THERMODYNAMIC LIMITS OF THE USE OF SOLAR ENERGY FOR COLD PRODUCTION

Lillo, I; Silva, M.
Escuela Superior de Ingenieros de Sevilla
Avenida de los Descubrimientos, s/n
41092. Seville (SPAIN)
e-mail: isidorolillo@etsi.us.es

ABSTRACT: The cold production with solar energy may be performed by absorption refrigeration cycles based on thermal solar energy collectors and using compression refrigeration cycles with photovoltaic solar energy systems. Which of the two procedures is thermodynamically more efficient? Which one would require the lowest collection surface to satisfy a given cooling demand? It has been determined, the minimum required surface ratio to meet the same cooling demand on the same site through the use of solar thermal or photovoltaic energy, depending on the yield of the respective facilities. It has been found that, taking into account the thermodynamic limits of compression refrigeration and absorption refrigeration cycles, the photovoltaic and solar thermal area ratio required only depends on the ratio between the hot source temperature of the refrigeration cycle, and the thermal fluid temperature of the solar thermal installation being independent of the cold source temperature relationship, besides the performance of each solar installations. We conclude that PV technology requires less collection surface than solar thermal technology of low temperature for the production of cold on a very wide range of values of photovoltaic and thermal installation efficiency.

Keywords: Refrigeration, PV System, Energy Options.

1 INTRODUCTION

The use of solar radiation, with or without concentration for cold production is mainly done by absorption cooling cycles (LiBr-Water, NH3-Water) with low temperature solar thermal energy and using compression refrigeration cycles with photovoltaic solar energy. [1,2,3].

In the case of solar thermal energy, there are different technologies that in turn can be applied to different absorption and cooling cycles [4].

From the standpoint of thermal solar energy, on one hand, there are the facilities that do not concentrate the solar radiation, by using flat plate or vacuum tube collectors and on the other hand, the technologies that concentrate the solar radiation with the use of fresnel lenses, parabolic trough, parabolic dishes, etc.. In the latter case, the temperature reached by the coolant T_T is greater than in the case of no concentration of solar radiation and is directly related to the level of concentration of the solar radiation.

Similarly, in the case of photovoltaic systems, different technologies of photovoltaic cells (crystalline silicon, amorphous, CIS, multifunction cells, gallium arsenide,...) may be applied to a compression refrigeration cycle, with or without concentrating the solar radiation. [5-11].

There are even applications that combine the use of solar thermal and photovoltaic solar energy for cold production or even the use of hybrid collectors.

Cold production has three major widespread uses depending on the required cooling temperature Tcool. For climatization, cooling temperatures, Tcool, ranges in the vicinity of 291K-295K. For food preservation, Tcool, ranges in 273K-285K and for freezing temperatures varies in the vicinity of 255K. This process occurs over a range of ambient temperatures T0 and of condensation temperatures Tb, which ranges between 265K and 323K approximately.

2 OBJECTIVE

When comparing the potential use of solar radiation for producing cold using solar photovoltaic technology and solar thermal technology means there are a number of advantages and drawbacks of one technology over the other. In a first approximation, the photovoltaic have today worse energy efficiency, η_{PV}, (varies between 5%-25% approximately) that solar thermal installations, η_T (varies between 30-50% approximately). Furthermore, the current performance of the compression refrigeration cycle (EERc approximately varies from 2 to 5) is greater than the efficiency in absorption cycles (EERA varies between approximately 0.5 and 2), affecting the thermal level to their performance. In addition, the exergy efficiency of a PV system η_{EXPV} (varies between 5% and 13% approximately) is usually higher than that of a solar thermal η_{EXPV} whose value depends on the temperature levels.

In the end, the aim of this work is to determine which of the two technologies (thermal and photovoltaic) would require less solar collection area to achieve a certain refrigeration effect, both for systems with and without concentration of the solar radiation according to three situations

Case 1: Actual situation: In this case it is considered the current yields values of absorption and compression cycles and the current values of the yields of the photovoltaic and solar thermal technologies.

Case 2: Potential from a thermodynamic cycle point of view: In this case, current yield values of the solar technologies are considered s and regarding the maximum thermodynamic efficiency of compression and absorption cycles.

Case 3: Potential from the simultaneous thermodynamic cycle and solar technology point of view: In this case we consider the maximum thermodynamic efficiency of absorption and compression cycles and maximum performance possible for solar technologies.

3 HIPOTHESIS

This paper answers this question under the following assumptions:

a.- It is assumed that the compression cycle works only on solar energy and it is only considered the energy consumption of the compressor neglecting all other possible consumptions such as those associated with fans, lighting, cameras, etc. ..

b.- It is assumed that the absorption cycle works only with solar thermal energy and it is only considered the energy consumption of the generator neglecting all other possible consumptions such as those associated with pumps between the absorber and the generator. It is recognized that the temperature of the heat input to the cycle is just the heat production temperature of the solar thermal installation T_T.

c.- It was considered that the photovoltaic and thermal installation operate without auxiliary power supply.

d.- There has not been taken into account any environmental or economic aspect at the design of the facilities that in reality affect to the choice of installation.

e.- It is indicated that both the energy collected by the PV installation and the solar thermal systems and the temperature of the solar collector vary significantly during the day. The aspects derivate from the thermal energy supply in quantity and quality at every moment for the solar installation are neglected.

f.- The value of the condenser cooling temperature Tb is usually the ambient temperature value T_0 for air-cooled cycles or water temperature for water cooled cycles. In this paper we have considered a range of Tb of 265K-323K.

The value of the temperature of heat input to the cycle TT has been considered in the range of 313-373 K, for systems without concentration of solar radiation (flat plate or vacuum tubes) and in the range of 373-1000 K for systems with concentrated of solar radiation.

For this reason, we have considered a range of the ratio $\frac{Tb}{T_T}$ between 0.75 and 0.95 for the case of solar thermal systems without concentrated solar radiation and a range of the ratio $\frac{Tb}{T_T}$ between 0.4 to 0.75 for solar thermal systems with concentration.

g.- For systems without concentration of solar radiation, both with photovoltaic and thermal, the global solar radiation H is considered over the plane of the module or collector of area A, whereas when there is concentration of the direct normal solar radiation, it is considered on the reflective surface Hd or collector aperture area Ap

h.- The actual overall performance of a solar photovoltaic installation η_{PV}, is variable depending on the system configuration, concentration of solar radiation and cell technology. It has been considered a range of 5%-25%, while the current performance of a solar thermal installation η_T significantly depends on the temperature T_T and the concentration level.

For higher temperatures of about 373 K it is common to use, concentrator systems, depending on the energy efficiency of these facilities on the concentration and Technology (Fresnel, parabolic trough, parabolic dish, etc…). It has been estimated, a range between 30-70%, decreasing when T_T temperature increases.

Accordingly, for this study, we used a range of the relation $\frac{\eta_{PV}}{\eta_T}$ between 0.1 and 0.95.

i.- From the energy point of view the energy efficiency of the photovoltaic and thermal installation cannot be greater than 1. At this upper limit must subtract the inevitable losses of the process of transformation. According to information provided by different authors, for systems without concentration it is obtained a range of η_{PVMAX} which depends on the solar cell technology and ranges between 30% and 68.2%. For systems with concentration, the maximum yield η^c_{PVMAX} depends on the level of concentration of the solar radiation and the technology, and whose current values range around 40% to 86.8% for maximum concentration (45900X) and infinite cell multifunction.

Moreover, for systems without concentration of solar radiation by using sensors or flat thermal vacuum tubes, the maximum achievable yield η_{TMAX}, oscillates in maximum values at around 60-90%, decreasing the maximum value increasing the temperature T_T. T_T operating temperatures are in the range of 313K-400K. In the case of systems with concentration of solar radiation (Fresnel, parabolic trough parabolic disc, etc.) the maximum achievable yield η^c_{TMAX} depends primarily on the concentration level of radiation, which at the same time is related to the temperature T_T which increases when the concentration level increases and whose values are reflected in the following table:

Therefore, for this study, we used a range of $\frac{\eta^c_{PVMAX}}{\eta^c_{TMAX}}$ between 0.2 y 0.9 for a ratio Tb/T_T between 0.4 y 0.75.

j.- Actual values of the compression performance EER_C are between 3 and 7, while the actual performance values of the absorption refrigeration cycle EER_A are around 0.5-0.8 for one-stage systems and for two-stage systems it ranges between 0.9 to 1.3. Consequently, it has been considered a ratio EER_C/ EER_A between 2 and 15.

4 THEORETICAL BACKGROUND

4.1 Compression refrigeration cycle with solar photovoltaic energy

A schematic view of the solar electric-vapor compression refrigeration (SE-VCR) system is shown in Fig 1. As shown in this figure, the solar–mechanical system consists mainly of photovoltaic panels and an electrical cooling device which works according to the vapor compression cycle. The biggest advantage of using solar electric panels for cooling would be their simple construction and high overall efficiency when combined with a conventional vapor compression system because of its commonly higher coefficient of performance which is more than 1.

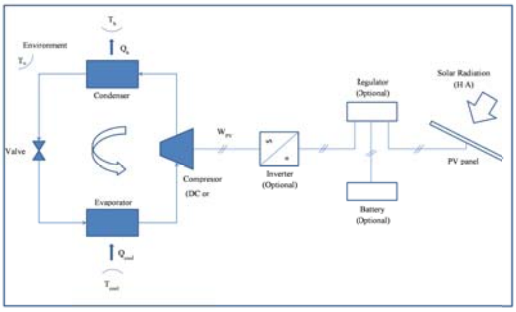

Figure 1: A schematic view of the solar electric-vapor compression refrigeration (SE-VCR) system

The production of electricity from the PV system can be performed directly (without battery) or by the use of batteries, affecting in this case to the overall efficiency of the PV system. The electrical energy supplied by the installation in a period is:

$$W_{PV} = \eta_{PV} \cdot H \cdot A_{PV} \qquad [1]$$

Where η_{PV} is the overall efficiency of the PV system, A_{PV} is the photovoltaic collection surface; H is the global radiation over the plane of the modules and W_{PV} is the electrical energy produced in a certain period.

The energy efficiency of a compression refrigeration cycle EER_C is defined as:

$$EER_C = \frac{Q_{cool}}{W_{PV}} \qquad [2]$$

To establish the thermodynamic limit of the compression refrigeration cycle and to obtain the maximum performance EER_{CMAX}, it is assumed a reversible process. Applying the First and Second Law of Thermodynamics, according to Scheme 1 there result the equations 1 and 2 respectively.

$$Q_{coolPV} + W_{PV} = Q_b \qquad [3]$$

$$\frac{Q_b}{T_b} = \frac{Q_{coolPV}}{T_{cool}} \qquad [4]$$

Substituting equations 3 and 4 into equation 2, the maximum performance of the cycle, EER_{CMAX} is:

$$EER_{CMAX} = \frac{Q_{coolPV}}{W_{PV}} = \frac{1}{\left(\frac{T_b}{T_{cool}} - 1\right)} \qquad [5]$$

Therefore, for a given cooling effect refrigerator Q_{coolPV}, the relationship between this, the refrigeration cycle efficiency and the efficiency of the photovoltaic installation, together with the photovoltaic collection surface, according to Eqs. [1] and [2] would be:

$$Q_{coolPV} = EER_C \cdot \eta_{PV} \cdot H \cdot A_{PV} \qquad [6]$$

4.2 Compression refrigeration cycle with solar thermal energy.

The general scheme of operation of a heat pump with a solar thermal system is represented in Figure 2.

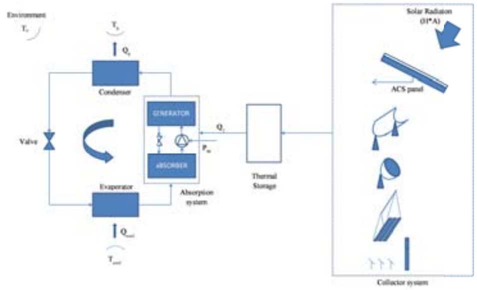

Figure 2: A schematic view of a heat pump with a solar thermal system.

The thermal energy provided by the solar installation, in a certain period, Q_T, is:

$$Q_T = \eta_T \cdot H \cdot A_T \qquad [7]$$

Where A_T is the solar thermal collecting area, H is the global radiation over the plane of collectors; ηT is the overall efficiency of the solar thermal system.

Equations 8 and 9 result from the application of the First and Second Law of Thermodynamics to a heat pump in a reversible process that establishes the thermodynamic limit, according to Scheme 2.

$$Q_{cool} + Q_T = Q_b \qquad [8]$$

$$\frac{Q_b}{T_b} - \frac{Q_{cool}}{T_{cool}} - \frac{Q_T}{T_T} = 0 \qquad [9]$$

The EER_A of the machine is defined like:

$$EER_A = \frac{Q_{cool}}{Q_T} \qquad [10]$$

Substituting equations 8 and 9 into Equation 10, it results the maximum cycle efficiency, EER_{AMAX}:

$$EER_{AMAX} = \frac{Q_{cool}}{Q_T} = \frac{T_{cool} \cdot (T_b - T_T)}{T_T \cdot (T_{cool} - T_b)} \qquad [11]$$

Therefore, for a given cooling effect Q_{coolPV}, the relationship between the cycle efficiency and the efficiency of the solar thermal installation, along with the collection photovoltaic surface, according to Eqs. 7 and 10, would be:

$$Q_{coolT} = EER_A \cdot \eta_T \cdot H \cdot A_T \qquad [12]$$

In the case where the cycle efficiency is maximized according to the second law of thermodynamics, while maintaining the performance of the solar thermal, the solar thermal collecting area $A_{TEERAmax}$ would be

$$Q_{coolT} = EER_{AMAX} \cdot \eta_T \cdot H \cdot A_{TEERAmax} \qquad [13]$$

In the limit case where the cycle efficiency is maximized according to the second law of thermodynamics and the performance of the PV system, the maximum according to different authors, it would be the minimum areaA_{TMIN}:

$$Q_{coolT} = EER_{AMAX} \cdot \eta_{TMAX} \cdot H \cdot A_{TMIN} \qquad [14]$$

4.3. Exergetic analysis

The maximum exergetic efficiency of the transformation process up to a given amount of solar radiation H, per unit area, [12] in a cooling effect Q_{cool} is indeed defined by equation 14, where one side is the exergy of solar radiation itself η_{EXrad} and secondly the performance of the process of obtaining the cooling effect η_{EXins},

$$\eta_{EXmax} = \eta_{EXrad} \cdot \eta_{EXins} = \frac{Q_{cool} \cdot (T_0/T_{cool} - 1)}{H \cdot A \cdot (1 - T_0/T_s)} \quad [15]$$

Resulting a value for T_0 between 263-373K

In addition, the exergy efficiency of the photovoltaic η_{EXPV} and solar thermal η_{EXT} installation in a given period would be:

$$\eta_{EXPV} = \frac{W_{PV}}{H \cdot Apv \cdot (1 - T_0/T_s)}$$

$$\eta_{EXT} = \frac{Q_T \cdot (1 - T_0/T_T)}{H \cdot At \cdot (1 - T_0/T_s)}$$

The exergy efficiency of the compression refrigeration cycle η_{EXC} and the absorption refrigeration cycle η_{EXA} in a given period would be

$$\eta_{EXC} = \frac{Q_{coolPV} \cdot (T_0/T_{cool} - 1)}{W_{PV}}$$

$$\eta_{EXA} = \frac{Q_{coolT} \cdot (T_0/T_{cool} - 1)}{Q_T \cdot (1 - T_0/T_T)}$$

5 COMPARATIVE ANALYSIS

It is presented, a comparative analysis of what would be the required solar collecting area if using a PV front of a solar thermal system for the same refrigerator effect, in three scenarios:

Case 1. - Actual situation

Assuming the current yields of the cooling cycle both with compression EER_C and with absorption EER_A and the current efficiency of photovoltaic η_{PV} and thermal η_T technologies according to the set scenario. In this case it will be attached a photovoltaic collecting area $A_{PV31,}$ and a solar thermal collecting area A_{T31} without concentration and a photovoltaic collecting area $A_{PV32,}$ and a solar thermal collecting area A_{T32} with concentration. Substituting in the equations it results:

$$Q_{coolPV31} = EER_C \cdot \eta_{PV} \cdot H \cdot A_{PV31} \quad [16]$$

$$Q_{coolT31} = EER_A \cdot \eta_T \cdot H \cdot A_{T31} \quad [17]$$

For the same cooling effect, $Q_{coolPV31} = Q_{coolT31}$, it results:

$$\frac{A_{T31}}{A_{PV31}} = \frac{EER_C}{EER_A} \cdot \frac{\eta_{PV}}{\eta_T} \quad [18]$$

Similarly to the case of concentrated solar radiation is an expression:

$$\frac{A_{T32}}{A_{PV32}} = \frac{EER_C}{EER_A} \cdot \frac{\eta_{PV}^c}{\eta_T^c}$$

According to the ranges indicated above, the curve representing $\frac{A_T}{A_{PV}} = 1$, is shown in figure 3:

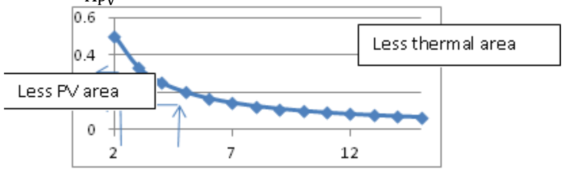

Figure 3: Evolution of the N/N as a function of the ratio EER_C/EER_A for an area ratio of 1.

The figure 3 separates the regions where the area required for the same cooling effect is lower in solar thermal than in photovoltaic based on the EER_C/EER_A ratio. The lower zone of the curve corresponds to an area lower for photovoltaic than for thermal. For example, for absorption machines where EER_A is about 0.7, and for compression machines with a EER_C of 4, it results a EER_C/EER_A=5.71. For this value, we find that the limit value of the efficiency ratio $\frac{\eta_{PV}}{\eta_T}$ is 0.18

Today considering the current efficiency values of 10% in photovoltaic and a 40% in low thermal temperature, it would result in a ratio of 0.25, which would require lower photovoltaic area than thermal. Specifically, according to Eq. 19, for every m^2 of photovoltaic surface, it would be needed 1.427 m^2 of solar thermal collectors.

However, for absorption machines where the EER_A is around 1.3 and compression machines with a EERc of 4, it result a value of EER_C/EER_A=3.07, considering the same photovoltaic and thermal yields it results a ratio $\frac{A_{T31}}{A_{PV31}} = 0.7675$ in with case it would be less thermal than photovoltaic surface required. Specifically, according to Eq. 19, for each m^2 of thermal collection surface it would be required 1.3 m^2 of photovoltaic surface.

We conclude that with the current efficiencies of the cycles of the solar technologies, the photovoltaic installations would require less collecting surface than the low-temperature thermal installations (without concentration), while it would be required more area than in high temperature (with concentration) because using concentrators, the EER_A is higher.

Case 2.- Potential only from the point of view of the thermodynamic cycle.

In this case the maximum yields are the ones of the compression EER_{CMAX} and absorption refrigeration cycles EER_{AMAX} are assumed according to the Second Law of Thermodynamics and simultaneously assuming current yields both for the photovoltaic η_{PV} and solar thermal η_T technologies.

In this case it will be attached a photovoltaic collecting area $A_{PV31,}$ and a solar thermal collecting area A_{T31} without concentration and a photovoltaic collecting area $A_{PV32,}$ and a solar thermal collecting area A_{T32} with concentration.

Substituting in the equations it results:

$$Q_{coolPV21} = EER_{CMAX} \cdot \eta_{PV} \cdot H \cdot A_{PV21} \quad [19]$$

$$Q_{coolT21} = EER_{AMAX} \cdot \eta_{T} \cdot H \cdot A_{T21} \quad [20]$$

For the same cooling effect, $Q_{coolPV31} = Q_{coolT31}$, substituting on equations 5 and 11, it results:

$$\frac{A_{T21}}{A_{PV21}} = \left(\frac{1}{1-\frac{Tb}{T_T}}\right) \cdot \frac{\eta_{PV}}{\eta_T} \quad [21]$$

Similarly to the case of concentrated solar radiation is an expression:

$$\frac{A_{T22}}{A_{PV22}} = \left(\frac{1}{1-\frac{Tb}{T_T}}\right) \cdot \frac{\eta^c_{PV}}{\eta^c_T} \quad [22]$$

In both cases, it is required less photovoltaic than thermal surface if it is met:

$$\frac{\eta_{PV}}{\eta_T} > \left(1 - \frac{Tb}{T_T}\right) \quad [23]$$

The expression shows that the area ratio is not dependent on the cooling temperature T_{cool}, while it does depend on the ratio between the cooling temperature of the condenser Tb and the heat input temperature, T_T.

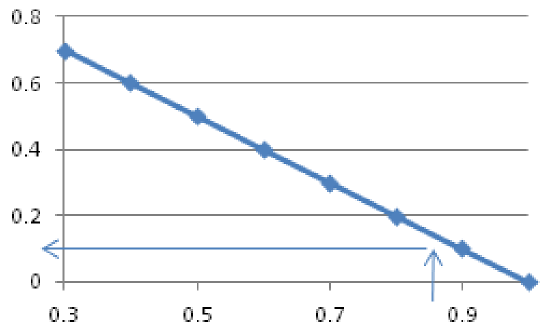

Figure 4: Regions where the area required for the same cooling effect is lower in photovoltaic than in solar thermal based on the Tb/T_T.

The figure 4 separates the regions where the area required for the same cooling effect is lower in photovoltaic than in solar thermal based on the Tb/T_T ratio assuming the maximum yields of the refrigeration cycles.

For example, considering that the current $\frac{Tb}{T_T}$ ratio can have a value of 0.85 (the actual range is between 0.75-1) it is obtained that the efficiencies limit value $\frac{\eta_{PV}}{\eta_T}$ is 0.15 (equivalent to a quotient EER_{CMAX}/EER_{AMAX} of 6.66)

Today considering the current efficiency values of 10% in photovoltaic and a 40% in low thermal temperature, it would result in a ratio of $\frac{\eta_{PV}}{\eta_T}$ 0.25>0.15, which would require lower photovoltaic than thermal area. Specifically, according to Eq.21, for every m^2 of photovoltaic surface, it would be needed 1.66 m^2 of solar thermal collectors.

By contrast, maintaining a ratio EER_{CMAX}/EER_{AMAX} of 6.66 considering the same photovoltaic yield, for requiting less solar thermal surface, this installation would need an efficiency higher than 66.6%

Case 3.- Potential of the thermodynamic cycle and the solar technology simultaneously

In this case the maximum yields are of the compression EER_{CMAX} and absorption refrigeration cycles EER_{AMAX} are assumed according to the Second Law of Thermodynamics and simultaneously assuming current maximum yields both for the photovoltaic η_{PVmax} and solar thermal η_{Tmax} technologies.

In this case it will be attached a photovoltaic collecting area $A_{PV31,}$ and a sollar thermal collecting area A_{T31} without concentration and a photovoltaic collecting area $A_{PV32,}$ and a solar thermal collecting area A_{T32} with concentration.

Substituting in the equations in the case of non-concentration of the solar radiation it results:

$$Q_{coolPV1} = EER_{CMAX} \cdot \eta_{PVMAX} \cdot H \cdot A_{PV31} \quad [24]$$

$$Q_{coolT1} = EER_{AMAX} \cdot \eta_{TMAX} \cdot H \cdot A_{T31} \quad [25]$$

For the same cooling effect, $Q_{coolPV31} = Q_{coolT31}$, substituting on equations 5 and 11 the EER_{CMAX} y EER_{AMAX}, it results:

$$\frac{A_{T31}}{A_{PV31}} = \left(\frac{1}{1-\frac{Tb}{T_T}}\right) \cdot \frac{\eta_{PVMAX}}{\eta_{TMAX}} \quad [26]$$

For a range of $\frac{\eta^C_{PVMAX}}{\eta^C_{TMAX}}$ between 0.2 y 0.9 and for a Tb/T_T entre 0.4 y 0.75, it results the attached graph:

Similarly to the case of concentrated solar radiation there is an expression:

$$\frac{A_{T32}}{A_{PV32}} = \left(\frac{1}{1-\frac{Tb}{T_T}}\right) \cdot \frac{\eta^c_{PVMAX}}{\eta^c_{TMAX}} \quad [27]$$

Substituting the designated maximum efficiency ranges it results the figure 5 in the case of non-concentration of the solar radiation

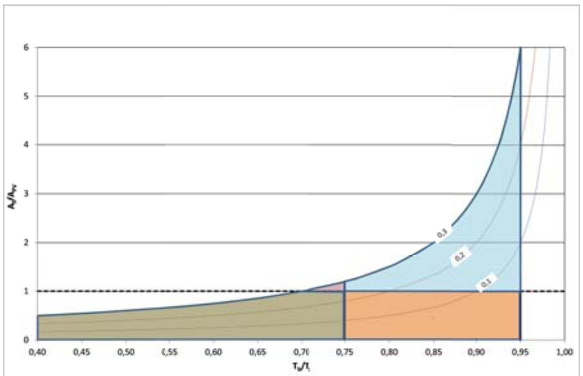

Figure 5: Equation 27 solved by substituting the designated maximum efficiency ranges.

It is noted as the operating points above the horizontal line $\frac{A_{TAmax}}{A_{PVCmax}}$ =1 corresponds to the region where the photovoltaic technology requires fewer surfaces than the thermal technology. For flat thermal or vacuum tubes collectors, where there is no concentration of solar radiation, $\frac{Tb}{T_T}$ is usually higher than 0.75, resulting that it would be preferable the use of photovoltaic in ranges of $\frac{\eta_{PV}}{\eta_T}$ between 0.01-0.25. When increased the ratio $\frac{Tb}{T_T}$ and the ratio $\frac{\eta_{PV}}{\eta_T}$, the area AT_{AMAX} increases as well.

6 CONCLUSIONS

We have determined the minimum area ratio required to meet the same cooling demand on the same site through the use of solar thermal and photovoltaic technology, depending on the performance of the respective facilities and the corresponding cycle performance.

At the area ratio for reversible compression and absorption cycles, it was found that only depends on the ratio of the hot spot temperature of the refrigeration cycle, Tb and thermal fluid temperature of the solar thermal installation T_T, being independent to the temperature of the cold spot.

$$\frac{A_T}{A_{PV}} = \left(\frac{1}{1-\frac{Tb}{T_T}}\right) \cdot \frac{\eta_{PV}}{\eta_T} \qquad [28]$$

Solved for different situations on figure 6:

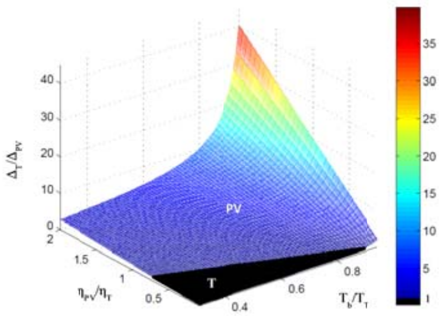

Figure 6: Equation 28 solved in a three dimension graphic for the different proposed scenarios.

In the case of a relation $\frac{\eta_{PV}}{\eta_T}$ of 0.25; 0.3; 0.5and considering Tb=300 K, it would be required less photovoltaic than solar thermal surface as long as T_T is smaller than 399.9 K, 428.57 K and 600 K respectively.

The obtained results show that, for cooling production, the solar PV has a greater ability to benefit from the technological point of view, than a solar thermal system in which there is no concentration of solar radiation, when T_T can never be high.

Even with the current values of efficiency of the photovoltaic and thermal systems, a lower surface of photovoltaic installation may be required when the solar thermal installations operates at temperatures T_T lower than about 340 K.

This suggests that it should be encouraged the use of solar photovoltaic power versus the low temperature solar thermal power in cooling production.

In the case of using solar thermal installations of flat collectors and vacuum tubes for cooling production auxiliary thermal energy should be used to increase the input fluid temperature at the cycle in order to increase the efficiency of the cycle.

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