Solar cooling - comparative study between thermal and electrical use in industrial buildings

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Abstract. The increase in the share of renewable energy sources together with the emphasis on the need for energy security bring to a spotlight the field of trigeneration autonomous micro-systems, as a solution to cover the energy consumptions, not only for isolated industrial buildings, but also for industrial buildings located in urban areas. The use of solar energy for cooling has been taken into account to offer a cooling comfort in the building. Cooling and air-conditioned production are current applications promoting the use of solar energy technologies. Solar cooling systems can be classified, depending on the used energy, in electrical systems using mechanical compression chillers and systems using thermal compression by absorption or adsorption. This comparative study presents the main strengths and weaknesses of solar cooling obtained: i) through the transformation of heat resulted from thermal solar panels combined with adsorption chillers, and ii) through the multiple conversion of electricity – photovoltaic panels – battery – inverter – combined with mechanical compression chillers. Both solutions are analyzed from the standpoints of energy efficiency, dynamic performances (demand response), and costs sizes. At the end of the paper, experimental results obtained in the climatic condition of Galați city, Romania, are presented.

1. Introduction
The Directive concerning the promotion of using energy from renewable sources [1] states the global national goals in this field together with the target of producing, in 2020, at least 20% from the final gross consumption of energy from renewable sources. According to the National Renewable Energy Action Plans of the European Member States, the most significant share (46%) in renewable energies consumption at the level of 2020 will be retrieved in heating & cooling, with an average increase rate of 22.2% between 2005 and 2020. The solar thermal energy accounts for 5.6% from the total amount of renewable energy used for heating & cooling, while the photovoltaic solar energy accounts for 2.4%. Moreover, in accordance with the Energy Efficiency Directive ([2]), the Member States have an obligation to draw up National Energy Efficiency Action Plans setting out the estimated energy consumption, the planned energy efficiency measures and the improvements the respective Member States expects to achieve [3]. The Energy Efficiency Directive sets up “legally binding measures to
step up Member States’ efforts to use energy more efficiently at all states of the energy chain” [4] including among other the promotion of efficient heating and cooling.

In the past years increasingly more attention was paid to the potential of using solar cooling for buildings, especially for the ones from subtropical [5] and Mediterranean [6] areas, where the solar radiation has significant levels. Simulation models lying on components of these systems have been developed. Producing conditioned air from solar energy remains an attractive perspective if noticing that a typical building presents the peak-requirement of energy for cooling along two or three hours from midday, when the solar irradiation is also maximal.

High costs obstacles regard the wide scale commercialization of solar cooling technologies. It is not decided yet which one between the thermal and electrical driven systems proves to be more competitive. The forecast [7] shows that the electrical solar cooling would require lower capital investments, because of a higher COP for refrigeration by vapor compression and of the strong interests for reducing the costs of PV technology. The state of the art for these systems [8] shows that the conditioned air can be produced by a chiller with mechanical compression using electrical energy, or by a chiller with thermal activation, which transforms the hot water in cold water whose energy, at its turn, is distributed through a water-air heat exchanger to the building ventilation system.

*The electrical driven cooling systems* work after the frigorific cycle of vapor mechanical compression and they include four main elements (figure 1-a): vaporizer, compressor, condenser and expansion valve.

The cooling fluid, as result of the mechanical compression realized by the electrical compressor, reaches high values of pressure and a temperature above the environmental one. The pressurized vapors come into the condenser, where the heat is transferred to the surrounding air and they condense in liquid. The high pressure liquid passes then by an expansion valve, as a consequence the pressure and temperature diminish. The low pressure liquid has a boiling temperature below the one of the environmental air. The refrigerant transfers the heat from the environmental air when the boiling process takes place in the vaporizer. The subsequent evaporation produces refrigerated vapors of low pressure hence the cycle closes. The coefficient of performance (COP) of these systems, defined as ratio between output versus input energy takes values between 3 and 5.

![Diagram](image1.png)

**Figure 1.** Mechanical compression versus thermal compression.

The absorption cycle of *cooling systems with thermal compression* is similar to the one with mechanical compression, the difference being given by the compressor. The absorption cycle lies on a “thermal compressor” that compresses the refrigerant vapors of low pressure to high pressure. The components from the right side of z-z line (figure 1-b), namely the generator, the absorber, the expansion valve and the pump form the thermal compressor. The vapors produced at low pressure in the vaporizer are absorbed into an absorbing liquid. The absorbent, which took in the refrigerant, is pumped towards the generator. Here the refrigerant is released and it transforms in vapors by absorbing the heat of the environment (vapors, hot water or hot evacuation gases). The absorbent liquid has a boiling temperature higher than the refrigerant hence it remains in solution while most of the refrigerant (under vapors form) gets out from the generator and reaches the condenser, where they
are again condensed. This liquid with high pressure flows by an extension valve, where the pressure becomes to drop before the solution turns back into the absorbent. The chiller with absorption needs a quantity of heat and an absorbing – refrigerating medium. The COP values for these systems are between 0.4 and 0.8.

2. Experiments

2.1. Experimental test bed
In the frame of RO-054 Project, financed through EEA Grant 2009 program, an experimental installation with tri-generation has been realized in the purpose to simultaneously produce electricity, heat and cooling for a building arisen inside “Dunărea de Jos” University of Galați campus with the occasion of the same project. Both the building and experimental installation constitute an experimental basis for doctoral studies in energy domain, in the university. These research facilities enabled to develop two comparative experiments: the performance assessment for PV cooling system (figure 2-a) versus thermal cooling system (figure 2-b).

This building of energy efficiency class A, with an annual specific consumption of 20 kWh/m² year for cooling, enabled the analysis of the hypothesis of generating a cooling capacity over the building needs. In this case, the available surplus of cooling capacity might be used to neutralize the heat released by the industrial processes from inside the building. Hereby, the targets of the performed study were: i) experimental proof of the design algorithms, ii) comparative analysis from technical and economic point of view, iii) the evaluation of the heat quantity that can be compensated by each of the two methods of air conditioning, in accordance to physical and architectural limitations of the building. This limitations are issuing from the methodology of the International Energy Agency Photovoltaic Power Systems Programme and can be synthesized with a simple rule of thumb: for every m² of building area ground floor, there is an average 0.4 m² of rooftop area and 0.15 m² of facade area with good solar potential.

![Figure 2. Cooling systems.](image-url)

2.2. Experimental testing of PV cooling system
In the case of the above presented experimental test bed, located in the Southeastern part of Romania, the efficiency is \( \eta_{PV} = 15\% \). This means that the electric energy delivered monthly by a panel with a surface of one m² \( E_{PV} \), can be calculated as \( E_{PV} = N_{eq/day} \cdot H \cdot \eta_{PV} \) and has the values from table 1.

The monthly total request of energy for the building is \( Q_c = A \cdot q_{C\text{ monthly}} \), where \( A = 200\text{m}^2 \) and \( q_{C\text{ monthly}} = \frac{q_c \cdot CDD_{monthly}}{CDD_{year}} \).

The surface of the photovoltaic panels, equation (1) needed to ensure the generation of the necessary energy can be found as ratio between the electrical energy required for space climatization, \( Q_c / COP \), and the one produced by a square meter of panel, \( E_{PV} \):
The photovoltaic panel nominal power of installed modules, for 2-10 kW of power, the recommended voltage of photovoltaic systems is $V_{CC} = 48$ V. By choosing photovoltaic modules with the peak power $P_{SM}$ it follows that the topology of photovoltaic panel is established according to the power and voltage of both the panel and its modules. The number of installed modules, $n_{SM}$, (4), has to be the even, integer and superior to the number resulted from the following relation:

$$n_{SM} > \frac{P_{PV_{panel}}}{P_{SM}} \cdot \frac{S_{SM}}{S_{SM_{n}}}$$  \tag{4}$$

The number of modules connected in series, $n_{SM}$, making up a branch, is $n_{SM_b} = V_{CC}/V_{SM} = 2$. The number of branches connected in parallel, $n_{SM_{np}}$ is $n_{SM_{np}} = n_{SM}/n_{SM_b} = 10$. The tampon battery between $PV$ system and chiller is the one that should accumulate/release the electrical energy necessary to the chiller. The capacity of the batteries system can be determined as, equation (5):

$$C_{batteries} = \frac{\text{max}\{E_{PV_{day}}\}}{V_{CC}} \text{ [Ah]}$$  \tag{5}$$

Table 1. Data for $PV$ cooling system design.

| Month | Jan | Feb | March | April | May | Jun | Jul | Aug. | Sep | Oct | Nov | Dec |
|-------|-----|-----|-------|-------|-----|-----|-----|------|-----|-----|-----|-----|
| $CDD$ [°C-d] | 0   | 0   | 0     | 33    | 208 | 300 | 363 | 363  | 234 | 53  | 0   | 0   |
| $H_s$[kWh/m²·d] | 1.47 | 2.31 | 3.34  | 4.94  | 5.94 | 6.69 | 6.56 | 5.75 | 4.39 | 2.97 | 1.64 | 1.19 |
| $d_s$[h] | 76  | 82  | 138   | 193   | 251 | 294 | 307 | 293  | 230 | 185 | 85  | 63  |
| $N_{eq_{days}}$ [days] | 3.17 | 3.42 | 5.75  | 8.04  | 10.46 | 12.25 | 12.79 | 12.21 | 9.58 | 7.71 | 3.54 | 2.63 |
| $E_{PV}$ [kWh/m²] | 0.70 | 1.19 | 2.88  | 5.96  | 9.32 | 12.29 | 12.59 | 10.53 | 6.31 | 3.43 | 0.87 | 0.47 |
| $q_{C_{monthly}}$ [Wh/m²] | 0   | 0   | 0     | 0.42  | 2.68 | 3.86 | 4.67 | 4.67  | 3.01 | 0.68 | 0   | 0   |
| $Q_{C_{annual}}$ [kWh] | 0   | 0   | 0     | 85    | 535 | 772 | 934 | 934   | 602 | 136 | 0   | 0   |
| $S_{PV}$ [m²] | 0   | 0   | 0     | 3.56  | 14.36 | 15.70 | 18.56 | 22.18 | 23.87 | 9.93 | 0   | 0   |
| $E_{PV_{day}}$ [kWh] | 0.54 | 0.59 | 0.99  | 1.38  | 1.79 | 2.10 | 2.19 | 2.09  | 1.64 | 1.32 | 0.61 | 0.45 |
| $P_{PV_{panels}}$ [kW] | | | | | | | | | | | | |

The available capacity of an accumulator is not the rated capacity $C20$ (corresponding to a discharge during 20 h at 25°C), but the real capacity, available during all the operating time. In
addition, an accumulator cannot be discharged under a certain level, otherwise it may be damaged. In the absence of problems related to low temperatures and for normal use, it is considered as acceptable a level of discharge \( ND = 0.7 \). The rated capacity is calculated, equation (6):

\[
C_{20} = \frac{C_{\text{batteries}}}{ND} \quad [\text{Ah}]
\]

where \( C_{20} \) is the rated capacity and \( ND \) – the maximum allowed discharge level.

Hereby, a minimum capacity of the batteries has to be higher than 430 Ah. By choosing 12V batteries of a 250 Ah capacity each, the batteries total capacity results of 500Ah. By considering the voltage limit values as \( V_M = 49.5 \) V and \( V_m = 47 \) V, the maximum value of the energy results \( W_M = 89.1\)MJ. The minimum value of the accumulated energy, when the battery is considered discharged (\( SOC = 30\%)\), is \( W_m = 25.38\)MJ. Corresponding to the value \( W_M - W_m = 63.72 \) MJ of the energy and to a time of duty of 8 hours, the batteries can supply an electrical charge of 2.2 kW.

2.3. Experimental testing of solar thermal cooling system

The thermal energy produced by the solar thermal panels is stocked into the heat stocking tank, where the thermal agent temperature varies between the imposed limits \( T_m \) and \( T_M \). The simplified model of temperature regulation is similar to the battery voltage regulation one. If considering the case of solar thermal panels in which the efficiency is of about \( \eta_{ST} = 70\% \), it results that the energy delivered monthly by a solar panel with a surface of 1 m\(^2\) is \( Q_{ST} = N_{eq\_day} \cdot H_b \cdot \eta_{ST} \), and has the values presented in table 2. The monthly total request of energy is \( Q_e = A \cdot q_C \) monthly. The needed surface of the solar panels that ensure the production of the necessary energy can be determined as ratio between the energy required for space conditioning \( Q_C \) and the one produced by a square meter of panel \( Q_{ST} \), equation (7):

\[
S_{PV} = Q_{C\_monthly} / (\text{COP} \cdot Q_{ST})
\]

(7)

The value chosen for \( S_{ST} \) is over the one resulted from monthly calculation, namely 34m\(^2\) for \( \text{COP} = 0.6 \). The daily production of utile energy of these panels can be found with equation (8):

\[
Q_{ST\_day} = \frac{Q_{ST} \cdot S_{ST}}{k \cdot N_{days}} = \frac{Q_C}{\text{COP} \cdot k \cdot N_{days}}
\]

(8)

The results of the calculus are presented below.

| Table 2. Data for thermal cooling system design. |
|-----------------------------------------------|
| Month | Jan | Feb | March | April | May | June | July | Aug | Sep | Oct | Nov | Dec |
|-------|-----|-----|-------|-------|-----|------|------|-----|-----|-----|-----|-----|
| \( H_b \) [kWh/m\(^2\)·d] | 1.47 | 2.31 | 3.34 | 4.94 | 5.94 | 6.69 | 6.56 | 5.75 | 4.39 | 2.97 | 1.64 | 1.19 |
| \( N_{eq\_day} \) [days] | 3.17 | 3.42 | 5.75 | 8.04 | 10.46 | 12.25 | 12.79 | 12.21 | 9.58 | 7.71 | 5.45 | 2.63 |
| \( Q_{ST} \) [kWh/m\(^2\)] | 3.26 | 5.53 | 13.44 | 27.80 | 43.49 | 57.37 | 58.73 | 49.15 | 29.44 | 16.03 | 4.06 | 2.19 |
| \( q_C \) [kWh/m\(^2\)] | 0 | 0 | 0 | 0.42 | 2.68 | 3.86 | 4.67 | 4.67 | 3.01 | 0.68 | 0 | 0 |
| \( Q_{C\_monthly} \) [kWh] | 0 | 0 | 0 | 85 | 535 | 772 | 934 | 934 | 602 | 136 | 0 | 0 |
| \( S_{ST} \) [m\(^2\)] | 0 | 0 | 0 | 5.09 | 20.52 | 22.43 | 26.52 | 31.69 | 34.10 | 14.18 | 0 | 0 |
| \( Q_{ST\_day} \) [kWh] | 5.28 | 8.95 | 21.77 | 45.01 | 70.42 | 92.88 | 95.09 | 79.57 | 47.66 | 25.95 | 6.58 | 3.55 |
| \( P_{st\_panels} \) [kW] | 3.59 | 3.88 | 6.52 | 9.11 | 11.85 | 13.88 | 14.50 | 13.84 | 10.86 | 8.74 | 4.01 | 2.98 |

The active solar cooling system uses solar panels which convert the solar energy into heat to obtain cooling. It is composed by ten solar thermal panels with a 3.4 m\(^2\) surface, each one built with a solar vacuum tube – model DF 100, a boiler of 2000 liters to store the thermal energy and an adsorption chiller [9] with 15kW thermal power of ACS 15 model with \( \text{COP} = 0.6 \).
3. Results and comparative analysis

The graphical representation of the energy demand for conditioning the building interior space together with the input energy for both types of chiller is shown in figure 3. One can observe a significant difference between the quantity of energy required by the chiller with absorption relative to the one required by the chiller with mechanical compression. This is due to the difference between the COP value for the two types of technologies.

![Energy Demand Graph](image)

**Figure 3.** Energy balances.

The utile surfaces of thermal solar panels versus photovoltaic solar panels when producing the same quantity of utile energy give a ratio of 34/24, while the ratio of daily energy obtained by solar energy conversion is 6.6. The last ratio resulted as product between the efficiencies ratio and surfaces ratio for the two types of conversion systems.

The global efficiency for the two types of solar cooling can be calculated with equation (9):

$$ EEF_{comp} = \eta_{PV} \cdot COP \cdot \eta_{inverter}, \quad EEF_{thermic} = \eta_{ST} \cdot COP_{a}. $$

(9)

If so, then by considering the values adopted above for the cooling systems parameters we can observe that systems efficiency presents close values, because the difference between COP’s is compensated by the reversed difference between the solar panels efficiency. More exactly, $EEF_{comp} = 48\%$, while $EEF_{thermic} = 42\%$. The inverter efficiency was considered $\eta_{inverter} = 80\%$.

During the winter season, one may notice a more significant difference between the two types of solar cooling, namely a loss of produced thermal energy and a surplus of electric energy that can be used for supplying other consumers.

The mathematical relations expressing the dynamical accumulation of energy in the battery and in the boiler are, respectively equation (10):

- The case of chiller with mechanical compression equation (10): 

$$ \frac{dW_b}{dt} = P_{EPV}(t) - P_{chiller}(t) \quad (10) $$

where $dW_b$ means the variation of the electrical energy stored/released by the battery [kWh], $P_{EPV}(t)$ – the electrical power of the photovoltaic source [kW], and $P_{chiller}(t)$ – the electrical power absorbed by the chiller [kW];

- The case of chiller with thermal compression: 

$$ \frac{dW_T}{dt} = m_w c_w \frac{dT}{dt} = P_{Th} - P_{Th,Chiller}(t) \quad (11) $$

where $dW_T$ is the heat variation of heat storage tank [kWh]; $P_{Th}$ – the thermal power produced by solar thermal panels [kW], $P_{Th,Chiller}(t)$ – the thermal power consumed for cooling [kW]; $m_w$, $c_w$ – the mass and the specific heat of the water from tank, and $T_c$ – the water temperature inside the tank.

In figure 4, the variation of PV voltage is drawn in blue, while the generated current is depicted in green. In figure 5, $I_{rad}$ means the solar radiation intensity, while $T_{ departure}$ and $T_{ return}$ are the departure, respective return temperatures of solar collectors.

The regulations of battery voltage respective of boiler water temperature have the same command law. The dynamical response of the system supplied by photovoltaic panels (figure 4) is faster than the
one of the system supplied by solar panels (figure 5). In the first case, the current is proportional to the solar radiation, while in the second the temperature depends on the solar radiation intensity and, due to the volume of water, the response is delayed. The responding manner can be observed from the experimental data gathered by the two recording systems.

![Figure 4. Time variation of PV voltage and current.](image)

![Figure 5. Time variation of solar panels temperature.](image)

The economical analysis, in comparison to other existing researches [10], refers to the cost of equipments (for the solar collecting area and the cooling equipment) for conditioning the interior space of the building. The component elements of the two systems, as well as their cost range [11] are presented in table 3.

### Table 3. Investments cost of solar cooling systems.

| Crt no. | Electrical driven cooling systems | Thermal driven cooling systems |
|--------|-----------------------------------|--------------------------------|
|        | Components                        | Cost range                     | Components                       | Cost range                     |
| 1      | Photovoltaic panels: 20           | $0.65-0.68/W                   | Solar thermal collector: 34m$^2$  | $200-300/m$^2                  |
| 2      | Solar charge controller: 1         | $370-430/unit                  | Pipeline and pumps               | $500-1000                      |
| 3      | Inverter: 1                       | $230-242/unit                  | Recooler: 1                      | $400/unit                      |
| 4      | Batteries: 8                      | $355-365/unit                  | Thermal storage: 1               | $800-1000/unit                 |
| 5      | Vapor compression cooling: 1      | $3500 – 10500/unit             | Adsorption cooling: 1            | $25,000/unit                   |
|        | Total                              | $9410 - 16672                  |                                 | $36300 - 41200                 |

Regarding the required investment, the cooling systems thermal driven are 2.5 to 3.8 times more expensive relative to the electrical driven cooling systems. In the first ones case, the most expensive components, excepting the chiller, are the solar thermal collectors. For the others, the batteries for storing the electrical energy have a significant cost.

### Table 4. The quantity of compensated energy of the industrial processes from the building

| Month | Jan | Feb | March | April | May | Jun | Jul | Aug. | Sep | Oct | Nov | Dec |
|-------|-----|-----|-------|-------|-----|-----|-----|------|-----|-----|-----|-----|
| $Q_C^{\text{month0}}$ [kWh] | 0   | 0   | 0     | 85    | 535 | 772 | 934 | 934  | 602 | 136 | 0   | 0   |
| $Q_C^{\text{max}}$ [kWh]  | 224 | 379 | 922   | 1906  | 2982| 3934| 4027| 3370 | 2019| 1099| 279 | 150 |
| $\Delta Q_C$ [kWh]      | 224 | 379 | 922   | 1822  | 2447| 3162| 3093| 2436 | 1416| 963 | 279 | 150 |

**PV cooling system**

| Month | Jan | Feb | March | April | May | Jun | Jul | Aug. | Sep | Oct | Nov | Dec |
|-------|-----|-----|-------|-------|-----|-----|-----|------|-----|-----|-----|-----|
| $Q_C^{\text{month0}}$ [kWh] | 0   | 0   | 0     | 85    | 535 | 772 | 934 | 934  | 602 | 136 | 0   | 0   |
| $Q_C^{\text{max}}$ [kWh]  | 156 | 265 | 645   | 1334  | 2087| 2753| 2819| 2358 | 1413| 769 | 195 | 105 |
| $\Delta Q_C$ [kWh]      | 156 | 265 | 645   | 1249  | 1552| 1981| 1884| 1424 | 810 | 632 | 195 | 105 |

**Thermal cooling system**

On the base of the dimensioning algorithm (relations (1) – (7)) and according to the physical and architectural limitations imposed by IEA, we have found a maximum surface of $PV$ or of solar thermal collectors of 80 m$^2$. 

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Note: The images and figures are not included in the textual representation.
Regarding the monthly quantities of heat coming from the industrial processes taking place in the building, which can be compensated by each of the two types of cooling systems, in this case, they are specified in table 4.

4. Conclusions
The technical and economical analysis of the results obtained through the comparative study developed in this paper leads to the following conclusions:

- The capacity of solar cooling system, no matter if it is with mechanical compression or thermal driven, meet the cooling needs if the quantity of heat released by the industrial installations is not very high and the energy efficiency of the building thermal insulation is high enough.
- In the case of the solar cooling system with thermal compression, the investment expenses are about three times higher than in the case of a system with mechanical compression.
- If the quantity of heat released by the industrial installations is important, then a possible solution could be the use of a cooling system with thermal compression, associated to the recovery of the released heat, followed by its transfer in thermal storage. In this manner, the investment expenses will be also diminished.

From the European energy policy perspective, 2016 will be a critical year as many proposals and initiatives will take shape. The COP21 summit in December 2015 generated the Paris Agreement, a breakthrough in the global fight against climate change [12]. The key issues to be tackled in 2016 are the following: quarter 1 - Heating and cooling strategy, quarter 3 - Review of EPBD and EED Directives and quarter 4 - electricity market design and RES Directive. In what heating and cooling is concerned, the Heating & Cooling Strategy will look for ways to make heating and cooling more efficient and sustainable.

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