Analysis of Total-Energy Solutions for a Shopping Centre
Part 2: Solar Assisted Cooling Solutions

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Introduction

In the last years primary energy demand for cooling has been growing quickly all over the world. A large amount of this requirement is in form of electric energy, which is used by compression cooling systems. Although COP of these systems is going to very high values, electric energy is a valuable form of energy and its cost will probably rise in the next years.

Solar Cooling technologies use solar energy provided by solar collectors to thermally drive cooling machines. In this way we can significantly contribute to a rising share of renewable heat sources in the building sector and a sustainable energy development in Europe: the solar energy (combination of thermal and cooling) has a high potential to replace conventional cooling machines electricity based [1] [2] .

At the present time, packaged systems of Solar Cooling are not available commercially. Despite that, on the market are available separately thermal solar systems and absorption chillers, that may be coupled to realize Solar Cooling but its economical feasibility should be investigated for each case.

In this paper a technical-economical analysis of a Solar System for a medium shopping centre is presented. In the first part different technologies are matched to evaluate the best solution in terms of coupling solar panel and chiller. Then a sensibility analysis on the components of costs is showed by applying the system to a shopping centre.

Nomenclature

a_1	Linear thermal loss coefficients
a_2	Quadratic thermal loss coefficients
$A_{installation}$	Plant amortization quota (20 year useful life and 8% interest rate)
C_{col}	Single collector cost
$C_{installation}$	Total installation cost
C_{kW}	Installation cost per kW
C_{kWh}	Cost of cold kWh produced
COP	Coefficient of performance
E_{year}	Annual cooling energy

I	Incident solar radiation (total for plane collectors, direct for concentrating collectors)	SC_{col}	Specific cost of collector
		S_o	Single collector optical surface
		T_a	Ambient temperature
PBT	Payback period	T_m	Average temperature between outlet and inlet flow of collector
P_{peak}	Peak cold power of solar system		
P_{target}	Target price	η_0	Optical efficiency

Technology overview

In a Solar Cooling System, medium temperature collectors should be used to provide hot water in the 80 - 150°C temperature range depending on the chosen absorption chiller technology. Different collectors available on the market are able to reach these temperatures:

- Classical glazed flat-plane collectors (FPC), the most common type characterized by simplicity and low cost, but with low performances at medium temperatures;
- Vacuum double-glazed flat-plane collectors (VDG), constructively similar to the classical type and it is characterized with lower heat losses for convection;
- Evacuated tube solar collectors (EVS), collector with good performances at higher temperatures but with higher production cost.
- Parabolic Trough Collector (PTC), the system, equipped with solar tracking, collects direct radiation and could reach higher temperature than flat panels. It is not yet commercially available, but different prototypes are ready for a commercialization: costs of prototypes are expected to greatly decrease, [3] .

Parameters and models of solar collectors used in the analysis are reported in Table 2.

The solar field drives a water-lithium bromide absorption chiller. Lithium bromide cycle is indeed a well widespread technology due to the low temperature level needed as driving source (LT collectors). The performance of this plant in Solar Cooling applications has been already studied and demonstrated in many European pilot and demonstration projects .

Two typologies of H_2O-LiBr chillers are used depending on the coupled solar panel, [4] :

§ Single-effect with inlet water temperature: 98 °C and COP: 0,75;

§ Double-effect with inlet water temperature: 170°C and COP: 1,39.

Therefore, all typologies of flat plane collectors are coupled to single-effect chillers, while concentrating collector is coupled to a double-effect chiller.

The different systems are compared in the period from May to October with a constant solar field area of 2500 m^2, adequate for the considered shopping centre.

In the analysis while chillers work at nominal condition, efficiency of collectors at operating condition is evaluated with equation $h = h_0 - a_1(T_m - T_a)/I - a_2(T_m - T_a)^2/I$ [5] .

For flat panel analysis, the incident total radiation on a horizontal surface hour by hour in the area of Florence [6] is used: direction North-South and 25° inclination maximize total radiation incident in the period from May to October. While for PTC, direct incident solar radiation with tracking system is derived from total radiation developed by the "S. Stecco" Energy Department (SoCool) [6] .

In Table 2 results of this analysis are reported. Cost of kW_c is then calculated as ratio of total costs of installation and peak power of solar system: $C_{kW_c} = C_{installation}/P_{peak}$; total costs of installation are the sum of installation, solar field, chiller and auxiliaries costs.

Cost of produced cooling energy is calculated as the ratio of plant amortization quota and the cooling energy produced in the working period. $C_{kWh_c} = A_{installation}/E_{year}$.

These values, so calculated, are compared with kWh_c cost produced by a standard compression refrigeration system (CRP) that takes into account plant and electricity cost. Details of the calculation are reported in Table 1: Italian electricity price, for the working hours of the Solar Cooling system are used.

Capital cost for CRP	€	150,000	Electricity cost	€/kWh	0.147
Annual rate (20 years life, 8% interest rate)	€	15,277.00	Compression system COP		2.6
Annual cooling production	kWh_c	1.758.054	**Energy cost**	**$€/kWh_{c\ el}$**	**0,0652**

Table 1 Energy from CRP, reference cost

Cost and performance are estimated referring to standard installation of equipments with the size equivalent of the studied solar systems. Total annual cooling production is considered equal to that produced by the PTC system.

Target price is calculated, as price of the panel for which cost of kWh_c produced by solar system equals that produced by compression system, Table 2.

PTC system, even considering prototype cost, is clearly the best alternative in terms of cost for both kWh_c and kW_c.

Type	Collector	η_0	a_1	a_2	S_n	C_{col}	C_{kW}	C_{kWh}	Ratio of cost	CS_{col}	P_{target}	$\frac{CS_{col}}{P_{target}}$
			$W/(m^2K)$	$W/(m^2K^2)$	m^2	$€/m^2$	$€/kW_c$	$€/kWh_c$	$\frac{€/kWh_c}{€/kWh_{el}}$	$€/m^2$	$€/m^2$	
FPC	Thermital SOL 25	0.806	3.680	0.0072	2.57	891	1510	0.186	2.9	405	109	**3.7**
	Viesmann VITOSOL 100	0.810	3.480	0.0164	2.30	837	1399	0.177	2.7	364	102	**3.6**
	Buderus SKN 3.0	0.750	3.600	0.0150	2.23	790	1524	0.202	3.1	354	84	**4.2**
	Buderus SKS 4.0	0.820	3.700	0.0100	2.10	1180	2013	0.250	3.8	562	109	**5.2**
VDC	Thermital SOL	0.641	1.059	0.0045	2.59	1410	2161	0.226	3.5	597	137	**4.4**
	Buderus VACIOSOL CPC	0.665	0.721	0.0060	2.56	1949	2513	0.241	3.7	761	163	**4.7**
EVS	Viesmann VITOSOL 300	0.825	1.190	0.0090	3.07	3620	3231	0.340	5.2	1179	176	**6.7**
PTC	**Solitem PTC 1000**	0.750	0.112	0.00128	-	400	**1072**	**0.078**	**1.2**	**400**	194	**2.1**

Table 2 Characteristics and results of analyzed solar cooling system

This result is due mainly to the possibility of PTC to produce higher temperature water, so double-effect absorption chiller with higher COP can be used.

This result is significant considering that: costs of PTC prototype are expected to greatly decrease, costs of chiller and auxiliaries could decrease as well in case of packaged production, while electricity cost is expected to rise and electricity cost is very high for shopping centre as shown in [8] .

Shopping centre

An analysis on a shopping centre is presented in order to consider the matching between a solar cooling plant and a real user during a year. Therefore a back-up burner and a storage system were considered into the model, in order to cover the requested load during periods of insufficient insulation.

The project is related to a shopping centre in Florence area whose cooling demand is shown in Figure 1 and Figure 2. Frequency distribution of daily cooling demand and monthly averaged value are useful to dimension the solar field. The maximum load is about 2.34MW in June while average monthly value reaches 1.3MW and the total yearly load is 1.57 GWh_c, more details of plant and its load are reported in [8] . Due to the high specific cost of solar field, the choice of its size on maximum requested load is not convenient, it would be used only few days a year (Figure 1). Smaller sizes require a back-up burner. Minimizing surplus energy produced by solar field and gas consumption for back-up burner, the size of solar field is 2274 m^2.

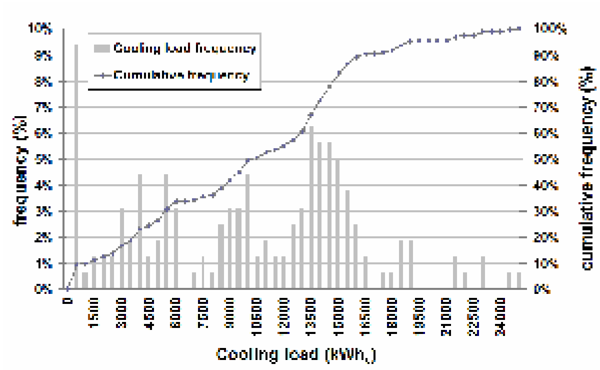

Figure 1 Daily load frequency distribution

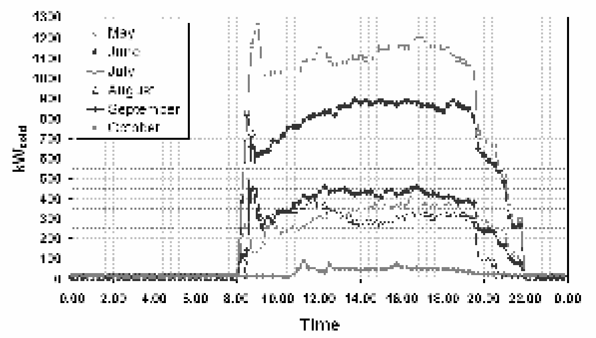

Figure 2 Averaged monthly value

The cold energy cost from Solar Cooling considers capital cost, plant and auxiliaries, and gas cost. Reference energy cost from CRP is calculated, as previously shown, for a size adequate to the requested load. Details are reported in Table 3. In this solution cost of energy produced by solar cooling system is higher than that produced by compression system (1.48 times) and PBT is about 17 years.

Energy-Economic Analisys - PTC 1000 + Double effect Chiller		
Solar field net surface	m^2	2.274
Colletctor cost	€/m^2	400
Chiller Cost	€	405.000
Auxiliary Burner cost	€	81.000
Auxiliary device cost	€	272.880
Annual rate	€/year	-169.938
Produced cold energy		
May	kWh_c	270.846
June	kWh_c	306.390
July	kWh_c	421.131
August	kWh_c	350.101
September	kWh_c	242.263
October	kWh_c	30.556
lack	kWh_c	286.409
surplus	kWh_c	336.496

Requested cold energy		
Requested cold energy	kWh_c/y	1.571.200
Gas cost	€/Nm^3	0,32
Gas for back-up burner	€/y	6.782
Energy cost from solar cooling plant	**€/$kWhe_c$**	**0,112**
PBT	year	16,7
Reference energy cost		
Electric energy cost	€/kWh_e	0,147
CRP COP		2,6
Cold production by electricity	€/kWh_c	0,057
CRP cost	€	300.000
CRP Annual rate	€/y	30.556
Electric energy for CRP	€/y	88.833
Energy cost from CRP	**€/kWh_c**	**0,076**
Cost ratio (€/kWhc $_{SC}$)/(€/kWhf $_{CRP}$)		1,48

Table 3 Energy and economic analysis with PTC and double effect chiller. Solar field size 2274 m^2.

It is important to point out that the size of solar field strongly affects economical performance of the system and the costs of PTC prototype, still under development, are expected to greatly decrease for large marketing and the electricity cost is expected to rise.

Figure 3 shows the influence on these parameters on cold energy cost. With existing solar field (400/€/m^2) and electricity cost, the size should be smaller that 900m^2 to have an economic benefit. With an expected cost of 200 €/m^2, a probable increasing of 10%

of electricity cost makes convenient size move from 1700m^2 to 2300m^2: in this case the system has a PBT between 5 and 10 years approximately for solar field size between 1000 and 2000 m^2.

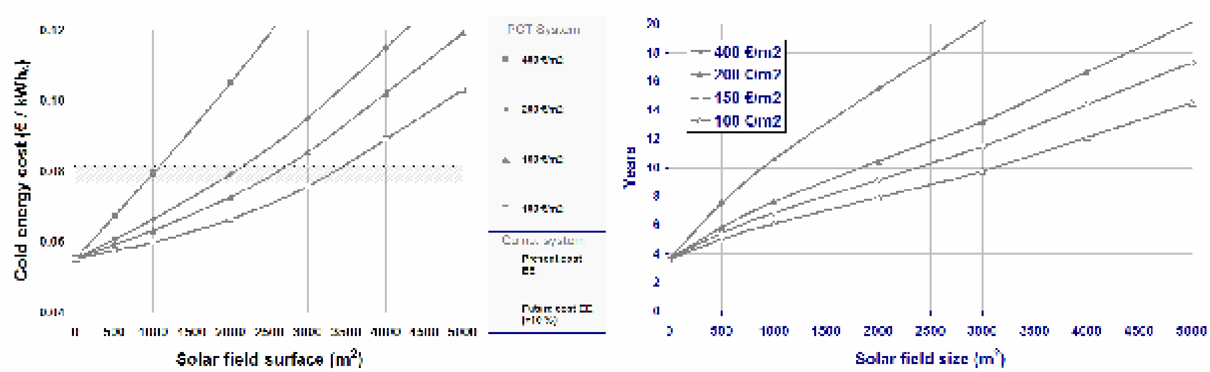

Figure 3: Cooling energy cost and PBT of PTC and CRP systems, without selling heat.

To complete the study, a further analysis was achieved, taking into account the possibility to sell the heat from solar collector during winter to a local district-heating network at a price of 0,056 €/kWh$_t$. Results of analysis are graphed on Figure 4.

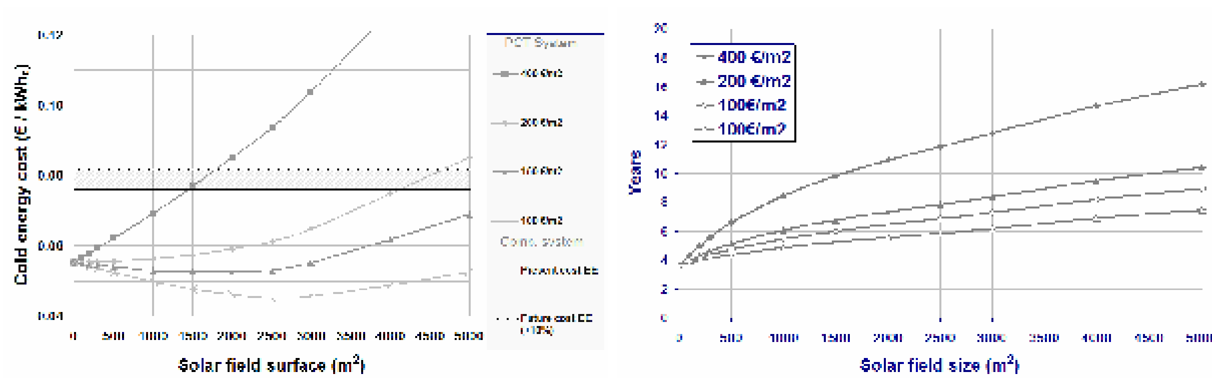

Figure 4: Cooling energy cost and PBT of PTC and CRP systems with heat benefits

It is possible to see that in this case the situation is greatly improved: for a solar collector price lower than 200 €/m^2, curve of specific cost presents a minimum in correspondence of 1500-2000 m^2 of solar field area, and PBT is significantly reduced. In addition, it can be noted that cost of energy, kWh$_c$ is significantly reduced and even for very large solar field area it remains lower than the cost of kWh$_c$ with traditional technology.

Conclusions

- The most convenient solar technology available at the present for Solar Cooling is parabolic trough collector (PTC) technology;

- In prevision of rise of electricity cost and reduction of solar field cost, solar assisted cooling systems using PTC technology can be economically competitive with compression systems;
- A deep analysis of cooling loads should be achieved in any specific case to have the best convenience;
- Where possible, selling heat during winter season greatly improves feasibility of the investment.

Acknowledgement

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References

[1] Solar Assisted Air Conditioning of Buildings – Task 25 of the Solar Heating & Cooling Programme (SHC) of the IEA. www.iea-shc-task25.org

[2] Bruno J.B., López J., Ortiga J., Coronas A., 2006, *" Tecnho-Economic design study of a large-scale solar cooling plant integrated in a district heating and cooling network" ",* SHC "Solar Heating and Cooling" -International Session, Perugia, 2006.

[3] Rommel, M., Siems T:, Kramer K., Schafer A., Haberle A., Berger M., 2006, *"Solar collectors for heating and cooling with operating temperature up to 250°C", ",* SHC "Solar Heating and Cooling" -International Session, Perugia, 2006.

[4] Henning H.-M., Häberle A., Guerra M., Motta M., 2006*, "Solar cooling and refrigeration with high temperature lifts thermodynamic background and technical solution",* SHC "Solar Heating and Cooling" -International Session, Perugia, 2006.

[5] Werner Weiss, Matthias Rommel*, Medium temperature collectors, IEA SHC Task 33, 2005*

[6] European Joint Research Center*, http://www.jrc.cec.eu.int/*

[7] Prussi M., 2007, *"Development of a model for the simulation and optimization of solar cooling plant",* Master Degree Thesis, University of Florence,

[8] DeLucia M., Mengoni C.P.,2007*, "Analysis of total-energy solutions for a shopping centre part 1 :trigeneration solution*", 2nd International Conference, Solar Air-Conditioning, Tarragona Spain, 18-19 October 2007