Technical and Economic Analysis of Solar Cooling Systems in a Hot and Humid Climate

Houtan Moaveni, Research Engineer

Florida Solar Energy Center, University of Central Florida

Cocoa, FL, USA

ABSTRACT

The aim of this paper is to promote efficient and cost effective implementation of advanced solar cooling systems and techniques for the hot and humid climates cities in the United States. After an introduction of basic principles, the development history and recent progress in solar cooling technologies are reported. Nevertheless, the economics of solar energy systems are particularly complex with much inevitable uncertainty due to several factors. In this paper, a simplified comprehensive economic optimization model is developed to determine whether a particular solar system is economically advantageous for a particular project. This model explains and illustrates with simple, but realistic examples the use of life-cycle cost analysis and benefit-cost analysis to evaluate and compare the economic efficiency of the solar cooling system. Consequently, under appropriate conditions, solar or solar-assisted air conditioning systems may be reasonable alternatives to conventional air-conditioning systems in a hot and humid climate.

INTRODUCTION

During recent years research aimed at the development of technologies that can offer reductions in energy consumption, peak electrical demand and energy costs without lowering the desired level of comfort conditions has intensified. However, the demand for cooling in building is still significantly increasing. Currently, the cooling technology is mainly based on electrically driven mechanic vapor compressor. This corresponds to a favorable amount of primary energy. Using solar energy and waste heat as the primary energy source for cold production are suitable for cooling demand of residential and commercial buildings. Solar energy can be transformed either to electricity or to heat to power a refrigeration cycle. Using solar cooling not only mitigate the fossil fuel demand and reduce the greenhouse emission, but also support in stability of electric grids by less electricity energy and peak power demand.

Solar cooling market is growing up rapidly mainly in Europe over the last few years. Newest small- and medium-scale cooling technologies are expected to enter to the market in the coming years. Despite the small number of installed solar cooling systems globally, solar cooling market has a huge unexploited potential for developing the solar energy and creating jobs in the solar industry.

SOLAR COOLING TECHNOLOGY BASE

When considering the potential solar contribution to different energy requirements in buildings (heating, cooling, electricity), it is necessary to analyze the transformation efficiency of the solar technology in question and the available surface potential in buildings as well as economically usable potential. Solar cooling technologies can be classified by using PV systems to operate a DC or an AC compressor in a mechanical vapor compression system or a thermal operating system consisting of either absorption, adsorption system or a desiccant system. While the thermal systems take the largest part of the market, under a wide range of economic conditions, the combined solar cooling and PV systems can be comparable to, and sometimes even significantly better than, the conventional alternatives. An introduction of basic principles, the development history and recent progress in solar cooling technologies are reported as followings:

Desiccant cooling systems

Desiccant cooling systems (DSC) are mature technology for air-conditioning buildings and are practically suitable for the application of solar thermal energy, due to low temperature demands around 45°C. The technology is based on the principal of outside air dehumidification by an adsorbent such silica gel or lithium chloride. After pre-cooling, the dried fresh air with maximally humidified room exhaust air, subsequent evaporative cooling produces the desired supply air temperature of 16-18°C. The desiccant cooling process can be continuously operated with slowly rotating sorption wheels, where the outside air humidity taken up in the adsorbent is transferred to the exit air heated by supply of solar or waste heat. Using evacuated tubes for desiccant cooling system are not economically feasible due to low temperature demands.

Adsorption System

Closed adsorption coolers operate similarly to open cycle adsorption systems with silica gel and water, the refrigerant water being led in the closed cycle. At low pressure, heat is extracted from environment by evaporating the water. Solar collector absorbs the incident solar radiation, convey the heat to the circulated water and store it in the water tank. The compression of water vapor to the pressure in the condenser necessary for liquefaction takes place via a thermal compressor: the water vapor is first adsorbed on silica gel (suction function) and afterwards desorbed by the heat supply and brought to the necessary pressure. Cold water at 5-15°C inlet temperature is produced by the closed refrigerant circulation, and can then be distributed in the building with small pipe cross sections. The main advantage of using adsorption chiller is the low heat supply temperatures requirement, beginning form 60°C. Adsorption chillers have a low COP values in the range of 0.4-0.6, because of low thermal conductivities and poor porosity characteristics of the adsorbents. Previously, adsorption technology was only embedded in huge buildings, due to a lack of small size commercial products, but there is currently a small unit with the cooling capacity in range 5-15 kW in the market. Based on the system size, either flat plate or evacuated tube collector can be used. The cost of small scale solar cooling system is between $5000-$6000 per ton, when the cost of large scale one is approximately $4000 per ton.

Absorption system

The two basic absorption systems are lithium bromide-water and the ammonia-water systems. The Solar absorption basically functions like a standard gas-fired absorption unit except that hot water from the solar collectors is substituted for the gas flame used in supplying heat for system operation. Presently only the lithium bromide-water absorption system is suitable for solar application. This is because the lithium bromide-water absorption unit will operate at lower temperatures than the presently available ammonia-water absorption units. The cycle begins when the lithium bromide-water solution in the generator is heated by 80°C hot water from the solar collector. Due to low pressure in the generator, the water in the lithium bromide-water solution is superheated to a vaporous form. This water vapor is directed into the condenser where it is cooled to about 40°C by a heat exchanger located inside the condenser. Upon being cooled, the water vapor condenses into liquid form. This water then passes through an expansion valve where part of the water is revaporized. This vapor-liquid then passes through the evaporator coils at about 4°C when warm air from the building to be cooled passes between the evaporator coils, after absorbing heat from the warm air in the building, is then transported back to the absorber where the refrigerant is mixed with concentrated lithium bromide solution from the generator at a temperature of about 38 °C. While the refrigerant from the evaporator is being mixed in the absorber, heat is released. This heat in the absorber is removed by the cooling tower water. The cooled absorber liquid is then pumped back to the generator repeat the absorption cycle. Most of the solar absorption systems are single effect with the average COP values of 0.7; however, there are double-effect absorption systems in the market with higher COP value in the range of 1.0-1.2. The chilling capacity of absorption system is mainly between the ranges of 35 KW to several hundred kW. Recently, several research groups are working with manufactures in order to develop the small and medium size capacity range absorption chiller. Due to lower required temperature, flat plate solar collectors are recommended for single effect solar absorption systems. Double-effect absorption systems require the heat supply temperatures higher than 130°C .This may be obtained with using evacuated tubes or concentrated thermal collectors , considering higher – costs of these in respect to flat plat collectors. Absorption chiller system using the flat plate collector take larger part of known worldwide installed solar cooling system. To date, the cost of small capacity absorption chiller very expensive to install is (approximately $10,000 per ton); however, this cost drops significantly for a medium or a large size chiller (approximately $1,200-2,500 per ton).

DC Air-conditioning System

There are new DC air-conditioning systems with a SEER above 20 coming on the market. For small residential and small commercial cooling DC (PV-powered) cooling has been the most frequently implemented solar cooling technology. The reason for this is debated, but commonly suggested reasons include incentive structuring, lack of residential-sized equipment for other solar-cooling technologies, the advent of more efficient electric compressor systems, or ease of installation compared to other solar-cooling technologies. This “PV” air conditioner is capable of cooling off a 500-800 square foot building and uses a maximum 1500 watts of power. The system claims to provide 18,000 BTU's of cooling as well as 20,500 BTU's of heating. Only a few photovoltaic modules are needed to power air conditioners, so most systems would have some excess power available for other electric devices, or when chilling or heating is not required. This Heat Pump has a high efficiency (either brushless or reactance) permanent magnet DC motor driving a conventional refrigerator compressor with a digital frequency driver that allows it to size itself based on load with a variable speed and variable refrigerant flow compressor, unlike a normal AC unit that has two speeds, stop and go. This system can be driven by a battery bank that is supplied power from an array of PV panels and/or an AC to DC power supply/charger. It installs without ducts, thereby eliminating nearly 30% of ducted systems cooling or heating losses, as well as the majority of installation and materials costs. By avoiding inverter losses, we can have a proportional decrease in the size and cost of the PV array. In order to extend the cooling time of the system into the evening hours, an AC to DC converter/charger is supplied from the conventional grid, which than can be integrated with an electric storage system (battery) in order to provide "peak shaving" benefits. Note that PV supply and electricity demand also match to a certain extent without storage, especially in the case of peak demand due to air conditioning and cooling. [8]

SOLAR COOLING ECONOMICS

The economics of solar energy systems are particularly complex with much inevitable uncertainty due to several factors. The principal reason for using solar energy for heating or cooling is to reduce the energy cost associated with operating buildings. Therefore, an economic analysis must be carried out to determine whether a particular solar system is economically advantageous for a particular project.

This section describes a simplified comprehensive economic optimization model of solar cooling systems. This model is probably adequate for most of the applications, but it can be easily developed for much more economic parameters.

The total cost of heating or cooling a particular building by use of both solar and backup energy can be expressed in terms of other quantities as shown below:

$$C_{Total} = \left(C_s + C_{Ch} - ITC\right) CRF\left(i, N\right) + \left(1 - \bar{f}_s\right) L \left(\bar{C}_{f_f} + \bar{C}_{f_e}\right) + M^* + S \quad (1)$$

Where:

C_s: The initial investment cost in the solar systems

C_{ch}: The initial investment cost in air-conditioning

ITC: Total state and federal Tax Credit

CRF(i,N): Capital Recovery Factor is the ratio of the annual payment to the total sum that must be repaid. In the other words, the capital recovery factor is the inverse of the present value function and measures the speed with which the initial investment is repaid. In equation form, the Capital Recovery Factor given by:

$$CRF(i,N) = \frac{i}{1-(1+i)^{-N}} \quad (2)$$

$\bar{C}_{f_f}$: The levelized cost of fuel $\bar{C}_{f_f}$ can be used to include both discount and inflation effects on future fuel price. $\bar{C}_{f_f}$ can be calculated from

$$\bar{C}_{f_f} = C_{f,0}\frac{CRF(i,N)}{CRF(i',N)} \quad (3)$$

Where $C_{f,0}$ is the unit cost of fuel in year zero, and the capital recovery factor in the denominator is based on an inflation-adjusted discount rate i' given by:

$$i' = \frac{i-j}{1+j} \quad (4)$$

In Eq.(4), j is the annual fuel inflation rate and i is the discount rate as used in previous equations.

$\bar{C}_{f_e}$: The levelized cost of electricity $\bar{C}_{f_e}$ can be used to include both discount and inflation effects on future electricity price. $\bar{C}_{f_e}$ can be calculated from

$$\bar{C}_{f_e} = C_{f,0}\frac{CRF(i,N)}{CRF(i'',N)} \quad (5)$$

Where $C_{f,0}$ is the unit cost of electricity in year zero, and the capital recovery factor in the denominator is based on an inflation-adjusted discount rate i" given by:

$$i'' = \frac{i - j}{1 + j'} \qquad (6)$$

In Eq.(6), j' is the annual electricity inflation rate and i is the discount rate as used in previous equations.

L: The annual heating or cooling load

$\bar{f}_s$: The annual solar heating or cooling fraction

M^*: The annual maintenance cost including replacement and repair cost per year

S: Value of building space occupied by solar cooling system components, evaluated as building cost/m2 multiply by the number of m2 occupied

There are several ways to formulate the annual cost equation. For example, the annual maintenance cost and the annual income from the sale electricity to grid can be entered directly without discounting or can be calculated by use of gradient series interest of formulas.

The Pay Back Time of investment in solar cooling systems can be calculated with several approaches. One approach is to use the annual cost formula as depicted by equation (1). With comparing the cost difference between different systems, the system with the lowest life-cycle cost can be identified. Another method is to use the benefit –cost analysis. Generally, the pay-back period (PBP) is the number of years needed for the net present value to reach zero, and can be described as the amount of time before the investment pays for itself. The yearly benefit of solar cooling system could be defined by the cost difference between conventional system and solar system. For solar cooling system, cash flows are generally negative. The best reliable approach is to use the net present value benefits method. Using this approach, the cost are defined as the present value of the extra costs of wounding and maintaining a solar system and the benefits as the present value of saving in energy costs for a solar system as compared with a conventional system. Finally, the simplest method to calculate the Pay Back Time (PBT) is given in equation below:

$$PBT = \frac{(C_s + C_{Ch} - ITC - B^*)}{\bar{f}_s L\,(C_{ff} + C_{fe}) + M^* + S} \qquad (7)$$

In this equation B^* is the annual income from the sale electricity to grid in the case of using PV system. This method can be used when the period of analysis is unknown. In order to use this micro-economic model, it is necessary to make a reasonable estimate of the cost of a solar energy system, heating and cooling load the building, cost of the auxiliary system (electricity, gas, oil, etc) and annual solar heating or cooling fraction. This general feasibility analysis will provide a feel for relative solar system feasibility for each particular climate, building sector and technology based on typical conditions that can be used for approximate solar cooling system sizing and economic analysis. This is necessary because each geographic location will probably have different fuel costs, state solar legislation incentives, equipment costs, labor installation charges, etc.

DEPLOYMENT OF SOLAR COOLING IN FLORIDA

The economics of solar cooling system are influenced by the application. It is the marginal system that is most likely to require a detailed economic analysis to determine its suitability for a particular application. Therefore, the economics factors that affect different applications of solar cooling system in Florida will be concerned in this study. Electricity is the main cooling source for residential and commercial buildings in Florida. The demand for electricity varies through the year as well as throughout the day. Electrically driven chillers cause high electricity peak loads of electricity grids, even if systems are used that reached a relatively high standard concerning energy consumption. Electricity demand has increased rapidly over the past decade in Florida approximately 2-4%annualy, accompanied by a significant shift to summer peaks, driven largely by increased air conditioner usage. Air conditioning and ventilation of commercial buildings incur approximately 35% of annual Florida electricity consumption. As the largest single source of energy consumption in Florida, a home's air conditioning laid represents the biggest challenge. The introduction of solar cooling systems could have a significant effect on the summer demand for electricity and might reduce the summer and winter differential as well as the maximum yearly demand. The average electricity price in Florida is 10.05 cents/kWh, when this number has been increasing approximately 6-8% annually over the last years. Therefore, Florida has a great potential for solar cooling system by comparing the electricity price with the other states in the United States.

Florida is one the strongest solar radiation states in U.S. The average number of days with sunshine in North Florida is 361 – and that number is even higher in the southern part of the state. According to National Renewable Energy Laboratory Resource

Assessment Program, the average daily solar radiation per month is between 5 to 6 kWh/m2/day. This is equivalent to 5 to 6 hours of full of sun per day. In the hot, humid Southeast, air-conditioning is needed more for dehumidification than for cooling. High temperatures during the summer average in the lower 90°F statewide. Florida has thus the highest need for cooling and also the large amount of radiation. Florida peak electricity consumption occurs during the summer months when the demand for cooling is high and the efficiency of heat pumps drop with the higher ambient temperatures. The maximum consumption usually occurs during the mid-day hours when solar radiation or solar generation capabilities are the maximum. The energy consumption of the existing buildings could be reduced at least 50% through the implanted solar cooling systems. While more than half this amount is potentially displaceable by solar cooling, even displacing only half of it would result in savings more than four billion dollars. Solar cooling fraction is defined by the cooling load of the building and the solar cooling production in a cooling season. Using all the solar cooling energy produced are possible by avoiding solar energy in surplus with prioritizing the strict comfort conditions to solar cooling energy or using the solar cooling system in order to cool the ambiance of building. Solar cooling system has the potential to be used with no back up and the cooling loads have no precise for some the building's users (fraction of 100%) or could be used as a part of large traditional cooling network.

The type of air conditioning system has an important role on the type of solar cooling machine selected. The system selection is mainly based on climate and load conditions analysis and on the energy (electricity, back-up fuel) and water costs and availability. Open systems like desiccant based air conditioning is used in all air systems while closed systems like absorption, adsorption and ejector cycles are used in water or air/water systems. Due to high humidity level in Florida, using desiccant systems in this area need some special pre-cooling of the air and higher regenerating temperature. For closed systems in Florida, using water cooling towers must be also taken by care. A combination of the systems is also possible based on technical and economical feasibility studies.

Solar projects are generally known by high investment and low operating cost in comparison with traditional solutions ones. The cost of solar thermal cooling system is including: solar collectors, piping, hydraulics, control, sorption machine, storages, monitoring and engineering. The largest part of initial cost of solar cooling system is for the collector. Thus, the collectors' area should have been selected to minimize the life-cycle costs. The optimum can be determined by separating the total installed system cost into fixed costs and those that vary with the collector area. Improvements such as reduced collector area because of improved system performance and reduced collector cost will lower the cost of solar components. Initial assessment results show that solar thermal cooling systems are feasible in areas like Florida with a confluence of high solar isolation, high cooling demand, and high electric rates, achieving payback of less than 8-10 years in typical buildings (depending upon the usage). In smaller commercial and institutional buildings, solar thermal absorption cooling system life-cycle costs are also favorable in comparison to conventional cooling systems. However, the pay-back time of solar thermal cooling will vary significantly with the particular application. There is growing interest in solar thermal cooling systems for offices, hotels, laboratories or public buildings such as museums. Nonetheless, The PV air-conditioning system is likely to be significantly more favorable in residential application than commercial ones. The results of previous studies show that a home in a climate such as Florida's can be engineered and built so efficiently that a relatively small PV system would serve the majority of its cooling need and even some of its daytime electrical needs. In a typical setting the pay-back time is about two years (depending upon the usage), although only a very small number of systems have been installed. Financing for solar cooling projects can come from multiple sources, including up-front equity, debt financing, incentives schemes (including subsidies, low-interest loans, grants and tax incentives). The level of subsidies is from 26 to 70% of the investment cost in the European countries. These subsidies are planned to help the development of solar cooling projects. The investments on most the solar cooling projects will be viable only if support helps can fill in the financial gap. These subsidies need to be planned to develop the demonstration of solar cooling projects. Considering the discussed benefits of solar cooling technologies, the state may have an interest in subsidizing this type of technology, reducing the return time for investments.

CONCLUSION

Primary results of this feasibility study indicate that solar cooling is optimistically on a good way for a close future in Florida. PV- air condition has the large potential for market penetration, while more tests to assess cooling energy performance need to be done. Solar thermal cooling technologies are not economically feasible at the present energy prices and without subsidies. As technology advances and increases the market penetration, their cost will decrease. At the same time the price of the electricity is expected to increase. These two factors lead us to believe that solar-driven cooling technology will become cost competitive with conventional cooling systems in the near future. These basic facts suggest consideration of the new policy options to enhance the economic feasibility of these solar energy applications to private decision makers including adoption solar tax credit, replacement cost pricing of fuel, elimination business tax deduction for costs of the fuel, etc. Continuation of research is highly encouraged to investigate systems or combination of systems that can initiate higher efficiencies and also to lead the path towards future advancements in solar cooling appliances.

BIBLIOGRAPHIC REFERENCES

1. ROCOCO, 2008, Final Report

2. ESTTP, 2008, Solar Heating and Cooling for a Sustainable Energy Future in Europe

3. Sandy Halliday, Clive Beggs and Tariq Muneer, 1999, Is solar air conditioning feasible?

4. Greeley Ouellette Cheremisinoff,1984, Solar Heating and Cooling of Buildings

5. Edward G.Pita, 1989, Air conditioning Principles and Systems an Energy Approach

6. E. baker, C.T. Floro, J.P. Gostelow, J. McCaffrey, 1984, Solar Heating and Cooling Systems

7. www.solcoproject.net, 2009, SOLCO Project Leaflet

8. www.solarpanelsplus.com,2010,dc-air-conditioning

9. Danny S. Parker, 2007, Zero Energy Homes Combining energy efficiency and solar energy technologies

10. www.eia.doe.gov,2010, Florida Quick Facts

11. Ursula Eicker, 2003, Solar Technologies for Buildings

12. Gilbert M. Masters, 2004, Renewable Energy and Efficient Electric Power System

13. www.NREL.gov, 2010, Resource Assessment Program

14. Sparber, W., Napolitano, A. and Melograno, P.,2009, Overview in worldwide installed solar cooling systems.

15. www.solair-project.eu,2010, Promoting SAC

16. Randy C. Gee, 2004, Solar Powering of High efficiency Absorption Chiller

17. Xiaoqiang Zhai, Ruzhu Wang, Yanjun Dai, Jingyi Wu, 2006, Experimental Research and Performance Analysis of a Solar-Powered Air-conditioning System in a Green Building

18. Miguel Marques da Silva, 2005, Solar Air Conditioning Potential for Offices in Lisbon