Energy Conversion and Management 171 (2018) 59–81

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Review

# Solar-powered absorption chillers: A comprehensive and critical review

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ARTICLE INFO

*Keywords:*
Solar cooling
Solar collectors
Absorption chiller
Air-conditioning
Refrigeration

ABSTRACT

Solar heating and cooling (SHC) systems are currently under rapid development and deployment due to their potential to reduce fossil fuel use and to alleviate greenhouse gas emissions in the building sector – a sector which is responsible for ~40% of the world energy use. The available technologies on the market for thermally driven cooling systems are absorption and adsorption chillers, solid and liquid desiccant cooling systems, and ejector refrigeration cycles. Of these, absorption chillers are considered as the most desirable method for harnessing solar thermal energy due to their relative maturity, reliability, and higher efficiency. In addition, absorption chillers can take advantage of economies of scale in large buildings to obtain a relatively good levelized cost of cooling as compared to other thermally-driven air-conditioning systems. In this paper, the background theory on solar-powered absorption chillers is presented followed by a comprehensive literature review of the recent existing theoretical and experimental investigations on this technology is conducted. The review shows that the majority of solar absorption chillers installed and much of the research around the world is based on single-effect chillers and low-temperature solar thermal collectors, while less emphasis has been placed on the combination of high-temperature solar thermal collectors and multi-effect absorption chillers, especially triple-effect chillers. Research studies indicate the use of gas-fired backup systems for single-effect chillers is inefficient due to its very low primary energy savings. It was also found that the storage tank and piping can be major sources of heat losses in solar absorption cooling systems. Thus, special care should be taken to ensure sufficient and appropriate insulation for all heat loss components. In regions with low direct normal incidence solar resources (e.g. most of Europe), solar multi-effect chillers are relatively inefficient, so single-effect chiller-based solar cooling systems are the best techno-economic choice in such regions. Conversely, multi-effect absorption chillers with high-temperature collectors are indeed promising in regions with high solar resources. However, the review shows that using currently available technology, SHC absorption chillers are not able to economically compete with conventional cooling without government subsidies and incentives. Therefore, improving the economic performance of these systems is essential. While there is clearly more that can be done on chiller and solar collector components themselves, we believe some R&D emphasis going forward should also be dedicated to the balance of the system, including optimization of the system configuration, minimizing parasitic losses, improved design and integration of thermal storage and auxiliary system, and numerous controls and operational aspects. To date, many of these topics have been largely overlooked in favor of chiller performance studies.

## 1. Introduction

Solar energy – a vast, renewable and relatively untapped resource – is freely and continually delivered to the rooftops of our global building stock. The total global solar irradiance striking the Earth's surface consists of two components: (i) direct beam and (ii) diffuse radiation. The beam component can be concentrated and converted to heat at high temperature whereas the diffuse radiation is typically harvested in collectors that operate at temperatures well below 100 °C. The average global annual solar energy resource potential is around 1.6 MWh $m^{-2}$, greatly exceeding the total average energy demand per unit area [1]. With increased environmental concern over fossil fuel consumption as well as government policies encouraging the use of solar energy, the global solar industry is rapidly accelerating [2]. The rapid fall in the cost of PV modules (in $/W) has dramatically increased the use of PV systems for electricity generation over the past

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https://doi.org/10.1016/j.enconman.2018.05.091
Received 29 January 2018; Received in revised form 3 May 2018; Accepted 25 May 2018

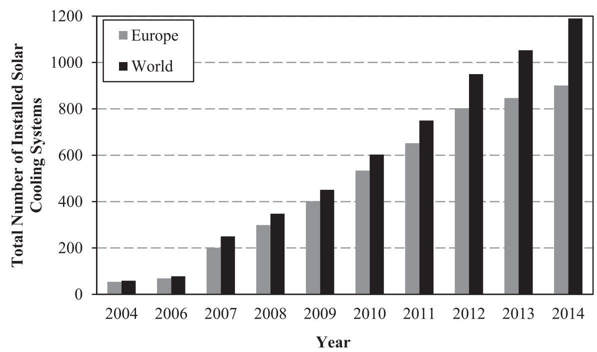


**Fig. 1.** Estimation of the number of solar cooling systems installed across Europe and the world [6].

few years. However, low efficiency levels and the high price of battery storage are the main barriers to stabilizing of this technology [3]. Solar thermal technologies continue to grow (albeit at more modest rates) for applications such as power generation, industrial processes, domestic hot water, and space heating and cooling. Although solar PV has garnered more public recognition, solar thermal technology still represents a significant part of the global installed capacity of solar energy [4].

## 2. Solar cooling overview

The aim of a solar cooling system is to utilize the solar energy landing on a building for useful space-conditioning for the occupants within. This is widely considered to be a sustainable and environmentally-friendly alternative to conventional air-conditioning systems [5], and, as such, interest in solar air-conditioning has grown steadily over the last 10 years. A relatively recent survey, as shown in Fig. 1, has estimated the number of solar cooling installations worldwide to be ~1200 systems in 2014 [6].

Solar energy can be used to produce a cooling effect via either *electricity-driven* or *thermally-driven* cooling processes [7]. Fig. 2 illustrates a classification of main solar cooling technologies. The most common solar electricity-driven cooling technology is based on driving high COP vapor compression chillers ($COP_e \approx 4–6$) connected to solar PV modules. This technology is relatively simple as it has low maintenance and is suitable for small-scale applications [5]. Although the price of solar PV cells has dramatically decreased in recent years, the high cost of battery storage has limited PV-driven cooling production to

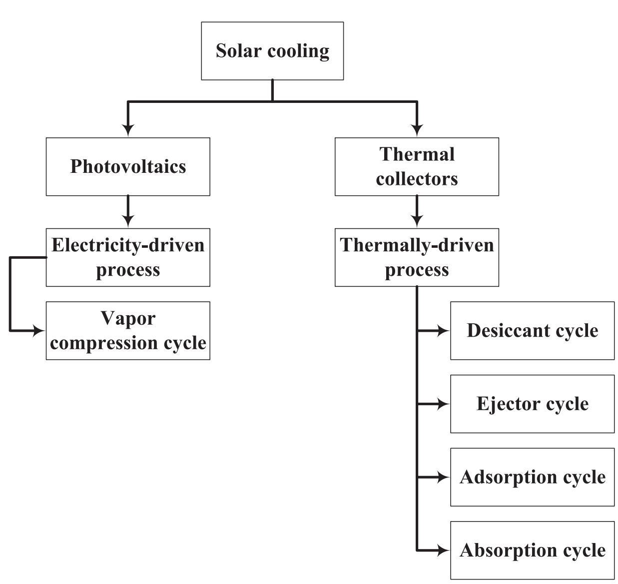


**Fig. 2.** Classification of main solar cooling technologies.

sunny hours [8]. Without batteries, a separate storage system (i.e. hot/cold water storage) may be required to cover the mismatch between available solar electricity gains and building loads. It should be noted that for a high COP system, 4–6 times as much thermal storage capacity is required to meet the capacity of an electrical storage system (e.g. for a $COP_e \approx 4–6$) [9]. Investment costs for solar-driven vapor compression chillers could be high due to the need for an additional electrical heat pump to cover the building heating demand in the winter. According to recent studies, the total cooling cost for solar PV cooling systems is not competitive without a feed-in-tariff for the PV-derived electricity surplus [10]. Currently, the average conversion efficiency of most commercial PV modules is relatively low (10–15%) [11]. This significantly reduces the overall sun-to-cooling efficiency of PV-driven systems (e.g. 10–15% × 4–6 = 40–90%). Although this technology may indeed become viable in the future, conventional compression chillers driven by solar PV panels is well-established [12–14], and will not be considered in the present dissertation.

As shown in Fig. 2 solar thermal cooling technologies span a wider range of potential options and, consequently, are less well-understood. Solar thermal collectors convert solar energy into thermal heat which can be used to run a thermally-activated cooling device, thereby generating chilled water or conditioned air for use in buildings. Thermally-driven cooling systems, compared to electrical vapor compression chillers, have a lower COP (0.6–1.8) but higher collector efficiency (35–70%). Since the chiller's COP and the collector efficiency are inversely related, total system efficiencies fall between 35 and 80%. This falls roughly within the same range as PV-driven systems. Thermally driven cooling systems can also be integrated with thermal storage (at a lower cost than batteries) and can be designed for excellent annual performance through dual design to meet the building's heating needs. Thermal storage, in particular, is seen as a big benefit of these systems since (relative to conventional HVAC) it alleviates peak cooling and heating loads on the grid [15]. Another advantage of thermal-driven systems is that by removing the compressor, they are characterized by low-vibration and low noise operation. To date, the vast majority of existing solar air-conditioning systems are driven by solar thermal heat [6,16]. In regions that require both cooling and heating throughout a year, these systems represent a year-round solution, improving the system efficiency and economics as compared to those producing either cold or heat alone. Solar thermal cooling systems are less likely to be taken up at residential scales (5–15 $kW_c$) due to their significantly higher price tag compared to conventional grid-connected split systems [17]. For large-scale applications (> 50 $kW_c$), however, economies of scale can make larger units more financially viable [18].

As shown in Fig. 2, the available technologies on the market for thermally-driven cooling systems are desiccant cooling systems, ejector refrigeration cycles, adsorption and absorption chillers [19]. A desiccant cooling cycle utilizes liquid or solid desiccant material to absorb water from an incoming air stream – using thermal heat as the driving source [20]. Water is then sprayed into the resulting dehumidified air stream, thereby lowering its temperature and providing a cooling effect (evaporative cooling). While there are relatively few suppliers of these systems, desiccant cooling systems have been used extensively in certain niche applications (e.g. supermarkets and hot and humid climates) [21], where the ability to independently control air humidity provides additional benefits. An ejector cooling cycle is basically the same as a conventional vapor compression chiller, but uses an ejector – a thermal compressor consisting of a supersonic nozzle, mixing chamber, and diffuser – to compress a refrigerant instead of an electrically-driven mechanical compressor [22]. The ejector requires thermal heat as a driving source in order to increase the pressure of the refrigerant. To date, this technology has not been widely used due to its relatively low efficiency [23]. An adsorption cooling cycle is based on the phenomenon of physical adsorption between the refrigerant vapor and a solid adsorbent to achieve a cooling effect. When heated, the solid absorber desorbs the vapor and pressurizes the vessel in which the vapor is