COMPARISON BETWEEN SOLAR THERMAL-POWERED ABSORPTION REFRIGERATION CYCLE AND PHOTOVOLTAIC-POWERED COOLING TECHNOLOGIES APPLIED TO DATA CENTERs

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Received: May 14, 2022

Revised: June 03, 2022

Accepted: June 05, 2022

ABSTRACT

The air conditioning system of a Data Center is a great challenge for mechanical engineers. At the same time, it is fundamental for computer safety, it is a great energy consumer. Considering that, the present work carried out an analysis in which a solar-powered absorption refrigeration cycle system is combined with a conventional electrical chiller system. The proposed system also introduces the use of PV panels to generate electricity to power the electric chiller. A decision algorithm was developed based on local solar parametric data and cooling demand. A case study was analyzed for a typical data center located in the city of São Paulo, Brazil. Electrical specific installed power demands of 0.5, 1.0, 2.0, 4.0, and 8.0 kW/m² at half and total load were studied. Local solar irradiation and temperature indexes were based on the data obtained from ASHRAE [1]. The results show that, for a typical year, the absorption solar system performs better than the photovoltaic system in most cases (0.5, 1.0, 4.0, and 8.0 kW/m²), except when the baseline of the installation operates near the optimum point of the consumption curve of the chiller, which occurs at 2 kW/m². Finally, the study shows that air conditioning systems powered by solar energy are a great alternative to reduce the energy consumption and operational costs of a Data Center.

Keywords: Air Conditioning, Absorption Refrigeration Cycle, Data Center, Solar Cooling

NOMENCLATURE

COP_{AB}	Absorption chiller Coefficient of performance (-)	$\dot{q}_E$	Heat flux demanded by cooling in absorption system (kW)
$\dot{q}_G$	Heat flux input in an absorption chiller vapor generator (kW)	η_{sol_heat}	Evacuated tube collectors efficiency (-)
I_n	Global Irradiance (kW)	C0	Constants for evacuated tube collectors (-)
C1 , C2	Constants for evacuated tube collectors (kW·°C-1)	η_{cins}	Yield of evacuated tube installation (-)
A_U	Solar collectors area	$\dot{W}_c$	Electric power of chiller (kW)
$\dot{C}_T$	Thermal load (kW)	COP_E	Electric chiller Coefficient of performance (-)
CH	Chiller Charge (Thermal Charge/ Cooling Capacity)	η_{sol_pow}	PV panels efficiency (-)
k_1,k_2	Constants for photovoltaic panel	k3, k4, k5, k6	Constants for photovoltaic panel (°C-1)
Tpanel	Temperature of surface panel (°C)	TBS	Dry bulb temperature of ambient air
I_T	Solar Irradiation (kW·m-2)	$h_{conv_{air}}$	Air convection coefficient (kW·°C-1·m-2)
η_{System}	Electrical system efficiency (-)	$\dot{W}_{PV}$	Power generation by photovoltaic panels (kW)
$\dot{W}_{STC}$	Constant of photovoltaic panel (W·m-2)	$\dot{I}_{pSTC}$	Constant of photovoltaic panel (W·m-2)
W_{acum}	Energy stored in battery banks (kWh)	t	Time of storage (h)
W_{ava}	Available energy (kWh)	$\dot{W}_U$	Power used for the batteries (kW)
tu	Time of utilization (h)		

INTRODUCTION

The electrical consumption for Data Center cooling steadily increases(Belizário, 2018; Belizário; José; Simões-Moreira, 2020; Papadopoulos; Oxidis; Kyriakis, 2003). In computer applications, as in data centers, the air conditioning system electrical demand can reach as much as 50 % of the final electricity bill (Strutt et al., 2012).

The goal of this paper is to compare a solar air conditioning system based on the solar absorption technology fed by hot water produced in evacuated tube collectors with a photovoltaic panel system that provides the electricity to power electrical chillers. The study analyzes which system is more advantageous from the overall energy saving point of view having both systems located in the same rooftop area.

According to Ashrae (Ashrae, 2016a), computers should operate in the 5 - 40°C range and in the 20 – 90 % relative humidity range. At A1 condition, the temperature must be between 15°C and 35°C and the relative humidity between 10% and 90%.

The climatization standard of Data Center states that temperature and humidity must be controlled at the inlet of the computer and servers, without any control in the discharge(Ashrae, 2016a; Strutt et al., 2012). This procedure reduces investments and operational costs, increases data processing efficiency, and reduces maintenance stops(Ashrae, 2016b).

SOLAR COOLING

Solar cooling techniques are basically classified as electric solar photovoltaic and thermal solar (Kim; Ferreira, 2013; Sarbu; Serbachievi, 2013), as schematically shown in Figure 1. The transformer energy elements (solar collectors and engines) are presented in diagonal stripes squares, the electrical chillers are presented in spotted squares, and the thermal chillers are presented in horizontal stripes squares.

Photovoltaic cooling and thermal absorption systems are more developed methods than others(Kim; Ferreira, 2014; Lazzarin; Noro, 2018; Schiavon Ara, 2010); therefore, the analysis is focused on those two technologies.

Thermal solar cooling by heat transformer based on absorption chillers.

The solar energy powered absorption refrigeration chiller operates with hot water (Kohlenbach; Jakob, 2014; Lazzarin; Noro, 2018), as shown in Figure 2. The total radiation is absorbed by the solar collectors and boils the water (A) that flows to a hot water storage tank (B). The hot water goes to the vapor generator in the absorption chiller (C). Heat input $\dot{q}_G$ is an energy heat flux provided by an external source (in this case, solar power) to distillate the fluid mixture to release the cooling fluid that causes the refrigeration effect(Hassan; Mohamad, 2012; Kim; Ferreira, 2014; Lazarin, 2014).

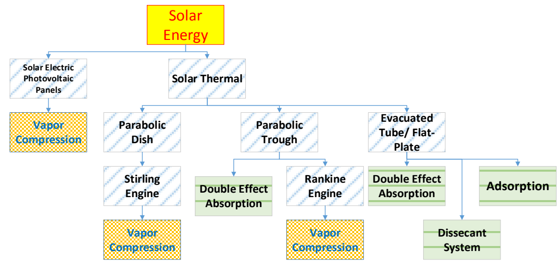

Figure 1 – Alternative ways of solar cooling, Adapted from (Kim; Ferreira, 2014).

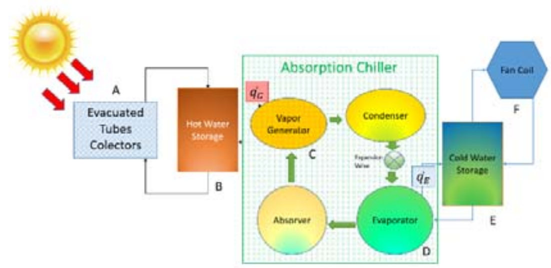

Figure 2 - Solar Absorption cooling procedure(Belizário, 2018; Belizário; Simões-Moreira, 2020).

A challenge in a Solar Thermal system is energy storage. Two strategies can be utilized: Hot Storage of thermal fluid provided by collectors (B) or Cold Storage of chilled water provided by chillers (E). A capacity of storage is dependent on the overall heat transfer coefficient, directly dependent on the construction material of the storage tank.(Kalogirou, 2004; Lazarin, 2014)

. In this work, the strategy was to store a minimum hot fluid to prevent chiller intermittences and storage cold water for 3 hours to utilize according to the Electricity tariff strategy.

$$\mathrm{COP_{AB}} = \frac{\dot{q}_E}{\dot{q}_G} \tag{1}$$

The efficiency of a solar collector strongly depends on its working temperature along with other parametric values as given by Eq. (2) and (3) (Infante Ferreira; Kim, 2014)

$$\eta_{sol\_heat} = C_0 - C_1.x - C_2 \cdot I_n \cdot x^2 \tag{2}$$

$$x = \frac{(T_{collector} - T_{ambient})}{I_n} \tag{3}$$

I_n (kW) is defined by the global irradiance for non-concentrating collectors, and the values of C_i coefficients to evacuate the tube solar collectors: C_0 = 0.84, C_1 = 2.02 kW·°C^{-1}, and C_2 = 0.0046 kW·°C^{-1} as given by (Gerbreslassie et al., 2010). In a solar system, there are other heat losses, such as heat transfer in pipes and in the thermal storage tank, which can reach 6% on average(Belizário; Simões-Moreira, 2017). Equation (4) takes into consideration those other heat losses

$$\eta_{cins} = \eta_{sol\_heat} \cdot (1 - \text{losses}) \quad (4)$$

The overall heat flow delivered to the collector, $\dot{q}_G$, is given by Eq. (5)

$$\dot{q}_G = A_U \cdot \eta_{cins} \cdot I_n \quad (5)$$

where, A_U is the collector area (excluding shading).

2.2. PV Cooling

A photovoltaic electric cooling system basically consists of a conventional electric chiller powered by photovoltaic electricity(Kohlenbach; Jakob, 2014; Lazzarin; Noro, 2018; Mokhtar et al., 2010). In this case, the total irradiation (direct + diffuse) is captured by the photovoltaic cells and transformed into electric energy (A). A charge controller (B) is also part of the system. Typically, PV panels are either grid connected or off grid. The first way would be to connect inverters to the public electric grid (E) either exporting or importing electric energy depending on the balance of consumption and production. This configuration depends on local rules and regulations. The second way is to provide energy to power a battery bank (C) to provide electric energy as needed. In any case, frequency inverters must be installed (D) for regulating the frequency and for transforming DC voltage into AC voltage. Losses are associated with photovoltaic panel efficiency, transmission, inverter yields and battery banks(Balaras et al., 2007; Belizário; Simões-Moreira, 2019).

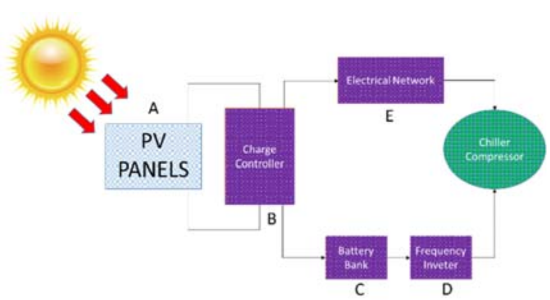

Figure 3 – Photovoltaic cooling procedure. (Belizário, 2018; Belizário; Simões-Moreira, 2019)

The energy efficiency is measured by the ratio between the power available from photovoltaic cells and the power used in chillers.

3. Environmental Conditions

For this work, we considered weather data for the city of São Paulo, Brazil, for a 24-hour period in 2016 (Ashrae, 2017), namely: dry bulb temperature, wet bulb temperature, solar irradiation per square meter, and direct irradiation per square meter.

To carry out the analysis, a typical data center plant was adopted and the associated facilities, as schematically shown in Figure 3. For this building, the 625 m² data hall was the only conditioned area (blue square), out of the 2030 m² total building area. The solar collectors were installed on the rooftop of the total building area (2030 m²).

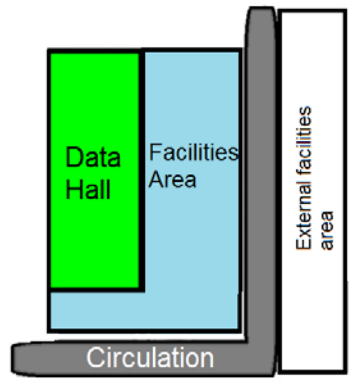

Figure 4 – Data Center plant analyzed.

The cooling load comprised the computer loads (we here considered 0.5 kW/m², 1 kW/m², 2 kW/m², 4 kW/m² and 8 kW/m²) and the environmental loads caused by irradiation, air infiltration, illumination, partition and people occupancy. The environmental loads are estimated around 270 kW, and the main factor component in Thermal Load is the computer dissipation (Belizário, 2018).

Conventional air conditioning systems use 24-h non-stop electric chillers. The power consumption by the chillers can be obtained from manufacturers data sheet and it can be calculated(Belizário, 2018; Trane, 2017) by Eq. (6) for the given thermal load to a chiller powered by a screw compressor. For other load densities, this equation would be corrected as suggested by (Belizário, 2018; Trane, 2017).

$$\dot{W}_c = -2 \cdot 10^{-7} \cdot \dot{C_T}^3 + 0{,}008 \cdot \dot{C_T}^2 - 0.7875 \cdot \dot{C_T} + 316.576 \quad (6)$$

Another important piece of information is the variation of the coefficient of chiller performance versus the required load of the equipment. Figure 5 shows the COP_E variation versus the percentage load equipment. The chiller mostly operates at partial load. This phenomenon is extended to combine the use of the solar thermal system and conventional electric chiller. Eq. 7 presents the third degree polynomial interpolation, with $R^2 = 0.9937$.

$$COP_E = 14.507 \cdot CH^3 - 36.005 \cdot CH^2 + 27.321 \cdot CH - 0.6495 \qquad (7)$$

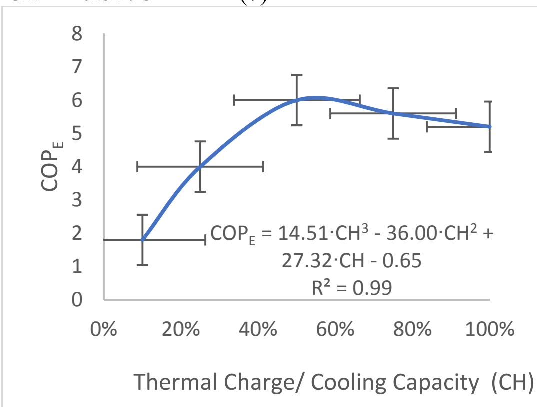

Figure 5 – Performance Curve of the complementary chiller(Trane, 2017)

Figure 5 presents the chiller curve, showing the chiller has the maximum performance around 60% of charge; however, for lower thermal charges, above 50%, the COPs are smaller than the thermal charges over 50%.

For solar absorption, the authors worked out a configuration in which during the day, water is heated by evacuated tubes and flows to a thermal storage tank. At hours when the electric bill is steeper (In Brazil, between 5:00 PM and 8:00 PM (Aneel, 2015)), the system works with the absorption chiller alone rather than the electric system. The system must provide air conditioning when the cold water storage is full at regular hours to relieve the electrical consumption in non-peak hours. The capacity cooling is estimated by Eq. (8), a combination between Eqs. (1) and (6). Solar Irradiance I_n is a value extracted during a correlated day according to the Ashrae database(Ashrae, 2017) on an inclined surface, calculated by the Liu e Jordan Model(Duffie; Beckman, 2006; Orgill; Hollands, 1977; Pacheco, 2017). The proposed equipment is a double-effect absorption chiller presented by (Lg, 2017) having a COP equal to 1.5. In this case, value q_E refers to the necessary cooling energy provided by a solar system.

$$q_E = COP \cdot A_U \cdot \eta_{collectors} \cdot I_n \qquad (8)$$

$$R_E = C_T - q_E \qquad (9)$$

If after the hours when the electric bill is more expensive, there is accumulated hot water at a proper temperature, the system is able to provide air conditioning. Figure 6 presents this proposition with a flowchart. The figure depicts the options for using solar thermal cooling with thermal storage and the alternative electric chiller. It also shows the PV Cooling strategy.

For PV Panels, this paper proposes that, during the day, when there is solar radiation, the collected energy is stored in a battery bank at hours when the electric bill is higher (In Brazil, between 5:00 PM and 8:00 PM), when the electric storage is full, the system can provide energy to the chiller in support to the electrical network.

The first step (η_{sol_pow}) is the PV panels efficiency. The calculation is presented in Eq. (9) (Huld et al., 2010):

$$\eta_{sol\_pow} = \{1 + k_1 \cdot \ln I_T + k_2 \cdot (\ln I_T)^2 + T_{panel} \cdot [k_3 + k_4 \cdot \ln I_T + k_5 \cdot (\ln I_T)^2] + k_6 \cdot T_{panel}^2\} \cdot \eta_{system} \qquad (9)$$

k_i values are presented in Table 1.

Table 1 – Constants for PV panels in Eq. (9). (Huld et al., 2010)

Constants for the PV					
k_1	k_2	k_3 (°C^{-1})	k_4 (°C^{-1})	k_5 (°C^{-1})	k_6 (°C^{-1})
-0.01716	-0.04029	-0.00468	0.000148	0.000169	0.000005

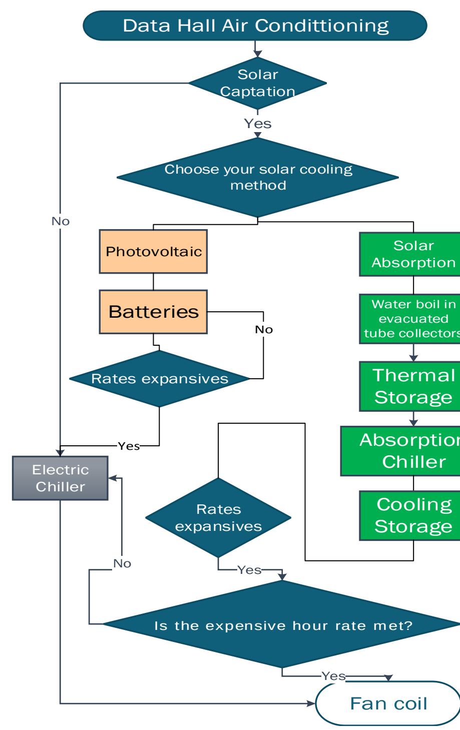

Figure 6 – Analyzed system operation flowchart

The PV electric power generation ($\dot{W}_{PV}$) is estimated by Kalougiru (Kalogirou, 2004) according to Eq. (10). The other constants considered are $\dot{W}_{STC}$ and $\dot{I}_{pSTC}$, respectively 150 Wm^{-2} and 1000 Wm^{-2} obtained in laboratory tests.

$$\dot{W}_{PV} = \dot{W}_{STC} \cdot \frac{\dot{I}_T}{\dot{I}_{pSTC}} \cdot \eta_{sol\_pow} \qquad (10)$$

The electric energy generated is stored in battery banks (W_{acum}), which can be calculated according to equation (11). Variable t indicates the time the energy is stored.

$$W_{acum} = \int_0^t \dot{W}_{PV}\, dt \quad (11)$$

In a previous schedule, those batteries are discharged for powering the chillers. The available energy (W_{ava}) will be the accumulated energy (W_{acum}), less the power used for the batteries ($\dot{W}_U$) in a time of utilization t_u, as shown in Eq. (12).

$$W_{ava} = W_{acum} - \int_0^{t_u} \dot{W}_U\, dt_u \quad (12)$$

4. Performance Analysis of Solar Cooling

According to the State of São Paulo Database, the thermal load was calculated in 1-hour periods for the five selected computer dissipation densities. The thermal load accumulated (C_T) is provided by the E-20 program (Carrier Corporation, 2016) and the results for different loads in a typical year are given in Table 2. The maximum hour thermal load is important because this value is the baseline to select the capacity of the chiller and our correlating curve.

Another important value presented in Table 2 is the chiller annual electrical consumption. These values correspond to the sum of the 8,760 consumption hour chiller. Local weather data are given by reference (Ashrae, 2017).

Table 2 - Thermal load and electrical consumption by a conventional system.

Installation (kW/m^2)	Maximum hour thermal Load (TR)	Annual Consumption (GWh)
0.5	173.8	887.24
1.0	259.6	1703.24
2.0	440.3	2049.49
4.0	795.8	4877.46
8.0	1506.88	7544.06

That part of the maximum thermal load and the annual consumption may vary linearly with the computer dissipation densities and there is a minor part correlated with the external conditions (outdoor temperature, building properties). As the load increases, this share is less influential.

The next stage is the evaluation of the solar absorption and PV cooling alternative. First, it is necessary to calculate the yield of the solar collector for both processes. Table 3 shows the average yield of the solar collector for evacuated tubes and photovoltaic cells. The third and fifth column present the chiller yield versus the solar irradiation when using the COP proposed by (Guillen-Gosalbez et al., 2010) in the Absorption System and (Mokhtar et al., 2010)in the Electric Chiller. The table allows observing that, for a hot day and on average, the solar thermal system has a better yield than the photovoltaic system. For winter days at dawn, the photovoltaic system is better, because this yield decreases when the temperature increases.

Table 3 - Yield of a solar cooling system

	Yield			
	Evacuated Tube	Absorption System	Photovoltaic Cells	Electric Chiller
Collector Average	51.0%	76.56%	8.2%	37.12 %
Collector on a summer day at mid-day	73.6%	110.36%	8.5%	38.36 %
Collector on a winter day in a winter day at dawn	3.6%	5.44%	8.5%	38.11 %

Nevertheless, the equipment rarely works at full load. When the solar thermal system is used, this phenomenon increases. Yet, to calculate the residual consumption, it is necessary to estimate the residual load for a solar absorption system in equation (9). At times, when the full thermal load is not totally accomplished, it is necessary to replace the thermal load with the residual load (R_E) in equation (7) for each load density and respective chiller curve. For PV systems, equation (12) must be solved.

Table 4 shows the electrical consumption for an Absorption Colling and PV System integrated in a typical year, and the savings in comparison with the base system. Note that, in most of cases, the solar absorption results in better energy savings than the photovoltaic system. In this case, this occurs in 4 of the 5 cases studied.

However, when the load densities are around 2 kW/m², the Photovoltaic System is a better option. This is due to the characteristic performance curve of the selected chiller (screw). At this density charge, the chiller works near the optimal point of performance against the electrical consumption; the PV system keeps the same performance. When the absorption system is used, the operation occurs at the unfavorable points in the COP curve presented in Figure 6, and the complementary electrical consumption is higher due to the cooling need.

Table 4 - Annual consumption for solar absorption and PV cooling

Thermal load (kW/m^2)	**Solar Absorption**		**PV Cooling**	
	Consumption	Savings	Consumption	Saving

	(GWh/ year)		(GWh/ year)	
0.5	568.94	36%	690.15	22%
1.0	1294.24	24%	1506.15	12%
2.0	1758.48	14%	1742.39	15%
4.0	4486.68	8%	4680.37	4%
8.0	7240.69	4%	7346.95	3%

Another relevant point observed is that in all the cases, on average, the cooling consumption is guaranteed by a solar system for at least one hour per day. For lower densities, the solar alternative system guarantees all the energy cooling necessary for the Data Center to work under the temperatures. This results in a minimum of 20% in electric bill savings when it costs 80% higher than the off-peak price is considered, which is common in Brazil (Aneel, 2017).

5. Conclusion

Solar cooling systems are presented for electric energy saving and for reducing the grid electric energy consumed in the air conditioning IT system. This is a sustainable alternative because IT decreases the fossil electric energy generation.

In this study, the Data Center Thermal load and cooling needs were estimated for all IT densities. The strategy used was to store cold water provided by an absorption chiller powered by hot water or to store electric energy in battery banks provided by photovoltaic panels.

In the first case, the energy provided by tube evacuated collectors and the cooling capacities to set the vapor generator of the absorption chiller were calculated. This value is debited from the initial thermal load of the Data Center and results in energy savings in the supplementary chiller.

In seccond, the electric energy generated by Photovoltaic Panels was calculated as well as its contribution to powering an electric chiller. Both solutions were compared in energy saving criteria.

Is the present case, solar absorption is more advantageous in most cases: in 0.5 kW/m², by 63%; 1.0 kW/ m², by 50%; 4.0 kW/m², by 50%; and in 8.0 kW/m², by 34%. The exception is the case in which the density is 2.0 KW/m², when the photovoltaic system savings are 6%, and performs better than solar absorption. This occurs because the supplementary chiller in solar absorption operates in disadvantageous operating ranges, increasing energy consumption.

Nevertheless, these studies must be frequently updated because new and more efficient absorption chillers and solar collectors have been developed. Recent developments indicate that trend, as well as the reduction in the acquisition and maintenance costs of these types of equipment.

6. Acknowledgments

This work has been developed and supported by the Laboratory of Alternative Energy Systems of Escola Politécnica, Universidade de São Paulo.

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