Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 91 (2016) 759 – 766

Energy Procedia

SHC 2015, International Conference on Solar Heating and Cooling for Buildings and Industry

Performance and economic comparison of solar cooling configurations

Roberto Gabbrielli[a]*, Piero Castrataro[b], Francesco Del Medico[a]

[a]*Dipartimento di Ingegneria Civile e Industriale, Università di Pisa, via Bonanno Pisano 25/b, 56126 Pisa, Italy*
[b]*Glayx Tech srl, Via Mattarella 27, 86170 Isernia, Italy*

Abstract

In this paper a performance and economic comparison of solar cooling configurations using a new integrated approach combining the hourly thermal-optical performance assessment of the solar systems with the economic aspects has been conducted. Evacuated tube solar collectors with single effect LiBr absorption chiller and compact solar linear concentrating Fresnel collectors with single effect or medium temperature double effect LiBr absorption chiller have been taken into account. Considering that all the produced cold thermal energy could be delivered to a final user, the latter solar cooling configuration shows the possibility to have the Levelized Cost Of Cooling (LCOC) comparable with standard electric compression cooling. However, technology improvements and economy of scale are necessary in order to reduce solar field cost in the range 150-250 €/m^2.

© 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG

Keywords: Solar cooling; thermal-optical performance; economic assessment; solar concentrating system; evacuated tube solar collectors

1. Introduction

Solar cooling technology based on solar thermal production coupled with absorption cooling is still in its development stage [1]. Absorption cooling is a mature technology but its cost coupled with solar thermal field cost has limited the widespread diffusion of solar cooling plants [2]. Another limiting factor is the capacity factor of solar

* Corresponding author. Tel.: +39-050-2217138; fax: +39-050-2218140.
E-mail address: r.gabbrielli@ing.unipi.it

1876-6102 © 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review by the scientific conference committee of SHC 2015 under responsibility of PSE AG
doi:10.1016/j.egypro.2016.06.241

cooling plant. In order to be cost competitive with standard electric chiller technology, solar cooling plants need to be used as much as possible lowering the amortization cost [3]. A detailed design of the plant coupled with technical and economic feasibility is fundamental to match the cooling demand with right solar field, absorption chiller and eventually thermal storage [4-5]. In [4-5] the techno-economic comparison of solar cooling configurations is executed without considering the variable cost of the solar field. They use the present cost data of the components and do not investigate the effects of the change of these costs on the economic results. In [4] the assessment takes into account only one location with very high solar irradiance. In [5] the parabolic dish collectors and parabolic trough collectors are taken into account.

In this paper, a deep investigation upon the performance and economic comparison between three different types of solar cooling systems for two locations with different solar irradiance is proposed. The comparison, that uses a new integrated approach combining the hourly thermal-optical performance assessment of the solar systems with the economic aspects, has been made considering the total yearly cooling energy production, the specific cost of the solar field and absorption chiller, the O&M expenses. Considering both conventional and concentrating solar collectors, the scope of the paper is to investigate how the specific cost of the solar field and absorption chiller and the climate location characteristics influence the specific cost of cooling in comparison with the conventional electric compression chillers.

2. Solar cooling configurations

The first configuration (S1) is a solar cooling system made up by a solar thermal field with evacuated tube solar collectors and a single effect LiBr absorption chiller. In the second one (S2) the solar thermal field is constituted by compact solar linear concentrating Fresnel collectors (CSLFC). The third one (S3) is a solar cooling system made up by a solar thermal field with CSLFC and a double effect LiBr absorption chiller. The same aperture area of 1000 m^2 has been considered. CSLFC have been chosen because there are already the cheapest solar thermal concentration collectors thanks to flat or almost flat mirrors, to lowest land occupancy compared to other concentration technologies and to easiness of mirror cleaning.

The maximum temperature of the working fluid (water) of the solar collectors has been set to 88°C for the first two systems and 170°C for the third system in order to have EER of the absorption chiller of 0.7 and 1.3, respectively. Fluid (water) temperatures of 7-12 °C have been considered for the cooling circuit. For the sake of simplicity, it has been supposed that all the cold thermal energy could be delivered to a final user (for example, industrial continuous end-users). The size of the absorption chiller has been chosen considering that during the day with the highest production the whole thermal energy produced by the solar field, thanks to an adequate thermal storage, could be converted by the absorption chiller in order to have a constant chilling power during 24 h operation.

In Table 1 the characteristics of the solar cooling configurations are summarized.

Table 1. Characteristics of the solar cooling configurations.

Configuration	Aperture area (m^2)	Solar field technology	Tmax (°C)	Absorption chiller	EER
S1	1000	Evacuated	88	LiBr single	0.7
S2	1000	Linear Fresnel	88	LiBr single	0.7
S3	1000	Linear Fresnel	170	LiBr double	1.3

In S1 configuration the solar field is made by evacuated thermal solar panels having aperture area of 1.912 m^2 each. The tilt angle of collectors has been choses in order to maximize the annual thermal energy production. In S2 and S3 configuration, the solar field is made by ThermeX linear Fresnel solar concentrators developed by Glayx Tech. A single ThermeX module has an aperture area of 35.33 m^2. Efficiency of evacuated tube solar panels and ThermeX concentrators are reported in the following paragraphs.

3. Evaluation of performances

The expected performances of different systems have been evaluated through Glayx Tech proprietary simulation code [6]. The code was subdivided in two parts, combining the geometry associated to the single solution and its thermal-optical efficiency, determined according to EN 12975-2. Once specified a geographical location and a set of geometrical parameters defining the technology configuration as well as the DNI values and ambient temperature for the selected location, an advanced tri-dimensional code computed both Transversal and Longitudinal Incidence Angle Modifier (IAMt and IAMl) in every yearly hour for the different systems. The resulting values of IAMt and IAMl were used to normalize solar irradiance and ambient temperature in every yearly hour to the standard EN 12975-2 condition, i.e. finding out the equivalent condition with sun position at the Zenith. The determination of an "equivalent" reference condition allowed the application of general thermal-efficiency expression given for each system through the combination of η_0, a_1, a_2 and T* parameters. The hourly estimated energy productions were used to simulate the complete system including different operating temperatures, storage size and cooling load.

4. Levelized cost of cooling (LCOC)

The comparison between the solar cooling systems has been made introducing the levelized cost of cooling (LCOC). LCOC is the minimum price at which cold thermal energy must be sold for a cooling generating system to break even. Typically LCOC is calculated over 20 year lifetime, and it is given in units of currency per kilowatt-hour, for example $/kWh or €/kWh or per MWh.

Proprietary simulation code has been used to compute LCOC assuming 20 years system life-time, 0.5 c€/kWht O&M cost and 5% loan interest rate and compared to LCOC of standard electric compression. Considering the following definitions:

CAPEX = Solar field cost + thermal storage cost + absorption chiller cost + aux components cost

O&M = Operation and Maintenance cost

PAY = Annual loan payment (total loan = CAPEX, annual loan interest = 5%, duration = 20 years)

OPEX = PAY + O&M

E_c = yearly production of cold thermal energy

A simple formula has been used to evaluate LCOC:

$$LCOC = \frac{OPEX}{E_c} \tag{1}$$

For the sake of simplicity, performance degradation of the systems has not been considered.

5. Thermal performances of the solar cooling systems

5.1. Evacuated tube solar collectors

For S1 configuration the evacuated tube collectors whose efficiency can be described by the following formula that is reported also in Figure 1 have been chosen.

$$\eta = \eta_0 - a_1 \frac{T_m - T_a}{G} - a_2 \frac{\left(T_m - T_a\right)^2}{G} \tag{2}$$

with

$$\eta_0 = 0.662; \quad a_1 = 0.735 \frac{W}{m^2 K}; \quad a_2 = 0.0096 \frac{W}{m^2 K^2}$$

where Tm, Ta and G are, respectively, the mean temperature of the heat transfer fluid, the ambient temperature, and the hemispherical global solar irradiance.

Evacuated tube collectors have poor performances with temperature greater the 100°C, for this reason they cannot be used with double effect LiBr absorption chiller which requires temperature near to 180°C.

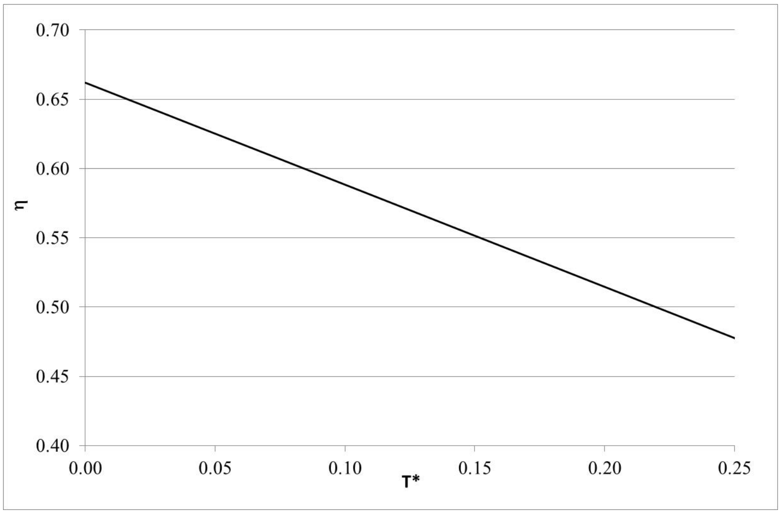

Fig. 1. Efficiency curve of the evacuated tube collector.

5.2. CSLFC

For S2 and S3 configurations the ThermeX CSLFC made by Glayx Tech srl has been chosen. In Fig. 2 the efficiency curve, that can be evaluated also through the following formula, is reported:

$$\eta = \eta_0 - a_1 \frac{T_m - T_a}{DNI} - a_2 \frac{\left(T_m - T_a\right)^2}{DNI} \tag{3}$$

with

$$\eta_0 = 0.692; \quad a_1 = 0.286 \frac{W}{m^2 K}; \quad a_2 = 0$$

ThermeX CSFLCs perform well at medium temperature thus making them the perfect choice for coupling to double effect LiBr absorption chiller.

Two given locations (Brindisi, 40°38' N latitude, Puglia, Italy, yearly DNI 1430 kWh/m^2yr; Gela, 37°40' N latitude, Sicily, Italy, yearly DNI 1780 kWh/m^2yr), whose Pareto distribution of cumulative daily insolation is summarized in Fig. 3, have been considered in the analyses. The thermal performances of the solar cooling systems are reported in Table 2 and Table 3.

In Brindisi, the annual production of thermal energy of 716 MWh, 725 MWh and 670 MWh has been obtained for S1, S2 and S3 respectively corresponding to cooling energy of 501 MWh, 508 MWh and 872 MWh, respectively. In Gela the annual production of thermal energy of 892 MWh, 921 MWh and 856 MWh has been obtained for S1, S2 and S3 respectively corresponding to cooling energy of 624 MWh, 605 MWh and 1112 MWh, respectively. Annual thermal cold energy production in Gela is about 20% more than in Brindisi and at the same time nominal cooling power of the absorption chiller is 20%. Indeed, in Brindisi there are several days during the year with higher daily insolation than in Gela, where on annual basis the overall insolation is largely higher than in Brindisi (Fig. 3).

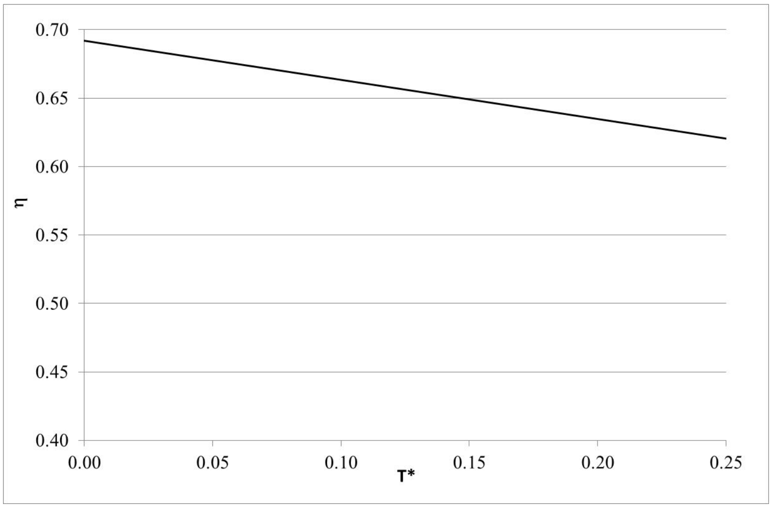

Fig. 2. Efficiency curve of the ThermeX concentrated solar linear Fresnel collector.

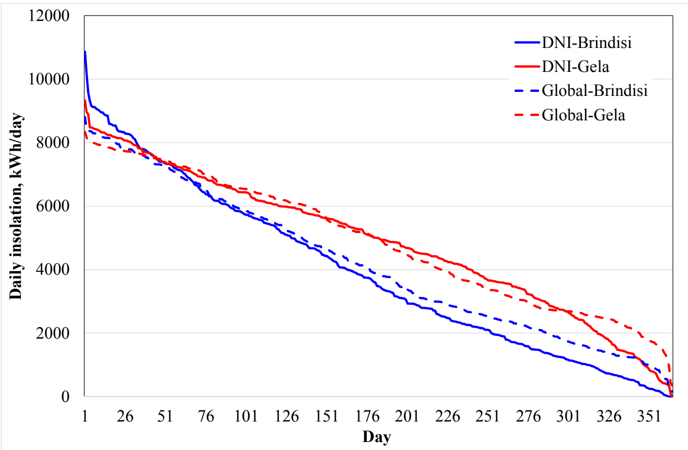

Fig. 3. Pareto distribution of the daily insolation in terms of DNI and global irradiance for Brindisi and Gela.

Table 2. Performances of the three solar cooling configurations in Brindisi.

Configuration	Nominal cooling power (kWth)	Maximum daily heat production (kWh)	Maximum daily cold production (kWh)	Annual heat production (MWth)	Thermal storage (kWh)	Annual cold production (MWh)
S1	124	4250	2975	716	435	501
S2	174	5960	4172	725	753	508
S3	308	5690	7397	670	478	872

Table 3. Performances of the three solar cooling configurations in Gela.

Configuration	Nominal cooling power (kWth)	Maximum daily heat production (kWh)	Maximum daily cold production (kWh)	Annual heat production (MWth)	Thermal storage (kWh)	Annual cold production (MWh)
S1	109	3720	2604	892	432	624
S2	143	4900	3430	921	779	605
S3	253	4680	6084	856	479	1112

In Fig. 4, monthly production of heat and cold in Brindisi and Gela has been reported showing that the productions in Gela and Brindisi are very similar during summer but in the other seasons the production in Gela is consistently higher.

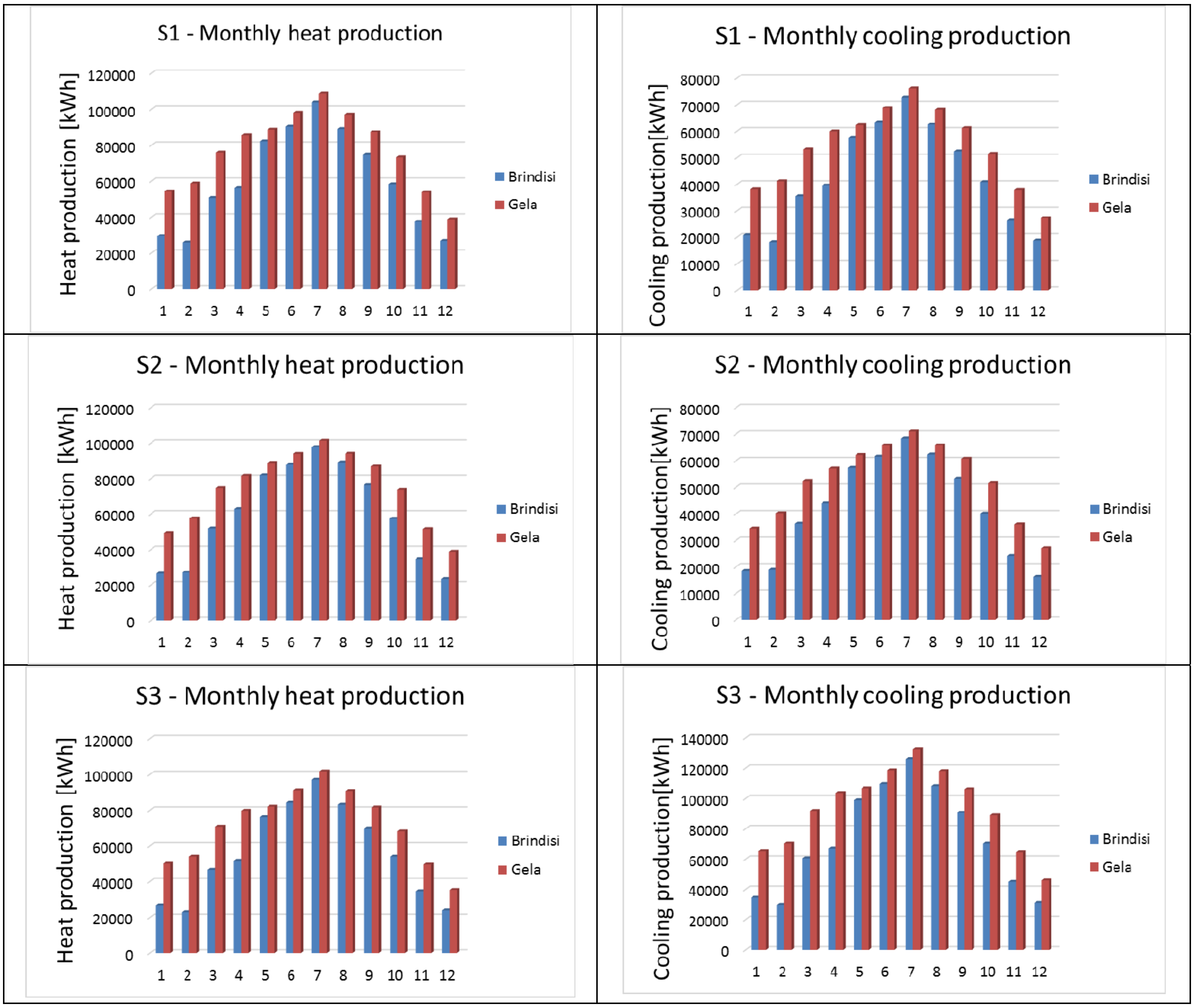

Fig. 4. Monthly production of heat and cold in Brindisi and Gela.

6. Economic assessment of the solar cooling systems

For absorption chiller technology the following specific cost has been considered: 400 €/kW and 320 €/kW of cooling power for single and double effect absorption chiller respectively (these values have been obtained as average of several quotations of the manufacturers).

In Fig. 5 and Fig. 6 the LCOC for S1, S2 and S3 considering a variable unit cost of the solar field and locations Brindisi and Gela has been reported. S3 is undoubtedly the most performing system thanks to good performance of the solar field in medium temperature and the EER of the double effect absorption chiller. In Figures 5 and 6 also the LCOC of standard electric compression chiller has been reported considering a capital cost of 100 €/kW of cooling capacity, an EER = 3 and a cost of electric energy from 0.085 to 0.115 €/kWh.

LCOC is lower in Gela than in Brindisi thanks to higher thermal energy production but also because the nominal power of the absorption chiller is 20% less than the one in Brindisi. In Gela the LCOC of CSLFC coupled with double effect absorption chiller can be competitive with the lower end electric compression LCOC if the specific cost of the solar field is lower than 200 €/m^2.

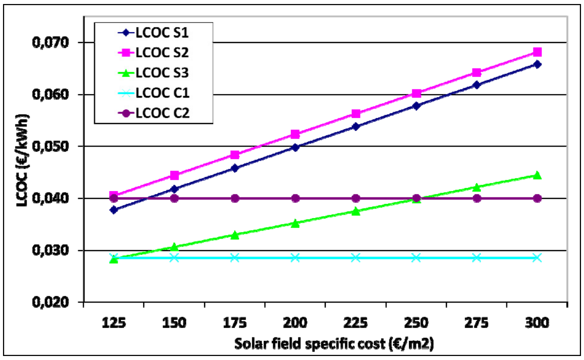

Fig. 5. LCOC (€/kWh) H24 of systems S1, S2 and S3 compared to LCOC of standard electric chiller (C1 and C2), location Brindisi.

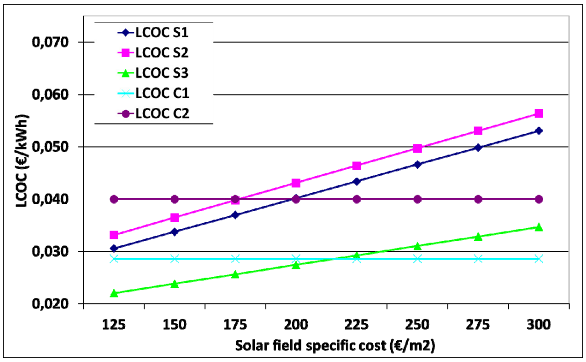

Fig. 6. LCOC (€/kWh) H24 of systems S1, S2 and S3 compared to LCOC of standard electric chiller (C1 and C2), location Gela.

At the same time, if cooling energy is used only 12 hours in a day, the cooling production is the same, the cooling power will be double and CSLFC coupled with double effect absorption chiller becomes competitive with electric chiller only if the solar field cost less than 150 €/m^2 (Fig. 7 and 8). This is due to the doubling of the capital cost for the absorption chiller.

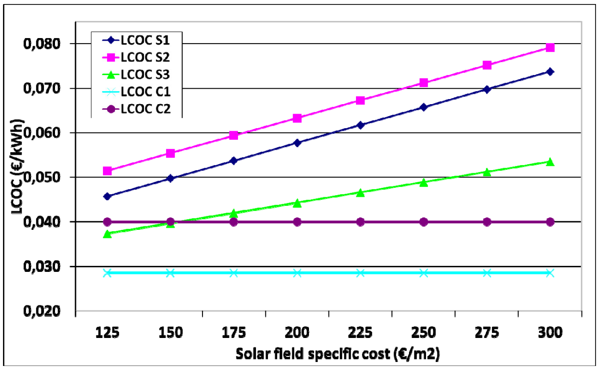

Fig. 7. LCOC (€/kWh) H12 of systems S1, S2 and S3 compared to LCOC of standard electric chiller (C1 and C2), location Brindisi.

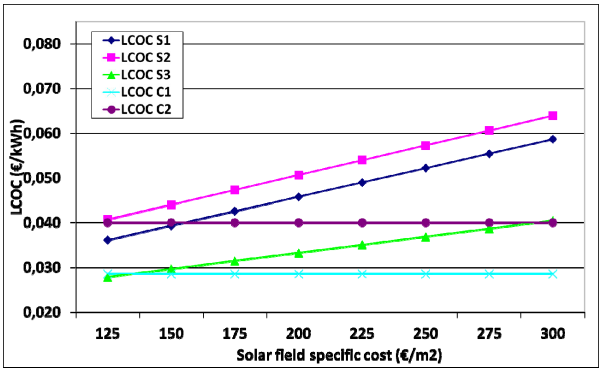

Fig. 8. LCOC (€/kWh) H12 of systems S1, S2 and S3 compared to LCOC of standard electric chiller (C1 and C2), location Gela.

7. Conclusions

In this paper three solar cooling configurations have been compared from the energy and economic point of view. Solar cooling will be a cost effective technology solution able to compare with standard electric compression cooling only for concentrated solar thermal field at medium temperature coupled with double effect absorption chiller. Deployment of the technology will be realized only if in the near, mid-term the reduction of future cost will be realized both in solar thermal concentration technology and double effect absorption chiller technology.

Local climate conditions affect the economic competitiveness of solar driven absorption cooling non only for higher thermal energy generation but also on the size of the absorption chiller.

Linear Fresnel technology has a high cost reduction potential compared to other solar thermal concentration technology. The present end-user prices for complete systems made by CLSFC are in the range 350-450 €/m^2. Projected cost reduction, thanks to incremental technological improvement and economy of scale, could lower end-user price to 150-250 €/m^2 in ten years.

In order to be cost competitive for the production of cold thermal energy incremental technological innovations have to be pursued in mirrors performances, receiver technology (materials, coatings and production technique), hybridization of collector fields with different performances parameters (i.e. different materials in different temperature field segments). Another important aspect in cost reduction is the easiness of installation.

The present analysis can be developed considering more complex and variable daily/weekly cold energy demand diagram of the end-users, where the role of the thermal/cold heat storage is fundamental for the full exploitation of the solar production.

References

[1] Kopasaki E, Nazos A, Psomopoulos C S. A Review of Solar cooling in EU. *Proceedings of the Fifth International Conference on Environmental Management, Engineering, Planning & Economics* 2015; 429:434.

[2] IRENA. *Solar Heating and Cooling for Residential Applications Technology Brief.* 2015.

[3] Otanicar T, Taylor R A, Phelan P E. Prospects for solar cooling – An economic and environmental assessment. *Solar Energy* 2012; 86:1287–1299.

[4] Mokhtar M., Tauha Ali M., Bräuniger S., Afshari A., Sgouridis S., Armstrong P., Chiesa M. Systematic comprehensive techno-economic assessment of solar cooling technologies using location-specific climate data*, Applied Energy* 2010; 87: 3766-3778.

[5] Ferreira C.I., Kim D.-S. Review - Techno-economic review of solar cooling technologies based on location-specific data, *International Journal of Refrigeration* 2014; 39: 23:37.

[6] Gabbrielli R, Castrataro P, Del Medico F, Di Palo M, Lenzo B. Levelized cost of heat for linear Fresnel concentrated solar systems*. Energy Procedia* 2014; 49:1340 – 1349.