Performance and Perspectives of Solar Cooling

Edo Wiemken *, Jakub W. Wewiór [1], Anna Petry Elias, Björn Nienborg, Lotta Koch

Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 2, 79110 Freiburg, Germany

[1] PSE AG, Emmy-Noether-Straße 2, 79110 Freiburg, Germany

* edo.wiemken@ise.fraunhofer.de

Abstract

Solar cooling with thermally driven processes allows primary energy savings, reduction in greenhouse gas emissions and reduction in peak load electricity consumption from the grid. But often the achieved performances, especially with respect to the auxiliary electricity consumption, still differ from the potential, as e.g. calculated in a simulation study of small solar cooling systems. Simultaneously, solar cooling faces another option: the simple electricity compensation of conventional cooling installations by electricity from grid connected PV systems. A systematic comparison of both technologies has not been performed yet, but an exemplary calculation indicates that the real-time coverage of the electricity demand in a PV/conventional system may not always compete with a solar thermally driven system without additional measures. However, for the market development of solar cooling, assistance through well designed support schemes is still necessary in order to improve the technical and system integration level of thermally driven solar cooling.

1. Introduction

Solar cooling is widely connected with the use of solar thermal energy as driving heat source for a thermally driven process, in which chilled water or directly conditioned air is provided (Fig. 1.1). The solar thermal plant is especially designed and configured for this purpose with respect to capacity, flow rates and driving temperature. Beside the substitution of electricity by heat as main driving source, the thermally driven chillers use in general environmentally harmless refrigerants.

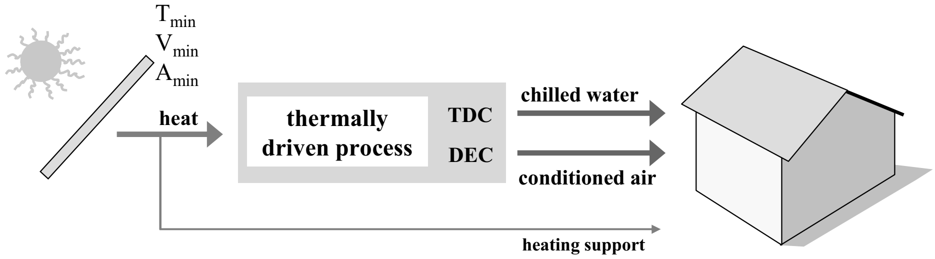

Figure 1.1. Basic solar cooling or air-conditioning scheme. Requirements on temperature, volume flow rate and on collector size (T_{min}, V_{min}, A_{min}) have to be fulfilled, to combine a solar collector system with a thermally driven process. Either a thermally driven chiller (TDC) may be applied, or an open cycle process (desiccant evaporative cooling, DEC), directly providing conditioned air. The latter technology is not topic of this paper

The current number of solar cooling and air-conditioning installations worldwide is projected at a few hundred systems [1]. The market development is below the high expectations, which rose a few years ago simultaneously with the presence of new chiller products in the small capacity range. Obstacles in the market penetration are high investment costs, which are connected with the development level:

- small production numbers of chillers;
- early stage of system development and standardisation;
- small number of experienced planners and installers;
- limited distribution and service network.

The development of solar cooling is accompanied by several market support activities, such as e.g. SOLAIR [2]. The best practice data base, prepared in this project, shows the large variety of solar cooling applications but indicates also that the systems are still far from standardised schemes. Experiences from existing installations are currently being prepared in the ongoing Task 38 in the Solar Heating and Cooling Programme of the International Energy Agency (IEA) [3].

2. Performance examples of solar cooling plants

2.1. Solar assisted air-conditioning in a large capacity range

Solar assisted air-conditioning in an adsorption chiller plant of 1.05 MW installed chilling capacity is realised at FESTO AG & Co. KG, Esslingen-Berkheim, Germany. While the chillers were installed in 2001 for air-conditioning of the new Technology Center of the company, the solar thermal collector system was added end of 2007 in the frame of the German Solarthermie 2000plus funding scheme. Figure 2.1 shows a sketch of the system. Adsorption chiller technology was chosen, since waste heat from the company's production facility is available at temperatures of approx. 70°C. Originally, driving heat for the chillers was thus waste heat and heat from gas boilers.

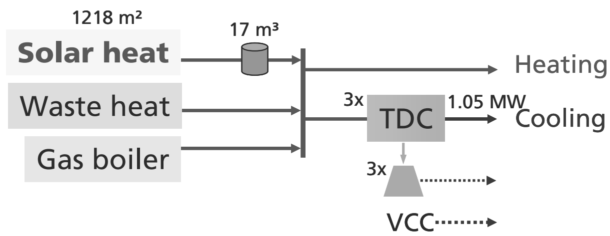

Figure 2.1. Three heat sources are supplying heat to the air-conditioning system of the Technology Center at FESTO AG & Co. KG. The solar thermal vacuum tube collectors (1218 m² aperture area) are supplied by Paradigma (type: CPC Star Azzurro); collector fluid is pure water. A special collector control prevents the collector array of freezing. The three chillers were supplied by Mayekawa (type ADR 100; 350 kW capacity each). One of the three closed wet cooling towers can be operated in a free cooling mode at low ambient temperatures.

The overall experience with the solar thermal assistance of the cooling plant is good. No major problems occurred so far. Some short stagnation periods in the collector system passed without any difficulties. In 2009, the annual solar system specific data were

Radiation sum in collector plane:	1320 kWh/m²
Net solar system yield:	440 kWh/m² (useful solar heat from storage)
Net solar system efficiency:	34 % .

Figure 2.2 shows monthly solar system yields and solar system efficiencies, monitored in 2009. During summer, net efficiencies of > 40% can be expected. In winter, the efficiencies are lower due to self-consumption of heat by the collector for freezing protection as well as due to some restrictions in the

use of heat for slab heating at low temperatures. Nevertheless, the data reveal in total a quite satisfactory collector operation and usage.

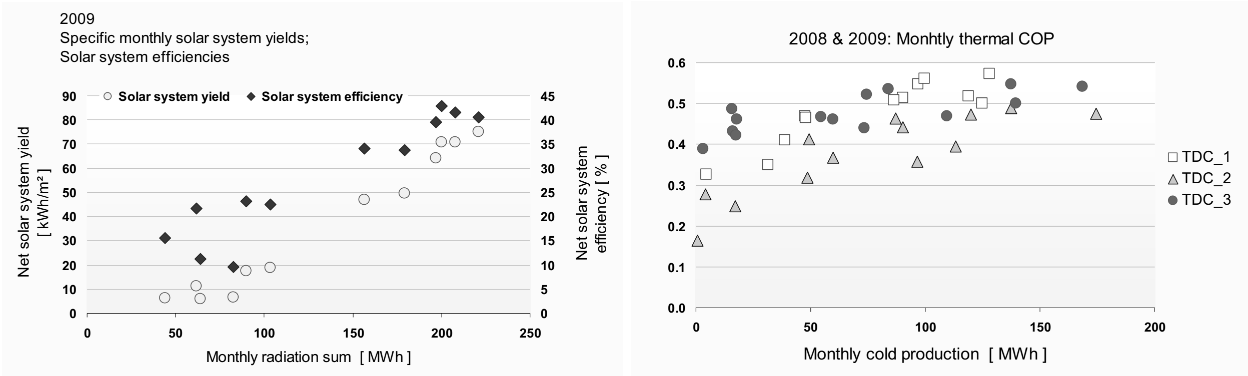

Figure 2.2. Left: monthly solar system yields (calculated from useful heat from the solar storage) and the respective monthly net solar system efficiencies in the collector plant.
Right: monthly thermal COP in the FESTO cooling plant, displayed versus the respective cold production.
COP = Coefficient of performance = cold production / driving heat input

Monthly values of the thermal Coefficient of Performance COP are also displayed in Figure 2.2. In periods with high cooling demand, the chillers were operated continuously for several hours per day, resulting in high monthly cold production numbers and with positive effect on the COP. However, especially in 2009 the chillers were often in operation for periods of approx. one hour or below; this led to a general decrease of the annual COP from 0.5 in 2008 to 0.42 in 2009.

Relative savings in 2009 *heating & cooling*	solar %	solar & waste heat %
Primary energy savings	7.1	50.9
CO_2 avoidance	7.4	52.3

Table 2.1. Estimation of savings, achieved in 2009 in the solar assisted air-conditioning plant of FESTO AG & Co. KG. The reference in this case is the existing plant before installation of the solar system, thus the adsorption chiller plant

Not really satisfying in this installation up to now is the high electricity demand for heat rejection; the ratio of annual cold production and total electricity input (pumps, cooling towers, control) was approx. 3.0. From the electricity input, 60% is required for the cooling tower fans. It was found that the control of the cooling tower fan speed is not optimal yet, further optimisations are intended and thus improved ratios of electrical efficiency are achievable. The electricity demand for the solar collector pumps contributed to < 1% of the total electricity input.

Table 2.1 summarizes savings, estimated through the use of solar and waste heat. They are estimated on the base that the reference cooling plant is identical with the existing adsorption chiller plant (reference: existing configuration, as it was found before installation of the solar thermal system) and that any quantity of useful solar and/or waste heat had to be covered by gas boilers otherwise.

2.2. Solar autonomous summer air-conditioning in a small capacity range

At the Technical College for Engineering in Butzbach, Germany, two small absorption chillers with a nominal capacity of 10 kW each are installed for air-conditioning of the seminar areas. The cold water is used in chilled ceilings, in a cooling panel and for air-conditioning in two supply air systems. 60 m² of evacuated tube collectors are installed as sole heat source for the chillers; the condensing gas boiler is activated in the heating season only. The system went into operation at the end of 2008 and was supported in the Solarthermie 2000plus funding programme. A basic scheme is shown in Figure 2.3.

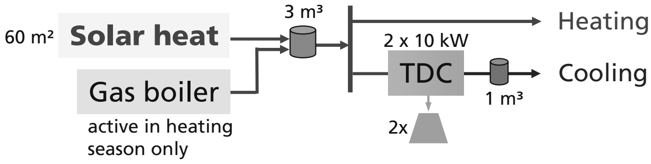

Figure 2.3. In the solar air-conditioning system at the Technical College in Butzbach, two absorption chillers from SK Sonnenklima, type Suninverse, are installed with a total capacity of 20 kW. 60 m² of evacuated tube collectors (Paradigma / Star Azzurro) provide driving heat to the chillers.

One of the two chillers was not in operation in 2009 due to a vacuum leakage and the problem was solved no more than in 2010. The monitored data of 2009 thus contain operation data of one of the chillers only. Figure 2.4 presents monthly collector yields and efficiencies (since in the heating season also heat from the gas boiler is added to the storage, collector yields are used here). In 2009, construction work at the façade caused additional shading to the collector. Thus, the collector yields are lower than expected for this reason and due to lower heat consumption than originally planned (only one chiller in operation). In 2009, the annual solar system specific data were

Radiation sum in collector plane:	1217 kWh/m²
Collector yield:	337 kWh/m²
Collector efficiency:	28 % .

Figure 2.4 additionally contains monthly COP values of the chiller. In several days, the solar power was sufficient to operate the chiller continuously for 6 hours or more. Hourly COP values between 0.6 and 0.7 in stable operation periods were detected. On an annual base, the seasonal COP in 2009 was calculated to 0.52.

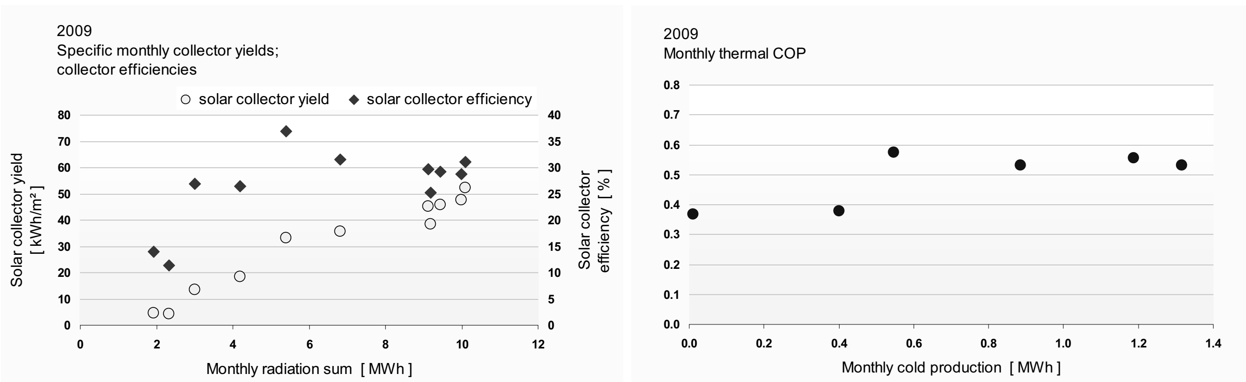

Figure 2.4. Left: monthly solar collector yields and the respective monthly collector efficiencies at the Technical College Butzbach. Right: monthly thermal COP's versus the respective cold production

Relative savings in 2009	heating & cooling %	cooling only %
Primary energy savings	14	36
CO_2 avoidance	14	36

Table 2.2. Estimation of annual savings, achieved in 2009 in the solar air-conditioning plant at the Technical College in Butzbach. The reference in this case is a conventional system: el. compression chiller (EER = 3.0) for cold production and a gas boiler for heating. In the reference, the chiller provides the identical amount of cold as the monitored cold from the solar autonomous driven absorption chiller.

The electricity consumption number for the solar cooling system (pumps, cooling tower) is nearly satisfying: on an annual average, 4.7 kWh cold was produced per kWh electricity input. For this system, the benefits regarding primary energy savings and CO_2 avoidance were calculated as well (Table 2.2). The reference system in this case is a conventional system, since no cooling system was installed before: cold is provided from an electrically driven vacuum compression chiller (EER = 3.0), heat is provided by a gas boiler. Typical conversion factors for natural gas and for the German public electricity grid were applied. Although the absorption chiller is operated only with solar heat, the savings in the cooling season are less than 100% due to the demand on electricity for pumps and heat rejection.

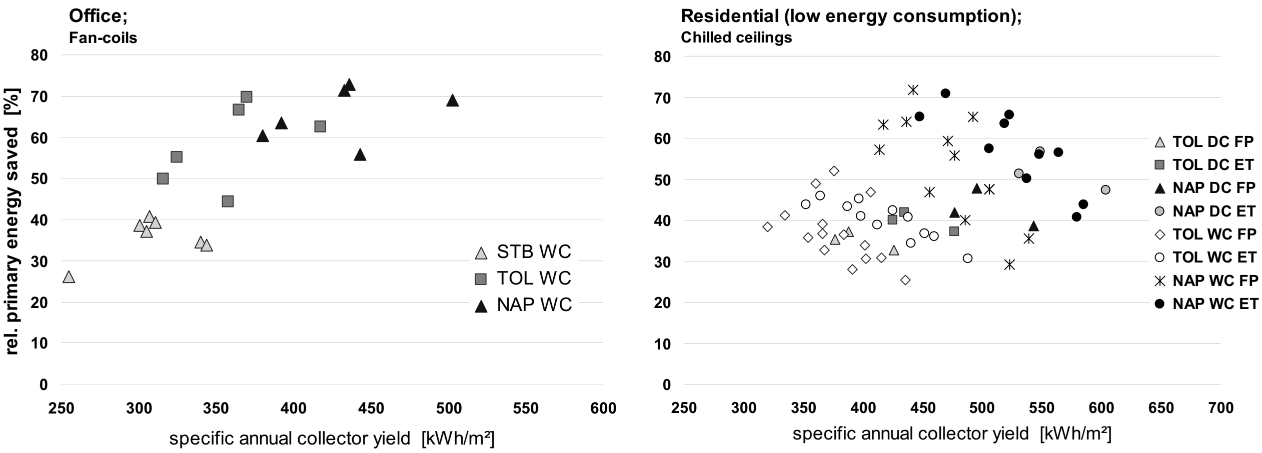

Figure 2.5. Relative primary energy savings per year achieved with solar assisted heating and cooling systems (calculations), compared to a conventional heating and cooling system. Exemplary results from the virtual case study in the Solar Combi+ project. The savings are displayed versus the annual collector yields. Left: office building, equipped with fan-coils; not sorted by collector type; Right: Residential building with chilled ceilings. Indices: STB Strasbourg; TOL Toulouse, NAP Naples; WC wet cooling tower; DC dry heat rejection; FP flat-plate collector; ET evacuated tube collector.

2.3. Potential of solar cooling performances in SolarCombi+ calculations

A virtual case study on the performance of small capacity solar cooling systems was prepared within the project Solar Combi+ [4]. Solar cooling systems for building cooling were modelled and different types of market available chillers considered. In case of non-sufficient heat from the solar system, a gas boiler was used in all calculations as back-up heat source. Parameters in the study were

- sites (three sites in Europe) and type of buildings (residential/office),
- cold distribution equipment (fan-coil/chilled ceiling),

- type of hydraulic schemes (reflecting preferences from suppliers/manufacturers),
- type of heat rejection (wet/dry),
- type and size of collector (flat-plate/evacuated tube) and size of heat storage.

Figure 2.5 presents from some of the calculations the achieved annually primary energy savings, determined from a comparison with conventional heating and cooling technology. The savings are including both, solar assisted cooling and heating and, in residential use, domestic hot water preparation. The figure shows the dependence from sites and technical features, such as applied heat rejection and collector technology. The primary energy savings range from approx. 25% to 70% with highest values calculated for Naples. Specific collector areas from 4 m² to 5 m² per kW chilling capacity were found most promising. However, the calculations reveal the *potential*; in realised systems, the savings are usually below this potential due to non-optimal system control and component behaviour.

3. Alternative: compression chiller with PV-power compensation?

In the recent years, the use of photovoltaic (PV) power with vacuum compression chiller techniques in building air-conditioning is frequently discussed. Since grid-connected PV systems are the common PV technology in Europe, this option is thus in the focus of interest. In the most simple concept, photovoltaic power is compensating on an annual base the electricity demand of a conventional chiller completely or to a certain fraction. This approach is attractive, since

- promising electricity feed-in regulations exist in some European countries;
- no electricity storage required;
- no interaction between PV and cooling operation; no multidisciplinary knowledge required;
- investment cost for cooling plant comparatively low, mainly caused through the technology lead in the development of conventional cooling technologies.

Disadvantages can be seen in the fact that

- no storage exists in the economic most attractive version: in short overcasted periods, still full capacity from public grid is required;
- refrigerants with usually high global warming potential are furthermore applied;
- space heating is not supported.

The use of the PV power is not direct allocated to the cooling power demand (the chiller may be one of several electricity consumers in the building), but in the following simulation example the photovoltaic generated electricity is only accounted for the compensation of the electricity demand of a conventional cooling system; no other consumers are considered, when the solar coverage is calculated. The total electricity generation is considered in the primary energy and CO_2 emission balance. The results are compared to a solar cooling system of identical size. Heating and cooling loads of an office building located at Strasbourg were determined. Subsequently, the loads are covered by

a) a solar assisted system: absorption chiller with 10 kW chilling capacity and a solar collector system. A back-up compression chiller is operated in case of low solar heat availability. The solar system also supports space heating; a gas boiler is the main heating source in winter.

b) a conventional system: electrically driven compression chiller and a gas boiler. Electricity demand of the chiller is compensated by a grid connected PV plant on an annual base.

In the comparison, the area of the regenerative converter (collector and PV) were kept identical, e.g., 30 m² PV/collector area; 40 m² PV/collector area, etc.

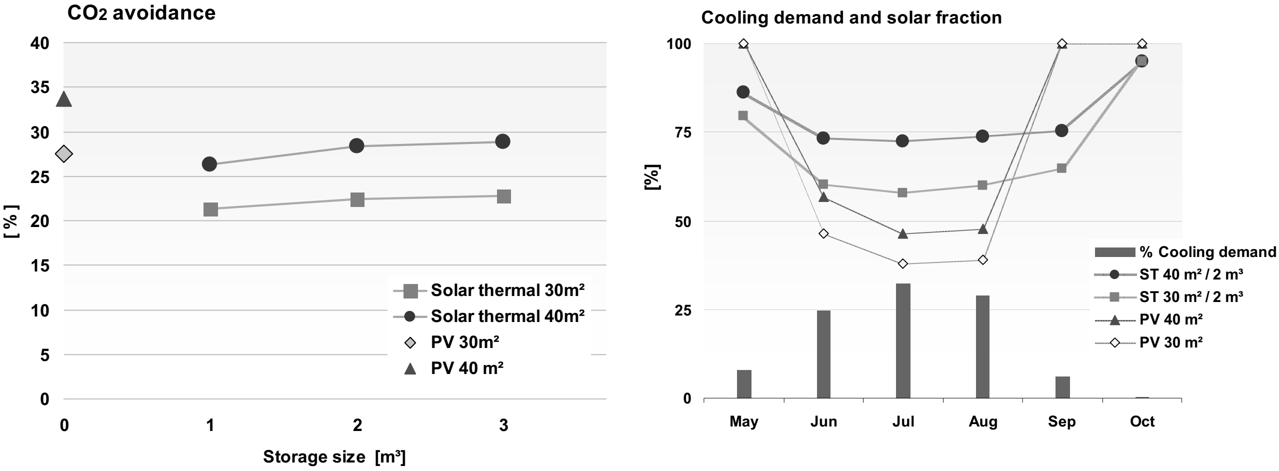

Figure 3.1. Example comparison of grid connected PV/conventional heating and cooling with solar thermal assisted heating and cooling system for an office building at Strasbourg. Two system sizes (30 and 40 m² of PV panels and collector area respectively) and three hot water storage sizes in the solar thermal plant are considered. <u>Left:</u> annual CO_2 avoidance; the PV-configuration avoids in this example more emissions than the solar thermal configuration with identical size. <u>Right:</u> percentage of cooling load, covered through monthly electricity compensation (PV system) or through solar heat driven cold production. Additionally, the monthly cooling demand (percentage of the annual total cooling demand) is included.

At first view, the PV/conventional system solution appears more favourable: the primary energy savings and CO_2 avoidance, shown in Figure 3.1 (considering both, heating and cooling) are higher than for the solar thermal assisted system with the same converter area. However, this is achieved on an annual base; the PV plant compensates the electricity, consumed by the cooling system in summer, throughout the year. Focussing on shorter periods, e.g. monthly values, the coverage of the cooling demand (in the solar cooling system: fraction of cold, supplied with solar driving heat; in the PV system: electricity compensation on monthly base) is significantly higher for the solar thermally driven system in this example. Consequently, capacity credits to the public grid can be expected more distinctive than with the PV system. This is an important issue especially for regions with weak electricity supply grids. Of course, also in the PV system solution the situation could be improved, e.g. by applying storages, either on the electric or cold side. However, measures in this direction decrease the economic benefits of the PV system.

The results of a comparison as shown above depend strongly on the load profile, on the site, on the performance assumption for the conventional system, and on the configuration of the solar thermal driven system as well (e.g., if any back-up source is used in the solar thermal system for cooling or not). This indicates that a systematic comparison of different system approaches remains an important task in the near future.

4. Perspectives of solar cooling (chilled water systems)

Small solar cooling systems have shown the highest growth rate on the total number of installations in the recent years and system providers have already entered the market. However, in the light of the number of total installations, more effort in system and component development is necessary to overcome the market niche situation. Main tasks to be solved are

- improvements in the system development level, e.g. further development of pre-packaged systems and increase of standardisation (with benefits to installation and system cost), development of adequate heat rejection control strategies;
- decrease in component costs through higher production numbers;
- continued activities to improve the performance of the chillers and to improve the application also in the heat pump mode, offering thereby the use of one investment for both, heating and cooling in an appropriate system environment.

Solar cooling for small offices and multi-family houses then becomes a more attractive option. This is especially of interest in places with insecure electricity supply and high electricity cost.

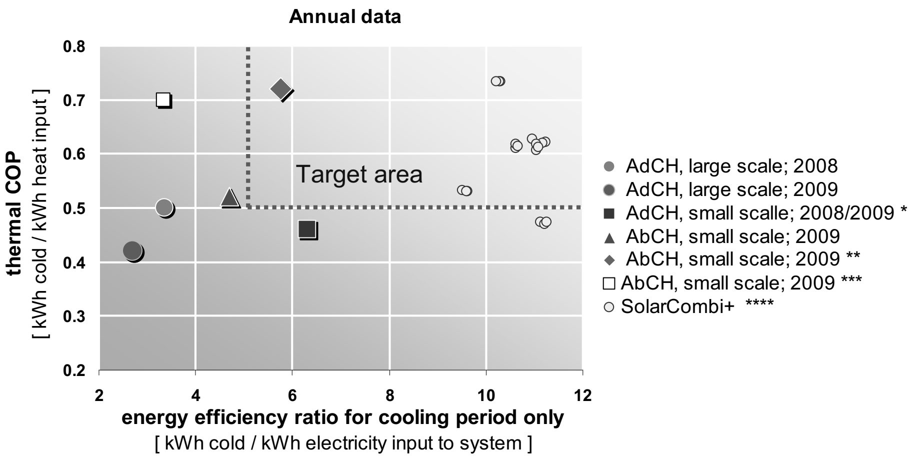

Figure 4.1. Seasonal thermal COP and cold production per electricity input. The marks represent 4 exemplary solar cooling applications; AdCH/ AbCH: Adsorption/Absorption chiller system.
* small capacity system with heat rejection via boreholes, operated at Fraunhofer ISE [5];
** small capacity system with latent heat storage in the heat rejection system, operated at ZAE Bayern [6];
*** small capacity absorption chiller system, installed in SOLERA [7];
**** simulation results from exemplary calculations in the SolarCombi+ project

Another perspective of solar cooling is the combination with other non-fossil heat sources. Likewise in the FESTO plant, waste heat and solar heat may be combined as driving heat source for cooling in several commercial and industrial sites, with solar heat production covering daily peak cooling loads. Especially in large industrial applications, the electricity peak price can stimulate the use of thermally driven solutions.

The component and system development has to ensure that both, the thermal COP and the electricity consumption of the system will be improved. Figure 4.1 summarises annual thermal COP's and electrical efficiencies of the two plants described in this paper and of some other small solar cooling installations. Additionally, some results from the virtual case study of SolarCombi+ are included, indicating the gap between the technical potential and real life data. It should be the effort in future installations with single-effect chillers, to achieve on an annual base at least a COP of > 0.5 and more than 5 kWh cold per kWh electricity input. From the examples presented, only one system meets already this target area. Although these targets alone are not sufficient to ensure environmental savings, any clear increase of both numbers will enhance the market position of solar cooling. In general, an increased thermal COP will decrease the demand on heat rejection capacity and will also decrease the collector area, thereby saving investment and operation costs.

Beside the considered system technologies, a challenge and perspective for solar cooling is the system development with medium temperature concentrating collectors (100°C < T_{drive} < 250°C) in areas with high irradiation availability; either for driving double- (or triple-) effect absorption chillers or to handle high temperature lifts between chilled water and heat rejection temperature. While in the first option the performance can be significantly increased (thermal COP values > 1.0), the latter option allows industrial cold production at temperatures below zero and/or solar cooling with dry heat rejection at high ambient temperatures. In the project MEDISCO [8] [9], two pilot systems were realised.

The potential of solar cooling is not fully exploited so far in many realised plants. A financial support framework is still necessary for the further market development and in order to approach to a technical level, which is already achieved in environmentally less friendly competitive technologies.

Solarthermie2000plus is supported by Projektträger Jülich (PtJ) on behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

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