber and cover glass is important to minimize the heat losses due to convection and conduction, it is important to get the optimum distance between the absorber and the convection barrier. The thermal expansion of a thin plastic foil must be taken into account since the foil should never be allowed to touch the absorber. In that case it will not function as convection barrier, but still decrease the total transmittance.

[‡] *EFTE ~ Ethylene tetrafluoroethylene. FEP ~ Fluorinated ethylene propylene.*
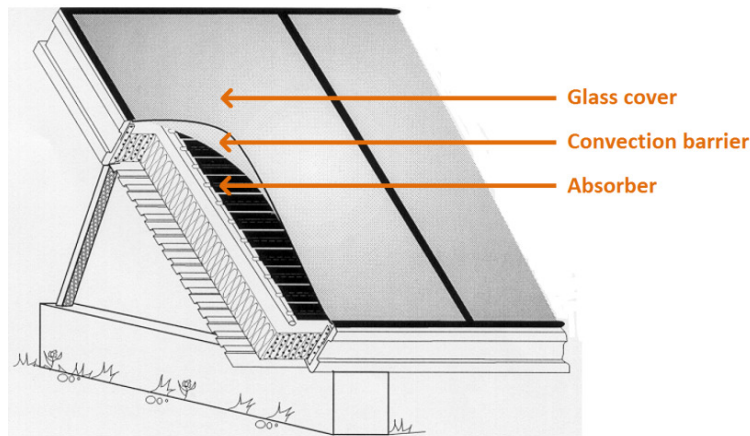
Fig. 7.1.5. Flat plate collector with convection barrier [4].
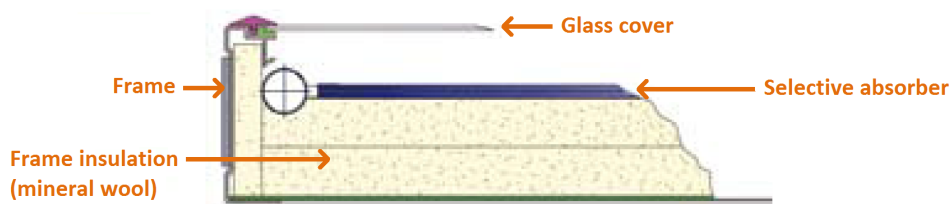

Fig. 7.1.6. Cross section of flat plate collector without heat barrier. [5].

The convection barrier shown in figure 7.1.5 reduces the circulation of air between the hot absorber and the colder glass cover. In this way it minimizes the heat loss from convection. Since the convection barrier is not 100 % transparent, it reduces the irradiance on the absorber slightly. This means that there is a certain (temperature) limit which distinguishes between whether or not it is advantageous to include a convection barrier, with regard to the efficiency.

In order to make the choice of collector type the extra costs due to the convection barrier should be compared with the extra annual energy output. To benefit from the optimal conditions from each collector type, a few collectors without convection barrier could be used in the first part of a series-coupled collector row and "convection barrier-collectors" then used as the rest of the row.

Evacuated tubular collectors

ETCs are made in many different ways, but all of them use vacuum to insulate the absorber. An example of a ETC-unit is seen in figure 7.1.7.

Fig. 7.1.7. Example of evacuated tubular collector unit [6].

In ETCs the heat can either be gathered by means of a solar collector fluid flowing through the absorber as in flat plate collectors or it can be collected by means of the heat pipe principle. In a heat pipe there is only a small amount of fluid sealed inside each evacuated tube. The energy transfer takes place in four steps:

1. This fluid is evaporated by the solar radiation.
2. The vapour rises to the top where it meets a (colder) pipe where a liquid flows through.
3. The vapour is condensed thus transferring the latent heat to the liquid in the top pipe.
4. The condensed fluid in the evacuated tubes runs back to the bottom of the tube where the process can start again.

In practice the process is continuous and not stepwise. The difference between heat pipes and direct flow ETCs can be seen in figure 7.1.8 and 7.1.9 below.
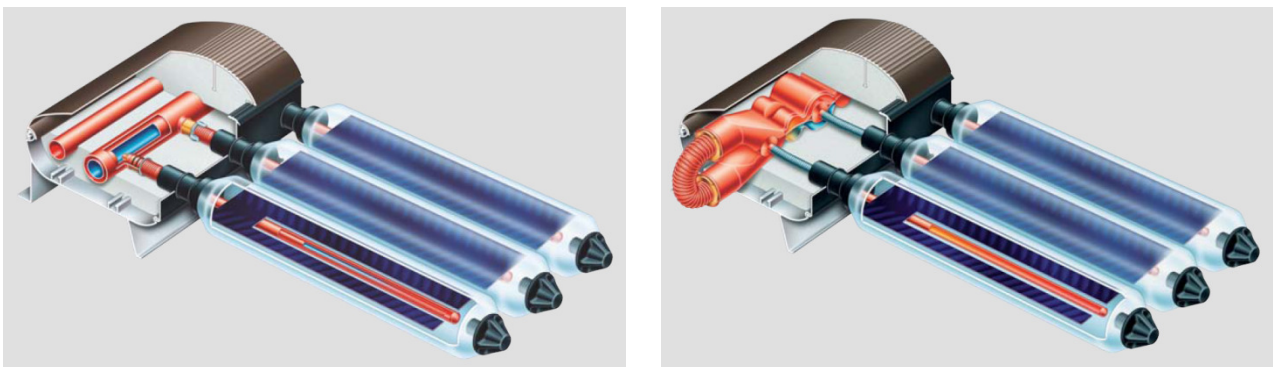

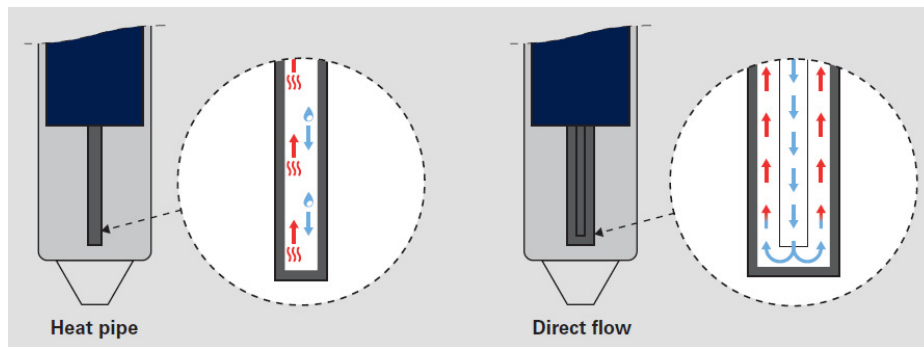*Fig. 7.1.8. Heat pipe (left) and direct flow ETC (right) [1].*

Fig. 7.1.9. Heat pipe principle (left) and direct flow ETC principle (right) [1].

Instead of co-axial direct flow, ETCs can also be made as "U-pipe" where the solar collector fluid runs through one single pipe shaped as a U.

Often concave mirrors are placed behind the collectors. This way almost all of the irradiation, which would otherwise slip between the collector tubes, will be reflected onto the tubes from behind. The reflectors can be made of cheap material e.g. polished aluminium. However for this solution to be efficient, it requires that the back side of the absorber have a selective surface just as the front.

Comparison of FPC and ETC

To illustrate how the efficiency parameters and the collector temperature affect the efficiency, the data for one evacuated tube collector and two flat plate collectors are listed in table 7.1.1 and the corresponding efficiencies are plotted in figure 7.1.10 assuming a solar radiation of 1000 W/m^2. B corresponds to a FPC with AR treated cover glass and convection barrier and C corresponds to a cheaper FPC without AR treatment or convection barrier.

Table 7.1.1. Efficiency expression constants for 3 different collectors – one evacuated tubular collector (ETC) and two flat plate collectors (FPC)[§].

Collector name	Collector type	η_0 [-]	a_1 [W/(K·m²)]	a_2 [W/(K²·m²)]
A	High performing ETC	0.75	1.0	0.005
B	High performing FPC	0.80	3.0	0.008
C	Medium performing FPC	0.75	4.0	0.010

[§] *The figures in the table are fictional. Collector efficiencies may range widely even within the same the category.*

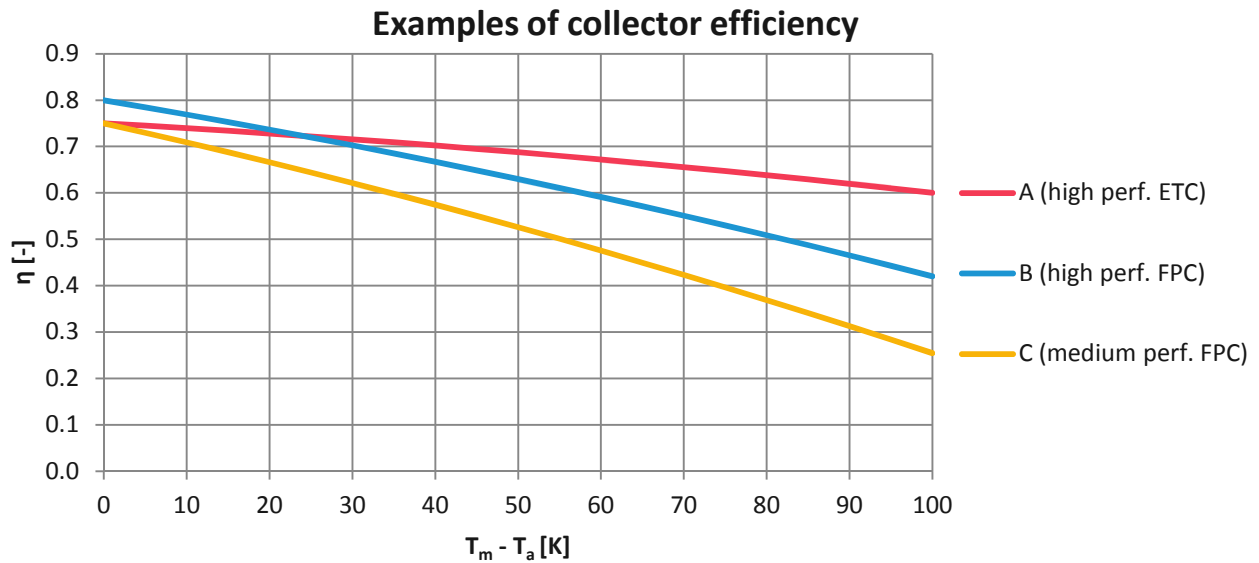**Examples of collector efficiency**

Fig. 7.1.10. *Examples of collector efficiency based on aperture area as function of temperature difference between collector fluid and ambient air. Total solar irradiation is 1000 W/m^2 on the collector plane.*

It is seen that in this example the ETC is best at high collector temperatures, the FPC with convection barrier is good at medium to high temperatures and that the FPC without convection barrier is good at low temperatures.

In many SDH plants FPC have been chosen instead of ETC because of the lower price/performance ratio. Using the efficiency expression above and weather data for a given location, the approximated annual output per m^2 collector is plotted for the three collectors in figure 7.1.11 and 7.1.13 based on aperture and gross area respectively (Copenhagen, Denmark chosen as example).
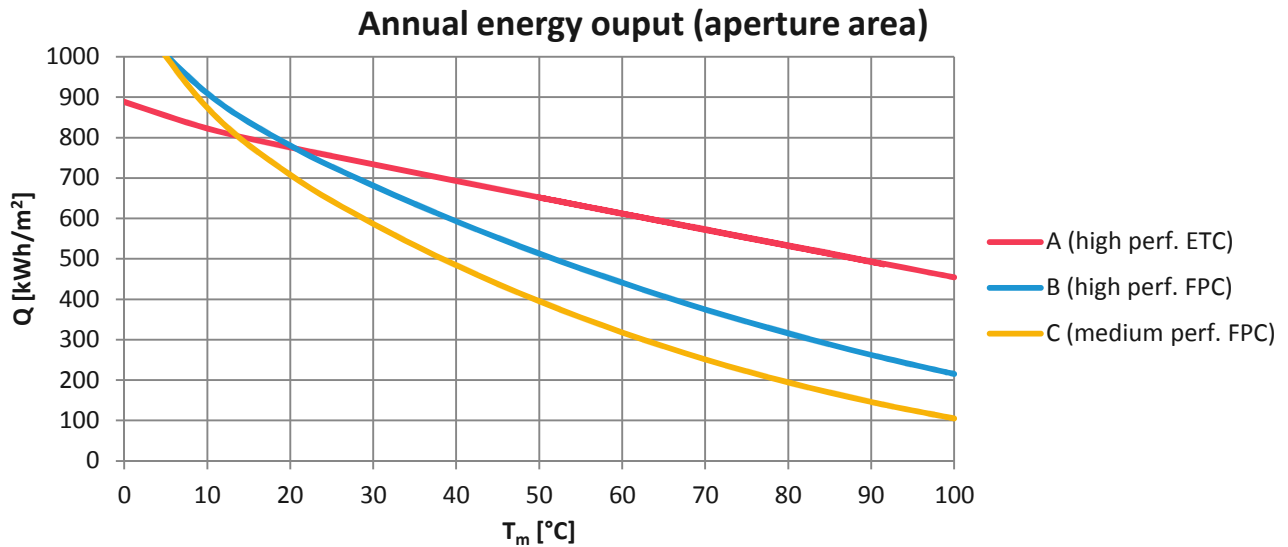
Annual energy ouput (aperture area)

Fig. 7.1.11. Annual solar output as function of collector mean temperature (T_m) for the ETC and the two FPCs described in table 7.1.1. Please note that the output (Q) is given in kWh per m² collector aperture area and per year. The aperture area can be much less than the gross area – see figure below and explanation in text below [**].

Figure 7.1.11 above shows the output per m² of *aperture* area. The aperture area is the area of the collector which actually takes part in the energy conversion. This is the area normally used for the collector efficiency parameters (collector test results). The standard ISO 9804 states: "...*aperture area is the maximum projected area through which un-concentrated solar radiation enters the collector*". Figure 7.1.12 illustrates the definition of this aperture area.
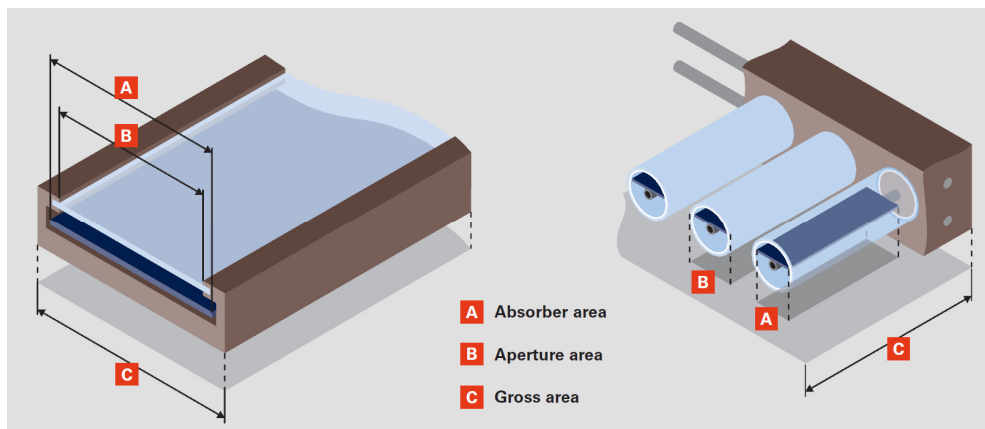

A Absorber area
B Aperture area
C Gross area

Fig. 7.1.12. Comparison of different ways to indicate the collector area [1].

[**] *The calculations are based on eq. 7.1.1 and 7.1.2 using Meteonorm hourly weather data.*

Due to the definition, the aperture area of a collector is always less than the area corresponding to the outer dimensions (gross area) of a collector. For evacuated tubular collectors the gross area is typically much larger than the aperture area (30-70 % larger). For flat plate collectors the gross area is typically only 5-10 % larger than the aperture area.
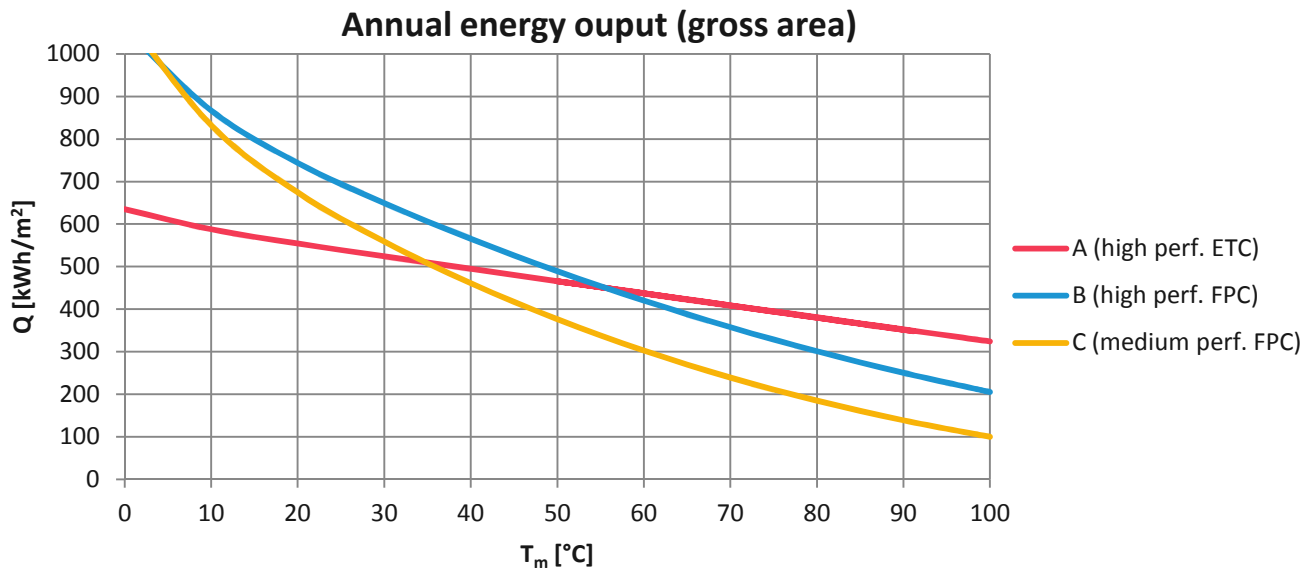

Annual energy ouput (gross area)

Fig. 7.1.13. Annual solar output as function of collector mean temperature (T_m) for the ETC and the two FPCs described in table 7.1.1. Please note that the output (Q) is given in kWh per m^2 collector gross area and per year.

This way it can be estimated roughly how much a certain temperature increase/decrease will affect the collector output, thus making it possible to choose the most profitable control strategy. The temperature is assumed to be constant during operation. More detailed calculations are needed for estimations which should include deviations in inlet and outlet temperatures.

The choice of collector type depends on several factors such as

- Price
- Efficiency
- Operating temperature
- Location (available solar radiation, ambient temperatures)

In most of the large systems flat plate collectors are used. One advantage of FPCs is that they are made in larger units compared to ETCs. The most commonly used collectors for large SDH plants in Denmark have

an aperture area of 13-14 m^2. Larger units mean a lower number of pipes connecting the collector units which normally contributes significantly to the pressure losses. Another reason for the larger amount of FPC in SDH is that the durability of ETCs so far has not been proved in large SDH systems.

Collector fluid

In most SDH systems a mixture of water and glycol is used as the collector fluid. This lowers the freezing point and the amount of anti freeze is determined by the minimum ambient temperature of the given location. Most SDH plants cannot be emptied and the solar collector fluid must therefore be able to withstand sub-zero ambient temperatures without freezing to avoid damaging the collectors and pipes.

The downside of glycol is that it decreases the efficiency due to the higher viscosity and lower heat capacity; hence the amount should be minimized. Another way to secure the plant from freezing is to activate the pumps whenever the temperature reaches a level where the risk of freezing is imminent. This way the plant is in "reverse operation" taking heat from the DH grid and heating up the collectors. Since the minimum ambient temperature will only occur rarely during the lifetime of the plant, it is probably not preferable to keep the glycol amount high enough to have the freezing point at this temperature at all times. The optimum solution often is a mix of the two solutions: Instead of using a high percentage of glycol all year around to secure the plant a few hours during the winter where it is needed, a lower glycol percentage secures the plant during most of the winter and minimizes the need for "reverse operation" to zero or a few times a year.

References

[1] "Technical guide – Solar thermal systems", Viessmann GmbH, 2009.

[2] "Buoyancy Effects on Thermal Behavior of a Flat-Plate Solar Collector", Jianhua Fan & Simon Furbo, Dep. of Civil Engineering – Technical University of Denmark, 2008, www.aseanenergy.info/Abstract/31029901.pdf

[3] "Optimering og afprøvning af solfanger til solvarmecentraler" (*Optimization and testing of solar collector for SDH plants*), Jianhua Fan & Simon Furbo, Dep. of Civil Engineering – Technical University of Denmark, 2007, www.byg.dtu.dk/upload/institutter/byg/publications/rapporter/byg-sr0706.pdf

[4] "Levetid for solfangere i solvarmecentraler" (*Lifetime for collectors in SDH plants*), Simon Furbo et al., Dep. of Civil Engineering – Technical University of Denmark, 2009, www.byg.dtu.dk/upload/institutter/byg/publications/rapporter/byg-r210.pdf

[5] Data sheet for Sunmark solar collector. www.sunmark.dk/files/14m2-dk-140D.pdf

[6] Sales brochure for Kingspan Solar collector www.kingspansolar.com/kingspansolar/pdfs/sales/thermomax8pp.pdf

⌐ *The SDH fact sheets addresses both technical and non-technical issues, and provide state-of-the-art industry guidelines to which utilities can refer when considering/realizing SDH plants. For further information on Solar District Heating and the SDHtake-off project please visit www.solar-district-heating.eu.* ⌐