Practical experience on design and sizing from worldwide documented solar cooling systems

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Abstract

In the present paper an overview is given on design options and sizes of the main components of worldwide installed solar heating and cooling (SHC) systems. Within an IEA project over 300 systems could be documented, including over 130 large scale custom made installations.

The implemented hydraulic schemes have been analyzed following 6 main criteria. References and examples are given where single solutions have been implemented. The analysis starts with the solar loop. The focus is on: possible connections of the collectors field with the heat store – if available – and possible layouts to supply heat to the thermally driven chiller (TDC) or to the heating distribution system. The layout by means cooling is supplied to the users is also analyzed, including possible cold stores. Interconnection between stores – if more than one is included – and integration of back-up systems, on both the hot and cooling sides, are discussed as well. Concerning the sizing, statistical analysis have been carried out to identify common practices for basic ratios, e.g. collectors 'area per nominal TDC power, storage capacity per unit of collectors area and so on.

The research shows that there are many different design options implemented worldwide. Only in recent years a standardization process of design and sizing has started, mainly driven by companies specialized on the installation of these systems relaying on in house proven solutions.

1. Introduction

Within the subtask B of the International Energy Agency (IEA) "Task 38 - Solar Air Conditioning and Refrigeration" a review of worldwide installed documented large scale SHC systems has been carried out. The review has focused on:

- Climatic locations and fields of application;
- Adopted technologies of heat driven cooling units and solar thermal collectors;
- Implemented hydraulic schemes;
- Selected sizes for the major components;
- Implemented control strategies.

The research work gives an overview of the state of the art of the solar cooling technology and the current standardization level of designing. A critical analysis of documented existing installations enables the performance evaluation of experienced design solutions. Reporting current practices may support planners during decision making on suitable selection of technologies, sizes, configurations and control strategies in dependence on location, final use and properties of the buildings.

The final goal is to provide knowhow on SHC design, promote proved solution sets and support planners towards the achievement of an optimised design.

2. Research Approach

Over 300 worldwide installed solar heating and cooling systems could be documented within IEA SHC Task 38 [1] [2] [3] including large and small scale systems. More than 130 of these systems have a cooling capacity over 20 kW, are therefore considered as large scale and are usually custom made. Data on location, application, adopted technologies and sizes for the major components have been collected and elaborated. Major components refer to: heat driven cooling units, solar thermal collectors, heat and cold storage systems, heat and cold back-up systems and heat rejection systems.

Detailed investigations have been carried out with respect to hydraulic schemes (Chapter 3) and sizing of the main components (Chapter 4). 20 large scale existing installations, have been in depth reviewed thanks to the task participants who provided data and lesson learnt. The reviewed systems are exclusively based on sorption chiller technology. The features of these systems have been analyzed at the light of pertinent literature and thanks to surveys to the managers of the plants and monitoring data, wherever available. The final result of the investigation here reported is a description of existing design solutions including advantages and disadvantages based on practical experience.

3. Hydraulic schemes

The hydraulic schemes of the reviewed systems have been analyzed with respect to six criteria (Table 1) . The goal is to identify common applied layouts.

Table 1. Survey on hydraulic schemes.

Solar loop	• How many solar loops are implemented? How are they interconnected? Which fluids are used? • How is the solar thermal field connected to the heat storage system? • Are there applied several heat stores and how are they inter-connected?
Heat back-up system	• Is there any heat back-up system installed and which technology is used? • How are the solar and the back-up systems connected (parallel or in series)? • Is there any storage system for the heat back-up ?Is it shared with the solar collectors?
Feeding the heat load	• Is the heat load exclusively fed by the heat storage? • Is the heat load fed by an hydraulic junction/heat collector? • Is the heat load fed by a heat exchanger?
Sorption chiller	• Are there several units of sorption chillers and how are they interconnected? • How is the connection between the sorption chiller and the cold storage system implemented? • Are there several units of cold storage systems applied. How a are they interconnected?
Cold back-up system	• Is there any cold back-up system implemented and which technology is used? • How is the connection between the cold back-up system and sorption chiller (parallel or serial)? • Is there any storage system for the cold back-up Is it shared with the sorption chiller?

Feeding the cooling load	• Is the cooling load exclusively fed by the cold storage? • Is the cooling load fed by an hydraulic junction/heat collector? • Is the cooling load fed by a heat exchanger?

In the following two paragraphs a short description to these aspects is given including several built examples where the different solutions have been implemented.

3.1. Solar integration in the SHC systems and feeding of the loads

The heat storage system is in many installations the point of connection between the solar loop and the different sub systems, i.e. the thermal heat driven chiller, the heating distribution system, the DHW circuit and so on.

The solar loop usually features a heat exchanger interposed between the solar collectors and the heat storage so two loops can be identified, primary and secondary solar loops, as shown in Fig. 1.

In some cases the connection between the solar collectors and the storage occurs without any heat exchanger. One only solar loop leads to decreased heat and pressure losses thanks to the missing heat exchanger, and to decreased electricity consumption thanks to the missing pump on the secondary circuit. On the other hand it implies that a unique fluid is used: pure water or antifreeze water solution. In hot climates, where no freezing risk is existing, pure water systems are commonly used (Fig. 1), as in [4]. In colder climates as well pure water systems can be used in combination with evacuated tube collectors (reduced heat losses) and a proper control strategy assuring that no freezing occurs in the collectors or the connecting tubes, e.g. the recirculation of relatively hot water from the tank to the collector, as in [5] In such cases a detailed evaluation of the electricity consumption of the pumps and the heat losses through the recirculation should be carried out.

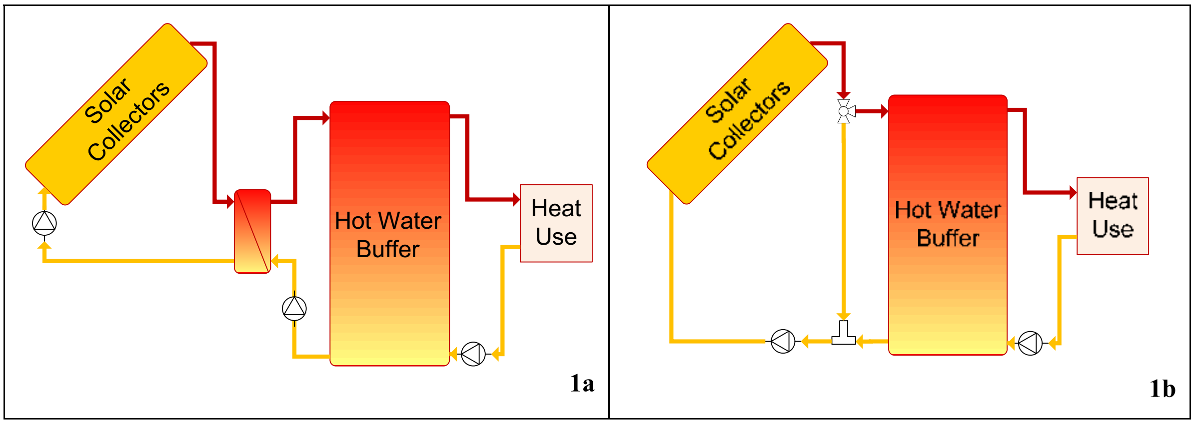

Fig. 1 Schematic drawing of the two main types of solar loop layouts: with (1a) and without (1b) heat exchanger

The connection between the solar collectors and the final subsystems can occur by means of a hydraulic junction or a heat distributor, skipping the tank as in [5] [6]. This solution enables the exploitation of the solar heat as soon as it is available at the set temperature without waiting for the tank to be charged up to the same temperature. However the chance to bypass the tank needs a special control strategy to be set which complicates the system [6].

3.2. Storage systems

Storage systems are usually integrated in solar heating and cooling systems to overcome the mismatch between the availability of the solar radiation and the cooling loads. Most current applications adopt storage technology based on water buffer tanks. In ca 50% of the overall listed systems (134), water buffer tanks are used to store solar excess heat instead of cooling production exceeding the demand – 27% of the total. The integration of water tanks to store solar heat is usually carried out so that temperature stratification can occur along the height of the tank.

When more hot water tanks are present, parallel and series connection are all used. Hybrid connection represents an optimal solution from the point of view of management of the heat storage but a more difficult solution from the point of view of control strategy effort. Such a connection enables the exploitation of a higher temperature stratification in wintertime with a series connection, hence lower return temperature to the collectors and higher efficiency of the latters; whereas in summertime, with a parallel connection, it provides a higher flexibility to respond to high solar radiation availability [7] [8].

3.2. Heat and cold back-up integration

Two main categories of solar heating and cooling systems can be identified on the basis of the fraction of solar use with the respect to the energy need [9]:

- solar thermally autonomous systems: systems where only solar collectors supply heat to the thermally driven chiller, and eventually to the heating and sanitary hot water systems;
- solar assisted systems: systems where the solar collectors represent an additional heat source assisting a conventional heat source or cooling equipment in order to reduce the (fossil) energy consumption for cooling, heating and sanitary hot water.

Nearly the totality of the listed plants (134) are equipped with a back-up system. This can be a second heat source to drive the same cooling system or a second cooling supply system. In some cases both back-up types are applied. The presence of heat back-up systems is preferred whenever the heating load is predominant compared to the cooling load. But in such cases it must be assured that the cooling in summer time through the back-up is a reduced percentage in order to reach a saving of primary energy and an economic efficiency as proved in [6]. The presence of both the systems complicates the installation and increases the investment costs, but it allows direct primary energy savings as the back-up system represents the reference system and the utilisation of the solar energy leads to a direct reduction of the energy sources used by the reference system.

Among the installations the most spread types of heat back-up sources are based on boilers, while electrical driven chillers are used as cold back-up systems. Another advantageous back-up system can be cogeneration units, which allow the exploitation also in summer time of the heat to be rejected by the electricity production systems such as engines or turbines. The heat back-up systems can be connected in parallel to the solar thermal collectors: in this case separated hydraulic circuits or a hydraulic junction, where all the hot flows are mixed, can be implemented [5] [6]. Separated hydraulic circuits can be necessary in case different temperature levels are supplied by different heat generation systems or required by different distribution systems. For instance in case gas based cogeneration units are installed a high attention has to be paid in avoiding temperature conflict between the variable solar source and the rigorous requirements for the engine to be cooled [10]. The heat back-up system can be connected to the same solar storage tank. In this case the temperature level is somewhat lower but the available storage volume for the solar system is reduced **Error! Reference source not found.**]. A connection in series enables to exploit lower temperature of the solar energy even without sharing the same tank (Fig. 2).

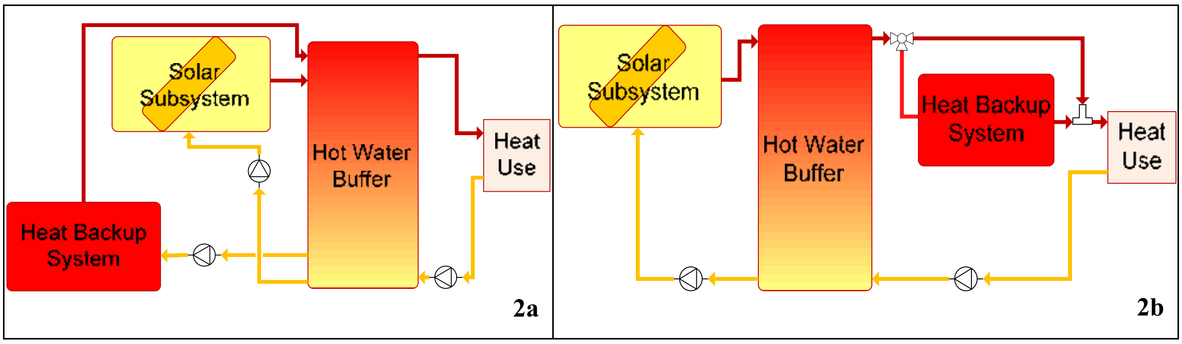

Fig. 2 Layouts for the integration of heat back-up systems in SHC plants: shared hot water buffer (2a) and connection in series without sharing the tank (2b)

4. Sizing of the main components

The present subchapter discusses the sizes selected for the solar thermal subsystem (solar collectors plus heat storages) and for the heat driven chiller subsystem (sorption chillers plus cold storages) in documented systems. Two different approaches can be defined with reference to the sizing of autonomous or assisted solar systems.

4.1. Sizing of solar thermal collectors and heat driven chillers in solar autonomous SHC systems

The major constraint in autonomous SHC systems is that solar energy is expected to match the entire heat demand, as no back-up systems are present. In such cases detailed dynamic simulations are need to be carried out to avoid or reduce the risk of unmatched demand [4].

In autonomous systems featured by cooling needs higher than heating needs, the cooling load determines the chillers' size and the heat requested by the chiller determines the solar collector's surface. However to reduce the risk of unmatched demand, chillers are usually oversized and solar collectors as well. Such approach requires a proper selection of storage systems which in these installations are recommended to be installed on both the hot and cold side to overcome the excess of heat and cooling supply. The drawback of this approach is that the solar cooling system is oversized for most days of the year, thus reducing the economic efficiency and leading to many working hours under part load conditions. If it is acceptable that in certain day's the load remains unmatched this drawback can be overcome by reducing the collector field and the cooling capacity of the chiller.

4.2. Sizing solar thermal collectors and heat driven chillers in solar assisted SHC systems

Solar assisted systems feature a higher number of degrees of freedom in the design process compared with autonomous systems. The relationship between the sizes of the solar thermal and heat driven chiller subsystems and the heat and cooling load is less evident as back-up systems can equilibrate the overall project and manage the mismatch of these sizes in comparison with peak loads.

Solar collectors surface can be determined according to a set solar fraction. Hence the surface depends on the overall heat demand for heating and cooling. In such cases the energy demand of the building is a constraint to the usability of solar energy: needed temperatures and the temporal load profile influences the duration and the amount of solar energy which can be exploited.

As far the chiller size is concerned, the selection is dependent on the building load but planners can also decide to cover just a fraction of the entire cooling load and leave the left demand to be matched by a back-up system. In this case, it can be decided to size the chiller to match the base load, or the peak load, or a range between these two values. On the other hand the size of the chiller could also be based on the solar thermal power installed, hence on the potential solar heat production during summer time.

The variety of degrees of freedom are reflected as well in the different sizes selection resulting from the review documented systems. Fig. 3 shows the collectors gross area per cooling power of TDC for different solar collector technologies. Ranges of variability turn out to be wide especially when flat plate collectors are used.

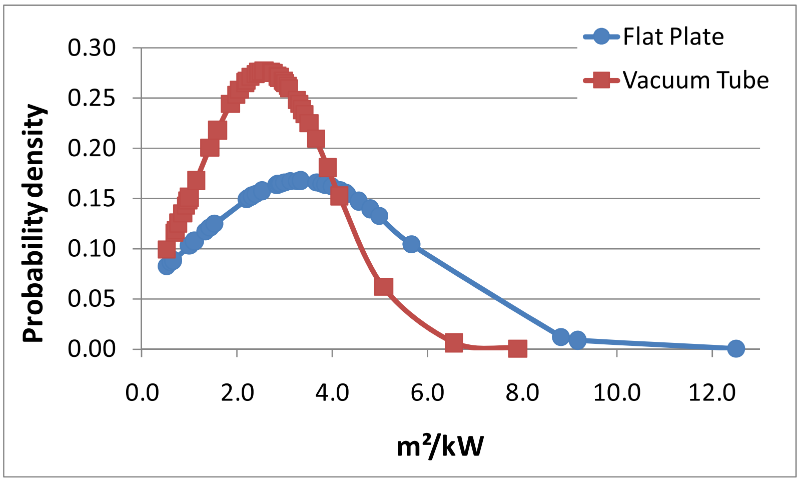

Fig. 3 Probability density for the ratio between the collector gross area (m²) and the nominal cooling capacity of the TDC (kW) applied in 88 documented installations for two solar thermal collector technologies.

A lower standardization level comes out when the sizes of hot water buffers are discussed with reference to the solar collectors surfaces, as it can be derived from Fig. 4. Similar results are obtained when the size of the hot water buffer is related to the nominal cooling power of the heat driven chiller Fig. 5.

Actually the selection of a volume for the buffer is related to the time mismatch between the solar availability and the heat demand. For instance if the main heat load occurs in the evening hours (as might be the case in hotels on the sea side for example), the buffers have to be large enough in order to store the thermal energy produced by the collectors during the morning hours entirely in order to be available in the late afternoon and evening hours. For a proper sizing of this components, the load profile and the solar potential should be investigated in detail.

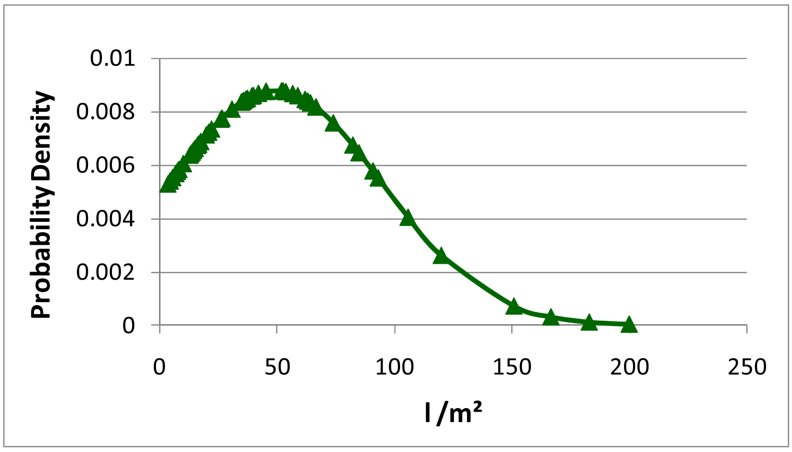

Fig. 4 Probability density of the ratios between hot water tank volume and collectors' area in 55 documented systems

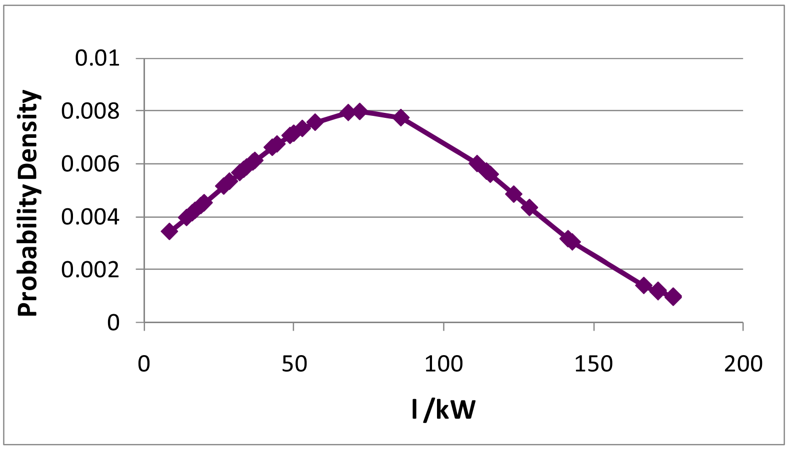

Fig. 5 Volume of the hot water tank compared to the kW of the corresponding absorption chillers in 43 documented systems. To have a more useful representation, ratios higher than 200 l/kW (14) have been neglected

5. Conclusion

The review of existing systems has shown that several design options are available for large scale SHC systems, even for very similar applications. Many degrees of freedom feature the design process and the identification of the best solution is not easily possible in the design phase unless detailed simulations are carried out. Even after the construction, an in-depth understanding of the performance of a plant is only possible thanks to monitoring data.

The penetration into the market of the solar cooling so far has been limited as well by the design complexity. Only in the recent two years a standardisation process seems to take place, driven by those companies who specialized on the installation of these systems and relay on in house proven solutions from own installations. This process has, according to the authors experience from the analysis of monitoring data and several discussions with plant managers of installed systems, a very important role. In fact it allows to drive down the planning cost and time and higher the probability that installed systems confirm during their operation the expected performance.

The availability of monitoring data of existing plants turns out to be fundamental to support and address planners towards the optimal design. In Task 38, monitoring data of 10 large scale installations are being reviewed at present and will be included in the second edition of the handbook on solar cooling.

6. Acknowledgements

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