MAXIMIZING THERMAL COOLING EFFICIENCY AND VALUE WITH SOLAR COGENERATION AND LOW-COST STORAGE

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ABSTRACT

Solar cogeneration is the combined production of photovoltaic electricity and heat. The ability of solar cogeneration to produce both controlled temperature water and electricity provides a flexible platform for solar cooling, addressing customers' need for heat in the winter, cooling in the summer, and electricity year-round. Solar cogeneration is ideal for use with either adsorption or single effect absorption chillers. Both single effect and adsorption chillers utilize driving temperatures below 210 F. At these temperatures, the hot water heat source can be stored in insulated, low pressure tanks at relatively low cost. This low cost storage allows the cooling system to address customer demand profiles and demand charges beyond the solar resource. Operating at temperatures below 212 F also improves the overall system efficiency. The dual energy streams of electricity and heat provide the highest solar cooling system performance.

1. INTRODUCTION

Solar cooling systems use solar energy (photovoltaics or solar thermal technologies) to generate cooling, thereby offsetting facility’s use of traditional energy sources like electricity, natural gas, propane, and others. While the need for heat and solar resource availability correlate negatively, the demand for cooling matches solar resource availability perfectly: cooling demand is highest when temperatures are highest.

In the United States and worldwide, regions with high irradiance values are found to also have a large number of cooling degree days. A cooling degree day is an industry standard unit used to relate temperature to cooling energy demands (ASHRAE 2012).

Solar cogeneration produces heat (which can be used for heating or cooling) and electricity in one product. One product addresses customers’ need for heat in the winter, cooling in the summer, and electricity year-round. Thermal storage and sophisticated controls that optimize for temperature, PV production, and demand charges ensure consistent chiller operation.

A solar cooling system consists of the solar collectors, buffer or storage tanks, thermally driven chiller or desiccant cooler and an optional backup heater, incorporated as a safe guard. Thermally-driven chillers are either absorption or adsorption chillers that produce chilled water in a closed loop process which is then used to condition the air to the desired temperature. Desiccant coolers are paired with evaporative coolers to directly condition air in an open loop process. Most solar cooling installations today use absorption chillers.

2. THERMAL CHILLERS

2.1 Absorption Chillers

There are four primary components of a basic absorption chiller: a generator, a condenser, an evaporator and an absorber. Three heat exchangers facilitate heat flows into and out of the chiller.

2.1.1 Generator & Condenser

During the cooling process, heat is introduced into the generator – this is where solar heat is first used. In a direct-fired chiller, this may be heat produced by combustion of a fuel such as natural gas or propane. In a hot-water driven chiller (solar or other heat), the heated water flows through a heat exchanger in the generator.

The heat delivered to the generator vaporizes the Lithium Bromide (LiBr) and water solution, causing the LiBr to desorb into a concentrated solution. The concentrated solution is then passed to the absorber, while the water vapor travels to the condenser where the water returns to liquid (rejecting latent heat to cooling water), and is then throttled and sent to the evaporator.

2.1.2 Evaporator & Absorber

The purpose of the evaporator is to cool the water, similar to how moisture cools skin when it evaporates. The evaporator is maintained at a very low pressure by the chemical affinity of the water to the LiBr absorber, which allows boiling and evaporation at low temperatures. Evaporation of the water creates cooling by removing heat from the chilled water coil in the evaporator. The water vapor is then passed to the absorber where it is absorbed by the LiBr solution. This diluted solution of LiBr and water returns to the generator where the cycle begins again.

2.1.3 Heat Exchangers

An absorption chiller contains three loops of incoming and outgoing water that are used to exchange heat in the cooling process:

- Hot water loop (≈200 F in): Transfers solar heat to drive thermal compression in the generator
- Cooling water loop (≈65 F in): Rejects latent heat to maintain low temperatures in absorber and condenser. Chiller efficiency is more sensitive to absorber temperature than condenser temperature so cooling water passes first through absorber and then through condenser.
- Chilled water loop (≈44F out): Cooled by vaporization of refrigerant in evaporator.

Absorption chillers are commonly available as single-effect or double-effect. A single-effect absorption chiller has one of each basic component described above. A double-effect absorption chiller is like a single-effect chiller with an additional generator and condenser to improve efficiency by cascading energy and pressure.

A standard efficiency metric for chillers is coefficient of performance, commonly referred to as COP. The COP is a measure of cooling energy out per unit of energy in.

Single-effect absorption chillers have a COP of approximately 0.7; double-effect chillers have a COP of approximately 1.2 but require pressurized vessels and much higher input temperatures. Research and development of triple-effect absorption chillers with a third generator and condenser set has been underway since the late 1990s. Triple-effect chillers achieve greater efficiency but with a high cost and added complexity. The simplicity, safety, and temperature requirements of single-effect chillers make them the ideal partner for solar cogeneration.

2.2 Adsorption Chillers

Adsorption chillers are less widely deployed and less commercially available than absorption chillers. Adsorption chillers have a growing presence in the European market. An advantage of the adsorption chillers are the low driving temperatures (beginning from 140 F), the absence of a solution pump and lower noise levels during operation.

Adsorption chillers use a solid sorbent material, typically silica-gel although other sorbents are being developed, to absorb and release refrigerant to create cooling. Adsorption chillers consist of two compartments, the evaporator and the condenser, both containing beds of the solid sorbent material. Solar heat input causes water in the evaporator to vaporize and desorb. The sorbent bed in the condenser adsorbs the water and rejects heat to start the process again. To efficiently manage heat, the beds will periodically switch from hot water to cooling water.

2.3 Desiccant Coolers

Thermally-driven open cooling cycles employ dehumidification with a desiccant cooler. The desiccant material can be either solid or liquid and uses lower solar heat input temperatures than absorption and adsorption chillers.

These types of coolers are most often found in developing regions, because while they are low-cost and simple to install, they are not a standalone cooling solution. However, the desiccant cooler dehumidification can be configured with evaporative cooling or chilled water to create a complete cooling solution.

3. COOLING WITH SOLAR COGENERATION

The ability of solar cogeneration to produce high-temperatures, in addition to electricity, in one product provides a flexible platform for solar cooling with the highest cooling efficiency. Cooling with solar cogeneration offsets demand charges, is eligible for government incentives, provides environmental benefits and integrates easily into existing cooling systems.

3.1 Energy Savings and Peak Demand Charges

Solar cooling uses solar thermal energy to displace cooling powered by electricity (a costly energy source in most regions of the world), which results in energy and costs savings. Summer time-of-use and demand charges constitute the highest part of most electric costs, but can be effectively offset by solar cogeneration with storage.

As shown in *Table 1,* solar cogeneration uniquely offers over 100% cooling performance, maximizing customers' financial benefits. Traditional photovoltaics, at 15% efficiency, provide electricity for high-efficiency mechanical chillers with a COP of 5. The resulting system cooling performance is 75%

Table 1: System Cooling Performance

	PV	**Solar Hot Water**
	AC Electricity	200C- 400C Hot Water
Energy	15%	60%
Integration Equipment		*Double Effect Absorption Chiller*
COP*	5X	1.3X
Cooling Performance**	75%	78%

Solar Cogeneration			
	AC Electricity	100C Hot Water	Total
Energy	15%	60%	75%
Integration Equipment		*Single Effect Absorption Chiller*	
COP*	5X	0.7X	
Cooling Performance **	75%	42%	117%

*COP: Coefficient of performance

** Cooling performance defined as cooling power delivered relative to solar power landing on aperture

*PV cooling performance: 15% PV * 5x COP = 75%.*

Standalone solar hot water capable of reaching very high temperatures at 60% efficiency can be integrated with a double effect absorption chiller with a COP of 1.3. This yields a slightly higher system cooling performance at 78%. For solar cogeneration, temperatures are lower than standalone hot water to optimize photovoltaic efficiency and minimize system complexity. Solar cogeneration captures 15% efficiency with photovoltaics and 60% efficiency with solar hot water. The sun's energy is captured and integrated to provide the most cooling to the customer with the combined production of cooling from PV and hot water produced by solar cogeneration yielding a 117% cooling performance.

*Solar cogeneration cooling performance: 15% PV * 5x COP + 60% HEAT * 0.7x COP = 117%*

3.2 Environmental Benefits

Solar cooling offers multi-faceted environmental benefits and displaces high life-cycle greenhouse gas emitting electric use with minimal life-cycle emission solar production. Additionally, solar air conditioning technologies use environmentally sound materials with virtually no global warming potential. Traditional fluorocarbon refrigerants used in electrically driven chillers have high global warming and ozone depletion potential.

Solar cogeneration offers similar advantages over competing technologies in terms of reducing air pollutants other than carbon dioxide — including volatile organic compounds, nitrogen oxides, sulfur dioxide, carbon monoxide and particulate matter — both locally and averaged across the grid. The absolute and relative reductions depend on the mix of generating sources in the regional grid.

Solar cogeneration also eliminates local emissions of pollutants compared with burning natural gas (either to heat water in boilers or generate electricity and heat water with CHP). In some air quality districts, elimination or avoidance of VOC and NOx can obviate regulatory burdens and eliminate fines.

4. SITE INTEGRATION

Solar cogeneration can be used with thermally-driven (absorption chillers and adsorption chillers) or desiccant coolers. Thermally driven chillers have low-noise levels and are virtually vibration-free compared to electrically-driven chillers that use pumps for compression (SOLAIR, IEA 2009).

Adsorption and single-effect absorption chillers are ideal for simple and safe integration with solar and existing chilled water systems. Both single-effect and adsorption chillers operate at temperatures below 100 C without the need for high pressure components as required by double-effect chillers. This makes single-effect chillers easier to maintain as well as install. Additionally, the lower input temperature ensures high electricity output from the photovoltaic cells.

In a typical site integration, a thermal chiller sized to meet approximately 20% of customer cooling demand ties into the existing chilled water system, displacing electrically driven cooling. Displacement of approximately 20% of load allows for a seamless integration to the existing system without the need for retrofits to piping or cooling towers. As electrical chillers operate at greater efficiency when not running at maximum capacity, the 20% load reduction optimizes the existing system as well (Leavell). Electric production from the cogeneration system is integrated with a standard inverter and fed back to the grid.

The chilled water produced can be stored to consistently meet customer demand in case of a drop in solar production. Other options for backup include storing solar heat or using a backup natural boiler. Both offer lower cost efficiency than storing chilled water ($/unit of energy stored) but unique requirements such as data center reliability make such options attractive.

5. APPLICATIONS AND MARKET OVERVIEW

Applications and market for solar cooling with solar cogeneration match the overall cooling market and include office complexes, manufacturing, data centers, hospitals, hospitality and other segments where cooling demand is high.

For example, in data centers, the exponential increase in server performance has greatly increased the need for reliable, efficient cooling. Cooling requirements have increased from 75 W cooling/sq ft. of data center floor space to as much as 750 W cooling/sq ft in the last 30 years (Fenwick and Patterson 2008). This is a huge demand that contributes the majority of non-IT infrastructure load to data center's energy consumption profile.

Using solar cooling lowers power usage effectiveness (PUE), a standard comparison metric for data center efficiency, as well as providing backup to ensure uptime during the case of electrical grid failure. A natural gas boiler can be connected in parallel offering the natural gas grid as an additional layer of redundancy for critical applications.

Cooling demands are huge and growing. Worldwide demand for air-conditioning is expected to more than double by 2050 driven by a growing population and rising income levels in the developing world. The energy and additional infrastructure needed to match these demands is staggering.

5.1 Cooling Consumption

Cooling consumed 13% of total world buildings' energy use in 2009 (EIA 2010). In the United States, air conditioning is a major buildings energy consumer with 484 billion kilowatt-hours consumed across all residential, commercial and industrial sectors in 2007 (Goetzman 2010). This is enough energy to provide the annual electricity for more than 800 million homes.

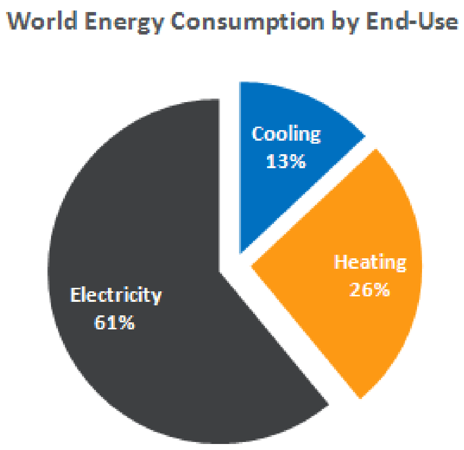

Fig. 1 Building Energy Consumption (excluding transportation), 2009

5.2 Thermal and Electric Chiller Market

Absorption chillers have been well established in the United States and worldwide since the early 1900's. In the United States, absorption chiller sales declined in the mid-1970's through the 1980's due to natural gas prices, governmental policies, and reliability issues with installed chillers. U.S. chiller manufacturers scaled back and eventually stopped absorption chiller production.

During this time, the Asian market for absorption chillers continued to expand and was matched by production from Asian chiller manufacturers. In the early 1990's, absorption chiller sales began to increase in the U.S. and the major U.S. chiller manufacturers began to source absorption chillers from Asia.

Due to the previous reliability issues with double effect, gas-driven chillers and an interest in waste heat recovery, the increase in U.S. sales have included a large number of single-effect, hot water-driven chillers. Over 55% of sales in the U.S. were for hot water driven chillers (Hongxi Yin 2006).

5.3 Solar Cooling Market

The market for solar cooling is small but growing. A new report by Global Industry Analysts predicts the "global market for absorption chillers to reach $924.2 million by the year 2017 prompted by rising environmental concerns, requirement for low cost, high efficiency cooling systems, and need for cutbacks in spiraling electricity charges"(Global Industry Analysts 2012).

At this time, solar driven chillers are a small component of this large and rapidly increasing growth of absorption chiller sales. However, the market for solar hot water driven chillers is showing a strongly positive trend. Technology advancement in packaged chillers and integration are driving down costs. Consumer interest is increased due to low ozone refrigerants, decrease in greenhouse gas emissions, energy savings and financial incentives offered by solar cooling systems.

The number of solar cooling installations shows an exponentially increasing trend. The majority of installations have relatively small cooling capacity compared to the overall absorption chiller market. For example, the largest solar cooling installation in 2011 was a cosmetic factory in Greece with two 100 ton adsorption chillers (Sparber, Napolitan, et.al 2009). Now the largest system is a 425 ton installation at the United World College in Singapore.

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