A comparative study of solar cooling technologies

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Abstract. The environmental impacts of refrigeration and air conditioning applications include synthetic refrigerant fluids use and the high demand for electrical energy for activation, being critical in places whose energy mix depends on fossil fuels. Brazil has advantages due to hydroelectricity and the high incidence of solar irradiation, enabling solar energy technologies in refrigeration cycles. This work aims to study the technical-economic feasibility of photovoltaic energy to drive the vapor compression refrigeration system, and solar thermal energy for the ammonia-water and water-lithium bromide absorption cycles. It developed thermodynamic models of both vapor compression and absorption cycles using the mass and energy conservation equations under steady-state regime. The systems of linear equations were solved by using the *Engineering Equation Solver - EES*. One obtained the air conditioning thermal load profile and the characteristics of the thermal collectors and photovoltaic panels from *EnergyPlus*, from São Paulo-Brazil solar irradiation. Results showed that the monthly energy consumption is reduced from 626 kWh to 196 kWh, achieving a 44% reduction in the value of the electric energy bill for the photovoltaic solar cooling proposed when compared to the conventional one. A 7-years payback time is achieved. For the absorption cycle, the use of a flat thermal collector is unfeasible due to the need for natural gas as a complementary source of energy. It is concluded that solar cooling with photovoltaic has advantages compared to thermal activation, as the overall efficiency has a performance 30% higher than solar cooling by the thermal collector. Results showed that $PREU_{PV}$ is always higher than $PREU_{ST.}$

Keywords. Solar refrigeration, Solar Energy, Absorption refrigeration cycle, Ammonia-water, Water-lithium bromide.
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1. Introduction

Air-conditioning refrigeration systems are widely used in commercial buildings to ensure thermal comfort. Compression refrigeration systems are the most commercially used type and convert electrical energy into cooling. However, it presents a high energy consumption and causes energy peaks on the power grid. In addition, air-conditioning system might be responsible for 60% to 80% of the energy consumed in commercial and public buildings [1].

Alternatively, the integration of solar-powered refrigeration systems, known as solar refrigeration, can reduce or eliminate the demand for electrical energy from conventional energy sources. In this way, renewable energy presents a good alternative because of the lower emission of greenhouse gases (GHG) throughout its life cycle, guaranteeing a safe energy supply. The potential depends on exploiting locally available resources and overcoming environmental challenges [2].

The high solar radiation in Brazil favors solar energy capturing and converting into electrical energy or thermal energy. Compression refrigeration cycles require electrical energy, while absorption refrigeration cycles use thermal energy. The most common absorption cooling systems working fluids are ammonia-water and water-lithium bromide. The ammonia-water is employed in applications including refrigeration systems with temperatures below 0°C [3,4]. The water-lithium bromide is used for air-conditioning applications due to the limitations of the water thermodynamic properties.

Three main groups that characterize the technologies available for solar refrigeration are solar photovoltaic, solar thermal, and hybrid. [5] found a return of investment of 22% to 28%, considering an air-conditioning system with photovoltaic energy for two Brazilian cities, São Paulo and Recife. It is worth mentioning that these technologies should be evaluated as a whole by modeling the refrigeration cycles by compression and absorption to coupling with thermal solar energy. Furthermore, there is no study in the literature comparing different solar refrigeration technologies and providing performance characteristics under the same operating conditions.

This work aims to study the technical-economic feasibility of the vapor compression refrigeration system using photovoltaic energy for partial or total activation, and solar thermal energy for the ammonia-water and water-lithium bromide absorption cycles. To evaluate each of the solar refrigeration settings, it was defined the simple return time and the energy conversion rate dimensionless factor between the input or primary power and the cooling capacity ($kW_{Ref.}/kW_{Prym.}$).

2. Solar refrigeration modeling

Next, the main refrigeration systems are detailed: the vapor compression refrigeration cycles (VCRC) and the absorption refrigeration cycles (ARC). These technologies are coupled with photovoltaic (PV) solar energy, and solar thermal (ST) energy, respectively.

2.1 VCRC driven by PV solar energy.

Figure (1a) shows the simple solar cooling configuration of a VCRC coupled with the PV solar energy under an on-grid electrical connection. VCRC mainly consists of a compressor, condenser, evaporator, and expansion valve. The compressor raises the pressure of the refrigerant gas, which carries out the working fluid from the low-pressure (7) to high pressure (4) sides, increasing the gas temperature at the compressor discharge. Then, the condenser rejects the heat in the high-pressure stage to condense the refrigerant (5). Next, an expansion valve reduces the pressure in an isenthalpic process, and the temperature also decreases due to the Joule-Thomson effect. As a result, a two-phase mixture is achieved in the evaporator inlet with a predominance of the liquid phase (6). After the cooling effect is provided, the refrigerant vapor is directed to the compressor, starting the refrigeration cycle again.

The electrical power demanded by the compressor is supplied by using the group of photovoltaic cells at times of high solar irradiation, and complemented by the electrical network during intermittency, a typical characteristic of renewable energy sources.

To cycle modeling, the mass and energy conservation equations are used. Equation (1) refers to the mass conservation equation for an open control volume in a steady-state regime. Equation (2) defines the conservation of refrigerant species or absorbent fluid, and equation 3 represents the energy conservation, neglecting changes in kinetic energy and potential energy.

$$\sum_{in}^{i} \dot{m}_i = \sum_{out}^{j} \dot{m}_j \qquad (1)$$

$$\sum_{in}^{i} x_i \dot{m}_i = \sum_{out}^{j} x_j \dot{m}_j \qquad (2)$$

$$\dot{Q} - \dot{W} = \sum_{out}^{j} \dot{m}_j h_j - \sum_{in}^{i} \dot{m}_i h_i \qquad (3)$$

2.2 ARC driven by ST energy

Figure (1b) shows the single-stage ARC driven by using ST energy. In contrast with conventional VCRC, ARC demands thermal energy in the generator to separate the refrigerant fluid of the absorbent. So, electrical power is substituted by a thermal compressor system. The ammonia-water not only might be employed in air-conditioning systems but also in freezing applications.

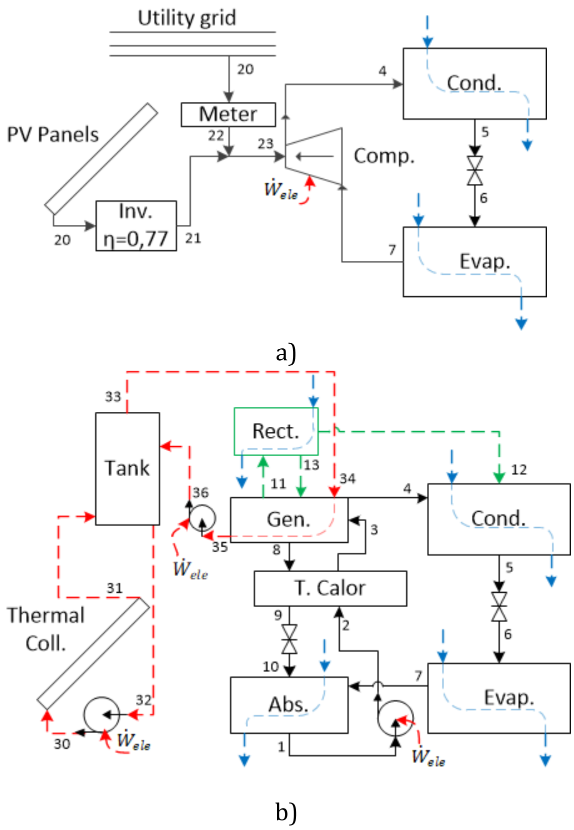

Fig. 1 - Schematic representation of solar refrigeration: a) VCRC coupled with PV solar energy, and b) ARC driven by ST energy.

In ARC, the vapor refrigerant produced in the generator (4) is led to the condenser, expansion valve, and evaporator as a conventional VCRC. The vapor refrigerant leaving the evaporator (7) is absorbed by the absorbent solution becoming the generator (8) after passing the heat recovery (9) and the expansion valve (10). Thus, the solution is pumped to the generator (3) to restart the cycle. For ammonia-water working fluid, a rectification system is coupled to increase the ammonia vapor purity as shown in Figure (1b), points 11, 12, and 13.

Figure (1b) depicts the ARC coupled with the ST energy. A hot water storage tank stores the water of the ST circuit, which is employed to drive the ARC. A natural gas burner is applied to supplement heat for the operating ARC during the low irradiation periods. Similarly, equations 1-3 are employed for ARC modeling.

The coefficient of performance (COP) is defined to evaluate these cooling technologies. The COP sets the ratio between the cooling capacity and the energy rate provided to the cycle. The VCRC uses the compressor's electrical power, and the ARC utilizes the generator. The electrical power of the solution pump is neglected.

Thermodynamic modeling for VCRC and ARC systems is performed with the *Engineering Equation Solver - EES* program. One solved the mass and energy conservation equations as a control volume under steady-state conditions. The results from the thermodynamic model have integrated with the results from the TS collectors and PV panels modeling. A case study of an office environment is defined with a typical thermal load profile and air-conditioning system. The *EnergyPlus* tool is used to evaluate the performance of solar refrigeration technologies.

2.3 Office building case study

An office building with 10.0 m x 10.0 m x 2.8 m in São Paulo is defined as the thermal zone, which is characterized by Cfa humid subtropical climate at Koppën-Geiger classification. The North and West walls are set as external walls with a 45% glazed area, while the East and South are adiabatic. The vertical closures are set with masonry, with a U-factor of 2.3 W/m^2°C, and 5.7 W/m^2°C U-factor laminated glass windows.

The simulation is carried out in *EnergyPlus* 9.4, on the 26th of January, which has a high global solar irradiation incidence according to the São Paulo climate file. The internal thermal loads are set by 5 m^2/person high occupancy density for office environments, 5.4 W/m^2 equipment power [6], and 14.1 W/m^2 lighting power density. The metabolic rate was approximately 110 W/person, a typical office activity [7]. The occupancy schedule was set 100% during most business hours, with 50% at lunchtime. Also, it was considered air renewal of 0.0025 m^3/s per person, plus 0.0003 m^3/s per meter square (m^2), adding up 0.08 m^3/s [8].

The panels were modeled with a 23° inclination from the horizontal in the North orientation. The photovoltaic panels achieved a cell efficiency of 20% with a photovoltaic generator of 150 W. The air-conditioning design settings were 12.4 kW refrigeration capacity demand, with 14 hours of daily operation (from 6 AM to 8 PM) totaling 420 hours per month. The condensation temperature was 45°C, and the evaporation temperature, 7°C. The inverter efficiency was 0.77, and the photovoltaic energy was an on-grid type, generating 20.9 kWh/day or 626 kWh/month. São Paulo's power distribution company defines tariff groups in which the energy cost depends on the contracted demand and peak hour consumption. After modeling it, we used the predictive method proposed by [9] to compare the thermal load profile of the *EnergyPlus* model.

Results of the VCRC and ARC modeling are shown in Table (1). The COP is computed by using an isentropic compression and pumping process. The heat rates are determined for each component of the cycle, for instance, $\dot{Q}_{abs}$ is the rejected absorber heat duty, $\dot{Q}_{gen}$ is the demanded generator heat duty, $\dot{Q}_{con}$ is the removed condenser heat duty, $\dot{Q}_{rec}$ is the removed rectifier heat duty, and $\dot{W}_{ele}$ is the consumed compressor electrical power. It is worthwhile to mention that VCRC only requires electrical power to be driven.

Tab. 1 - Heat duty and power for each component in the cooling technologies.

	Results for $\dot{Q}_{eva}$=12.4 kW, T_{con}=45°C, T_{eva}=7°C,
CRA-H_2O-LiBr COP=0.88	$\dot{Q}_{abs}$=14.0 kW; $\dot{Q}_{gen}$=14.3 kW; $\dot{Q}_{con}$=12.9 kW
CRA-NH_3-H_2O COP=0.68	$\dot{Q}_{abs}$=18.6 kW; $\dot{Q}_{gen}$=19.3 kW; $\dot{Q}_{con}$=12.8 kW; $\dot{Q}_{rec}$=0.85 kW
VCRC-NH_3 COP=6.3	$\dot{Q}_{con}$=14.7 kW; $\dot{W}_{ele}$=2.13 kW

3. Results and discussion

3.1 VCRC driven by PV solar energy.

Figure (2) compares the electrical power required for the VCRC and the power converted by the PV cells throughout the day. The electrical VCRC consumption, obtained by using the *EnergyPlus* along with the COP_{VCRC}, is consistent with the predictive method proposed by [9]. It can be noted that electrical power required by the air-conditioning system follows the same fashion of the photovoltaic energy conversion curve, enabling the solar refrigeration. However, the complementarity with the on-grid electrical grid is mandatory for the activation where energy demand is greater than the solar energy supply. It is determined that the simple payback time is 7 years.

For the case study of São Paulo-SP (Brazil), the results established a photovoltaic area equivalent to approximately 75% of the climatized area, with a power generator equivalent to 2.23 kWp. The monthly energy consumption is reduced from 626 kWh to 196 kWh, achieving a 44% reduction in the value of the electric energy bill for the photovoltaic solar cooling proposed when compared to the conventional one. Reductions in the electricity bill are limited, as the refrigeration system demand coincides with the low conversion time of photovoltaic energy, i.e. in the first and last hours of the day, and due to the difference in the invoice value at peak hours. On the other hand, the option of photovoltaic generation at off-peak hours to generate credits and consume at peak hours is economically unfeasible, since five times more energy must be generated at off-peak hours to consume at peak hours, demanding greater investment in the photovoltaic collectors acquisition.

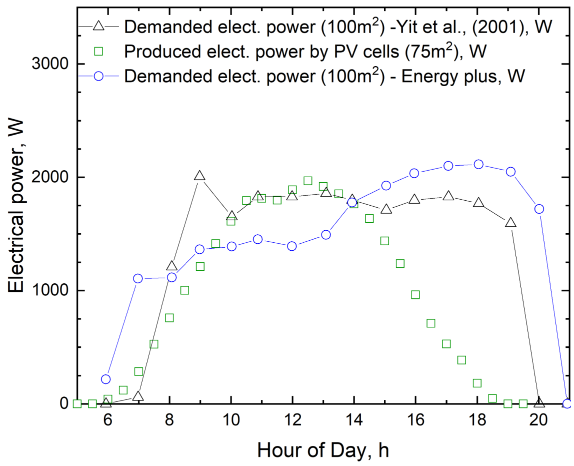

Fig. 2 - Electrical power comparison between the demanded air-conditioning system (VCRC) and the PV generation as a function of the time.

The same analysis was run in five cities with different latitudes to check PV energy generation: Abu Dhabi (24.43°N) in the United Arab Emirates, Acapulco (16.77°N) in Mexico, Bucharest (44.5°N) in Romania, Munich (48.13°N) in Germany, and Seville (37.42°N) in Spain. PV collectors were oriented South and inclined according to their maximum theoretical efficiency.

Simulations were run according to the weather file day's maximum value of incident solar radiation. In this way, the days selected for the cities and the panels' inclinations were Abu Dhabi (May 14/25°), Acapulco (Apr 20/20°), Bucharest (Jun 20/34°), Munich (Jun 9/37°), and Seville (Jun 11/33°).

The daily irradiation was obtained through the design day and converted to solar energy. The energy generated per day was 39.21 kWh for SãoPaulo, 37.31 kWh for Abu Dhabi, 37.19 kWh for Acapulco, 41.36 kWh for Bucharest, 38.63 kWh for Munich, and 39.8 kWh for Sevilla. When comparing these values to São Paulo solar energy generation, given the PV relative performance, results demonstrated that Seville and Bucharest presented positive relative performance of 1.5% and 5.2%, respectively. Abu Dhabi, Acapulco, and Munich showed negative PV relative performance of -5.1%, -5.4%, and -1.5%. Even though Abu Dhabi has a subtropical desert climate, with high solar irradiances peaks, the accumulated energy generated by the PV cells was lower than in São Paulo because of the incidence of radiation distribution along the day on May 14th.

The solar energy generation was similar among the cities, given the highest solar radiation incidence day criteria. Even in different latitudes, it is possible to assign PV solar energy, but it is necessary to consider solar geometry and solar radiation power local characteristics.

3.2 ARC driven by ST energy

Results of solar cooling modeling using the H_2O-LiBr ARC are presented in Figure (3). The thermal load profile is similar to that modeled with the VCRC, as can be seen in Figure (3a). However, the thermal power demanded by the generator, obtained by using the *EnergyPlus* along with the COP_{ARC}, should be constant throughout the day, since ARC does not have the ability to operate at partial loads like VCRC. For the activation of the cycle, thermal solar collectors with a total area equivalent to 35 m^2 are defined.

The study determined that natural gas to complement the water-lithium bromide ARC is economically unfeasible, since the monthly natural gas consumption bill reaches up to three times the value of the local electricity bill when compared to the refrigeration driven with the conventional energy source.

While the water-lithium bromide mixture demands temperatures above 76 °C in the generation process, as shown in Figure (3b), the ammonia-water separation process can require temperatures close to 100 °C. Thus, the economic return is even more critical in the operation of the ARC by using the ammonia-water mixture, due to the higher energy demand and higher operating temperatures of the generator. It is evident that cogeneration can be a better application for the use of ARC, since the residual use of thermal energy can be replaced by the direct burning of natural gas.

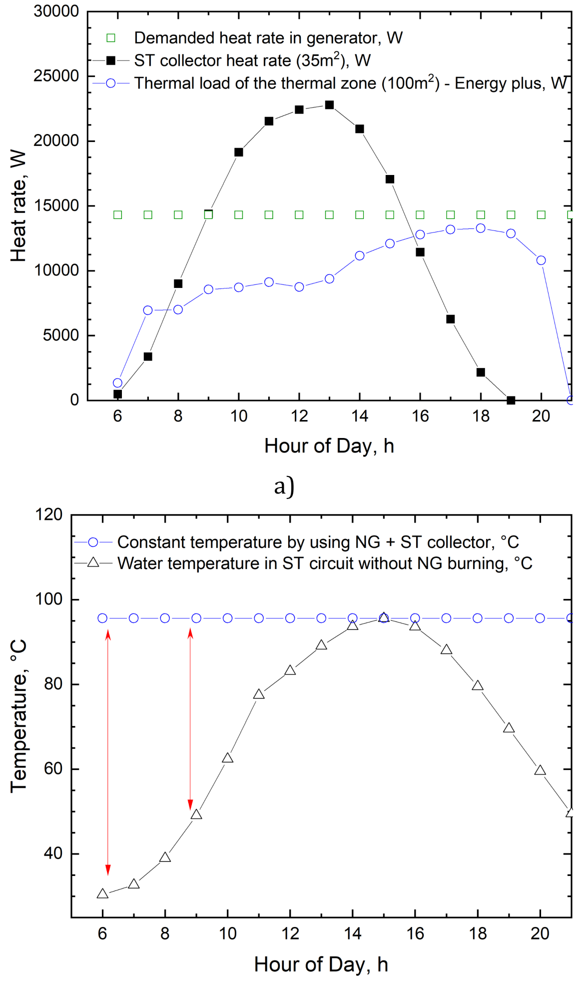

Fig. 3 - Thermal power comparison between the demanded air-conditioning system (ARC) and the ST collector as a function of the time.

3.3 Primary Energy Usage - PEU and Primary Renewable Energy Usage - PREU

Considering the characteristics of the Brazilian electricity mix, which is composed mainly of hydroelectric and thermoelectric plants, as shown in Table (2), an energy conversion rate efficiency of 55.3% is determined [10]. Thus, the Primary Energy Usage – PEU is defined to take into account the energy conversion rate efficiency. This means that for a refrigeration capacity of 12.4 $kW_{Ref.}$, a 3.4 kW_{Prim} of input power is required from the utility grid when operated with a VCRC with a COP of 6.3. In other words, 3.61 $kW_{Ref.}$ cooling capacity are supplied for every 1 $kW_{Prim.}$ of primary energy from the Brazilian electricity mix.

To evaluate solar refrigeration, the Primary Renewable Energy Usage – PREU is defined, considering the energy conversion rate efficiency. For photovoltaic solar cooling, it is found that 1 kW_{Sol} is converted into 0.72 $kW_{Ref.}$ cooling capacity. Finally, ARC are characterized by performances of 0.55 $kW_{Ref.}$ and 0.42 $kW_{Ref.}$ for the water-lithium bromide and ammonia-water solution, respectively.

Tab. 2. A comparison between the PEU (Brazil) and PREU for solar refrigeration.

	Value - $kW_{Ref.}/kW_{Prim\text{-}Sol}$
PEU - VCRC + Utility grid	3.61
$PREU_{PV}$ - VCRC + PV	0.72
$PREU_{ST}$ - NH_3-H_2O ARC+ST	0.42
$PREU_{ST}$ - H_2O-LiBr ARC+ST	0.55

These cooling technologies are a function of the operating parameters such as condensation temperature, evaporation temperature, absorption temperature, and generation temperature, just to mention a few.

Based on the refrigeration cycles simulations, a sensitivity analysis of the COP for different evaporation temperatures was run, fixing the condensation temperature and the other operating parameters of the absorption cycle. Results show a decrease in the COP for lower evaporation temperatures; which affected mainly the compression refrigeration cycles.

Figure (4) comparatively presents the energy conversion rate - PEU ($kW_{Ref}/kW_{Prim.}$) and PREU ($kW_{Ref}/kW_{Sol.}$) as a function of the refrigeration cycles evaporation temperature. The use of refrigeration systems with energy from the electricity grid is convenient as compared to the other ones due to the high conversion rates. A 62.5 % hydroelectricity contribution in the Brazilian electrical mix is achieved, explaining the PEU behavior. For solar cooling, the PV solar energy with VCRC should be used for HVAC applications, as this configuration has an advantage when compared to absorption cycles, including water-lithium bromide. On the other hand, ARCs with ammonia-water solar thermal collectors could be used in frozen food refrigeration applications, or in cogeneration.

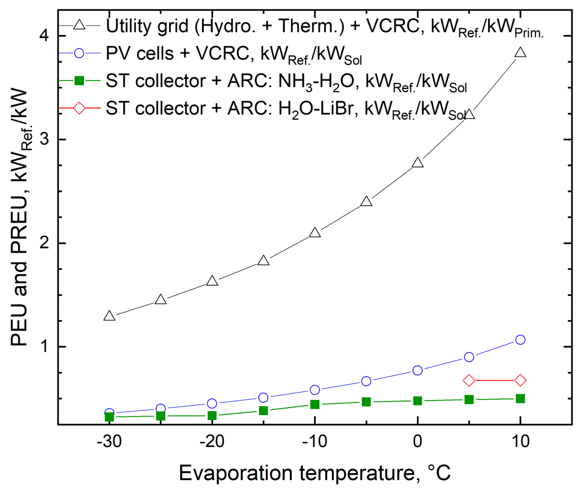

Fig. 4 - PEU and PREU as a function of the evaporation temperature of the cooling technologies.

Spite of the use of conventional hydroelectric energy has better performance than solar renewable sources, more energy demand is growing, thus, solar refrigeration might become a solution for several applications, even though, its usage can be extended for isolated places or as a part of the distributed generation.

4. Limiting efficiency of solar refrigeration

The limiting efficiency of solar refrigeration is defined as a function of the theoretical efficiency of each component. For the PV cells, a tandem solar cell system is calculated by [11]. Semiconductor properties might be neglected over the conversion efficiencies, achieving 68% at 300K when unconcentrated sunlight is employed for one sun. A 33.3 % theoretical maximum efficiency is obtained for a single-junction solar cell [12]. On the other hand, ST collectors might achieve about 80% of the conversion efficiency for extremely low water flow rates. However, the efficiency is a function of the water inlet temperature, surface temperature, glass transmittance, etc. Thus, a 100% of thermal efficiency for the ST collector was assumed, in which no losses are defined.

The theoretical efficiency for refrigeration systems is defined by using Carnot's theory. Efficiencies are only limited by defining the operating temperature; vaporization temperature (eva), generation temperature (gen), absorption temperature (abs), condensation temperature (con). Equation 1 and 2 represent the coefficient of performance for the ARC and the VCRC, respectively. Temperature must be defined as the absolute temperature.

$$COP_{ARC} = \frac{T_{eva}}{T_{gen}}\left(\frac{T_{gen}-T_{abs}}{T_{abs}-T_{eva}}\right) \quad (1)$$

$$COP_{VCRC} = \frac{T_{eva}}{T_{con}-T_{eva}} \quad (2)$$

Figure (5) shows the results of the limiting efficiency of solar refrigeration as a function of evaporation temperature for three different intensities of solar irradiance; 1.2, 1.0 and 0.8 kW/m^2. It can be seen that $PREU_{PV}$ is always higher than $PREU_{ST}$ due to the COP_{VCRC} are greater than COP_{ARC}, about five times for all evaporation temperature range. Moreover, the PREU of the solar refrigeration improves as the intensity of solar irradiance increases.

It can be noted that the operating conditions of the cycle strongly affects the PREU. Higher evaporation temperature and lower condensation temperature enhance the PREU for both cooling technologies. The PREU behavior is more sensible to the operating temperatures than the intensity of the solar irradiance.

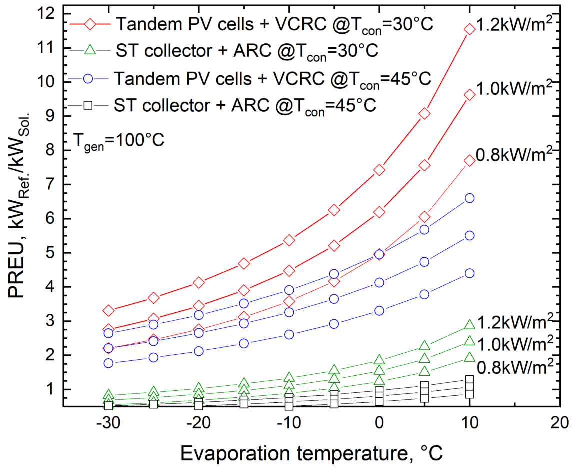

Fig. 5 - PREU of the solar refrigeration as a function of the evaporation temperature for 1.2, 1.0 and 0.8 kW/m^2 intensity of solar irradiance.

5. Conclusions

A study of solar refrigeration with PV cells with VCRC and ST collectors coupled to ARC was carried out. An office building case study was defined to compare both cooling technologies, showing that solar cooling with grid-connected photovoltaic systems might provide a 44% reduction of the electrical energy bill for the 100 m^2 air-conditioned space. The payback time was calculated in 7 years, as the acquisition cost of photovoltaic panels is relatively high.

The ARC solar cooling cycle driven by ST energy presented economic disadvantages compared to the VCRC, as it required energy integration with direct burning of natural gas. The average monthly billing of natural gas was three times higher than the local electric energy bill from the distribution company, making the system unfeasible. The payback time was even more critical for the ammonia-water absorption refrigeration cycle since it requires an even higher operating temperature.

Moreover, it was concluded that solar cooling through the use of PV energy has advantages as compared to ST collectors, as the overall efficiency allows achieving performance values 30% higher than solar cooling by the thermal collector. Even in different locations, those performance ratings are obtained, as the simulated cities presented similar results in energy efficiency. Despite its lower efficiencies, absorption refrigeration with a thermal collector cycle could be used in frozen food applications. Cogeneration can be applied for absorption refrigeration technology since the residual use of thermal energy may be replaced by the direct burning of natural gas.

Additionally, the direct activation of the VCRC with the primary energy use presents advantages over all the solar refrigeration configurations proposed in this work due to the Brazilian electrical mix having high efficiencies in the conversion by hydroelectricity. Finally, results showed that $PREU_{PV}$ is always higher than $PREU_{ST}$.

The constraints of this paper comprise a set of computational tests with simplified refrigeration modeling, and a hypothetical building and thermal load. Primary Renewable Energy Usage (PREU) present theoretical values. Future works may consider experimental investigation and model validation to compare different solar power supply arrangements.

6. Acknowledgement

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Data Access Statement

The datasets generated during and/or analyzed during the current study are not available because the study is under development and has not been finished yet, but the authors will make every reasonable effort to publish them in near future.