LOAD AND SEASON ADAPTED SOLAR COLLECTORS

Svante Nordlander and Mats Rönnelid
Solar Energy Research Center, Dalarna University, S-781 88 Borlänge, Sweden,
Phone +46-23-778700, Fax +46-23-778701, snr@du.se

Björn Karlsson
Vattenfall Utveckling AB, S-814 26 Älvkarleby, Sweden

Abstract – In Sweden, solar irradiation and space heating loads are unevenly distributed over the year. Domestic hot water loads are nearly constant. At higher latitudes it is difficult to attain high solar fractions for solar combisystems, due to overheating in summer and high load to irradiation ratios in winter. Truncated asymmetrical CPC collectors with east-west alignment can be designed to match seasonal variations in irradiation and load. Typically, the optical efficiency of the collector should be lower during periods with risk for overheating, and higher when the load is higher. This paper contains estimations of solar heating system performance with relevance for season and load adaption. Results regarding attainable solar fractions as a function of collector features, load profiles and load levels are reported. Calculation results are presented for a solar combisystem with 3000 kWh DHW load and 6000 kWh space heating load with different collector types and collector areas. With small collector areas the solar fraction is close to the level indicated by calculated yearly output at a fixed 50 °C absorber temperature. For higher solar fractions a simplified method using monthly load and collector output sums, and detailed TRNSYS simulations deliver realistic results. According to the calculations, a load adapted CPC collector with an internal reflector delivers as much useful energy as a high performance flat plate collector in a 30 m² system. The load adapted collector has a simple design, it may cost appreciably less to produce and it causes much less overheating in summer than the flat plate collector.

1. INTRODUCTION

An important aspect of the performance of a solar thermal system is the solar fraction (SF), defined as the annual useful heat produced by the solar collectors divided by the total solar and auxiliary energy supplied to the system.

Generally, it is desirable to have a high SF for installations in single family houses since the investments in the installation (piping, storage tank and equipment) is better utilised and the need for auxiliary energy is reduced. Many auxiliary energy systems based on combustion, e.g. oil or biofuel systems work better if the SF is high. These systems are usually dimensioned for periods with rather high load. In summer, operating periods tend to be infrequent and short, resulting in poorer combustion, higher levels of pollutant emissions and flue gas losses. With a high SF the combustion system will work at higher load levels, with a resulting better overall system performance.

In the south of Europe there are installations with solar fractions of 50% or more. In north of Europe, almost all installations have a considerably lower SF, and a typical well working combisystem for DHW and heating in a modern Swedish single family house may have a SF of 17 – 23% (Lorenz et. al., 1998). The reason for this low SF at high latitudes is demonstrated by figure 1, which shows the annual solar irradiation on a 45° tilted surface and the DHW and heating loads for a typical Swedish house. A test reference year for Stockholm, latitude 59.4°N, was used for climate data, and the heating load was calculated according to the degree-day method (Bourges, 1992). A proportion between DHW and heating load of 1:2 was assumed, a ratio common in new-built single family houses.

![Figure 1. Total irradiation on a south-faced, 45° inclined surface and heat demand (DHW and heating) for a modern Swedish single family house. Climate data for Stockholm, latitude 59.4°N.](image)

Since solar system commonly are designed to produce 100 % of the hot water need during summer, but not...
more, today’s solar thermal systems have an inherent limit in the possible contribution to the annual load.

There are, however, several ways to increase the solar fraction:

- The solar collector area may be increased, but this will also increase the number of stagnation hours with subsequent overheating problems of the thermal system. Another problem is that the system may become too expensive if standard collectors are used, since the marginal output decreases quite rapidly with collector area.

- Higher inclination of the collector does help. Most roofs have an inclination of 25-45°, which is suitable for the summer half of the year. With an inclination of 60-90° there will automatically be a more even annual heat production. However, it is seldom possible to mount collectors vertically on a roof in an acceptable way. In practice, these collectors should be mounted on (or integrated into) the façade, which increases the risk of shading from nearby buildings or vegetation. It may also be difficult to find sufficiently large free façade surfaces on a normal houses.

- In theory, the storage capacity can be increased, either by an increased storage volume or innovative storage materials with a large volumetric heat capacity. A large hot water storage will only slightly affect the FS. When unwanted heat losses from a traditional hot water storage are deducted from the solar energy collected only a smaller improvement in FS is possible for storages larger than approximately 1 m³ of water.

In this paper, we propose the use of modified CPC collectors with internal reflectors as a mean to attain a large SF in solar installations at high latitudes. Such collectors have several advantages over flat plate collectors:

- The efficiency of the collector depends on the solar incidence angle. This type of collector may be designed to work optimally during autumn, winter and spring, but with a lower optical efficiency during summer. Thus the collector may be optimised for a large SF rather than for a large annual production per m² at a lower SF. It is possible to practically eliminate the summer overheating problems.

- Solar collectors based on internal reflectors may be less expensive since the absorber area is reduced and replaced by less expensive reflector material. The absorber area will be smaller, reducing the collector heat losses and the need for collector insulation will be reduced or eliminated. This type of collector can therefore be manufactured to a lower cost since the amount of absorbers, piping and insulation is reduced. One example of this type of collector, showing promising results, is the Mareco collector (Karlsson and Wilson, 1998).

2. ENERGY COLLECTION WITH DIFFERENT COLLECTOR GEOMETRIES

The possible solar fractions for DHW and heating loads for Stockholm (latitude 59.4°N) were investigated. Five different collectors, specified in table 1, were investigated by use of the MINSUN simulation programme. Of these collectors, one is a standard flat plate collector, while the others are reflector-based collectors with restricted angular acceptance regions.

The main difference between these collectors is that they accept radiation from different regions of the sky. They are characterized by their upper acceptance angles. The acceptance angle is expressed in effective solar height, defined as the solar height of the component of the solar vector parallel to the north-south vertical plane. Since all collectors are assumed to be tilted towards south and all of the reflector geometries are east-west aligned, the solar acceptance of these collectors is conveniently expressed in terms of a thus defined effective solar height. The two principal types of collectors are illustrated in figure 2.

<table>
<thead>
<tr>
<th>Collector type</th>
<th>Figure</th>
<th>Coll. slope</th>
<th>Upper accept. angle</th>
<th>( F' \eta_{\text{inc, beam}} ) inside accept. region</th>
<th>( F' \eta_{\text{inc, beam outside accept. region}} )</th>
<th>( F' \eta_{\text{inc, diffuse}} )</th>
<th>( F' U_L ) [W/m².K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Flat plate</td>
<td>2a)</td>
<td>30°</td>
<td>-</td>
<td>0.77</td>
<td>-</td>
<td>0.69</td>
<td>3.7</td>
</tr>
<tr>
<td>2. Mareco 60</td>
<td>2 b)</td>
<td>30°</td>
<td>60°</td>
<td>0.72</td>
<td>0.27</td>
<td>0.43</td>
<td>2.5</td>
</tr>
<tr>
<td>3. Mareco 47</td>
<td>2 b)</td>
<td>30°</td>
<td>47°</td>
<td>0.71</td>
<td>0.22</td>
<td>0.36</td>
<td>2.1</td>
</tr>
<tr>
<td>4. Mareco 37</td>
<td>2 b)</td>
<td>30°</td>
<td>37°</td>
<td>0.71</td>
<td>0.19</td>
<td>0.30</td>
<td>1.75</td>
</tr>
<tr>
<td>5. Mareco 25</td>
<td>2 b)</td>
<td>30°</td>
<td>25°</td>
<td>0.70</td>
<td>0.14</td>
<td>0.23</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Table 1. Specification of collectors investigated
For each collector the annual energy delivered at a constant absorber temperature of 50° C was calculated by MINSUN, using an hourly algorithm with climate data for a test reference year in Stockholm. No storage effects were assumed. The hourly energy data were summed up to monthly values. A monthly space heating load was calculated as a pure degree-day load from the same climate data. A domestic hot water (DHW) load was defined as a constant load. The resulting data are demonstrated in fig 3 and table 2. A third of the load consists of a constant DHW load and two thirds of it is a varying degree day space heating load. The yearly sum of the load is 600 kWh, and the yearly output of the flat plate collector is 408 kWh.

It is evident that a large part of the summer production from the flat plate and the collector with 60° acceptance angle is useless. The diagram indicates that a collector adapted to the load level in this example should have an upper acceptance angle around 47°.

A useful monthly energy was defined as the lowest of monthly collected energy and the monthly load. A useful annual energy was defined as the sum of the useful monthly energies. A nominal solar fraction was defined as the annual collector energy output at 50 C divided by the annual load, irrespective of monthly loads.

Figure 2. Principal collector geometries investigated. a) Flat plate collector b) Mareco type collector. Collector tilt is \( \beta \).
usefulness. A useful solar fraction was defined as the useful annual solar energy divided by the annual load.

In Sweden, official testing reports characterize collectors by an annual energy production calculated at certain fixed operating temperatures, 50° C being recommended for the dimensioning of domestic systems. Thus the nominal solar fraction for a certain system would be the collector area multiplied by the official test value, divided by the load of the building. For example, 15 m² of collector with a nominal yield of 400 kWh/(m²*year) on a house with a yearly combined heating and DHW load of 12,000 kWh would have a nominal solar fraction of 50 %. From tests and simulations we know that in reality such a solar system would rather deliver between 2400 and 3000 kWh, the useful solar fraction thus being between 20 % and 25 %. For small systems, up to approximately 5 m² for a family house, the nominal and the useful solar fractions are essentially equal, but as the area rises, the useful fraction lags more and more behind the nominal fraction.

Figure 4 shows calculated nominal and useful solar fractions for collectors with a constant load, e.g. a DHW load. Up to 50 % nominal SF, all collectors deliver full output, due to the lack of summer overproduction. At 100 % nominal SF the most load adapted collector delivers 30 % more useful energy than the flat plate. In order to cover 75 % of the DHW demand a flat plate system would have to have two and a half times the area indicated by the nominal output. The next-best reflector collector covers 75 % of the load with 100 % of the nominal area. The collector with the highest useful fraction, Mareco 25, may be impractical and expensive though, as it delivers much less energy per unit area.

Figure 5 is a similar diagram showing useful SF for a degree day load, approximating a pure space heating system. Lower useful solar fractions are attained than with the DHW load, because of the larger demand in winter. For a Swedish climate, it seems possible to attain slightly less than 50 % SF with a flat plate system with 250 % of the nominal area. With the 37 and 47 degree collectors it may be possible to attain a SF of 47 % with a 100 % nominal area system.

3. SIMULATION OF SOLAR SYSTEMS WITH LARGE SOLAR FRACTIONS

In order to investigate realistically attainable solar fractions, we performed more thorough calculations, using the TRNSYS simulation programme. Two system models, tested in earlier works (Lorenz et al. 1998), were slightly modified for use with the load adapted collectors. The systems have the following basic data:
- Location Stockholm, Stockholm, latitude 59.4°N.
- Collector slope 30°
- 0.75 m³ combined storage tank
- 3000 kWh DHW load
- 6000 kWh space heating load
- Solar loop with heat exchanger in storage tank
- Electric auxiliary heating in top of tank
- Storage losses without solar heating: Standard system 490 kWh/year, advanced system 220 kWh/year
- Maximum storage temperature 95° C

Any energy collected when the storage was hotter than 95° C was assumed useless.

We simulated two versions of the system, a standard system commonly installed in Sweden in the 1990's,
and an advanced system, exemplifying a modern system at the state of the art. The most important difference is that the advanced system heats the DHW with an efficient external heat exchanger and has a well stratified tank both during charge and discharge.

![Figure 6. Useful solar fractions attained with different collector areas.](image)

Some results of the TRNSYS simulations are demonstrated in figure 6. It displays the solar fractions for the flat plate collector and the Mareco 47 with the standard and advanced solar systems. The solar fractions exclude tank losses exceeding the losses computed for a reference system with the tank heated by auxiliary energy only. As some of the surplus losses induced by the solar heating occur during periods with a heat demand, this definition of solar fraction slightly underestimates the solar fraction.

As expected the flat plate collector outperforms the adapted one at 10 m². At 30 m² collector area the collectors are almost equal when used in the advanced system. In the standard 30 m² system the flat plate is somewhat better.

### 4. COMPARISON OF CALCULATIONS

Table 3 compares the solar energy output from two collector types estimated with three different methods:

- Collector output computed by MINSUN at a constant 50° C operating temperature
- MINSUN calculation from monthly sums at 50° C adjusted by monthly load values, as described in section 2
- Detailed simulation with the TRNSYS model of the advanced combisystem

<table>
<thead>
<tr>
<th></th>
<th>MINSUN constant 50° C</th>
<th>MINSUN monthly</th>
<th>TRNSYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat plate</td>
<td>408</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>Mareco 47</td>
<td>213</td>
<td>136</td>
<td>122</td>
</tr>
</tbody>
</table>

Table 3. Energy output calculated with different methods, in kWh/year/m², from collectors in a 30 m² system.

The constant temperature output method disregards the influence of the load seasonal variation and is thus quite useless at predicting the actual performance of the system, whereas the simple monthly MINSUN and the detailed TRNSYS methods delivered comparable results. Figure 7 shows the calculated yearly output per m² for the flat plate and the Mareco 47 collectors at different collector areas, calculated with the two methods. The differences may largely be explained by differences in the modelling of the storage and of the operating temperatures.

![Figure 7. Collector output for systems with different collector areas, calculated with TRNSYS detailed and MINSUN monthly methods.](image)

### 5. OVERHEATING

The overheating problem was studied with data from simulations of the advanced 30 m² system. The energy collected at periods when the storage temperature was higher than 95° C was recorded in monthly sums, the sum calculated as collector energy output at 95 C. Figure 8 a) shows the useful and overheat energy for the flat plate collector and figure 8 b) shows the same for the Mareco 47 collector. With the adapted collector the amount of overheating is less, and the maximums occur in april and september when it probably is
possible to use some of the surplus heat for useful purposes. The flat plate system generates most of the overheating in summer when it is more difficult to dispense of. The Mareco 37 collector generates almost no overheating at all in a 30 m² system, but has a slightly lower solar fraction, 34 % as compared to 37 % for the Mareco 47 collector and 38 % for the flat plate.

Calculations show that the solar fraction for solar heating installations in single family houses can be significantly increased if the solar collector area is increased from 10 m² to 30 m². The increase of useful produced energy when the solar collector area is increased is larger for the load-adapted collector than for the flat plate collector since less “useless” energy is produced. Due to this, there will be a similar annual useful energy production from the two types of solar collectors if the collector area is large.

Furthermore, it has been shown that high solar fractions at high latitudes demand developed system designs, e.g. storage tanks with good stratification and efficient DHW production, to ensure that the heating system can take advantage of the produced solar energy. This is in accordance with results found for more traditional solar collector areas (Lorenz et. al., 1998).

To increase the collector area in order to increase the solar fraction is not obviously cost effective if the solar collectors are expensive. However, development work going on at research institutes and companies in Sweden shows that there is a substantial potential for cost reduction of the solar collectors if they are based on internal reflectors instead of the traditional flat plate design. Therefore, a successful development of this kind of solar collectors could open up a new market for large area collector installations in the order of 20-40 m² for single family houses.

Future work on load-adapted solar collectors will include detailed collector analysis and system simulations to define the optimal designs necessary for systems with high solar fractions. New solar collector models have to be developed, capable of modelling the optical and thermal performance of solar collectors with internal reflectors of different designs. In future projects, systems based on these principles will be built and tested.

ACKNOWLEDGEMENTS

This study has been financed by the Swedish Council for Building Research and Vattenfall Utveckling AB.
REFERENCES

