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Baseline evaluation of potential to use solar radiation in air conditioning applications

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Abstract

The study presents a global evaluation of the potential to use solar radiation in the air conditioning with application to an office building located in Cluj-Napoca, Romania. The study was realized for a one year period, based on multiannual average values for solar radiation and ambient temperature. It were compared the performances of two types of solar cooling systems, one based on absorption chiller and one of photovoltaic type. It is presented the methodology for calculation of the efficiency of the solar thermal field and of the equivalent photovoltaic field, placed on the terrace roof of the building, considered completely filled with evacuated tubes solar collectors tilted at 45° and facing south was taken into account or with photovoltaic field of collectors oriented in the same position. The solar collectors were arranged to completely avoid each other shading, for any solar altitude angles higher than 30°. The one year variation of several calculated parameters is presented together with the corresponding variation in the period of (10-20) June. The one year thermal solar cooling fraction was found to be of 24.5% and the one year photovoltaic cooling fraction was found to be of 36.6%.

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Keywords: Solar radiation; air conditioning; absorption cooling; solar collectors; solar cooling fraction

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1. Introduction

The Sun is representing the only source of energy, capable to sustain life on Earth having a huge potential of conversion in several forms of useful energy [1]. One of the most challenging ways of using the solar energy is for cooling and air conditioning, the last one being treated in this study.

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Several reviews are presenting in detail technical, technological, economical and scientific aspects concerning the solar cooling [2-7]. Between the technical solutions of solar refrigeration, can be distinguished the following categories: photovoltaic refrigeration is converting the solar energy into electricity used to drive classic electric chillers while the thermoelectric refrigeration is using the solar energy for heating the hot welding of a circuit for providing electricity used for extracting heat from the cold welding [4, 8]. Solar energy can be used as heat source for equipment operating under different thermodynamic cycles that transform the heat into mechanical and then into electrical energy used again to drive classic refrigerating equipment. These cycles can be: Organic Rankine Cycle (ORC) or Stirling [4, 9]. Solar thermal energy can be also used directly as heat source in different equipment capable to directly produce cooling: absorption refrigeration[2-6, 9] or adsorption refrigeration [2-5, 9].

Economic aspects and comparison between the different solar refrigeration technologies are presented in several studies [4, 7, 8, 10].

Air conditioning is one of the most important applications of solar cooling because on one side the request of air conditioning is increasing worldwide and because the cooling is simultaneous needed when the solar energy is available. Solar cooling in air conditioning is reported in many studies [8, 9, 11-13].

In this context, the study and the evaluation of potential to use solar radiation in air conditioning applications is of high importance and interest worldwide and also in Romania, particularly in Cluj-Napoca.

This evaluation is continuing the previous studies in the field of solar energy and its applications, at the Technical University of Cluj-Napoca [14-17].

The goal of the study is on one side to present and apply a methodology for evaluation the potential of solar energy by presenting the local variation of solar radiation and of outside temperature and on the other side to present the potential of using the solar radiation in the air conditioning of an office building.

2. Material and method

This study is focused on two mature and concurrent technologies, capable to provide enough cooling power for air conditioning in buildings: absorption solar cooling and photovoltaic cooling.

Both technologies are considered for the air conditioning of a virtual office building with ground floor and first floor, located in Cluj-Napoca, Romania at 46.8° N latitude and 23.571° E longitude, with the dimensions of (80 x 18.75 x 8) m. The roof terrace of the building was considered covered with solar thermal collectors in the case of the absorption solar cooling and with equivalent photovoltaic collectors in the case of photovoltaic cooling. The image of the building with solar thermal collectors is presented in figure 1.

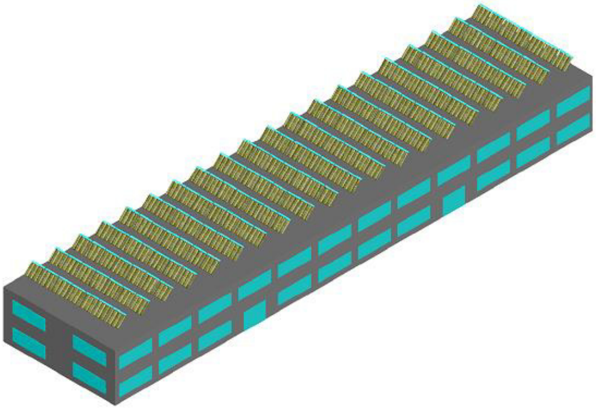

Fig. 1. The image of the building with solar thermal collectors

The thermal collectors were considered to be with evacuated tubes, of type Vitosol 300T, manufactured by Viessmann, DE.

The energy scheme of the absorption solar cooling system is presented in figure 2.

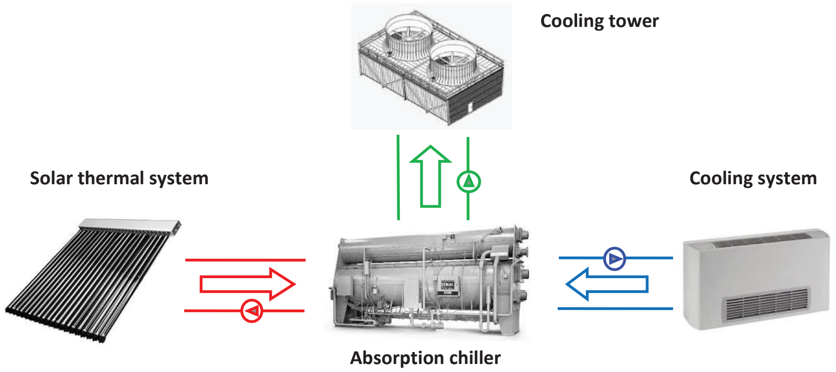

Fig. 2. Energy scheme of an absorption solar cooling system

The energy scheme of the photovoltaic cooling system is presented in figure 3.

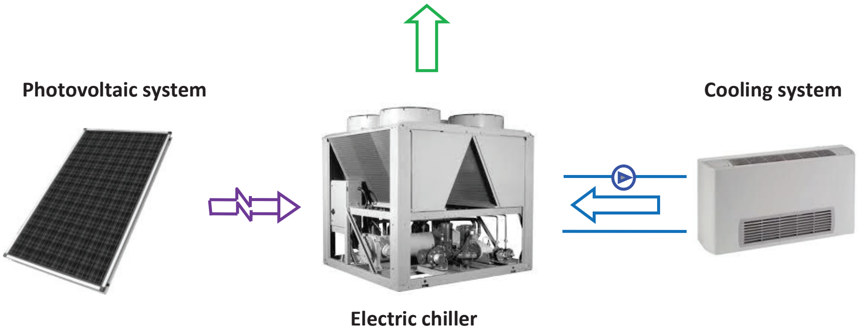

Fig. 3. Energy scheme of a photovoltaic cooling system

The photovoltaic collectors were considered by polycrystalline silicon, of STP075S-12/Bc type, manufactured by Suntech, UK.

As input data of the study, were considered multiannual average climatic data corresponding to Cluj-Napoca, Romania, for the global solar radiation on horizontal plane and for the ambient temperature. Both are presented in figure 4 for one year and in figure 5 for the period 10-20 June.

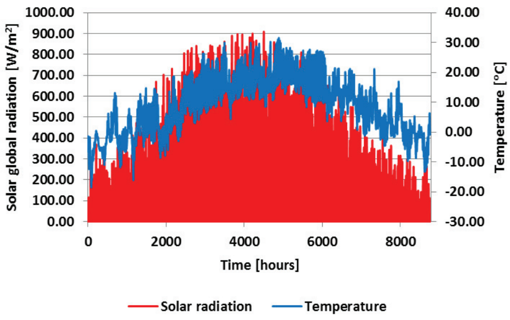

Fig. 4. Multiannual average variation of solar global radiation on horizontal plane and ambient temperature,

for Cluj-Napoca, RO (one year)

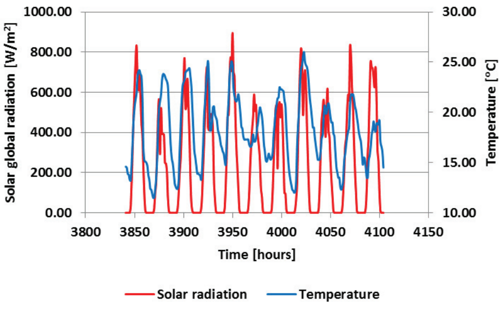

Fig. 5. Multiannual average variation of solar global radiation on horizontal plane and ambient temperature,

for Cluj-Napoca, RO (10-20 June)

Both solar radiation and ambient temperature are available as hourly variation, for the whole 8760 hours in one year.

The thermal efficiency of the thermal solar collectors (η [%]) was calculated as [9, 18, 19]:

$$\eta = \eta_0 - k_1 \frac{\Delta t}{I_{gt}} - k_2 \frac{\Delta t^2}{I_{gt}} \tag{1}$$

where:

η_0 = 0.804 – Optical efficiency of the considered thermal solar collectors
k_1 = 1.33 W/m^{2}K – Correction factor of the considered thermal solar collectors
k_2 = 0.0067 W/m^{2}K^2 – Correction factor of the considered thermal solar collectors
Δt [°C] – Temperature difference between the average temperature of the solar thermal agent (considered of 85°C) and the ambient temperature
I_{gt} [W/m^2] – Global solar radiation, normal at the collector surface

The thermal regime of the solar thermal agent was considered with 80°C at the inlet and with 90°C at the outlet of the thermal solar field, with an average of 85°C.

The global solar radiation, normal at the collectors surface, was calculated based on a consecrated algorithm, that calculates the following data [15, 19]: Day angle; Declination of the Sun; Equation of time; Mean local time; Solar time; Hour angle of the Sun; The angle of the solar altitude; The angle of the solar azimuth; Solar angle of incidence on a tilted surface; Global solar radiation on a tilted surface; Direct normal radiation on a tilted surface; Diffuse normal radiation an a tilted surface; Reflected normal radiation on a tilted surface.

This algorithm provides errors at low values of solar altitudes, so it was applied only for solar altitudes higher than 15°. For lower angles, the thermal efficiency of the thermal solar collectors (η) was considered 0%.

The thermal power of the solar field ($\dot{Q}_S$ [kW]) was calculated as:

$$\dot{Q}_S = \frac{I_{gt} \cdot S \cdot \eta}{1000} \tag{2}$$

where S = 452.2 m^2 – The total aperture surface of the collector.

The cooling power of the absorption solar cooling system ($\dot{Q}_{0a}$ [kW]) was calculated as:

$$\dot{Q}_{0a} = Q_S \cdot COP_a \tag{3}$$

where COP_a = 0.7 [4, 20] is the considered coefficient of performance (COP) of the absorption chiller.

The yearly cooling energy provided by the solar absorption cooling system (Q_{0ay} [kWh) was calculated as the sum of the hourly cooling power for the whole number of hours in a year.

The electrical efficiency of the photovoltaic collectors (η_{PV} [%]), function of the outside temperature and of the nominal parameters of the collectors, was calculated as [21]:

$$\eta_{PV} = \eta_{Tref} \left\{ 1 - \beta_{ref} \left[T_a - T_{ref} + (T_{NOCT} - T_a) \frac{I_{gt}}{I_{gNOCT}} \right] \right\} \tag{4}$$

where:

η_{Tref} = 0.11 (0.104 … 0.124) [21, 22] – Electrical efficiency at the reference temperature
$\beta_{ref} = 1/(T_0 - T_{ref})$ = 0.04 (0.032 … 0.0046) [21, 22] – Temperature coefficient

T_0 [°C] – The high temperature at which the PV module's electrical efficiency drops to zero
T_{ref} = 28 °C [21, 22] – The reference temperature
T_a [°C] – The ambient temperature
T_{NOCT} = 20 °C [21] – The normal operating cell temperature
I_{gNOCT} = 800 W/m^2 [21] – The nominal global solar radiation

Similar with the case of solar thermal collectors, the electrical efficiency of the photovoltaic collectors (η_{PV}) was considered 0% for angles of solar altitudes lower than 15°.

The conversion efficiency (η_c [%]) from the direct current (**DC**) provided by the photovoltaic collectors to the alternative current (**AC**) consumed by the electric chiller, was considered at 86% [7] or between (80…95)% [23], function of the global radiation (I_g [W/m2]) as follows:

for I_g < 300 W/m^2 => η_c = 80%;
for I_g = (300…500) W/m^2 => η_c = 85%;
for I_g = (500…800) W/m^2 => η_c = 90%;
for I_g > 800 W/m2 => η_c = 95%.

The global efficiency of the photovoltaic system (η_{gPV} [%]) was calculated as:

$$\eta_{gPV} = \eta_{PV} \cdot \eta_c \tag{5}$$

The electric power provided by the photovoltaic field (P_e [kW]) was calculated as:

$$P_e = \frac{I_{gt} \cdot \eta_{gPV} \cdot S}{1000} \tag{6}$$

where S = 452.2 m^2 is the total surface of the photovoltaic collectors, considered equal with the total aperture of the solar thermal collectors, considered in the case of the absorption solar cooling.

The COP of the electric chiller (COP_e) is depending by its operating conditions, representing by the temperature of the cooled water and the temperature of the cooling (ambient) air. The thermal regime of the chilled water was considered constant of (5…12)°C and the evaporating temperature of the refrigerant in the chiller (t_0 [°C]) was considered equally constant of 3°C, corresponding to the thermal regime of the chilled water. The condensing temperature of the refrigerant in the chiller (t_k [°C]), was calculated as:

$$t_k = t_a + 15 \tag{7}$$

The refrigerant was considered to be R410A which is very common in the electric chillers and the thermal calculation of the refrigerating cycle was realised with the very popular free software Coolpack [24]. The values calculated for different ambient temperatures, were interpolated and it was obtained the following original equation of interpolation, for calculating the COP_e [%] function of ambient temperature t_a [°C]:

$$COP_e = 0.0035 \cdot t_a^2 - 0.3372 \cdot t_a + 10.287 \tag{8}$$

The equation is valid for ambient temperature between (0…45)°C, for electric chillers with R410A, providing air conditioning.

The cooling power of the photovoltaic cooling system ($\dot{Q}_{0PV}$ [kW]) was calculated as:

$$\dot{Q}_{0PV} = P_e \cdot COP_e \tag{9}$$

The yearly cooling energy provided by the solar absorption cooling system (Q_{0PVy} [kWh) was calculated as the sum of the instant cooling power for the whole number of hours in a year.

The hourly cooling load of the building ($\dot{Q}_{0b}$ [kW]) was calculated based on national regulation, similar with the European regulations. It was also calculated the yearly cooling load of the building (Q_{0by} [kWh]) as sum of the instant cooling load for the whole number of hours from the year.

The hourly solar cooling fraction in the case of absorption solar cooling (f_a [%]), the hourly solar cooling fraction in the case of photovoltaic cooling (f_{PV} [%]), the yearly solar cooling fraction in the case of absorption solar cooling (f_{ag} [%]) and the yearly solar cooling fraction in the case of photovoltaic cooling (f_{PVg} [%]), were calculated as:

$$f_a = \frac{\dot{Q}_{0a}}{\dot{Q}_{0b}}\ ;\ f_{PV} = \frac{\dot{Q}_{0PV}}{\dot{Q}_{0b}}\ ;\ f_{ag} = \frac{Q_{0a}}{Q_{0b}}\ ;\ f_{PVg} = \frac{Q_{0PV}}{Q_{0b}} \tag{10}$$

By calculating the whole algorithm, the potential of using the solar radiation in the air conditioning, was completely evaluated and the results obtained for the two technologies could be compared.

3. Results and discussions

Both mathematical models, for the solar absorption cooling and for the photovoltaic cooling, presented above, were implemented in Excel for the whole 8760 numbers of hours in the year.

The variation of the angle between the solar beam and the normal direction of the plane of the collectors, during the year, is presented in figure 6, for the day of 15, in the period of (March - September).

It can be observed that in March (03) and September (09), in April (04) and August (08) and also in May (05) and July (07), the angle between the Sun and the collectors is similar, because the path of the Sun on the sky is also similar in the mentioned pairs of months. These results are in perfect agreement with [14].

The angle between the Sun and the collectors is of outcome importance because is affecting the global radiation on the plan of the collectors.

The variation of global solar radiation on horizontal plane and on the tilted plan of the collectors, for the period of 10-20 March, is presented in figure 7.

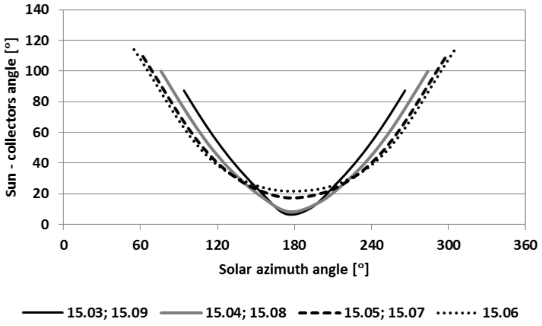

Fig. 6. The variation of the angle between the solar beam and the normal direction of the collectors' plane

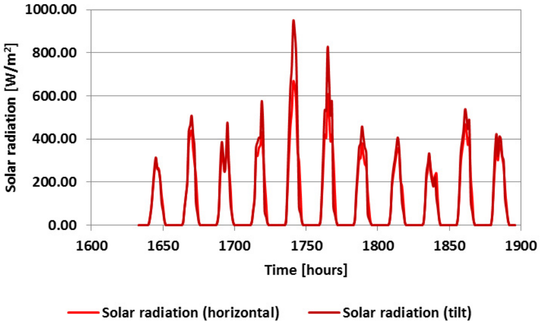

Fig. 7. The variation of global solar radiation on horizontal plane and on the tilted plan of the collectors (10-20.03)

It can be observed that on the tilted plan, the global solar radiation presents higher values than in the horizontal plane. This effect is higher in spring and autumn, when the solar angles of altitude are lower.

The variation of the thermal efficiency of the thermal solar collectors and of the electric efficiency of the global photovoltaic system, for the period of 10-20 June is presented in figure 8.

The variation of the cooling power of the absorption solar system and of the photovoltaic cooling system, comparing with the cooling load of the building, for the period of 10-20 June is presented in figure 9.

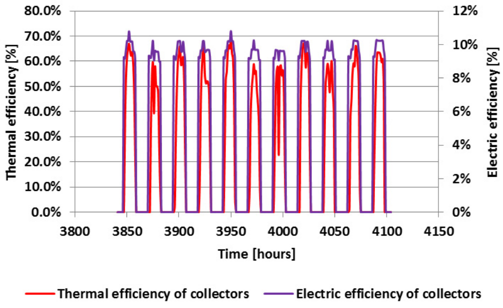

Fig. 8. The variation of the thermal and global electric efficiencies of the solar systems (10-20.06)

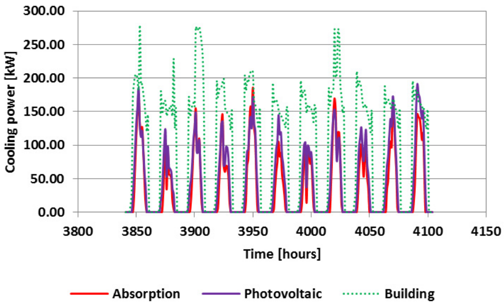

Fig. 9. The variation of the cooling power of the cooling systems, and of the building (10-20.06)

Under the influence of both solar radiation and ambient temperature, the two solar cooling systems are providing comparable cooling powers, with some advantage for the photovoltaic system. Generally both solar cooling systems provide only a part of the required cooling load of the building, but for short periods both systems can provide more than required. In these periods the photovoltaic system is more versatile because the excess of electricity can be easily used by the building, but the absorption system need storage capacities of cooled water.

The solar cooling fraction of the absorption cooling system and of the photovoltaic cooling system, for the period 10-20.06 are presented in figure 10.

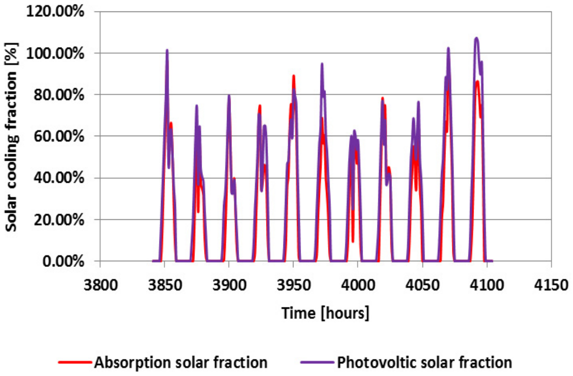

Fig. 10. The variation of the solar cooling fraction of the two cooling systems (10-20.06)

It can be observed that the photovoltaic cooling system can provide in some periods, higher solar cooling fractions than the absorption cooling system. In the first day of the presented interval, both systems have excess of cooling power, but in the rest of the interval only the photovoltaic system is situated in this position. The maximum hourly solar cooling fraction was found to be of 122% and the maximum hourly photovoltaic cooling fraction was found to be of 174%.

The yearly solar cooling fraction of the absorption cooling system was determined at 24.5% and the global solar cooling fraction of the photovoltaic cooling system was determined at 36.6%.

From the technical performances point of view, the photovoltaic cooling system is superior, but from the initial investment point of view the absorption cooling system is in advantage. Similar information is presented in [4], where the following investments costs are presented: Photovoltaic collector: 1700 Euro/kW$_{cool}$; Electric chiller: 200 Euro/kW$_{cool}$; (Total: 1900 Euro/kW$_{cool}$) and Thermal collectors: 700 Euro/kW$_{cool}$; Absorption chiller: 500 Euro/kW$_{cool}$; (Total: 1200 Euro/kW$_{cool}$).

A comparison between the efficiency of the maximum value of the solar thermal collectors calculated in this study and reported in the literature is presented in table 1.

Table 1. Reported thermal efficiency of solar thermal collectors

Reference	Year	Efficiency	Location
[6]	2002	(60-70)%	N.A.
[12]	2005	68%	Madrid, ES
[10]	2010	(35-50)%	Mediterranean area
[25]	2010	(50-60)%	Taiwan, TW
[26]	2013	(45-60)%	Shanghai, CN
[7]	2014	(47-70)%	Europe
[27]	2014	(58-75)%	N.A.
This	*2015*	*69%*	*Cluj-Napoca, RO*

A comparison between the efficiency of the maximum value of the photovoltaic systems, calculated in this study and reported in the literature is presented in table 2.

Table 2. Reported thermal efficiency of solar thermal collectors

Reference	Year	Hourly (instant) (max.)	Yearly (global)	Location
[4]	2008	15%	10.3%	Overall
[28]	2011	13%*		Europe
[29]	2012		10%	General
[30]	2014	(13-17)%		Mediterranean
[17]	2014	12.7%		Cluj-Napoca, RO
[7]	2014	13%	(11%)*	Netherlands, NL
This	*2015*	*13%*	*11%*	*Cluj-Napoca, RO*

* Calculated based on other data presented in the reference

A comparison between reported solar cooling fractions of the solar cooling systems is presented in table 3.

Table 3. Reported thermal efficiency of solar thermal collectors

Reference	Year	Hourly (instant) (max.)	Yearly (global)	Location
[12]	2005		11%	Madrid, ES
[10]	2010	75%		Mediterranean area
[25]	2010	90%	52%	Taiwan, TW
[11]	2010	90%		Almeria, ES
[8]	2014		(29-37)%	Europe
[7]	2014		(23-25)%	Netherlands, NL
[31]	2014	100%		Doha, QA
This	*2015*	*100%*	*22%*	*Cluj-Napoca, RO*

It can be observed that reported data are in agreement with the values determined in this study.

4. Conclusions

The study proved that in Romania, particularly in Cluj-Napoca, the solar radiation presents enough potential for providing air conditioning in a large office building.

Two different solar cooling technologies were evaluated and both seem to be capable to satisfy the required need of cooling.

The influence of solar radiation and of ambient temperature was considered for both solar thermal collectors and photovoltaic collectors.

All the major results were compared with similar data available in the literature and proved to be in agreement with the reported range of values.

The solar absorption cooling system can provide a yearly solar cooling fraction of 24.5% at lower initial investment, while the photovoltaic cooling system can provide a higher yearly solar cooling fraction of 36.6% but with higher initial investment.

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