DESIGN AND ECONOMIC ANALYSIS OF A SOLAR AIR-CONDITIONING SYSTEM: CASE OF STUDY IN MONTERREY, MÉXICO

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ABSTRACT

This article shows the procedures and considerations to evaluate a solar air-conditioning project considering both technical and economical analysis. Moreover, this work presents the design of a solar absorption air-conditioning system driven by solar thermal collectors as a primary energy source. The system generates air conditioning and heating for a residential home. A thermodynamic analysis is conducted in order to determine the capacity of the equipments that will be used in the solar air-conditioning system. It also shows the economical analysis of the solar air-conditioning system comparing with conventional cooling and heating systems. Trough a developed computational model is possible to analyze different scenarios under which the solar air-conditioning system meets conditions of economical feasibility based on criteria such as the internal rate of return among others parameters. Tecnológico de Monterrey has a solar air-conditioning system that uses a single effect ammonia-water absorption chiller of 10.55 kW (3 tons of refrigeration) that works with evacuated tubes solar collectors. The system has a back-up heater that uses natural gas. This article concludes that under very specific conditions of energy costs, equipment costs and operation time, the solar air-conditioning system described here can become economically viable.

Key words: Solar air-conditioning, solar refrigeration, absorption refrigeration, solar thermal collectors.

1. Introduction

Due to growing environmental problems and the need to make proper use of energy resources, the use of solar energy for residential, small office buildings, is an important contribution to reduce fossil fuel consumption and avoid the generation of greenhouse gases. The solar air conditioning systems are slowly emerging, although this technology has already several years and it has been sufficiently developed (Henning, 2007). In many cases, solar air-conditioning applications have been constrained by the lack of integration between the heating and air conditioning to meet the demands of heat and cool throughout the year e.g. in a residential house. One of the advantages of this technology is that the peak demand for air conditioning coincides in many cases with the availability of solar energy.

Solar air-conditioning technology is being applied and developed in Europe countries like Spain, Germany, Italy, among others, for example in 2006 they had 100 solar systems installed air conditioning (ESTIF, 2006). In Mexico, one of the installed solar air-conditioning systems is at the Tecnológico de Monterrey (Manrique, 1997), however in Mexico there are several drawbacks for the development of renewable energies such as: high capital investment, lack of information, lack of regulation, lack of incentives, among others. To address these challenges, in August 2009, the Federal Government released the "Programa Especial para el Aprovechamiento de las Energías Renovables" (Special Programme for the Development of Renewable Energy), which establish that the renewable energy installed capacity will reach 7.6% in 2012, this program excludes hydroelectric projects with capacities greater than 30 MW (SENER, 2010). Currently in Mexico, solar energy is applied in most of the cases just to generate hot water or electricity in small scales.

In addition we must consider that during the last decades the energy consumption for air conditioning increased dramatically in most industrialized countries, even in climates where heating dominates. One of the main reasons is the increase in living standards and demands for occupant comfort (Henning, 2004). It could say that the sun is an inexhaustible source of energy (estimated life of 5 billion years), the irradiation reaching the earth from the sun has a maximum average of 1.000 W/m2 (Peuser et. al. 2002).

Thanks to technological advances, is expected a growth in the number of solar air conditioning systems by developing new and better equipment on the market at competitive prices especially for solar panels and absorption chillers, which are the most expensive equipments. Nowadays there are solar panels with efficiencies of 70% and absorption units with capacities of 4 kW (1.1 tons of refrigeration) with a Coefficient of Performance (COP) between 0.6 and 0.8. This makes it possible to install solar air conditioning systems for many sizes of residential houses and / or buildings (Mateus et. al. 2008). Moreover there is an increased environmental awareness of governments and society in general.

Many authors have published detailed analysis of absorption refrigeration cycles, particularly Lithium Bromide-Water and Ammonia-Water (Uppal et. al. 1987, Wang et. al. 2009, Keith et. al. 1996, Srikhirin et. al. 2001, Kim et. al. 2008) that are of interest for this article. The same happen for solar thermal collectors where there are studies of the efficiency measures at different temperatures, optimum tilt angles, applications and types of solar thermal collectors like flat plate and vacuum tubes (Kalogirou 2004, Gunerhan et. al. 2007, Georgiev 2004, Duffie et. al. 2006). Applications of solar energy for air conditioning has a lot of work developed by Europe and Asia as well as U.S. which are the regions where this technology is being implemented (Mateus et. al. 2008, Desideri et. al. 2009, Atmaca et. al. 2003, Eicker et. al. 2009).

2. Work methodology

Thermodynamic and economical analyses were performed for the solar air conditioning system. Data from the solar irradiation available in Monterrey, Nuevo León were analyzed considering the average values and on clear days. It is known the thermal load requirement of the "Casa Solar" at Tecnológico de Monterrey for one day and for the different months of the year. To make the analysis more representative, the most important months of the year were considered and analyzed, i.e. warmer months (July and August) where there is a higher demand for air conditioning and colder months (December, January) where there is a higher demand for heating. The absorption cooling equipment will be for this case of Ammonia-Water from which Tecnológico de Monterrey has a patent (Manrique 1997), the developed model does not exclude the use of lithium bromide - water absorption chillers since the model works with the design value of COP of the refrigeration equipment provided by the manufacturer and/or reported by actual performance data of the equipment. The solar thermal collectors used in this project are of vacuum tubes. With this initial data were evaluated the area of solar collectors, the capacity of storage tanks, the capacity of the back-up equipment, and the coincidence in time between the available solar energy and heat load requirements for the house. This helped to determine the project feasibility.

It must be noted that solar radiation and heat load required may vary over time, the same happen with the efficiencies of solar collectors and absorption equipment. In addition it makes no sense to design the area of solar collectors for the maximum thermal load since it could be oversized for most of the operating time of the system, for it is considered a typical solar fraction between 70% and 80% (Henning, 2004), the remaining demand will be covered by the back-up equipment which in this case is a natural gas heater.

3. Description of the Integrated Solar Air Conditioning System

The solar air-conditioning uses solar thermal collectors to heat water which is taken to a storage tank. This hot water or is directly used for heating or is used for the operation of absorption refrigeration equipment which generates cold water for air conditioning. Hot or cold water is taken to the air handlers, see Fig 1. The system has backup equipment to heat water for those days where solar irradiation is not available and air conditioning is required. Depend on the absorption chiller equipment, a Cooling Tower or a Fan will be used.

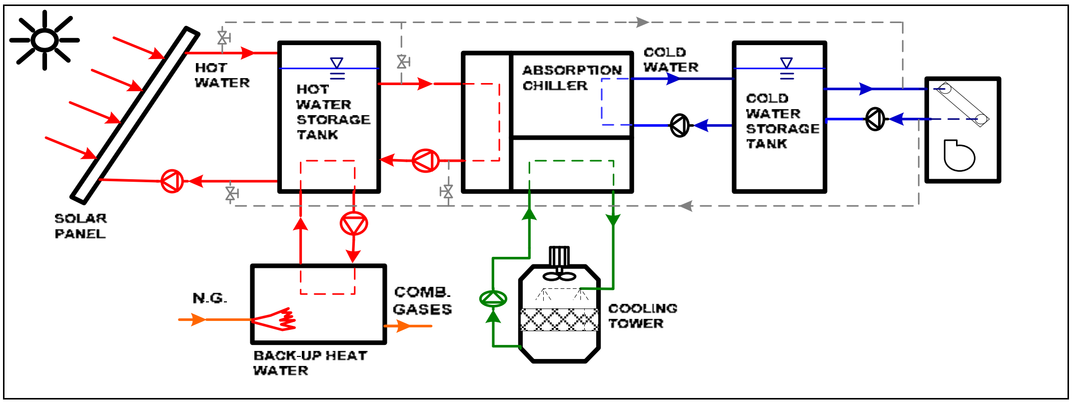

Fig. 1 Scheme of the solar air-conditioning system

For the pumps design, the pressure drop in the equipments of the solar air-conditioning system must be evaluated, especially in the solar thermal collectors. The pump power required for the solar thermal collectors could vary according to site conditions and the way in which collectors will be installed (Henning, 2004). For the back-up equipment, a natural gas boiler is considered with an efficiency of 90%, the power of the back-up equipment is evaluated according to the maximum heat demand required by the solar thermal collectors to cover the demand for both air conditioning and heating.

Storage tanks are used to meet the demand of thermal loads in the hours that do not have solar gain. It can be installed both storage tanks of cold water and hot water to obtain more optimal performance of the solar air-conditioning system, however one must consider the economic aspect to avoid falling into excessive expenditure that make the project unfeasible. The heat loss in the equipments and pipe lines is another important factor to take into account; it must choose a good insulation and optimal thickness. Heat losses are greater in the hot water tank due to the higher delta temperature between the hot water tank temperature and the ambient temperature. Henning, 2004 recommend to have a good stratification in the tank for better temperature homogenization. Mateus et al. 2008 proposed a volume between 50 and 70 liters per square meter of collector for the hot water tank. The heat loss of the storage tank is considered from 5 to 10% of the total heat of the tank (Peuser et al. 2002). It is recommended that temperatures inside the hot water tank are less than 100 °C when operating at atmospheric pressure in order to avoid further cost of equipment and boiling points that do not allow proper operation of the pump. Henning, 2004 recommends the following equation for the cold water tank:

$$Q_{cold} = (\rho \cdot c \cdot \Delta T)_{water} \approx 1.16 \left[\frac{kW.h}{m^3.K}\right] \cdot \Delta T \qquad \text{(eq. 1)}$$

Where ρ is the water density (988 kg /m3), c is the specific heat of water (4.184 kJ/kg) and ΔT is the difference between the inlet and outlet temperature in the cold water tank.

The absorption cycle is based on the principle that uses physical-chemical affinity of two substances e.g. lithium bromide with water or ammonia with water, where one substance absorbs the other, and due to they have different boiling points, the separation of the mix substances is facilitated by heating. In this process one of the substances acts as a coolant and the other as an absorbent. The most widely substances used commercially in absorption chillers are Lithium Bromide-Water and Ammonia - Water. The main difference between both solutions is the heat requirement to get the separation of the substances, equipment LiBr-water single effect can work at temperatures from 70 to 85 °C while the NH_3-water requires temperatures from 90 to 120 °C. Jakob et al. 2008 have reported the operation of ammonia-water absorption chiller of 10 kW that works with temperatures from 65 to 115 °C to obtain evaporator outlet temperatures from 15 °C to -5 °C respectively with a COP of 0.6. Ammonia-water absorption chiller of the brand Robur initially worked with natural gas has been adequate to work with hot water (Manrique, 1997). Zetzsche et. al., 2008 developed an experimental investigation and simulation of the thermally driven single-effect ammonia/water absorption chiller for air-conditioning and refrigeration systems for residential, commercial and industrial applications. At driving temperatures of 100°C cold water temperatures of 15°C could be achieved with a cooling capacity of 10 kW and a COP of 0.66

Absorption chillers differ from the more prevalent compression chillers in that the cooling effect is driven by heat energy, rather than mechanical energy. Absorption chiller can use not only fossil fuel but also the waste thermal energies (hot water, steam and exhaust gas) for cooling, using that waste thermal energy can improve overall efficiency rate and save energy. Typical COP values for single effect absorption chillers are 0.5 – 0.6, for double effect is possible to get 0.8 – 1. COP for electrical chillers have tipically values between 3 and 4.

Fig. 2 shows the basic single effect absorption chiller cycle. The evaporator allows the refrigerant to evaporate, a process that extracts heat of the room to be cooled, then the refrigerant is mixed with the absorber, the combined fluids then go to the generator, which is heated by gas, steam or in this project by hot water that separates the refrigerant and the absorbent. The refrigerant then goes to the condenser to be cooled back down to a liquid, while the absorbent is pumped back to the absorber. The cooled refrigerant is released through an expansion valve into the evaporator, and the cycle repeats (Wang et al., 2009). In the absorber the ammonia solution needs to be cooled to be able to absorb the water in a more efficient way. Depending on the cooling capacity a cooling tower or a fan will be used to condense the refrigerant in the condenser and cooled the ammonia solution in the absorber. The average specific water consumption of solar-assisted sorption systems is 5.3 kg/h per kW of average cooling capacity, (Balaras et al. 2005). When ammonia-water is used as a solution then and analyzer and rectifying are needed, also heat exchangers (precooler, HX) can be used to improve the COP of the equipment (Dossat, 1997).

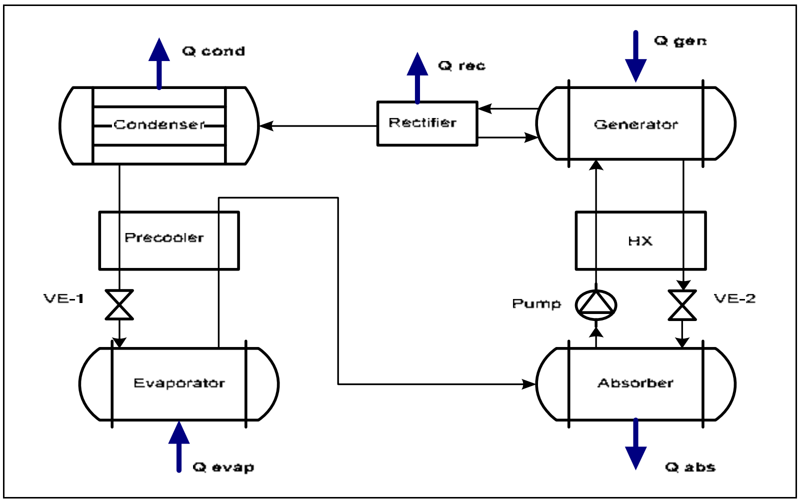

Fig. 2. Absorption cycle operation principle

The following data of the absorption chiller will be used for the design of the system: COP design of 0.6 cooling capacity of 10.55 kW (3 tons of refrigeration), cold water temperature of 12.7°C and 7.2°C at inlet and outlet respectively, hot water temperature of 150°C and 140°C at inlet and outlet of the generator respectively. The cooling tower temperature is 35°C and 27°C at inlet and outlet respectively. The electric consumption of the absorption chiller is considered of 20 W per kW of refrigeration (Henning, 2004).

The following basic equations are used to evaluate the design of absorption equipment:

$$Q_{\text{cold water}} = (\dot{m} \cdot c \cdot \Delta T)_{water} \qquad \text{(eq. 2)}$$

$$Q_{hot\ water} = Q_{cold\ water} \,/\, \text{COP}_{\text{abs}} \qquad \text{(eq. 3)}$$

$$Q_{cooling\ tower} = Q_{hot\ water} + Q_{cold\ water} \qquad \text{(eq. 4)}$$

Where $Q_{\text{cold water}}$ is the cooling capacity, $\dot{m}$ is the mass flow, c is the specific heat of water, ΔT is the temperature difference between the inlet and outlet of the cold water. $Q_{hot\ water}$ is the heat required in the generator, $Q_{cooling\ tower}$ is the heat required in the cooling tower or fan and COP_{abs} is the coefficient of performance of the absorption chiller.

The solar collectors are one of the major components of the solar air-conditioning system to convert solar energy into thermal energy required to operate the absorption chiller. There is a variety of solar thermal collectors that can be applied to the solar air-conditioning system but the most used are flat plate collectors and vacuum tubes. There are several factors for selecting one from another solar thermal collector but the most important are the temperatures of operation, available irradiation, efficiency and cost.

The efficiency evaluation of solar thermal collectors is typically determined with the following equation:

$$\eta_{col} = k(\theta) \cdot \eta_o - a_1 \cdot \frac{(T_{av} - T_{amb})}{G_\perp} - a_2 \cdot \frac{(T_{av} - T_{amb})^2}{G_\perp} \qquad \text{(eq. 5)}$$

$$k(\theta) = 1 - 0.239(1/\cos\theta - 1) \qquad \text{(eq. 6)}$$

Where $k(\theta)$ is the tilt angle factor of the solar collector, η_o is the optical efficiency of the solar collector, a_1 and a_2 are the linear and quadratic coefficients respectively, Tav is the average temperature of the fluid in the solar collector, $Tamb$ is the ambient temperature, $G_\perp$ is the global solar radiation in W/m2. These data is mostly provided by the manufacturer. One of the organizations responsible for certifying these values is the SPF (Solartechnik profung Forschung). The efficiency equation is obtained from the thermodynamic analysis of the collector where the heat transfer coefficient for losses and heat removal factor are evaluated among others (Kalogirou, 2004).

The tilt angle plays an important role in the efficiency of the collector, as a rule if you are in the Northern Hemisphere, the collector should face south and if you are in the southern hemisphere, the collector should look north. For example, to Monterrey 25 ° 40' north latitude the tilt of the collector should be south 25° ± 5°.

Henning, 2004 propose the following equation to determine the solar collector area for air conditioning:

$$A_{coll,} = \frac{\dot{Q}_{cooling}}{G_{\perp} \cdot \eta_{collector} \cdot COP_{absorption}} \quad \text{(eq. 7)}$$

Where A_{coll} is the solar collector area in m^2, $\eta_{collector}$ is the solar collector efficiency. For heating the following equation can be used

4. Characteristics of the "Casa Solar" and weather data in Monterrey, Mexico

The *"Casa Solar"* is located in Monterrey, N. L., México (25° 39.24' N latitude and 100° 17.32' E longitude) –see Fig. 3, it has a heat transfer global coefficient *U* of 1.9 W/m2.K and an area of 350 m^2 (considering windows, walls, ceiling, doors, etc.). The house wall consists of three layers: an outer layer with a thickness of 4 inches, a polyurethane layer of 1 inch in the middle and a layer at the inside of the house with a thickness of 6 inches, both the inside and outside of the wall are covered with a layer with a thickness of 0.5 inches. The environmental conditions required inside the house are from 23 to 25 °C in hot days and 20 °C in cold days. In both cases it is recommended a relative humidity inside the house of 50%.

Monterrey has an annual average temperature of 23.3 °C, in winter the average temperature is between 9 and 15 °C with an average solar radiation of 400 W/m2, while in summer it has an average temperatures between 25 and 30 °C with an average solar radiation of 650 W/m2. The annual average relative humidity is 60% and the annual average atmospheric pressure is 1,010 mbar.

Fig. 3 Residential House using solar air-conditioning (Monterrey, México)

5. Thermodynamic Analysis of the Solar Air Conditioning System

Con las ecuaciones presentadas y los datos de entrada se obtiene las capacidades de los equipos del sistema de refrigeración y calefacción solar para 10.5 kW (3 TR), ver Tabla 1.

The cooling capacity determine for the "Casa Solar" is 10.5 kW (3 TR). Using the presented equations above and the input data, the following results can be obtained:

Table 1. Thermal analysis results of the solar air-conditioning system

Equipment capacities		
Solar Collectors	*19.48*	*kW*
Back-up heater	*19.54*	*kW*
Hot water tank	*17.57*	*kW*
Absorption chiller	*10.63*	*kW*
Cooling Tower	*28.02*	*kW*
Cold water tank	*9.55*	*kW*

An area of 54.28 m^2 of solar thermal collectors is considered as a first approximation using eq. 7 considering an efficiency of the solar collector of 0.6, solar irradiation of $G_{\perp}$ = 600 W/m^2, a coefficient of performance of the absorption chiller of COP = 0.6. The capacity that the solar thermal collector must supply for 10.5 kW of cooling capacity considering the efficiencies of the equipments and the losses due to the line pipes is 19.48 kW –see Table 1. The pumps power for this case has a value of 0.4 kW, however this value must be considered carefully since their value will depend of the configuration and location of the solar thermal collectors.

The demand of air conditioning and heating of the house are analyzed and compared with the availability of solar energy that is obtained with the solar collector area along the year. The average solar radiation of each month, a tilt angle of 20° of the solar collectors, the average temperature for each month are considered to analyze the energy that can be used from the available solar radiation -see Table 2. The values for the efficiency of the Thermomax - Mazdon vacuum tube solar collectors are $\eta o = 0.804$, $a_1 = 1.15$, $a_2 = 0.0064$, certified by SPF.

Table 2. Annual Thermal Energy provided by solar thermal collectors and energy demand of the "Casa Solar"

Available Solar Irradiation				*Solar collector efficiency*				*Useful energy*	*Cooling Demand*	*Heating Demand*
Month	*G, W/m2*	*kW.h/m2*	*H, kWh/month*	*Tm, °C*	*Tamb, °C*	*Gc, W/m2*	*η colect*	*kWh/month*	*kWh/month*	*kWh/month*
Jan	*348.33*	*67.23*	*3,698*	*80*	*10.15*	*344.9*	*0.48*	*1,777*	*0*	*7,886*
Feb	*313.50*	*42.95*	*2,362*	*90*	*16.5*	*310.4*	*0.42*	*993*	*0*	*2,928*
March	*522.50*	*80.99*	*4,454*	*145*	*20.2*	*517.3*	*0.33*	*1,487*	*0*	*958*
April	*557.33*	*93.07*	*5,119*	*145*	*25.2*	*551.8*	*0.39*	*1,986*	*1,162*	*0*
May	*592.17*	*96.52*	*5,309*	*145*	*28.7*	*586.3*	*0.43*	*2,273*	*2,513*	*0*
June	*627.00*	*111.61*	*6,138*	*145*	*30.0*	*620.8*	*0.45*	*2,791*	*5,227*	*0*
July	*661.83*	*128.40*	*7,062*	*145*	*29.2*	*655.3*	*0.47*	*3,318*	*5,401*	*0*
Aug.	*682.73*	*154.30*	*8,486*	*145*	*28.1*	*676.0*	*0.48*	*4,037*	*4,119*	*0*
Sept.	*661.83*	*110.53*	*6,079*	*145*	*26.6*	*655.3*	*0.46*	*2,792*	*3,006*	*0*
Octob.	*592.17*	*84.09*	*4,625*	*145*	*24.6*	*586.3*	*0.41*	*1,894*	*1,560*	*0*
Nov.	*487.67*	*95.58*	*5,257*	*145*	*19.4*	*482.8*	*0.30*	*1,555*	*0*	*1,384*
Decem.	*418.00*	*77.33*	*4,253*	*80*	*12.13*	*413.9*	*0.54*	*2,314*	*0*	*5,255*
			62,842					***27,218***	***22,988***	***18,412***

The results in Table 2 shows the energy that can be used from the solar collectors' area to cover the energy demand of the "Casa Solar" in hot and cold months, with these values the solar fraction for each season can be obtained. A solar fraction of 0.85 can be obtained for the hot months (April to October) and 0.45 for the cold months (November to March). Henning, 2004 recommends solar fractions values between 70% and 80%. With the results presented in Table 2 is possible to get an estimate energy consumption of the back-up equipment throughout the year.

It is observed in Fig. 4 that thermal loads are higher in the months of July, August for air conditioning, and December, January for heating. To get a better idea of the evolution of the thermal load, heat load is analyzed for hot and cold days, where it can observe the evolution of solar radiation and thermal load demand along the day -see Fig. 5 and 6.

The figures 5 and 6 show the available solar energy in solar collectors for a typical hot day and for a typical cold day. Similarly, the energy demand required by the house was estimated. The average efficiency of solar collectors is 50% for air-conditioning and 40% for heating. It is possible to meet the energy demand for summer if the system has a good heat storage tank, while in winter it has a deficit of solar energy where the back-up equipment must be used.

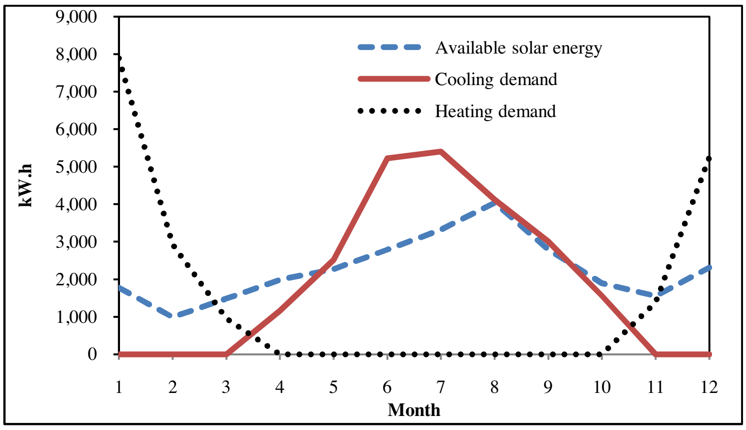

Fig. 4. Cooling and Heating demand along the year.

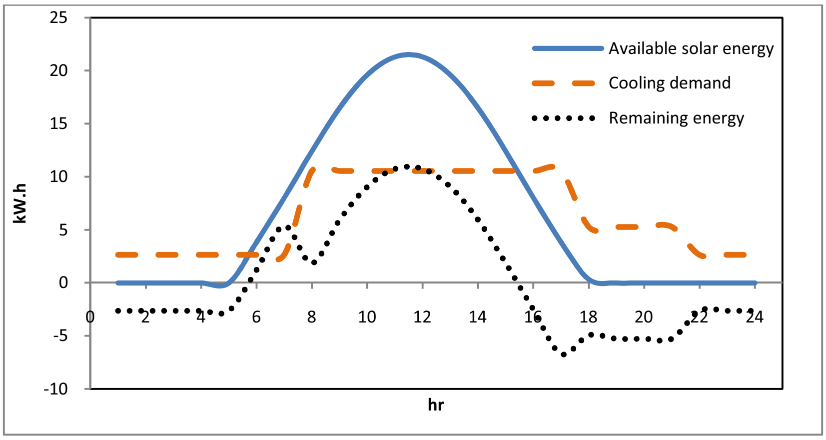

Fig. 5. Cooling demand in a typical day.

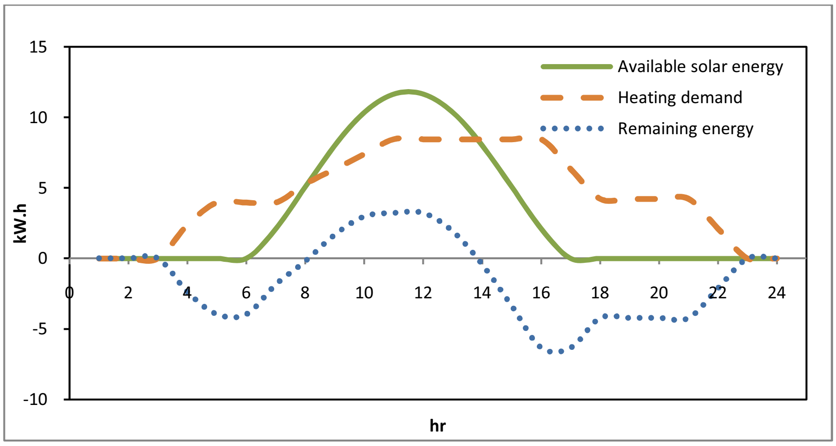

Fig. 6. Heating demand in a typical day.

6. Economic Analysis of the Solar Air-Conditioning System

Economic analysis is one of the most important points that must be performed in order to determine the acceptance or rejection of the project. For the economic analysis of solar air conditioning system, Eicker et al., 2009 suggests to consider three important points: the initial investment, operating and maintenance costs, and energy and supplies costs.

The economic analysis presented here is based in an annual cash flow. A comparative table cost is proposed between a conventional air-conditioning system and a solar integrated air-conditioning system for a cooling capacity of 10.55 kW (3 tons of refrigeration).

Table 3. Comparative table of the Investment cost of the solar air-conditioning system and conventional system of 10.55 kW (3 TR).

Description	*Conventional*	*Solar*
a. Absorption Chiller	*1,500*	*6,000*
b. Cooling Tower	*0*	*1,800*
c. Solar Thermal Collectors	*0*	*11,000*
d. Heating (back-up heater)	*2,442*	*2,828*
e. Hot water tank	*0*	*1,516*
f. Cold water tank	*0*	*1,388*
g. Fan Coil	*600*	*600*
h. Pumps	*276*	*604*
i. Accessories (pipes, insulation, etc.)	*1,205*	*2,445*
j. Equipment Installation	*2,553*	*3,107*
k. Instrumentation	*1,807*	*2,268*
l. Civil Construction	*301*	*1,409*
m. Engineering	*602*	*1,127*
Total Investment U$D	***11,287***	***36,092***

Once the thermodynamic analysis has been finished, the capacities of the equipment can be determined in order to assess their costs. The installation cost, engineering cost, technical costs, among others are also considered. The initial investment cost compares two alternatives: the conventional air-conditioning system and the solar air-conditioning system designed to cover both cooling and heating energy demand. The conventional air-conditioning system has the following costs: refrigeration equipment 500 U$D/TR, heating equipment 800 U$D/TR. The solar air-conditioning system has the following costs: solar thermal collectors 200 U$D/m2, absorption chiller 2,000 U$D/TR, cooling tower 600 U$D/TR, back-up equipment 900 U$D/TR. The total investment cost for the conventional air-conditioning system is 11,287 U$D while the investment cost for the solar air-conditioning system is 36,092 U$D taking into account the costs of the pumps, installation, engineering, etc. -see Table 3

To evaluate the annual costs of energy and, operation and maintenance (O&M), it is assumed that the average requirement of air conditioning and heating along the day will be of 12 and 10 hours respectively. The system will operate 350 days per year. From the meteorological data available for Monterrey, it is assumed that 75% of the time, cooling is required and the remaining time, heating is required. This means, from the 350 days per year of operation, 263 days are for hot days where cooling is required and the remaining days for cold days where heating is required. The solar fraction for cooling is 75% and the solar fraction for heating is 25%. This means that from the total hot days, 197 days are covered by solar energy and the remaining days with back-up equipment; from the total cold days, 39 days are covered by solar energy the remaining days with back-up equipment. The COP of the cooling equipment of the conventional system is 3 and 0.6 for the absorption cooling equipment. It is assumed a cost of electrical energy (EE) of 0.09 U$D/kWh (1.2 MX $ / kWh) and natural gas cost 4 U$D/GJ. Thus, the O&M costs can be obtained -see Table 4.

Table 4. Operation and Maintenance Cost

	Conventional	*Solar*	*Backup-Solar*
Cold days	*$ 347*	*$ 57*	*$ 191*
Hot days	*$ 1,903*	*$ 591*	*$ 313*
Total	*$ 2,250*	*$ 648*	*$ 504*

The costs in Table 4 include energy, supplies and maintenance costs.

To perform the feasibility analysis of the project considering the two presented options (conventional air-conditioning system and solar air-conditioning system), the following equations are used:

$$VPN = \sum_{t=1}^{N} FC_t \frac{(1+f)^t}{(1+i)^t} - Dif.Inv._{t=0} \qquad \text{(eq. 8)}$$

$$TIR = 0 = \sum_{t=1}^{N} FC_t \frac{(1+f)^t}{(1+i)^t} - Dif.Inv._{t=0} \qquad \text{(eq. 9)}$$

$$PB = \frac{Dif.Inversión}{FAE} \qquad \text{(eq. 10)}$$

The net present value (NPV) permit to evaluate the present value (t = 0) of a number of future cash flows at a given interest. The internal rate of return (IRR) evaluates the interest that can be obtained from a given net cash flow. The pay back (PB) determine in how many years the investment is recovered, it can be used when the net cash flow is constant (Ostwald et al., 2004).

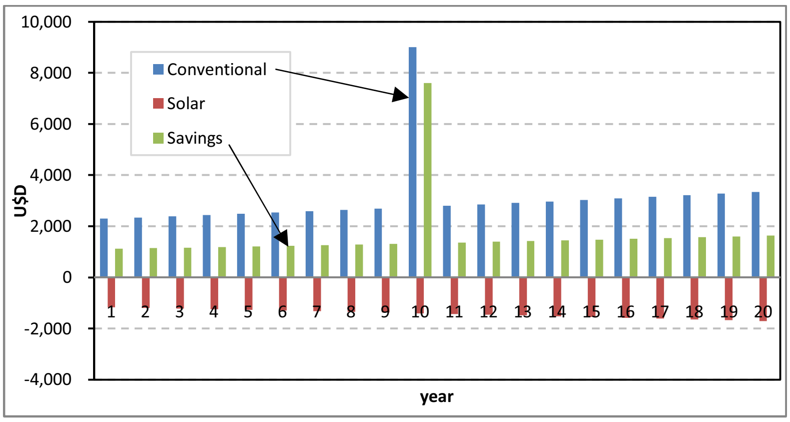

Fig. 7. Cash Flow of the project.

Fig. 7 shows the cash flow of the project from the first year, it can observe that in the ten year there is greater savings due to major cost in maintenance of the conventional equipment.

Considering a 20-year period, which is the life of the solar air-conditioning system (solar collectors, absorption chiller), an annual inflation of 2%, an expected interest (MARR) of 5% and using the equations proposed, Table 5 shows the result of the economic analysis of the project.

Table 5. Economic Analysis of the solar and conventional air-conditioning system

Description	*Conventional*	*Solar*	*Unit*
Investment	*11,287*	*36,092*	*U$D*
Operation cost	*2,250*	*1,152*	*U$D/year*
Specific investment	*3,762*	*12,031*	*U$D/TR*
Investment difference	*-24,805*		*U$D*
Total savings	*1,099*		*U$D/year*
Life cycle	*20*		*Years*
IRR	*3.26*	*%*	
Pay Back	*14.7*		*Years*
Net Present Value NPV	*5%*	*-3,773*	*U$D*

The results indicate that under the initial conditions proposed above, the project is not economically attractive because just a IRR of 3.26% is achieved and the NPV is a negative value, but there are other factors that can change like the cost of electricity and/or natural gas, the hours of operation per day, cost of equipments, among others that can make the project economically feasible.

Carbon credit can be considered in the solar air-conditioning system since electric energy, which is produced by fossil fuels, is reduced significantly. These credits can help to improve the economic performance of the project, but their contribution is not decisive on the feasibility of the project (Florides et al., 2002).

7. Results of the economic analysis of the solar air-conditioning system

A model was developed in Excel® with Visual Basic macros, considering both technical and economical aspects as have seen above. For all cases the data show in Table 3 are considered, a solar fraction of 75% for hot days and 25% for cold days. The collector efficiency is of 0.6 and the annual inflation of 2%. It is considered a cooling capacity of 10.55 kW (3 tons of refrigeration), COP of 3 and 0.6 for conventional refrigeration and absorption chiller respectively, operation of 350 days per year, cost of electrical energy (EE) of 0.09 U$D/kWh (1.2 MX $/kWh), natural gas cost of 4 U$D/GJ, global solar radiation of 600 W/m^2, a lifecycle of 20 years and a MARR of 5%. Considering all these assumptions, the following results are obtained:

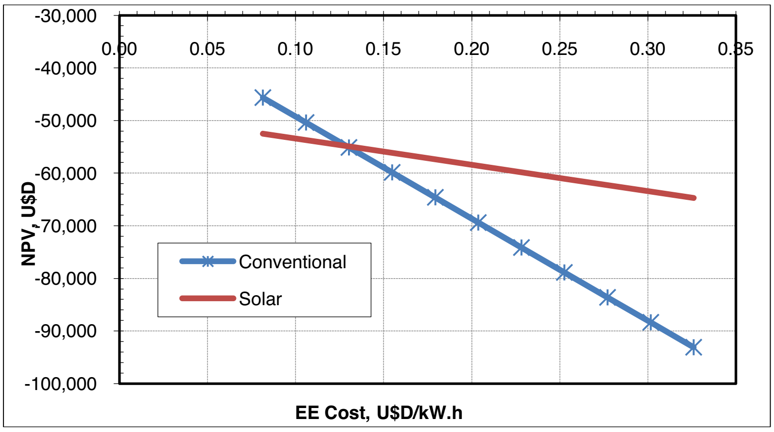

Fig. 8. NPV break-even point of the solar air-conditioning project considering electricity cost

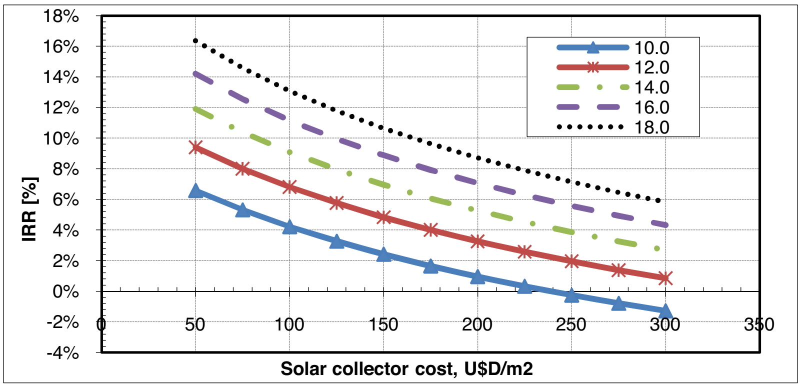

Fig. 9. IRR for different values of operation (hr/day) and cost of solar collector

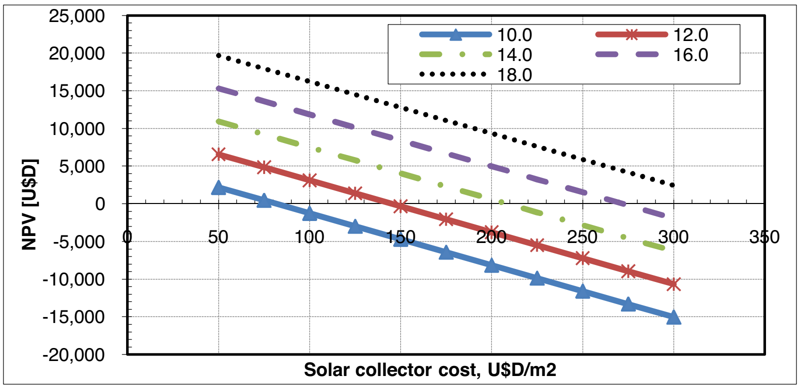

Fig. 10. NPV for different values of operation (hr/day) and cost of solar collector.

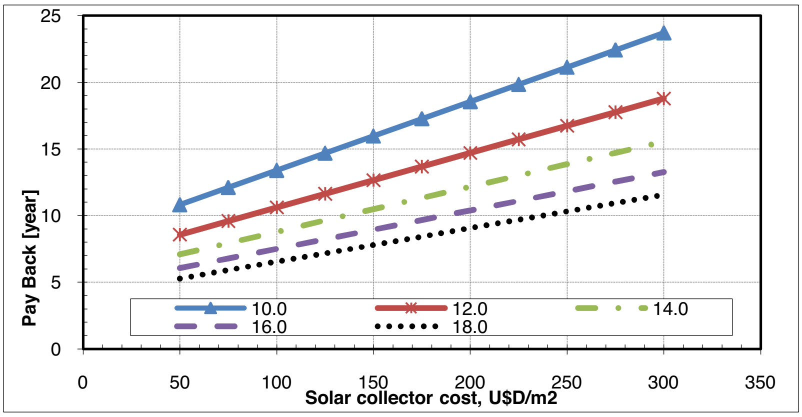

Fig.11. Pay back for different values of operation (hr/day) and cost of solar collector.

Fig. 8 shows the break-even point of the project considering the initial conditions mentioned above (MARR 5%) and the variation of the cost of the electric energy, it can observe that the solar air-conditioning system is a better option when the cost of the electric energy is greater than 0.141 U$D/kW.h (1.7 M$X/kW.h) since the total cost of the project is smaller compared with the conventional air conditioning system. If a MARR of 10% is required then the solar air conditionign system is a better option when the cost of electicity is greater than 0.21 U$D/kW.h (2.5 M$X/kW.h).

When the hours of operation per day of the solar system increase and the cost of solar collector is lower, the project has a more attractive project. It is possible to obtain IRR above 9% when the specific cost of the solar collector is less than or equal to 100 U$D/m2 and it has an operation time above 14 hours a day for 350 days a year, a, positive NPV is obtained and the recovery time of investment is less than 10 years–see Fig. 9, 10 and 11. The Project feasibility increases when the cost of electricity increases.

8. Conclusions

It has performed a thermodynamic and economic analysis of the solar air conditioning system that generate cooling and heating to meet the energy demand of a residential home of 10.5 kW (3 tons of refrigeration). A scheme of the solar air-conditioning was proposed and technical considerations of absorption chiller, solar collectors, and storage tanks among others were considered for the model developed in Excel ® with Visual Basic macros. The model allows performing sensitivity analysis from both technical and economical scenarios.

The results shows that the project is technically viable, the biggest problem is the economic aspect due to the solar air conditioning system has a high investment cost compared to the investment cost of a conventional air-conditioning and conventional heating system besides, the savings related to the solar air-conditioning system due to the less consumption of electric energy are not too significant to make the project feasible, where it has interests of less than 5%, higher periods of capital recovery (more than 20 years) and negative NPVs. Thanks to sensitivity analysis, opportunity areas were found that can make this technology more competitive. The cost of the absorption chiller, cost of solar collectors, cost of electricity, cost of natural gas, hours of operation per year, among others, are the most important variables that change significantly the profitability of the solar air-conditioning project compare with conventional systems.

One of the best options found for this case is shown in Figure 9, 10 and 11 where it is needed 350 days of operation per year, 14 hours of operation per day, a cost of electricity greater than 0.1 U$D/kW.h (1.2 MX$ / kW.h), a specific cost of solar collectors equal or less than 100 U$D/m^2 in order to obtain a IRR (internal rate of return) above 9% till 15% in the best scenario.

Although the operation and maintenance costs of the solar air-conditioning system is lower than the conventional one, the initial investment cost is currently too high for the Mexico market. The investment cost is higher due to the cost of equipments, the lack of trained personnel related to this technology (opportunity area), and the lack of local regulations that encourage the use of this technology. In order to get a project with the best technical and economical scenario considering the current costs of energy (electricity and natural gas), it is necessary that the costs of the absorption chiller and solar collectors are reduced.

9. Acknowledgments

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10. References

Atmaca I., A. Yigit. 2003. Simulation of solar-powered absorption cooling system. Renewable Energy. 28, 8, 1277-1293.

Desideri U., S. Proietti, P. Sdringola. 2009. Solar-powered cooling systems: Technical and economic analysis on industrial refrigeration and air-conditioning applications. Applied Energy. 86, 1376-1386.

Dossat J. Roy. 1997. Principles of Refrigeration. Fourth edition. Prentice Hall.

Duffie J. A., W.A. Beckman. 2006. Solar Engineering of thermal processes. Third Edition. Wiley.

Eicker U., D. Pietruschka. Design and performance of solar powered absorption cooling systems in office in buildings. Energy and Buildings. 2009.

ESTIF. 2006. Solar assisted cooling – state of the art. Report of project key issues for renewable heat in Europe.

Estrategia Nacional de Energía. 2010. Secretaría de Energía de México, www.energia.gob.mx.

Florides G. A., S.A. Kaligirou, S.A. Tassou, L.C. Wrobel. 2002. Modeling, simulation and warming impact assessment of a domestic-size absorption solar cooling system. Applied Thermal Engineering. 22, 12, 1313-1325.

Georgiev A. 2005. Simulation and experimental results of a vacuum solar collector system with storage. Energy Conversion and Management. 46, 1423-1442.

Gunerhan H., A. Hepbasli. 2007. Determination of the optimum tilt angle of solar collectors for building applications. Building and Environment. 42, 779-783.

Henning H. M. 2007. Solar assisted air conditioning of buildings – an overview. Applied Thermal Engineering. 27, 1734-1749.

Henning H. M. 2004. Solar-assisted Air-conditioning in Buildings – A Handbook for Planners. Springer, New York.

Herold K. E., Radermarcher R., Sanford A. K. 1996. Absorption Chillers and Heat Pumps. CRS Press.

Jakob U., W. Pink. 2007. Development and investigation of an ammonia/water absorption chiller – chillii® PSC – for a solar cooling system. Proceedings of the 3rd European Solar Thermal Energy Conference. Germany.

Kalogirou S. A. 2004. Solar thermal collectors and applications. Progress in Energy and Combustion Science. 30, 231-295.

Kim D. S., C.A. Infante Ferreira. 2008. Solar refrigeration options –a state of the art review. International Journal of Refrigeration. 31, 3-15.

Manrique-Valadez J. A. Solar Driven Ammonia-Absorption Cooling Machine. United States Patent N° 5,666,818-1997

Mateus T., Oliveira. A. C. 2008. Energy and economic analysis of an integrated solar absorption cooling and heating system in different building types and climates. Applied Energy. 86, 949-957.

New Buildings Institute, Absorption Chillers Guideline, 1998 (www.newbuildings.org).

Ostwald P. F., T.S. McLaren. 2004. Cost analysis and estimating for engineering and management. Pearson education Inc. New Jersey.

Peuser F. A., K-H. Remmers, M. Schnauss. 2002. Solar Thermal Systems Successful Planning and Construction. Solarparxis Berlin.

Srikhirin P., S. Aphornratana, S. Chungpaibulpatana. 2001. A review of absorption refrigeration technologies. Renewable and Sustainable Energy Reviews. 5, 343-372.

Uppal A. H., T. Munneer. 1987. Cost analysis of commercial solar absorption coolers using a detailed simulation procedure. Applied Energy. 26, 75-82.

Wang R. Z., T.S. Ge, C.J. Chen, Q. Ma, Z.Q. Xiong. 2009. Solar sorption systems for residential applications: Options and guidelines. International Journal of Refrigeration. 32, 638-660.

Zetzsche M., Koller T., Müller-Steinhagen H. 2008. Solar Cooling with an Ammonia/Water Absorption Chiller. 1st International Congress on Heating, Cooling and Buildings. Portugal.

11. Nomenclature

Qcooling	*Cooling capacity of the absorption chiller, kW*
c	*Specific heat, kJ/kg.K*
Tav	*Average temperature of the solar collector, °C*
Tamb	*Ambient temperature, °C*
COP	*Coefficient of Performance*
η *col*	*Solar thermal collectors efficiency*
A col	*Solar thermal collector area, m2*
G	*Solar global radiation, W/m2*
$k(\theta)$	*Tilt angle factor*
Gc	*Solar global radiation corrected, W/m2*
EE	*Electric energy cost, U$D/kW.h*
GN	*Natural gas cost, U$D/GJ*
NPV	*Net present value, U$D*
IRR	*Internal rate of return*
PB	*Pay back, years*
CF	*Cash flow*
AEF	*Annual equivalent flow*
i	*Interest*
f	*Inflation*
MARR	*Minimum attractive rate of return*
TR	*Tons of refrigeration*