Building integration of concentrating systems for solar cooling applications

Daniel CHEMISANA[1*], Jesús LÓPEZ-VILLADA[2], Alberto CORONAS[2], Joan Ignasi ROSELL[1]

[1] Applied Physics Section of the Envirommental Sciences Department, University of Lleida. C/ Jaume II, 69, 25001, Lleida (Spain).
[2] Universitat Rovira i Virgili (URV), Av. Països Catalans, 26, 43007 Tarragona, Spain
* Correspondence: daniel.chemisana@macs.udl.cat

Abstract

The high energy consumption in buildings in Mediterranean countries, especially in the spring and summer months due to the massive use of air conditioning, requires immediate action to minimise the energy costs and environmental impact in the current energy crisis context. Solar cooling systems offer a solution to this particular problem, but the main handicaps of this type of systems are the low efficiency of the currently used single-effect absorption chillers and the large areas of thermal collectors needed to produce the thermal energy. A way to overcome these obstacles is the use of high efficient integrated solar concentrator systems able to achieve temperatures around 150 ºC that could be used to activate the more energy efficient double-effect absorption chillers. In that sense, in this work we compared a conventional cooling system with evacuated tube collectors and a single-effect absorption chiller with one with a solar concentrating system and double-effect absorption chiller for an specific three-floors building. The results show a 87.5% reduction of the solar collectors area in the concentrating system compared with the standard solar thermal installation. In addition, the rejected heat in the double-effect chiller is lower, implying that the investment and operation costs of the solar concentrating cooling system are reduced significantly.

Keywords

Building integration, solar concentration, solar cooling, thermal collectors, Fresnel reflector.

Introduction

Most of the solar energy systems in buildings have increasingly been applied and studied since the 90's. These systems are usually used to produce separately electricity and heat through standard flat collectors with the collectors installed on the roof. However, there are some recent developments of trigeneration systems to produce simultaneously electricity, heating and cooling using concentrating solar thermal collectors installed on the façade or roof and double-effect absorption chillers, reaching a global higher efficiency and higher operating temperatures. These systems are used for the air-conditionig of the buildings during the whole year.

For building integration, concentrating systems (CS) applied to solar generation processes can offer several advantages over conventional thermal collectors, being the most noticeable: better use of space, ease recycling of constituent materials, flux regulation to achieve variable proper flow conditions, higher levels of power density and thus higher temperature of the fluid,

Corresponding author: daniel.chemisana@macs.udl.cat, +34973003711, +34973003575

reduction of the hottest parts areas and therefore increasing the overall efficiency of the system (reducing the heat losses), etc. However, the viability of building-integrated concentrating systems would depend on the economic comparison over systems with flat plate or evacuated tube collectors, whose market prices are decreasing from day to day and offer some important advantages such as easy replacement of structural elements.

The major advantage of working with CS for cooling is that the higher operation temperatures allow the use of double-effect absorption chillers that are much more energy efficient that the single-effect absorption chillers, which means that the solar system would need less collectors area to produce the same amount of chilled water.

A comparative analysis is presented of the main existing CS' suitability for use in solar cooling, heating and electricity applications, in which the different specific challenges to integration of each system are discussed. A further building integrated CS is described and studied. The system is constituted by a Fresnel reflective solar concentrator converging solar beam to the thermal modules.

2 Solar concentrators building integration statements

In addition to being technically and structurally sound, solar concentrators suitable for architectural integration must fulfil the following requirements, which are a generalization of the criteria formulated by the IEA PVPS Task 7 workgroup for the evaluation of the aesthetic quality of buildings integrated photovoltaics [1, 2]:

- Natural integration.
- Architecturally pleasing design.
- Good composition of colours and materials.
- Dimensions that fit the gridula, harmony and composition.
- Conformity to the surroundings of the building.
- Well-engineered and innovative design.

The integrability of a reflective or refractive concentrator depends directly on its concentration ratio CR, defined as the ratio between the aperture area of the primary concentrator and the active cell area. Concentrating systems with CR > 2.5X generally use a system to track the sun, whereas systems with CR < 2.5X can be static. Low and medium concentrating ratio systems in the rage 10X-20X are of particular interest as they are of linear geometry and thus one tracking axis is sufficient for efficient operation [3].

The building integration categorises different grades as a function of the impact in the building appearance and the building functions of the concentrating system. The lowest level of integration appears when the system is not visible and the highest when it constitutes in itself an architectural concept.

Considering that a higher concentration factor results in a more cost-effective device mainly due to the thermal losses reduction and the efficiency increase, it can be seen that within the concentration range where single axis tracking may be used, the most desirable concentration factor is the one that approaches or, if possible, exceeds the upper limit of 20X.

3 Solar cooling requirements

Most of the solar cooling systems in the EU [4] are based on single absorption chillers and use the Flat Plate Collector (FPC) or the Evacuated Tube Collector (ETC) as solar thermal technology. The solar collectors usually operate at temperatures around 85-95 ºC. However, double-effect absorption chillers require temperatures in the generator around 150 ºC that can only be achieved by concentrating solar collectors. The building integration of the usual concentration technologies as Linear Fresnel Reflectors or especially Parabolic Through Collectors (PTC) is difficult and that's the reason why is of major interest the development of CS integrated in buildings.

4 Concentrating systems matching building integration and solar cooling conditions

According to the concentration ratios of the systems mentioned above, ranged between 10X and 20X, the following review is focused on concentration systems converging incoming radiation by refraction or reflection in the mentioned interval. Within these devices, at present the research development is focused on Fresnel technologies because they may be produced in wide range sizes; their aspect ratio can be designed to be small leading to a compact concentrating system; they may use metallic components as reflectors with great properties; they may be very thin to minimize the cost of optical material and reduce the mechanical load on the supporting structure; and they may be made of reliable and durable materials [5].

In the following point, the most representative Fresnel reflective and refractive concentrating systems are described. All of them can reach adequate temperatures for the double-effect absorption chillers if the absorbers' characteristics are in consonance.

4.1 Linear Fresnel Reflectors

Within this range of concentrations good versatility is offered by systems which work using Fresnel reflection, some of which are worthy of note (some of the systems described below are included due to their importance as concentrating technologies, despite being photovoltaic collectors):

(1) Concentrators with 2-axis trackers in which tracking is achieved by movement of the entire system, such as the BiFres system developed at the University of Lleida (equipped with a PVT receiver), whose integration in buildings would be restricted to flat (horizontal) roofs [6].

(2) Static concentrators in which solar tracking is achieved by movement of the receiver. This option offers greater scope for integration in buildings as it may be easily installed on either flat or inclined roofs. Installation on façades however presents certain problems: the mirrors prevent light from passing into the building and the mobile receiver must protrude outward from the building creating strain on the building structure and an anaesthetic appearance. The main exponent of this technology is the CCStaR system developed at the University of the Balearic Islands (equipped with a thermal receiver). It should be mentioned that in the most recently presented CCStaR prototypes the Fresnel reflectors are replaced by parabolic trough reflectors [7].

(3) Concentrators in which the tracking is achieved by the movement of the individual mirrors. The possibilities for integrating such systems are similar to those for the previous cases of a stationary concentrator. The most important design within this group is the Compact Linear Fresnel Reflector (CLFR) presented in 1997 by Mills and Morrison [8] and commercialized by Ausra. The CLFR system is used for the direct steam generation. Similar systems to the CLFR have been developed as the solar collector Solarmundo presented by Häberle *et al.* in 2001 [9] and commercialized by Power Group GMBH and the Mirroxx Fresnel collector

commercialized by Mirroxx GMBH, a spin-off of PSE-AG [10]. Using the same concentration principle, the company HelioDynamics have presented a collector, HD211, for integration in buildings with a receiver which can be thermal or PVT. Usually, the HD211 renamed to HD10, only incorporates a thermal receiver [11]. Very recently the company Chromasun is offering an analogous system to the previous ones for solar cooling applications and for rooftop integration [12].

A new concept in the field of Fresnel reflection systems is the so called Non-imaging Reflective Lens (NIRL) concentrator. There are two types: the axially symmetric Ring Array Concentrator (RAC) and the linearly symmetric Slat Array Concentrator (SAC) [13]. These operate by using mirrors to concentrate light directly onto a receiver behind the optical element emulating a lens. The high concentration, RAC, requires two axis tracking, whereas the medium concentration SAC can be employed with either one or two axis tracking [14]. This type of concentrator combines the high optical efficiency achievable by mirrors with the flexibility of design which is characteristic of lenses. The principle drawback of these systems is that solar tracking is achieved by movement of the whole system, incurring the aforementioned restrictions with regard to architectural integration.

The University of Lleida is currently developing concentration technology which uses reflection, in a similar way to the systems developed by [15], but with a design which prioritizes architectural integrability. The system consists of a linear Fresnel reflector which focuses radiation in a analogous manner as a lens. The receiver remains static and solar tracking is achieved by a simple and effective way by rotation of the individual mirrors. Thus, the overall movement is minimized facilitating incorporation into buildings and offering different possibilities for suiting the varied requirements of specific installations.

4.2 Linear Fresnel Lenses

Firstly, before commenting the different properties and characteristics of Fresnel lenses when applied to building integrated CS, two systems must be mentioned. Although of low architectural integrability, as the systems described previously, they are the first references of this kind of linear concentrators.

These products are both formed by arched Fresnel Lenses located on a solar tracker. The first, designed by Entech Solar (USA) [16], uses a two axis tracker and a PV or PVT receiver. The second, designed by SEA Corp. (later Photovoltaics Internacional) [17, 18] uses a one axis tracker and a PVT receiver. Recently, Entech Solar has announced two new systems; TermaVolt™ II (PVT) and SolarVolt™ II (PV). Both systems are based on the same technology but using different receivers. Entech has resized the initial prototypes designed in the 80s into these two smaller and low-cost devices applicable for both ground and roof-mount applications.

The ability of linear Fresnel lenses to separate the beam from the diffuse solar radiation makes them useful for illumination control in the building interior space. The Fresnel lenses are advantageous because they can combine both the concentrating element and the optically transparent window. The use of Fresnel lenses as a transparent covering material for lighting and energy control of internal spaces has recently attracted special attention [19].

In addition to mentioning the general benefits of Fresnel lenses, some comparison should be made between those which are image forming and those which are anidolic. Image forming Fresnel lenses for solar applications require high precision tracking. Non-imaging lenses, often convex and arched in shape and designed for medium concentration, using one axis tracking, have been devised as highly competitive solar collectors. If the tracking requirements are minimized, the cost reduction achieved by reduction of the PV cells' surface area outweighs the cost of the optical elements [20, 21].

The concept of using a fixed concentrator with a tracking absorber has been mentioned in the past [22-24]. It is based on a stationary wide angle optical concentrator that, whatever the location of the sun, transmits the input radiation onto a small moving focal area, which, in turn, is tracked by the receiver. Following this approach, the University of Lleida has developed a prototype based on a stationary Fresnel lens which focuses solar radiation onto a PVT receiver which tracks the moving focal area [24, 25]. The advantages of this type of CS make it architecturally versatile, allowing integration onto flat or inclined roofs or as lightweight façades, windows etc. Thus their characteristics correspond perfectly to the requirements of well integrated systems described in section 2.

5 System proposed

5.1 Solar concentrator

The proposed concentrator is based on a Fresnel reflector system [15]. The device concentrates radiation toward a static receiver by means of an array of mirrors which rotate collectively. All rotation axes are coplanar and parallel. This permits the use of a single linear driver, an important mechanical and economical advantage. The maximum concentration ratio reached is 20.42 suns.
The system has been designed fulfilling the following criteria: architectural integrability (environmental integration, appropriate materials, dimensions that fit the composition and harmony of the building, light weight), high compactness (this is the inverse of the aspect ratio, the aspect ratio being the ratio between the focal distance and the concentrator aperture). The aspect ratio of the studied system has been fixed to 0.5.

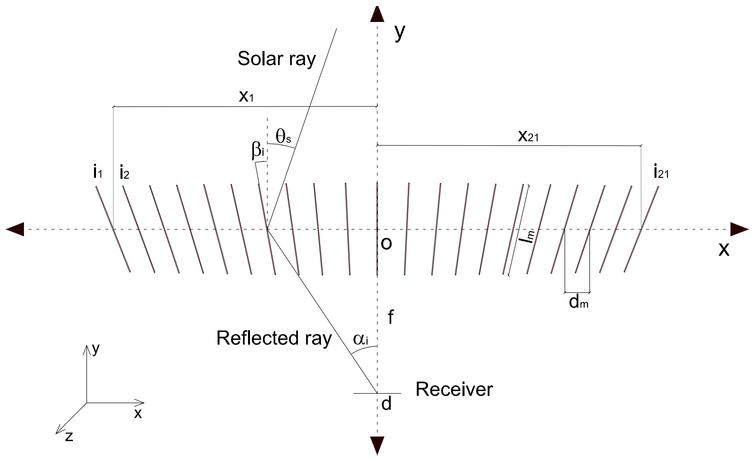

Figure 1: On the left: Fresnel reflector 3D view and on the right: Fresnel concentrator schematic.

The optical performance of the concentrator has been analyzed through simulation in the ray tracing program OptiCad®. In this configuration, an important impact in decreasing the transmission efficiency of the received radiation onto the receptor surface appears due to blocking and shading effects. That is, part of the incident radiation for certain sun angles is not reflected as a consequence of shading occurred between mirrors. From the reflected solar rays, there will also be a percentage that in certain circumstances not reaches the receiver because other mirrors block them. The impact of shading and blocking can be easily deducted in Fig. 1.

The objective function maximised by the system is the daily global efficiency (η_G), defined as the quotient of the solar energy captured by the receiver Q_R to the solar energy incident on the aperture Q_A over the course of a day where the irradiation conditions for the day are defined to be 6 hours of uninhibited AM 1.5 illumination centred at solar midday and with an angular variation of solar incidence from -45° to 45° over this period. Only direct radiation is considered, diffuse and reflected radiation are ignored. Under these conditions η_G takes a value of 56.4%.

As it can be observed in figure 2, the system is placed vertically and oriented to the South (azimuth 0º). In this configuration the concentrating system is located on a ledge (eaves) of the building, so that the receptor is placed on the same wall of the building. At the same time it can be anchored or not to the wall, finding provided its possible setting and its connection to the thermal installation. Ledges parts are registrable zones that allow for both window cleaning and maintenance (cleaning) of the concentrator. Aesthetically speaking, the impact is similar to the vertical lattices which are widely used in recent years for lighting control. The concentrator system is perfectly integrated, and is at the same time an aesthetic element that defines the building style and replaces a closing element. The sun is therefore tracked by the mirrors in azimuth from - 45 º to 45 º.

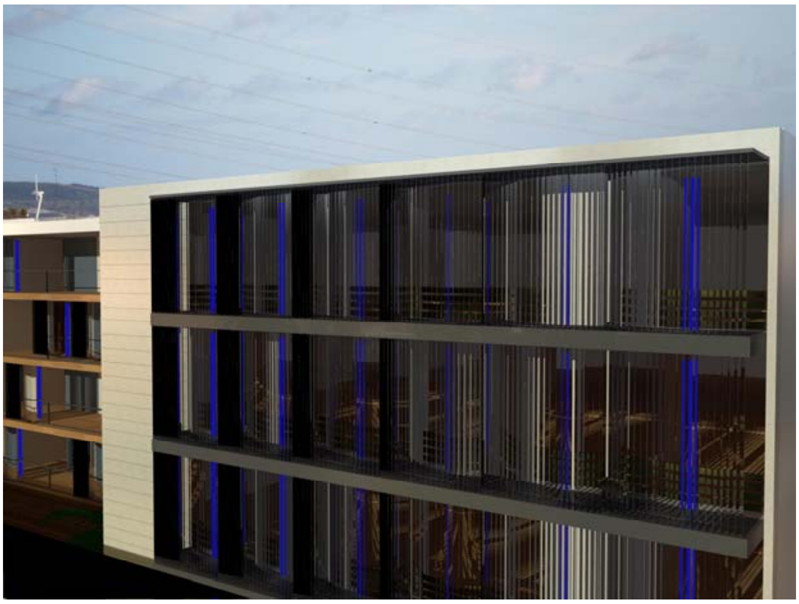

Figure 2: Architectural design of the building integrated concentrating system.

The concentration ratio is determined as the ratio between the beam irradiance received at the focal area and the beam irradiance incident on the Fresnel reflector. The optical concentration has been evaluated for a wide range of incidence angles, using the data to adjust the next mathematical function, Eq. (1):

$$|C(\theta)| = -2.762 \times 10^{-6}\theta^5 + 2.961 \times 10^{-4}\theta^4 - 1.067 \times 10^{-2}\theta^3 + 1.460 \times 10^{-1}\theta^2 - 5.646 \times 10^{-1}\theta + 17.91 \quad (1)$$

where θ corresponds to the solar azimuth.

Concerning the solar altitude, the concentrator, as it works as cylindrical optic, only converges to the receptor the beam incoming in a perpendicular direction to the plane of symmetry, where the receptor is located (see figure 1). This translated to solar angles means that only the solar azimuth affects to the concentration. The solar altitude impacts negatively in the fact that a fraction of the absorber is not illuminated. The higher the solar height, the higher the non-illuminated fraction. In the case analysed, the absorber length is dimensioned considering an average solar height of 35º. Therefore, as the aspect ratio of the systems is 0.5, the non-illuminated fraction is:

$$\frac{L_{NI}}{L} = 0.5 \tan 35^{\circ} \qquad (2)$$

where L_{NI} is the non-illuminated length and L is the absorber length.

As it is depicted in figure 2, the building analysed has three floors. Each floor is three meters high and the longitude of the building façade where the concentrating system is installed is 60 m. Reflectors length is fitted to the floor height, taking the non-illumination fraction for this situation a value of 0.35, which in terms of absorber length means that the considered absorber is 1.95 m.

One absorber that fits approximately these dimensions is the evacuated tube of a commercial ETC collector whose characteristics are specified in Table 1. According to the geometry of the building, the South façade could have up to 90 tubes with a total absorber area of 15.6 m^2.

Table 1: Characteristics of the evacuated tube collectors

Tube	Length	2000	mm
	Width	100	mm
	Weight	4.6	kg
Absorber	Length	1925	mm
	Width	90	mm
Energy Performance	Optical factor	0.798	-
	First Thermal Losses Factor	0.9937	$W\ m^{-2}\ K^{-1}$
	Second Thermal Losses Factor	0.0097	$W\ m^{-2}\ K^{-1}$

5.2 Solar storage and cooling system

The energy collected by the CS is carried to a pressurized water storage tank of 10 m^3. In order to operate at temperatures around 150 ºC and avoid boiling of the water, the pressures must be around 6 bar. The cooling system for that CS system consists of a double effect-absorption chiller of 100 kW of cooling capacity and a nominal COP of 1.35.

5.3 Results

This system is compared with a reference solar cooling system able to produce the same amount of cooling. Table 2 illustrates the main characteristics of the CS and the reference cooling systems. I can be seen that coupling the CS implies using a 12.5 % of the absorption collector area in comparison with the reference cooling installation; contrarily, for the same solar storage volume, it is necessary to double the cooling capacity of the absorption chiller and then to increase the nominal capacity of the cooling tower.
Both systems described above are simulated using the TRNSYS software. The thermal chillers have been modelled using the characteristic equation approach [27]. For the simulation of the

CS, Eq. (1) is implemented to calculate the concentration ratio as a function of the solar azimuth. TRNSYS is also used to calculate the values of the solar radiation over a vertical surface of the available Typical Meteorological Year and to model a modified ETC solar collector to consider the thermal capacitance. This model was also used to determine the performance of the solar collectors of the reference system.

Table 2: Characteristics of the CS and the reference solar cooling plant.

Characteristic	CS cooling plant	Reference cooling plant	Units
Absorption surface	15.6	125	m^2
Tilt angle solar collectors	90	35	º
Storage tank volume	10	10	m^3
Absorption chiller capacity	100	50	kW
Absorption chiller COP	1.35	0.75	-
Operation pressure	6	3	bar
Operation temperature	150-155	90-95	ºC

The energy results are shown in table 3 and represented in figures 3 and 4 to facilitate comprehension. According to them, the CS systems with only 15.6 m^2 of absorption surface is able to produce the half of the solar production of the reference cooling plant with 125 m^2 and at higher temperature level. Also the heat rejection is lower when using CS collectors because of the higher efficiency of the double-effect absorption chillers. This means that the operation costs of the cooling tower will be reduced in the case of the CS cooling system.

Table 3: Energy results for CS and the reference cooling plants.

	CS cooling plant	Reference cooling plant	Units
Solar irradiation	336	686	kWh
Solar gains	246	490	kWh
Solar Collectors Performance	73.2	71.4	%
Cooling production (Q_E)	312	313	kWh
Heat energy consumption (Q_G)	230	419	kWh
Heat rejection (Q_{AC})	542	732	kWh

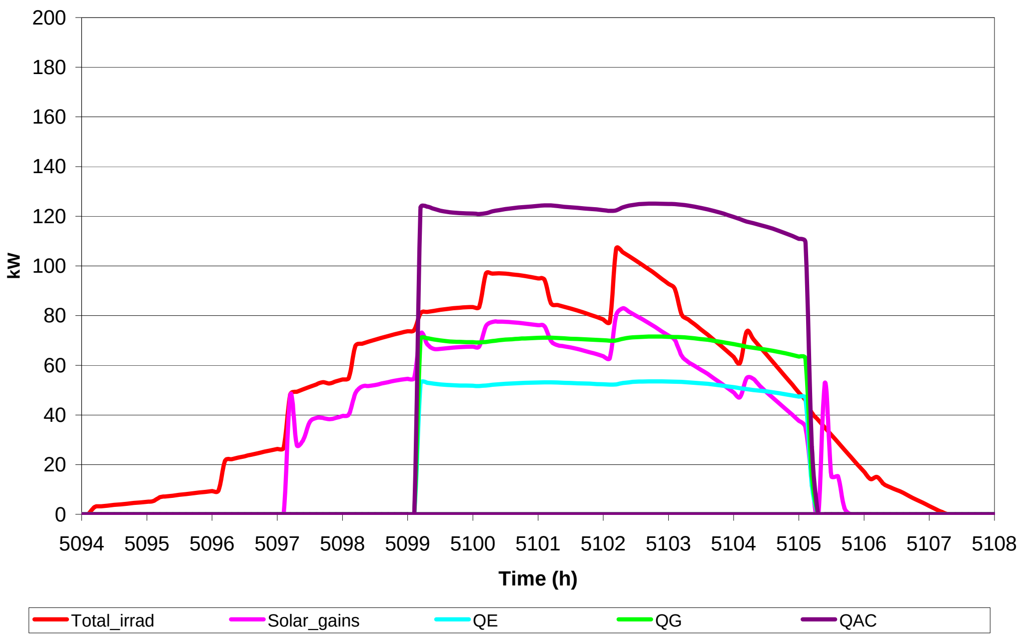

Figure 3: Evolution of the Energy performance of the reference solar cooling system on 1st August of a Typical Meteorological Year

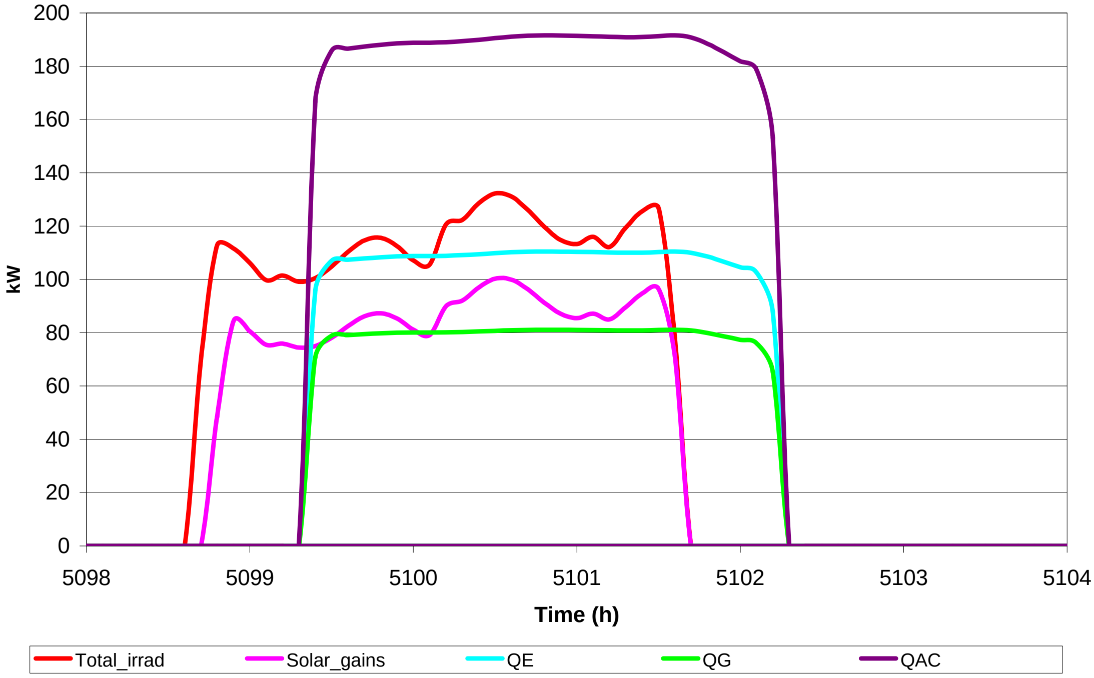

Figure 4: Evolution of the Energy performance of the CS solar cooling system on 1st August of a Typical Meteorological Year

Despite the advantages of the CS cooling system (the more energy efficiency, the less solar absorption area, the lower heat rejection and the better building integration), the final decision between this system and a conventional solar cooling system using a single-effect absorption chiller will depend on the costs of the whole systems. At this stage, although it is not possible to quantify the differential costs of both systems, it must be indicated that in the design requirements the costs attributed to the tracking systems and the reflectors were considered to be minimised through the system proposed.

6 Conclusions

The main characteristics and energy performance of CS cooling systems have been compared and evaluated with a reference system achieving the same cooling production.

The results obtained show that the CS system needs only the 12.5 % of the solar collector area, taking into consideration that, for the same solar storage volume, the cooling capacity of the absorption chiller must be doubled and the nominal capacity of the cooling tower must be around a 60% higher.

Another important advantage is that CS allows operating at higher temperatures, which permits the use of the more efficient double-effect absorption chillers, whose heat rejection is lower than in single-effect technologies.

In spite of all this positive characteristics make the CS cooling systems much more energy efficient in comparison to standard solar cooling installations, to finally decide in economic terms which is the best solution it would be necessary to consider the total costs including the optical and tracking elements. At design stage, what is has been considered as a requirement is to try minimising costs by using reflectors and a single tracking system.

Acknowledgements

This work has been supported by the Spanish Ministerio de Ciencia e Innovación (MICINN) under grant ENE2007-65410.

References

[1] Reijenga T. Photovoltaic Building Integration Concepts – What do Architects need? In: Proc. IEA PVPS Task7 Workshop Lausanne Featuring A Review of PV Products, IEA PVPS Task7, 2000.
[2] Reijenga T. Photovoltaics in the Built Environment. In: Proc. 2nd World Solar Electric Buildings Conference, 2000.
[3] Tripanagnostopoulos Y. Building Integrated Concentrating PV and PV/T systems. In: proceedings of the Eurosun 2008, 2008.
[4] International Energy Agency (IEA), Task38 Solar Air-Conditioningand Refrigeration. State of the art on existing solar heating and cooling systems. A technical report of subtask B (2009).
[5] Chemisana D. Building integrated concentrating photovoltaics: A review. Renewable and Sustainable Energy Reviews 2011; 15: 603-611.
[6] Rosell JI, Vallverdu X, Lechon MA, Ibanez M. Design and simulation of a low concentrating photovoltaic/thermal system. Energy Conversion and Management 2005; 46: 3034–3046.
[7] Pujol R, Marínez V, Moià A, Schweiger H. Analysis of stationary Fresnel like linear concentrator with tracking absorber. In: 13th SolarPaces Symposium, 2006.
[8] Mills DR, Morrison GL. Modelling of Compact Linear Fresnel Reflector Powerplant Technology: Performance and Cost Estimates. In: Proceedings of the International Solar Energy Society Conference 1997, 1997.
[9] Häberle A, Zahler C, Lerchenmüller H, Mertins M, Wittwer C, Trieb F, Dersch J. The Solarmundo line focussing Fresnel collector. Optical and thermal performance and cost calculations. In: proceedings of SolarPACES 2002, 2002.
[10] Berger M, Häberle A, Louw J, Schwind T, Zahler C. Mirroxx Fresnel Process Heat Collectors for Industrial Applications and Solar Cooling. In: Proceedings of SolarPACES 2009, 2009.
[11] HelioDynamics (2004) HD211 product sheet. Available from: www.heliodynamics.com
[12] D. Walter et al., "A 20-sun Irbid PVThermal linear micro-concentrator system for urban rooftop applications" *Proc. of the 35th IEEE Photovoltaic Specialist Conf.*, Honolulu, USA, 2010.
[13] Vasylyev S. Nonimaging Reflective Lens Concentrator. In: Proceedings of the International Conf. on Solar Concentrators for the Generation of Electricity or Hydrogen, 2005.

[14] Vasylyev S. Performance Measurements of a Slat-Array Photovoltaic Concentrator. In: American Solar Energy Society, Solar 2004 Conf., 2004.

[15] Chemisana D, Rosell J.I. Design and Optical Performance of a Nonimaging Fresnel Reflective Concentrator for Building Integration Applications. Energy Conversion and Management, submitted in 2009.

[16] O'Neill MJ, Walters RR, Perry JL., McDanal AJ. Jackson MC, Hess WJ. Fabrication, installation and initial operation of the 2000 sq. m. linear fresnel lens photovoltaic concentrator system at 3M/Austin (Texas). In: Proc. 21th IEEE Photovoltaic Specialists Conference, 1990.

[17] Kaminar N, McEntee J, Stark P, Curchod D. SEA 10X concentrator development progress. In: Proc. 22nd IEEE Photovoltaic Specialists Conference, 1991.

[18] Bottenberg WR, Kaminar N, Alexander T, Carrie P, Chen K, Gilbert D, Hobden P, Kalaita A, Zimmerman J. Manufacturing technology improvements for the PVI SUNFOCUS™ concentrator. In: Proc. 16th European Photovoltaic Solar Energy Conference, 2000.

[19] Tripanagnostopoulus Y, Siabekou Ch, Tonui JK. The Fresnel lens concept for solar control of buildings. Solar Energy2007; 81: 661-675.

[20] Leutz R, Suzuki A, Akisawa A, Kashiwagi T. Design of a nonimaging Fresnel lens for solar concentrators. Solar Energy 1999; 65(6): 379-387.

[21] Leutz R, Suzuki A. Nonimaging Fresnel Lenses. Design and performance of solar concentrators. Ed. Springer, 2001.

[22] Kritchman EM, Friesem AA, Yekutieli G. Efficient Fresnel Lens for solar concentration. Solar Energy1979; 22: 119-123.

[23] Kritchman EM, Friesem AA, Yekutieli G. Convex Fresnel lens with large grooves. Solar Energy 1981; 27: 129–37.

[24] Kritchman EM, Friesem AA, Yekutieli G. A fixed Fresnel lens with tracking collector. Solar Energy 1981; 27: 7-13.

[25] Chemisana D, Ibáñez M, Barrau J. Comparison of Fresnel concentrators for building integrated photovoltaics. Energy Conversion and Management 2009; 50: 1079-1084.

[26] Chemisana D, Ibáñez M. Linear Fresnel concentrators for building integrated applications. Energy Conversion and Management 2010; 51: 1476-1480.

[27] Puig-Arnavat, M., López-Villada, J., Bruno, J. C. and Coronas, A. (2010) Analysis and parameter identification for characteristic equations of single- and double-effect absorption chillers by means of multivariable regression. International Journal of Refrigeration 33 (1) pp 70-78