Monitoring Program of Small-Scale Solar Heating and Cooling Systems within IEA-SHC Task 38 – Procedure and First Results

Alexander Thür[1*], Dagmar Jähnig[1], Tomas Núñez[2], Edo Wiemken[2], Martin Helm[3], Daniel Mugnier[4], Pietro Finocchiaro[5], Bettina Nocke[5]

[1] AEE INTEC Department of Solar Thermal Components and Systems, Feldgasse 19, 8200 Gleisdorf, Austria

[2] Fraunhofer Institute for Solar Energy Systems (ISE), Thermal Systems and Buildings, Heidenhofstraße 2, 79110 Freiburg, Germany

[3] Bayerisches Zentrum für Angewandte Energieforschung e.V., Walther-Meißner-Straße 6, 85748 Garching, Germany

[4] TECSOL SA., 105 av Alfred Kastler - BP 90434, 66 004 PERPIGNAN Cedex, France

[5] Università di Palermo, DREAM, Viale delle Scienze bd. 9, 90128 – Palermo, Italy

* Corresponding Author, a.thuer@aee.at

Abstract

Within IEA-SHC Task 38 (Solar Air Conditioning and Refrigeration), a monitoring procedure for solar heating and cooling systems was developed. This methodology includes measurements of all relevant energy flows (heat, cold, electricity) to be able to derive key figures such as primary energy ratio, electrical coefficient of performance, solar heat management efficiency, fractional savings for heating and cooling compared to a conventional (non solar) heating and cooling system. A number of small-scale systems for solar heating and cooling are currently being monitored across Europe. For a handful of systems monitoring data of at least a full year of operation is already available. These systems include different chiller, heat rejection and collector technologies and are used for different applications (office buildings, canteen, school etc.). Key figures derived from the monitoring data of these systems will be presented in this paper as well as a comparison of the systems with each other.

1. Introduction

One of the central objectives of Task 38 (Solar Air Conditioning and Refrigeration) of the International Energy Agency's Solar Heating and Cooling Programme is a monitoring program of installed solar heating and cooling systems [1]. The aim is to show the functioning of as many systems as possible and to compare the results of the different systems in order to identify optimized system configurations and control strategies for different applications.

Subtask A of Task 38 deals with pre-engineered systems for solar heating and cooling. The goal is to develop pre-engineered systems that do not require a lot of planning effort but can be ordered "off the shelf" from the manufacturer or distributor and can be installed by plumbers without having to size each component of the system by themselves. This kind of pre-engineering makes sense for small-scale systems with a cooling capacity of up to approximately 20 kW. These pre-engineered packages should include the solar thermal system, the chiller, the heat rejection system and all required pumps, piping and controller. Because there are still only very few completely pre-engineered packages on the market, the monitoring campaign of Subtask A includes all small-scale systems (< 20 kW cooling capacity). The goal is to identify optimized configurations that can be developed into pre-engineered packages by manufacturers.

2. Monitoring Procedure

The methodology includes measurements of all relevant energy flows (heat, cold, electricity) to be able to derive key figures such as primary energy ratio, electrical coefficient of performance, solar heat management efficiency and fractional savings for heating and cooling compared to a conventional (non solar) heating and cooling system. Figure 1 shows a general scheme with all possible energy flows for various configurations of solar heating and cooling systems. In real applications only a reduced number of energy flows is applicable (see examples next chapter).

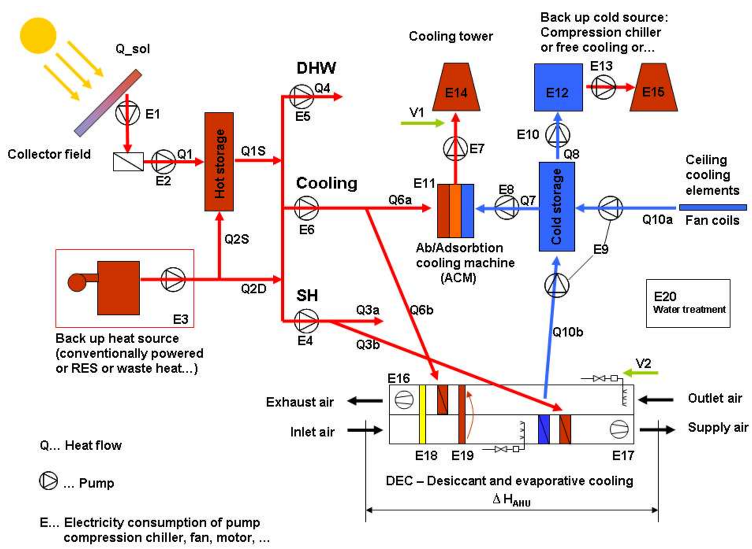

Fig. 1: General monitoring scheme for solar heating and cooling systems

An excel tool as a template was elaborated where all monitored data can be inserted on a monthly basis according to the nomenclature of the general monitoring scheme shown in figure 1.

For desiccant evaporative cooling (DEC) air handling units an additional excel tool was developed which allows the calculation of the monthly enthalpy difference for both cooling and heating based on small time step measurement results. Additionally also reference enthalpy differences are calculated based on different reference scenarios. In all cases it is assumed that a conventional compression chiller is used to cool and dehumidify the inlet air to the identical absolute water content (g per kg dry air) as measured in the supply air of the DEC unit. The supply temperature in the reference system can be chosen to be:

a) identical to the measured value of the DEC unit based on post heating by the natural gas boiler
b) a fixed value (can be different for each month) chosen by the user to be a reference set supply temperature and realized by post heating by the natural gas boiler
c) any temperature which is reached without any post heating or with post heating by any other measure but not using the auxiliary heater, e.g. by heat recovery in the air handling unit or using waste heat from the compression chiller.

A number of key figures are defined in 3 different levels and calculated directly based on all inserted data in this excel monitoring tool.
In the first level overall evaluation for the entire system is done by calculating coefficients of

performances (COP) and primary energy ratios (PER). The total electrical COP ($COP_{el,tot}$) calculates the ratio of useful heat and/or cold in relation to the electricity consumption needed but excludes the electrical consumption of pumps and fans which are used to distribute heat and/or cold in the building by pumping water or blowing air. Therefore the $COP_{el,tot}$ is just for the production of useful heat and/or cold. The overall electrical COP ($COP_{el,overall}$) includes also all the electrical consumers for distribution.
Primary energy ratios (PER) are calculated for systems with fossil and/or renewable energy sources (RES) as the ratio of useful heat and/or cold in relation to the primary energy demand. As primary energy factors are used: 0.9 (kWh final energy per kWh primary energy) for fossil fuel like natural gas or oil, 10 for biomass (pellets, wood chips) and 0.4 for electricity for comparison at international level (for CHP's a calculation procedure is integrated as well). These values can be changed in the tool according to national or local boundary conditions by the user.
If a system is powered by RES it might happen that the system performance is very bad but due to the primary energy factor of 10 (instead of 0.9 for fossil fuels) primary energy consumption still could be very low. In order to compare different systems (RES or fossil powered) additionally also for RES powered systems a PER_{fossil} is calculated, which enables to compare the quality of different systems based on comparable boundary conditions.
In the second level mainly the quality of the subsystems solar thermal heat production and heat management within the system are evaluated by key values like "collector loop efficiency", "collector gain per m^2", "solar energy utilization", "storage efficiency" and "system efficiency".
In the third level the deepest evaluation is done. Several specific defined COP's evaluating the thermal and the electric performance of the subsystems sorption chiller and DEC unit are calculated. For example beside the thermal COP_{th} the electrical COP_{el} for "sorption chiller itself", "sorption chiller plus generator/cold water/heat rejection pump and cooling tower" and "sorption chiller plus generator/cold water/heat rejection pump and cooling tower plus collector loop pumps" is calculated (analogue for DEC units). Also the water consumption of the wet cooling tower and the DEC system is evaluated in different forms like: water consumption in relation to cold production, electricity consumption for water treatment in relation to water consumption or in relation to cold production.

Finally, to be able to determine, if the solar heating and cooling system performs better than a conventional system that covers the same loads, a reference system was defined. The reference system consists of a condensing natural gas boiler to cover the space heating load (average annual boiler efficiency 0.95 based on lower heating value) and for the domestic hot water a small storage tank with typical heat losses based on the measured domestic hot water consumption was assumed that is also heated by the natural gas boiler. The cooling load is covered by a compression chiller (seasonal performance factor SPF = 2.8) in the reference system. The consumed primary energy is calculated for both the reference system and the solar heating and cooling system. The primary energy savings $f_{sav,shc}$ finally are calculated based on equation Eq 1:

$$f_{sav,shc} = 1 - \frac{\frac{Q_{boiler}}{\varepsilon_{fossil} \cdot \eta_{boiler}} + \frac{Q_{RES}}{\varepsilon_{RES} \cdot \eta_{RES}} + \frac{E_{el}}{\varepsilon_{elec}} + \frac{Q_{cooling,missed}}{SPF \cdot \varepsilon_{elec}}}{\frac{Q_{boiler,ref}}{\varepsilon_{fossil} \cdot \eta_{boiler,ref}} + \frac{E_{el,ref}}{\varepsilon_{elec}} + \frac{Q_{cooling,ref}}{SPF_{ref} \cdot \varepsilon_{elec}}} \qquad \text{Eq 1}$$

Legend: ε…primary energy factor, Q…heat, E…electricity, η… boiler efficiency, SPF…seasonal performance factor

3. Monitored Systems

A number of small-scale systems for solar heating and cooling are currently being monitored across Europe. For four systems monitoring data of at least a full year of operation is already available. All four systems are used for both space heating and cooling. Two of them also generate domestic hot water.

System 1: ABSORPTION Chiller in Office Building in Garching, Germany

The system includes a 10 kW absorption chiller (Sonnenklima) and a dry cooling tower that is operated during day and night. During the day, part of the rejected heat is stored in a latent heat storage unit which is regenerated during night. The system has a wood pellets boiler as heat backup for space heating and a water well for cold backup in summer. The collector field consists of 57.4 m² flat plate collectors. Both heat sources charge a 2000 l hot water tank; more details in [2].

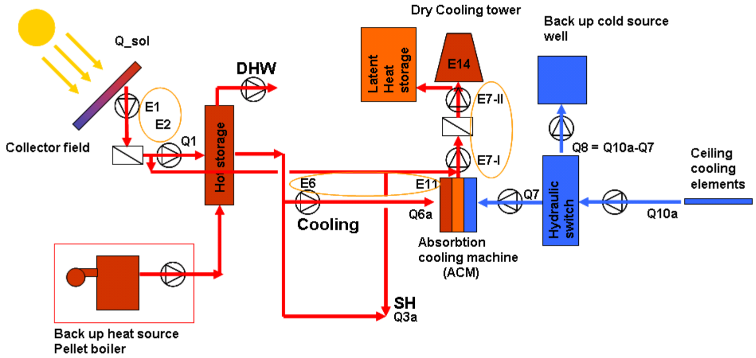

Fig. 2: Monitoring scheme of system 1 (Absorption chiller in office building)

System 2: ABSORPTION Chiller in School Building in Butzbach, Germany

The second system includes again a 10 kW absorption chiller (Sonnenklima). Here, the chiller is connected to a wet cooling tower and a cold storage tank of 1000 l. The heat backup source is a condensing natural gas boiler, activated for space heating only. 65.8 m² of evacuated tube collectors are used to charge the 3000 l heat storage tank. There is no backup system for cooling operation. The system is also presented in [3].

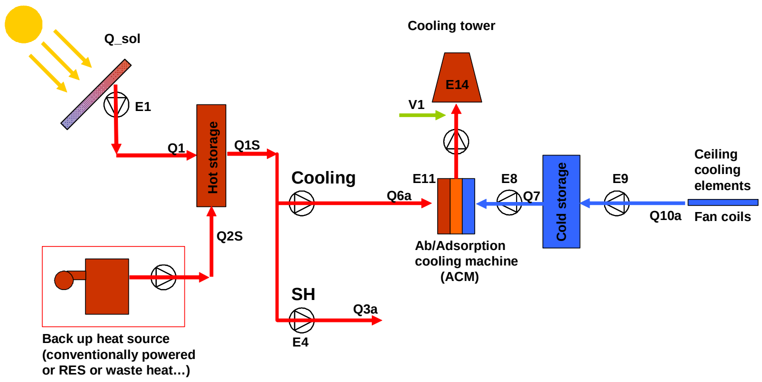

Fig. 3: Monitoring scheme of system 2 (Absorption chiller in school building)

System 3: ADSORPTION Chiller/heat pump in Ventilation System for a Canteen in Freiburg, Germany

The third system consists of a 5.5 kW adsorption chiller (Sortech) that is also used as a heat pump in winter time. The chiller and heat pump are used to precool and preheat air in the ventilation system of a canteen. A relatively small collector area of 21.9 m² flat plate collectors is connected to a 2000 l heat storage tank. The backup heat source is a 380 kW CHP unit feeding the building's heat network from which the driving heat is taken. The backup is used both for heating and for cooling purposes. Waste heat of the chiller is rejected via three boreholes in the ground (depth: 80 m each). See [4] for more details.

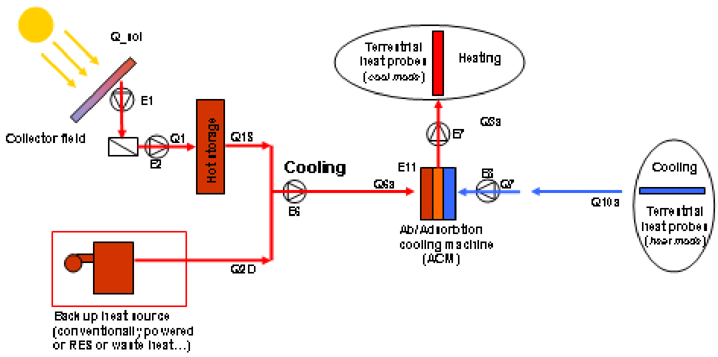

Fig. 4: Monitoring scheme of system 3 (Adsorption chiller/heat pump in ventilation system)

System 4: ADSORPTION Chiller in Laboratory Building in Perpignan, France

Finally, the fourth system contains a 7.5 kW adsorption chiller (Sortech) that is connected to a hybrid heat rejection unit and a 300 l cold storage tank. 25 m² of double-glazed flat plate collectors charge a 300 l heat storage tank. The system is not connected to the conventional space heating system but provides heat and cold to the rooms by means of separate fan coil units. Therefore, the monitored data includes only the heat and cold produced by the solar heating and cooling system and not the conventional heating system. There is no backup system for cooling operation.

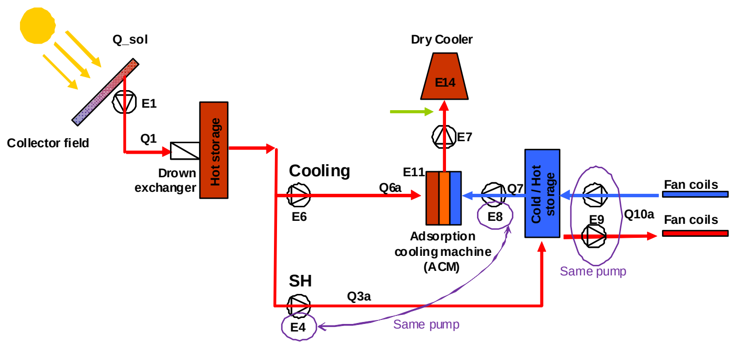

Fig. 5: Monitoring scheme of system 4 (Adsorption chiller in laboratory building)

4. Results

In this section, key figures such as coefficient of performance (COP), fractional savings ($f_{sav,shc}$) and collector yield are presented for all four systems. For some systems the monitoring equipment was incomplete. Therefore, some of the figures are not available for all systems. The first thing to look at when analyzing the operation of solar cooling systems is the thermal COP of the chiller. It is defined as the cold production of the chiller divided by the driving heat. Figure 6 below shows the monthly average thermal COP of the four analyzed chillers. It can be seen that the thermal COP of the two absorption chillers is higher than the COP of the adsorption chillers. This had to be expected. However, the differences between the different systems are very large. In system 1, the thermal COP is almost identical to the nominal value. The value of system 2 is significantly lower. The thermal COP of the chiller doesn't depend only on the chiller itself but on how it is operated. For example, if the chiller was operated a lot in cycling operation, the COP will be lower. It also depends on the temperature levels in the system (driving temperature, heat rejection temperature and chilled water temperature). While it is desirable to operate at a high thermal COP, the most important figure to look at is the primary energy consumption. A first step is to analyze the electrical COP of the chiller. Only two of the four chillers have a separate electricity meter. One of them is system 2 with an absorption chiller, the other one is system 3 with an adsorption chiller. It can be seen that the adsorption chiller's electricity consumption is significantly less than that of the absorption chiller. The reason for that is that the absorption chiller unlike the adsorption chiller contains a solution pump.

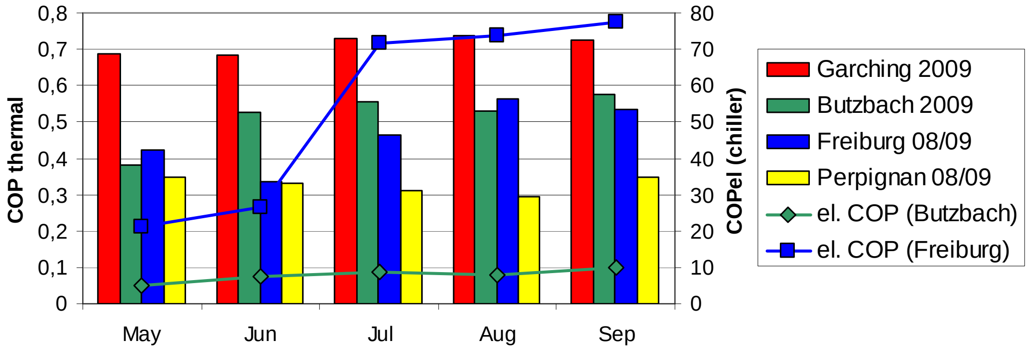

Fig. 6: Thermal COP (bars) and electrical COP of chiller (lines)

Even more significant than the electrical COP of the chiller is the total electrical COP of the system. This is defined as the generated cold and heat divided by the consumed electricity for all components such as pumps, fans, controllers, boilers and chillers. Not included is the electricity used by pumps for heat and cold distribution or domestic hot water preparation that would be necessary also in a conventional system. Figure 7 below shows this total electrical COP of all four systems only for the summer months. The figure shows that system 3 with a relatively low thermal COP is actually among the top two systems in terms of total electrical COP.

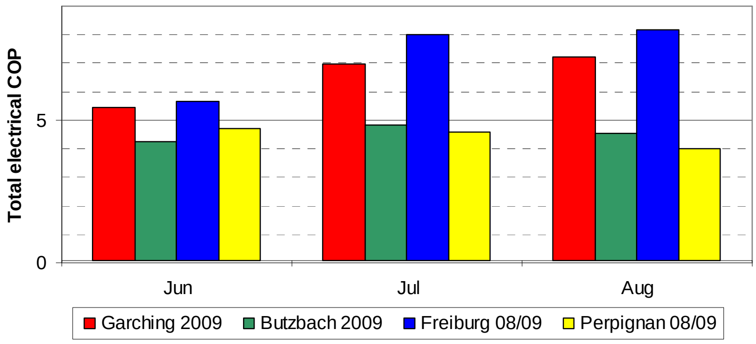

Fig. 7: Total electrical COP for the summer months.

The differences between the 4 systems are again large. The system concepts influence largely the electricity consumption of the system (e.g. the type of heat rejection – dry heat rejection with latent heat store, wet cooling tower or boreholes). But the measurements show that a high total electrical

COP of 5 to 8 is possible. Systems that don't reach this value probably still need some optimizations e.g. in terms of control strategy and electricity consumption of components.

The next step is to compare the solar heating and cooling system to a conventional reference system. Within the monitoring procedure described here, this is done by comparing the primary energy consumption of both systems. Figure 8 below shows the monthly fractional energy savings $f_{sav,shc}$ based on Eq 1 of the four analyzed systems. In system 1, fractional savings are only available for the summer months without backup. Unfortunately, the backup energy for space heating and domestic hot water preparation was not measured.

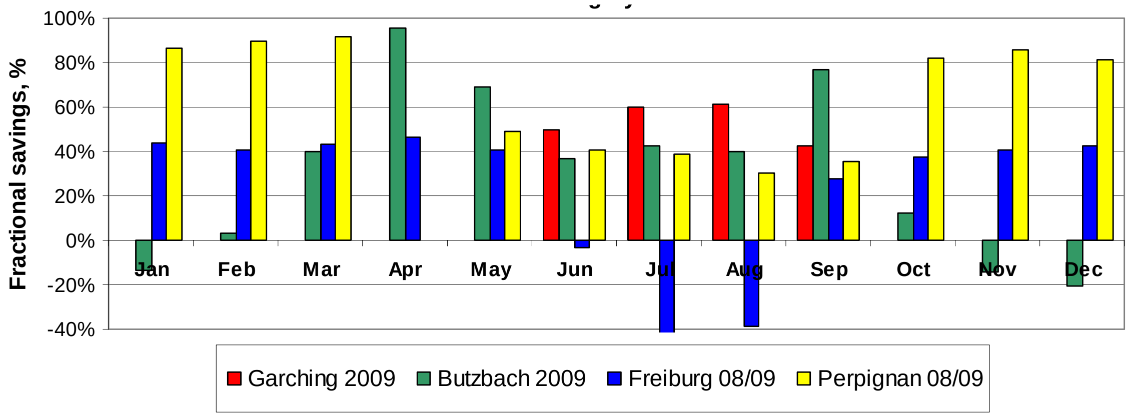

Fig. 8: Fractional energy savings (based on primary energy) $f_{sav,shc}$

Fractional savings in the summer months range between 30 and 60%. Only system 3 has lower values, even below zero. The reason for that is that in the other three systems no heat backup is used to drive the chillers in summer. System 3 uses heat from a CHP plant to drive the chiller when there is not enough heat available from the solar collectors. In addition, the solar collector field is small leading to a small solar fraction. Thus the adsorption chiller is operated a lot with a non-renewable energy source resulting in a negative fractional savings compared to a conventional system. Further, the solar energy is not used effectively in winter as it is used only if sufficiently high temperatures are reached to drive the adsorption machine. This happens very seldom. A more effective use of the solar energy would be to use it directly. This is not a disadvantage of the chiller or the solar cooling system itself but only of the system design. An enlargement of the collector field is necessary to improve this performance and is currently in preparation.
In winter, fractional savings depend a lot on the fact whether the monitored part of the system includes the backup system or not. In case of system 4 where the backup system is excluded values lie above 80%. For system 3, values are around 40% taking into account that the backup heat source is a natural gas powered CHP unit with an improved primary energy factor of 1.32 kWh_{final}/kWh_{prim} (thanks to the electricity production) compared to 0.9 for pure natural gas heat sources. The adsorption system is operated as a heat pump in winter time, but the solar energy is mostly wasted as it is not used directly for heating as in system 4. System 2 shows very low or negative fractional savings for the months with no or little yield from the solar thermal collectors. The reason for that is that (unlike in the reference system) the natural gas boiler heats a storage tank before distributing the heat to the space heating system. Therefore, heat losses in the system are higher leading to negative fractional savings (but tank heat losses also could be counted at least partly as useful space heating which would improve the fractional energy savings in winter time).

Another interesting figure to look at is the annual yield per square meter collector area.

Figure 9 shows annual values for all four analyzed systems. The values range between 290 and 400 kWh /(m² a). The lowest value shows system 3 probably due to the system concept where solar heat is only used if the temperature in the storage tank is high enough for the heating or cooling application and not for pre-heating. Thus a large portion of low temperature solar heat is wasted in winter. Furthermore, an existing collector was used that was designed for conventional solar heating purposes and was therefore not specially selected for operation in the temperature range, required for solar cooling. A change in the system concept might improve this value. The collector yield at Butzbach (system 2) was reduced due to shading, caused by a scaffold for construction work at the building façade.

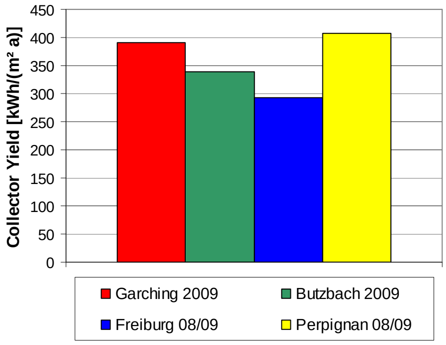

Fig. 9: Annual specific collector yield in kWh/(m² a)

5. Conclusions

The most important performance figures of a solar heating and cooling system are the total electrical COP and the primary energy ratio or even more striking the primary energy saved compared to a conventional system.

The four analyzed systems show that good or very good performance figures can be reached even if in some cases e.g. the thermal COP of a chiller is not so good. The overall performance (i.e. the primary energy that can be saved with a solar heating and cooling system) depends mostly on the system concept, the control strategy of the entire system and the parasitic electricity consumption of the auxiliary components such as pumps and fans. The thermal performance of the chiller accounts for only a small part of the overall performance of the system.

Although the most performance figures of the four systems are already in a good range, both system concept and control strategies can probably still be improved for most of the systems leading to even better performance.

References

[1] W. Sparber, (2008). 240 - Unified Monitoring Procedure and Performance Assessment for Solar Assisted Heating and Cooling Systems, Eurosun 2008, Lisbon

[2] M. Helm, C. Keil, S. Hiebler, H. Mehling, C. Schweigler. Solar heating and cooling system with absorption chiller and low temperature latent heat storage: Energetic performance and operational experience, International Journal of Refrigeration, Volume 32, Issue 4, June 2009, Pages 596-606

[3] E. Wiemken et al. Performance and Perspectives of Solar Cooling. Proceedings of the EuroSun 2010, Graz, Austria, September 28 – October 1, 2010

[4] Tomas Núñez, Florian Mehling, *Heating and Cooling with a Small Scale Solar Driven Adsorption Chiller Combined with a Borehole System –Recent Results–*.Conference Proceedings 3rd Int. Conference Solar Air-Conditioning, Sept. 30th – Oct. 2nd, 2009, Palermo, Italy