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Solar cooling technologies: State of art and perspectives

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ABSTRACT

The energy demand for cooling and air conditioning systems is increasing worldwide, especially in regions with high solar radiation intensity. One of the reasons for this is the increase of comfort demands worldwide. The most cooling and air conditioning systems are the conventional electrically driven one type such as compression refrigeration machines and air conditioning systems.

Through the huge electricity consumption for cooling and air conditioning, the environmental problems get bigger and bigger, because of carbon dioxide (CO_2) and other pollutant emissions.

One of the possibilities to reduce the primary energy consumption is through the use of solar energy for driving the thermal driven absorption or adsorption refrigeration systems, or desiccant cooling. Another possibility is using solar energy to produce electrical energy and this can be used to drive the conventional refrigeration systems.

Many research and developmental efforts in the last years have been done to enforce the spreading of solar-driven cooling systems.

This paper will illustrate the state of the art about the energy consumption for cooling and air conditioning systems, available solar-driven cooling systems and the potential of the utilization of such systems in comparison to the conventional ones. Moreover, this paper highlights some different methods of optimization, which used to maximize the performance and minimize the cost.

1. Introduction

Today, the expanding interest and growing market for refrigeration and cooling have prompted the consumption of primary energy to operate it, negative environmental issues, and cause for the increment of electricity peak load. As the quantity of customary vapor compression cooling machines develops (in excess of 100 million units sold in 2014) [1]. The refrigeration and air conditioning systems consume around 30% of total worldwide energy consumption [2]. Therefore, the main advantages of using solar cooling technology are the high consistency of the cooling demand and solar irradiation profile [3]. According to the International Institute of Refrigeration in Paris (IIF/IIR), 15% of the total of the electricity produced in the all world is consumed for cooling purposes and it represents 45% of the energy consumed by the use of air-conditioning systems for domestic and commercial buildings [4].

In Canada, the total number of cooled residential areas had almost tripled in size from 267 million square meters in 1990 to 749 million square meters in 2008. Therefore, within the same period, the total power demand for space cooling has dramatically increased more than doubled in a similar time span. In Ontario, up to half more the amount of carbon dioxide that discharges power created in the late spring months when contrasted with the winter months [5]. In Greece, the number of air conditioning units were increased rapidly from 76,000 to more than 200,000 units during the period 1990–2000 respectively [6]. In Jordan, it is expected the demand for air conditioning purposes to double by 2030 in contrast with 2015. As a result, a significant emission increase in CO_2 emission will definitely contribute considerably to climate change and as a consequence may lead to violations of climate agreements. Therefore, the replacement of conventional cooling systems with energy-efficient solar cooling chillers with a penetration rate of 25%, may result in a 3.74 Mt CO_2 eq/year reduction of emission [7]. More than 60% of Australian houses have a minimum of one air conditioner [8]. European Union (EU) consumes 385.6 Mtoe for building energy, which is responsible for about 40% of the total energy consumption and 20% of total CO_2 emissions [9]. Solar cooling technologies appear to represent an encouraging alternative for conventional

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Nomenclature

ADI	Alternating direction implicit
ANOVA	Analysis of Variance
CC	Cooling capacity
CFCs	Chlorofluorocarbons
CO_2	Carbon dioxide
COP	Coefficient of performance
CPC	Compound parabolic collector
EES	Engineering equation solver
ETC	Evacuated tube solar collector
EU	European union
FPC	Flat plate solar collector
GA	Genetic algorithm
GHG	Greenhouse gases
H_2O–LiBr	Water- lithium bromide
H_2O–LiCl	Water-lithium chloride
I/O	Input/output
IEA	International energy agency
IIF	International institute of refrigeration
LiCl	Lithium chloride
MATLAB	Matrix laboratory software
PCA	Principle component analysis
ANN	Artificial neural network
PCM	Phase change materials
PS	Particle swarm
PSO	Particle swarm optimization
PTC	Parabolic trough solar collector
PV	Photovoltaic
RT	Refrigeration ton
SAR	Solar-powered adsorption refrigeration
SCOP	Solar coefficient of Performance
SCP	Specific cooling power
SDWP	Specific daily water production
SG	Silica gel
TIM	Transparent insulation material
TRNSYS	Transient system simulation

cooling devices, especially in developing countries and rural areas where electricity is not typically available, and in industrial countries wherever peak cooling loads coincide with available solar power.

This manuscript outlines and examines all the current strategies and techniques of solar cooling technologies that have been developed and employed for use in different sector applications. A comprehensive description of these technologies combined with numerous solar collectors is demonstrated. Many of solar cooling systems including designs, developments, challenges, improvement, optimization, potential marketing and feasibility are presented and discussed. This manuscript summarizes the method of optimizations that maximize the specific cooling power (SCP) and the performance of solar cooling systems and minimize the system cost. Case studies of existing solar cooling manufactured and developed in the world are provided. Therefore, this manuscript summarized the solar cooling status in all worlds for marketing and available product perspectives. Finally, the paper is concluded by discussing some of the solar cooling research areas and a recent trend in solar cooling technology that deserved more investigation. Furthermore, highlighting on the execution of small and medium scale solar cooling systems that could be used for residential and commercial applications.

2. Sorption refrigeration technology

Sorption refrigeration technology can be divided in two groups: closed and open cycle systems. Closed-cycle systems consist of several types as absorption cooling, adsorption cooling, ejector, and solar assisted heat pump systems. Open-cycle frameworks give a direct treatment of air, for example, desiccant cooling [10].

2.1. Closed sorption cycle

Based on the sorption material, closed sorption cycles are divided mainly into liquid sorption and solid sorption. The liquid sorption refers to the absorption, while the solid sorption refers to the adsorption. Absorption involves a liquid or solid sorbent that absorbs refrigerant molecules into its inside and changes chemically and/or physically in the process. The most widely used working pairs in the absorption processes are water-lithium chloride (H_2O–LiCl), ammonia-water and water -lithium bromide (H_2O–LiBr). There are some research works about using of a new working pair Acetone- Zink bromide [11–15]. This working pair is especially suitable for the use in solar thermal driven absorption refrigeration machines by low driving temperatures as flat plate solar collectors.

Adsorption, on the other hand, refers to a solid sorption process where a solid sorbent attracts refrigerant molecules into its surface by chemical or physical force and without changing its form in the process. The adsorption refrigeration process is achieved using a combination of adsorbate and adsorbent. Ammonia-activated, methanol-activated carbon, ethanol-activated carbon, water–silica gel and water-zeolite are the most widely used working pairs in the adsorption processes [16].

2.1.1. Absorption systems

The absorption chiller is popular worldwide in the solar cooling market due to its higher coefficient of performance (COP) values compared to other solar cooling technologies, which are in the range from 0.6 to 0.8 for single stage chillers, and achieve a higher COP of 0.9–1.3 for two stage machines by utilizing the rejected heat from the first stage as the input for the second stage [3,10]. The common heat supply temperature required 80 to 95 °C for a single stage and 130–160 °C for double stages, which requires a more expensive solar collector as evacuated tubes, parabolic troughs or concentrating collectors [3,10]. Typical solution pairs were used in absorption chiller are ammonia as a refrigerant and water as a sorbent or water as the refrigerant and lithium bromide as a sorbent. For ammonia and water pairs, the evaporator temperature can be below 0 °C, and heat rejection temperatures of 50 °C. Consequently, they can be utilized for freezing purposes by the use of dry air-cooled condensers for heat rejection. For water and lithium bromide pairs, the evaporator temperature is restricted to 4 °C and the condenser temperature is beneath 35 °C. The condenser temperature implies that an expensive and high water expending wet cooling tower is regularly required [17].

In the last 10 years, various numbers of absorption frameworks have been exploited and developed for small capacity underneath 100 kW and specifically beneath 20 kW down to 4.5 kW. Most of these small capacity systems operated by a single effect of various kinds, utilized essentially for domestic buildings and small commercial applications. While the medium and large absorption chiller with cooling capacity existed for a long while. In general, the absorption chiller is available with the cooling capacity in the range 10.5 to 500 kW [18]. These chillers were mainly manufactured in Japan, China, South Korea, India, Europe and the United States. Many research works have been undertaken to investigate and improve the performance of absorption air conditioning. Syed et al. [19] investigated experimentally a single stage, 35 kW cooling capacity of water- lithium bromide (H_2O–LiBr) absorption system powered by a flat-plate collector with a total surface area of 49.9 m^2 for Spanish houses in Madrid. The heat rejected and generation temperatures were in the range of 32–36 °C and 57–67 °C respectively. The average, daily and maximum COP achieved were 0.34, 0.42 and 0.6 respectively. Ajib et al. [20–23] presented experimentally the investigation results of 5 kW solar thermal driven absorption for water- lithium bromide (H_2O–LiBr) refrigeration machine. This machine was investigated under different working temperatures (generation, rejection and refrigeration temperatures). The generation temperature has been changed from 70 °C till 95 °C. The rejection (cooling) between 28 till 38 °C and the refrigeration temperature between 6 °C and 13 °C. The COP varied between 0.1 and 0.6 depending on operation temperatures as depicted in Figs. 1, 2 and 3.

A numerical analysis using Transient System Simulation (TRNSYS) program to model and simulate the water- lithium bromide (H_2O–LiBr) absorption for Malaysian weather was conducted by Assilzadeh et al. [24]. The author revealed that the optimum surface area for 3.5 kW cooling capacity under Malaysia's climatic is 35 m^2 of evacuated tubes with a tilt angle of 20°. To improve the performance of the solar absorption system, thermal energy storage based on phase change materials (PCM) has been used by Hirmiz et al. [25]. The thermal energy storage was modeled by the use of TRNSYS17 software. The results indicated that the PCM thermal storage has the ability to reduce storage volume by 43% in the absorption system, maintaining the same performance under a temperature range of 30 °C. Shirazi et al. [26] employed a TRANSYS software for a 1023 kW absorption with different control strategies for the solar collector output, including a variable versus constant speed pump, and the use of the auxiliary heater in series and parallel with the storage tank. The results indicated that an improvement in system performance up to 20% when using a variable speed pump combined with a parallel auxiliary heater and a variable temperature set point linked to the instantaneous cooling load. In a similar study to the one described above, Shirazi et al. [27] simulated the impact of using a single, double, and triple effect chiller with capacities of 1023–1163 kW implementing TRNSYS software. The simulation revealed a storage capacity changed as a function of the chiller. Furthermore, the appropriate storage capacity depends on a complex function of the load requirement, temperature set point, and system size. A transient simulation of a 5-ton (17.58 kW) capacity solar absorption cooling was carried out utilizing the TRNSYS software by Sokhansefat et al. [28]. The authors investigated the parameters affecting the absorption chiller namely storage tank capacity, collector area, a mass flow rate of the solar system, and the temperature set point for switching to the auxiliary boiler. The optimum parameters for this system were the collector area of 55 m^2, solar collector mass flow rate of 1000 kg/h, storage tank volume of 1 m^3, and temperature set point of the auxiliary boiler of 77 °C. To achieve the best configuration of solar-driven absorption chiller systems, a systematic simulation-based on coupling TRNSYS and Matrix laboratory (MATLAB) was done by Shirazi et al. [29]. A multi-objective optimization model by the use of a genetic algorithm was developed. Three absorption chillers in terms of a single, double, and triple effect chiller powered by evacuated flat plate collectors, evacuated tube collectors and concentrating parabolic trough collectors. The simulation showed that the double-effect chiller had the best configuration for the energetic, economic and environmental performance of the system. Aisyah et al. [30] developed an Artificial Neural Network (ANN) based on experimental data to predict the performance of the solar absorption chiller system at Indonesian Universities. A Principle Component Analysis (PCA) was used in this study to reduce the number of input variables for performance prediction. The ANN & PCA model of this study showed good accuracy of the prediction model. Jianting Yu et al. [31] investigated experimentally solar absorption-subcooled compression hybrid cooling system powered by 27 m^2 of stationary compound parabolic collector. The results showed that the daily average COP and daily mean solar COP (SCOP) of the absorption subsystem in a sunny/cloudy day are 0.52/0.47 and 0.2/0.13 respectively. Moreover, the daily mean rise of the COP in a compression subsystem at sunny/cloudy day is 22.2%/13.3%.

2.1.2. Adsorption system

The adsorption cooling system can be a suitable selection in most industrial countries. About 25% of the total industrial energy demand is needed for thermal process heat applications in the range up to 300 °C. More than half (57%) of this energy is used to produce heat below 150 °C [3]. Therefore, this technique allows us to utilize renewable energy or low temperature gains from solar energy, waste heat and cogeneration to drive the cooling cycle. It can also save a global energy

Fig. 1. Test plant of 5 kW solar thermally driven absorption chiller [22].

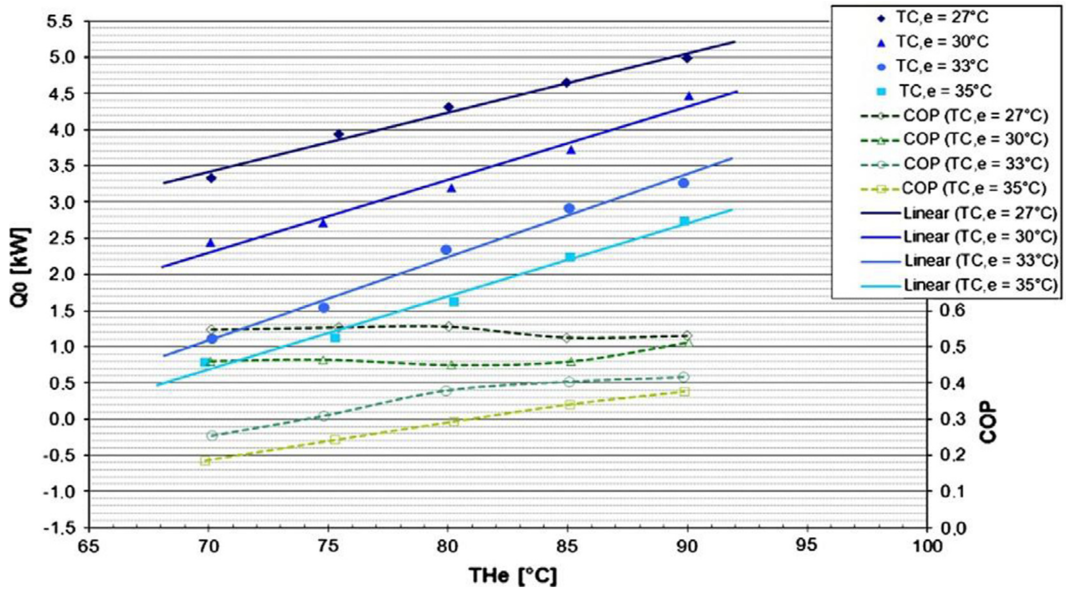

Fig. 2. Results of measuring of the refrigeration capacity and COP depending on the cooling temperature by chilled water temperature of $T_{ch,a} = 15$ °C [22].

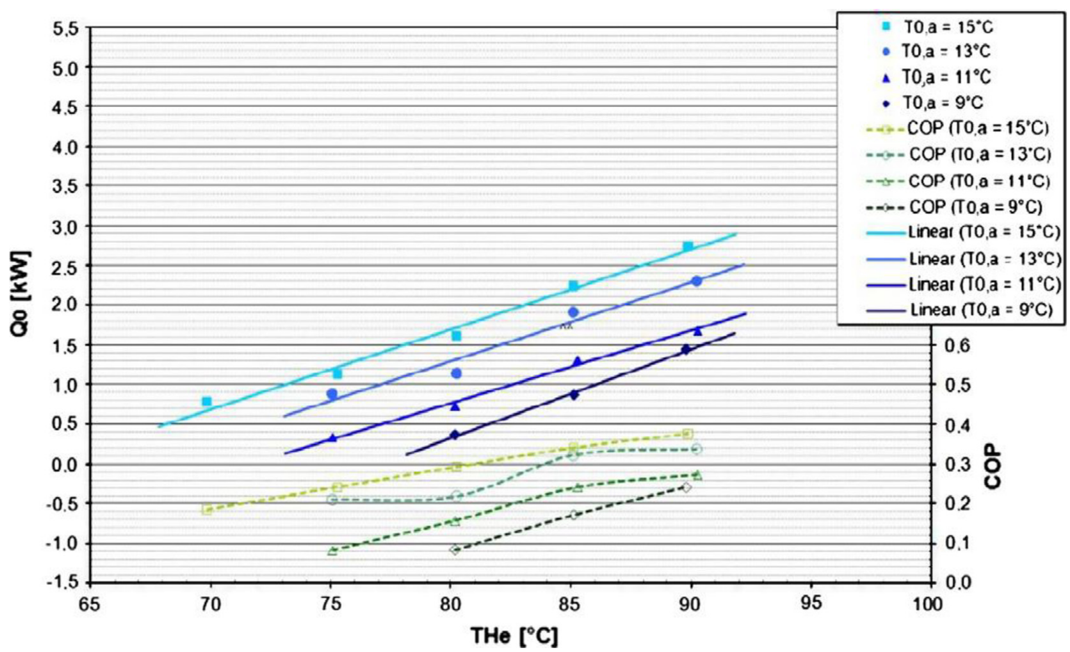

Fig. 3. Results of measuring of the refrigeration capacity and COP depending on the chilled water temperature by cooling temperature of $T_{C,e} = 35$ °C [22].

and it is environmentally sound since it reduces chlorofluorocarbons (CFCs) and CO_2 emissions. Besides, adsorption systems can be operated with no rotating parts, no corrosion problem, and are less sensitive to shocks and the installation position. They also do not require a solution pump and rectifier. Table 1 displays a comprehensive comparison between two solar cooling systems in terms of absorption and adsorption systems [32–37]. In addition, the solar powered adsorption chillers are very promising in the widespread, but due to their low COP value and higher product cost, they are not feasible for commercialization. In general, the adsorption chiller is available with the cooling capacity in the range of 8 to 370 kW [17]. Many research works have been undertaken to investigate and improve the performance of adsorption air conditioning systems by employing a heat recovery, mass recovery, multi-bed and multi-stage technologies.

Wang and Chua [38] evaluated the performance of two distinct heat-recovery schemes for two beds, water/silica gel adsorption chiller by the use of a verified distributed-parameter model at different operating conditions. The adsorption cycle includes two main processes: evaporation-adsorption-cooling and heating-desorption- condensation. They found that the passive heat recovery technique could be adopted in the commercial chiller with a simple modification instead of the Nishiyodo water-circulation heat-recovery technique. Khalifa et al. [39] stated that the use of the mass recovery process in methanol/active carbon, two beds adsorption chiller with the generator will improve the pre desorption concentration in the desorption generator, and therefore, improving the cycle COP and specific cooling power (SCP) based on the experimental results. Chen et al. [40] examined experimentally the two-bed, silica gel-water, heat and mass recovery, two-condenser and two-evaporator adsorption chiller. The check valves that regulate the flow from the condenser and evaporator were removed and an alternative actively controlled valve was used to improve the heat and mass recovery. The results indicated that an improvement of the system

Table 1
General comparison of two cooling systems: Absorption and Adsorption systems [32–37].

Comparison criteria	Adsorption system	Absorption system
Initial cost	Higher	Lower
Phenomenon	It is a surface phenomenon	It is a bulk phenomenon
Heat exchange	Exothermic process	Endothermic process
Temperature	It is favoured by low temperature	It is not affected by temperature
Rate of reaction	It steadily increases and reach to equilibrium	It occurs at a uniform rate
Concentration	Concentration on the surface of adsorbent is different from that in the bulk	It is same throughout the material
Example	- Water vapors adsorbed by silica gel - NH_3 is adsorbed by charcoal	- Water vapours absorbed by LiBr - NH_3 is absorbed in water
Continuous operating	More than 8000 h per year	Require two times yearly shutdown for dilution of lithium bromide solution.
Life span	The silica gel up to 30 years	20 years with continuously maintenance
Maintenance	Replacement vacuum pump every 5 years, annual cleaning of condenser tubes	Require more preventative maintenance for pumps, heat exchanger. Replacement, controls, and air leakage
Refrigerant	Water, methanol	Water or ammonia.
Adsorbent/absorbent	Silica Gel, zeolite or activated carbon	Lithium bromide or water
COP	Water/silica gel Single stage 0.3–0.7 Two Stages0.35–0.8	Water-LiBr Single stage 0.5–0.75 Two stages 0.8–1.2 NH_3-Water Single stage 0.5–0.6 Two stages 1.2–1.3
Corrosion	None	Lithium bromide is corrosive in nature.
Crystallization	None	Yes, can occur in low temperature cooling water by H_2O/LiBr-System
Frequent Replacement Adsorbent/ absorbent	Not necessary	Every 5 years
Required hot water temperature	Variable 50–100 °C	Variable 80–120 °C, Back-up heat is required if the temperature below 80 °C to prevent crystallization
Typical Cooling Capacity (kW Cold)	8–370 kW	5 kW–5 MW
Cooling water requirement	30–40 °C, lower temperature increases system capacity	It should be between 20 and 40 °C
Chilled water output	3–9 °C	Higher than 4 °C for H_2O/LiBr; and unlimited by NH_3/H_2O until till −50 °C
Solar collector	Vacuum tube, Flat plate collectors	Vacuum tube + flat plate collectors by small cooling capacities
Refrigeration cycle	Closed Refrigerant Cycle	Closed Refrigerant Cycle
Evaporator temperature	Water- Silica gel or zeolite 6–20 °C	Water-LiBr 6–20 °C NH_3-Water −30 to +20 °C
Heating temperature	Water-Silica gel or zeolite 50–95 °C	LiBr-Water 60–95 °CWater-NH_3 65–150 °C
Heat rejection temperature	Water-Silica gel or zeolite 25–35 °C	Water-LiBr 25–35 °C NH_3-Water 25–50 °C
Cooling capacity range (per unit)	Water-Silica gel or zeolite 5–430 kWr	Water-LiBr 10–20,500 kWr NH_3-Water 19–1000 kWr

performance, but they did not quantify the amount of improvement. Nasruddin [41] simulated a two bed, silica gel/water adsorption chiller, solar energy powered based in the tropical climate of Indonesia. The adsorption chiller system was mathematically modeled and calculated numerically using MATLAB software. To improve cooling capacity, mass recovery and heat recovery were applied. The simulation results showed that the 0.26 of average COP was achieved during the maximum value of irradiation and 0.15 of COP was achieved during the minimum value of irradiation with a range of 5.3–37.8 kW of cooling capacity. More improvement by the use of the cascading cycle investigated by Marlinda et al. [42]. The authors proposed a cascading adsorption cycle, silica gel/water based on the double adsorption effect which utilizes the condensation heat generated in the upper cycle to drive heat source in the lower cycle. A numerical investigation based on energy balance was used in this study. They found that the COP resulted from the double-effect adsorption refrigeration is about twice that of the conventional single stage cycle at driving temperature of 130 °C, while the SCP of the double-effect cycle is much smaller. One of the shortcoming for solar-powered adsorption refrigeration (SAR) systems is the intermittent operation due to the intermittent nature of solar radiation. Continuous cold production in SAR systems was developed and discussed by Hassan et al. [4]. There are many advantages of using multi beds which included to maximize the cooling capacity; reduce the temporal fluctuation of the chilled outlet temperature; and improved the quality of instantaneous cooling compared to a two-bed chiller at the same cooling capacity [43]. Khan et al. [44] experimentally evaluated a performance for three-bed, silica gel/water, mass recovery advanced adsorption chiller. The three-bed adsorption chiller includes of three sorption elements (Hexs), one condenser and one evaporator. The mass recovery only occurred between two sorption elements and no mass recovery with the third sorption element. A heat source driven temperature in a range of 55 °C to 80 °C incorporated with 30 °C and 14 °C for coolant inlet temperature and chilled water inlet temperature respectively. The results showed that the cooling capacity (CC) with three-bed with a mass recovery scheme superior to those without a mass recovery scheme and provides more COP values in the range 65–75 °C for heat source temperature. Alsaqoor et al. [45] experimentally optimized the switching time for three beds with dual evaporators silica gel/water adsorption chillers driven by low temperature heat from cogeneration to achieve the highest performance. They found that the highest cooling capacity and COP of 90.5 kW and 0.645 were achieved respectively by switching time on 900 s. Performance analysis of using a novel composite adsorbent consists of silica gel permeated with lithium chloride, paired with methanol as the adsorbate to operate a two bed adsorption chiller was experimentally studied by Ishugah et al. [46]. The average hot water inlet temperature, chilled water inlet temperature and cooling water inlet temperature are 83 °C, 15 °C and 26 °C respectively. The COP and SCP of 0.48 and 286 W/kg were achieved. The experimental tests indicated the following points: with the increase of cycle time, the SCP decreases while the COP increases; with operating by an adsorption system with heat and mass recovery schemes, both the COP and the SCP increased with recovery time until reaches maxima at optimize time, beyond optimal time, both COP and SCP start to decrease. The combination of the heat pipe into the adsorption bed leads to reduce of cyclical time and then improved of COP. Wang [47] proved experimentally that the heat pipes could be used as heat exchangers for adsorbers, condensers or evaporators. Which lowering the adsorption cost and eliminate the corrosion problem. Lu et al. [48] proposed different types of techniques could be used to improve the heat/mass transfer in the adsorption bed. These techniques can be summarized as (i) increase of heat transfer area by the use of plate-finned bed, porous bed, spiral plate bed and pin-fin bed; (ii) reduction of the thermal resistance between the adsorbent and wall and also of adsorbent itself; and finally (iii) use of heat pipe to boost the heat transfer. Furthermore; more strategies were suggested by Thomas et al. [49] to increases the performance of an adsorption chiller as the increase of hot mass flow rate loops to the chiller, install of a spraying kit in the cooling tower to decrease the electrical consumption of the fan during hot days, and finally added more electrical resistance in the hot water storage. Wang et al. [50] improved the performance of a conventional two bed adsorption chiller with a circular fin sorption heat exchanger. A numerical method based on a distributed-parameter approach was developed to show the behaviours of the operated adsorption chiller. Alam et al. [51] studied mathematically the effect of heat exchanger design parameters on the performance of a two-bed silica gel–water adsorption chiller. The non-dimensional equations were solved numerically by employing the alternating direction implicit (ADI) method. The authors stated that a cycle time is strongly dependent on the configuration of the heat exchanger. Extensive research efforts have been conducted to improve the system performance of two-bed adsorption cooling systems through optimized operating adsorption conditions. Ali [52] and Ali et al. [53–55] optimized an adsorption refrigeration system for ice production under using of two beds silica gel and activated carbon with methanol as a refrigerant. The analytical model was simulated using MATLAB software. They found that the combined system has many advantages regarding the specific produced ice mass (kg ice/kg methanol) and COP. The simulation results showed that the COP of the combined system was improved by 30% in opposite to the methanol/silica gel system.

Sim [56] optimized the operating parameters for driving the solar thermal cooling system using evacuated tube collectors under Doha, Qatar weather conditions using Transient System Simulation (TRNSYS) tool. The results showed that the adsorption cooling system of a 4.5 kW was required for an area of 23.4 m^2 of evacuated tubes. The optimized solar collector angle is 24° from the base of horizontal with a water storage tank of 0.3 m^3. Moreover, the adsorption cooling technology could be reduced the electricity consumption by 47% compared to a conventional cooling system. Alahmer et al. [57] stated the use of a solar adsorption cooling system driven by a compound parabolic collector (CPC) solar panel collector could reduce the electrical power consumption by 34% and 28% under Perth and Amman weather conditions respectively compared to conventional air conditioning system. A TRNSYS simulation was applied to theoretically analyze the performance of the solar adsorption cooling system. Another study was performed by Alahhmer et al. [58] to show the feasibility of using a solar adsorption system under a climatic weather condition of Perth, Australia. Life Cycle Saving and Payback Period was used to optimize the area of the solar collector needed. Both methods showed that the optimum of solar collector is 38 m^2 to provide an 11 kW of average cooling capacity at peak hour (13:00). The payback period was about 11 years and Life Cycle Saving was about \$3500 for this collector area. Alkhair et al. [59] investigated the effect of different parameter of chilled water, cooling water and inlet hot water temperatures, with addition to hot water and chilled water flow rates to optimize the performance of a one refrigeration ton (RT) solar assisted two beds, activated carbon fiber/ethanol adsorption air-conditioning refrigeration. A simulation strategy was adopted using MATLAB software to calculate the cooling capacity and COP of the system according to the operating parameters. Recently, adsorption desalination technology can utilize a low temperature waste heat source to produce two useful effects; cooling and desalination. It can be produced fresh water of 10 ppm of low salinity particles with a low running cost of 0.2 \$/m^3 and minimal CO_2 emissions of 0.6 kg/m^3 [60,61]. Most places in arid or semi-arid regions have a shortage of water, the air cooling systems were used to reduce water loss during heat rejection. Thu et al. [62] developed a model to evaluate the performance of the 4-bed adsorption desalination cycle incorporating with an internal heat recovery between the evaporator and the condenser. A numerical investigation based on energy and material balance together with the thermodynamic models was used in this study. The model was validated using experimental data for the range of heat source temperatures of 50–70 °C. The results indicated that the specific daily water production (SDWP) of the present cycle amounts around 10 m^3/day/ton of silica gel at 70 °C of the heat source temperature. Moreover, the performance of the proposed adsorption desalination cycle is more than of the conventional configuration of the adsorption desalination cycle especially at low heat source temperature.

2.2. Open sorption cycle

The open sorption cycle is classified as liquid or solid desiccant systems that are used for either humidification or dehumidification. Basically, there are two processes to transfer moisture from one air stream to another in the desiccant systems: desorption or regeneration process and sorption process. Liquid or solid desiccants behave similarly because their water vapor pressure is a function of moisture content and temperature [33].

The liquid desiccant system mostly uses liquid desiccant materials to absorb moisture through physical or chemical processes. Lithium bromide (H_2O–LiBr), lithium chloride, and calcium chloride are the most popular materials typically in liquid desiccant systems. However, the solid desiccant system is mostly used solid desiccant materials to adsorb the moisture without chemical reaction, such as silica gel, or zeolite, which means there is just a physical process in solid desiccant systems [63].

2.2.1. Desiccant system

The desiccant cooling system can be a suitable selection for thermal comfort, especially in climates with high humidity. Moreover, this technique allows us to utilize renewable energy or low-temperature gains from solar energy, waste heat and cogeneration to drive the cooling cycle. It can also save global energy and its environmental issues through avoid CFCs and CO_2 emissions. The desiccant air conditioning system utilizes the capability of desiccant materials in removing the air moisture content by the sorption process by the use of the vapor pressure differences between the air and the desiccant surface to attract and release moisture [64]. A wheel desiccant dehumidifier rotates two separate air streams, the process airstream and the regeneration or reactivation airstream. When the wheel rotates, the outside humid air enters the rotating wheel through the desiccant, which absorbs the moisture of airstream to leave as warm and dry. At the same time, in a regenerative section, a waste heat from the combustion process or solar energy is used to heat the desiccant and, consequently, dries the desiccant [65]. The main advantages of using solid desiccant can be summarized in the following points [66–69]: (i) high drying capability compared to liquid desiccant; (ii) more efficient when the latent heat load is larger than the sensible load; which leads to air dehumidification for 40–60% of the cooling load for air conditioning in hot and humid weather [70]; (iii) utilizing different energy sources especially low grade energy; (iv) clean technology, which operates without the use of harmful refrigerants; (v) control of humidity is better than conventional cooling system; (vi) cost of energy to regenerate the desiccant is less than the cost of energy to dehumidify the air by cooling it below its dew point; (vii) improves indoor air quality; (viii) capable of removing airborne pollutants and finally (ix) compact construction, resistance to corrosion, and ability to work continuously. The main disadvantages it requires a higher regeneration temperature of more than 70 °C and a high pressure drop in the air stream, also requires a high energy system. The comparison between the desiccant system and conventional systems is listed in Table 2. There are many required properties of any desiccant materials selected in open-cycle cooling based on [71,72]: (i) mechanical and chemical stability; (ii) large moisture capacity per unit weight; (iii) low heat of adsorption/absorption to regenerate; (iv) sorption rate; (v) large adsorption/ absorption capacity at low water vapor pressures; (vi) cheap cost; (vii) sorption at low relative humidity; and finally (viii) ideal isotherm shape. The performance of wheel desiccant depends on key design and operating parameters such as [73,74]: process air moisture, process air temperature, process air velocity through the desiccant, air volume flow rates, desiccant rotor thickness, regeneration temperature, regeneration air velocity through the desiccant, sector angle of regeneration section, regeneration air moisture, rotational speed, amount of desiccant presented to the reactivation and process airstreams, and finally desiccant sorption–desorption characteristics.

Many research works have been undertaken to investigate and improve the performance of desiccant systems. Elgendy et al. [75] proposed three configurations of desiccant evaporative cooling systems that constitute desiccant evaporative cooling, inserted before and after the rotating heat exchanger, with the addition of an extra desiccant evaporative cooling in the opposite manner. The system simulations were implemented using two software TRNSYS and Engineering Equation Solver (EES). They found that using desiccant evaporative cooling before the rotating heat exchanger yields the highest cooling capacity, while the added extra desiccant evaporative cooling has the highest thermal COP, higher than the conventional system with 54% over the range of ambient air humidity. Nia et al. [76] developed a numerical model to evaluate the desiccant performance and predict the temperature and humidity states of the outlet air from a desiccant wheel. The simulation was carried out by the use of MATLAB Simulink for a combined heat and mass transfer processes that occur in a solid desiccant wheel.

Vitte et al. [77] proposed a control strategy to improve the performance of hybrid desiccant evaporative cooling systems while satisfying the thermal comfort. The effect of outdoor and indoor conditions is evaluated using numerical strategy by taking the differential of enthalpy between indoor and outdoor situations. Alahmer et al. [78] optimized some of operating parameters such as a ratio of the reactivation to process air flow, rotational speed, flow rate, humidity ratio, and temperature in order to get a higher amount moisture removal by the use of two types of desiccant materials namely wound silica gel and molecular sieve. The author found that the silica gel is more efficient to absorb moisture than molecular sieve at a regenerative temperature of 80 °C. Moreover, the authors confirmed that the regeneration temperature significantly affects the moisture removal ability and the coefficient performance of the system (COP). Cx et al. [79] examined a hybrid of a rotary solid desiccant system combined with a conventional air conditioning model. The authors fabricated a composite desiccant by the impregnate of the saturated Lithium chloride (LiCl) solution into the pores of silica gel (SG). The results revealed that the hybrid desiccant system is more effective than a conventional cooling system by the reduction of electrical energy to 37.5% in air temperature and relative humidity 30 °C and 55% respectively. Furthermore, the adsorption capacity of a composite desiccant was 2–3 times higher than pure silica gel at high relative humidity. Yaningsih et al. [80] evaluated experimentally the capability and the performance of the desiccant dehumidification system under low desorption temperature. The results revealed that the effectiveness factor and dehumidifying rate increase in case of increasing desorption temperature. The highest dehumidifying rate of 1.12 g/s and the highest effectiveness factor of 0.71 was achieved for 35 °C and 55 °C desorption temperature respectively. Farooq et al. [81] developed a dynamic simulation using TRANSYS software for three configurations based ventilation mode on a solar desiccant cooling system operated by a photovoltaic-thermal (PV/T) solar collector for Lahore weather conditions. The results showed that the existence of the auxiliary heater in the air conditioning loop leads to improving the energy saving. On the other side, the existence of the auxiliary heater in the solar water heating loop leads to lower energy saving. Moreover, the desiccant cycle without evaporative cooler is not feasible for a solar cooling system. Recently a new technology was introduced to the market by the use of a liquid water-lithium chloride as sorption material in desiccant cooling systems. Two main advantages were attained: (i) with the same driving temperature, a higher air dehumidification were achieved; (ii) high energy storage in terms of storing the concentrating solution. Many systems were installed in Germany in a pilot application [82].

3. Solar collector

There are an enormous number of solar collectors available in the market. The main three types of solar collectors are flat plate solar collector (FPC), evacuated tube solar collector (ETC), and parabolic trough solar collector (PTC). A comprehensive comparison of three types of solar collectors is depicted in Table 3 [7,65,83]. Fig. 4 depicts the temperature variation and their applications which can be achieved by the use of different solar collectors. Below, more details and development for various types of solar collectors.

3.1. Flat plate collector

The most two important parameters that affected the performance of a flat plate solar collector (FPC) are: the number of glazing and the selective coating material. To significantly reduce the area of flat plate solar collector required for solar heating and cooling purposes, Ghoneim and Abdullah [84] suggested the FPC with honeycomb material. Kaushik and Mahesh [85] found that the COP of adsorption chiller driven by flat plate black coating for single glass cover, double glass covers, selective coating for single glass cover and selective coating for double glass cover were 0.116, 0.113, 0.145 and 0.193, respectively. Yong and Sumathy [86] recognized a model of simple lumped parameter for a flat plate solar collector with three different configurations of glazes: single and double glazed cover and transparent insulation material (TIM) cover as heat source driven a two-bed adsorption chiller to examine the thermal performance of the solar adsorption air conditioning system. The authors stated that from the economic point of view, a FLC with double glazed cover could be used as a heat source. Chang et al. [87] constructed experimentally a silica gel-water, single-stage, two-bed, flat plate solar heat driven adsorption chiller in a golf course in Taiwan. The system could achieve a COP, CC and SCP of 0.37, 9 kW and 72 W/kg, respectively. Sumathy et al. [88] presented a lumped parameter model for a two-bed adsorption air-conditioning working with activated carbon and methanol pair. The

Table 2
The comparison between desiccant system and conventional systems [5,32,78].

Parameter	Conventional system	Desiccant system
Operation cost	High	Low
Performance	High	Low
Energy source	Mainly electricity	Low grade energy
Environmental safety	less	High
System care	less	High
Control over humidity	Average	Accurate
Indoor air quality	Less	more
System installation	Simple	More Complicate
Energy storage capacity	Mainly not applicable	Applicable
Installation cost	High	Low
System Control	Average	Complicate

Table 3
Comparison of solar thermal collectors [7,65,83].

Item	FPC	ETC	PTC
Working fluid	Water	Water	Pressurized water, heat oil or steam
Concentrating	No	No	Yes
Typical collector temperatures range (°C)	55–85	85–105	150–450
Area usage	Low	Low	High
Efficiency	40–80%	55–75%	65–77%
Cleaning complexity	Low	Medium	High
Maintenance complexity	Low	Low	High
Cost (€/m^2)	100–120	130–150	600–1000
Tracking	Fixed	Fixed	Single axis tracking

system was driven by a simple flat-plate solar collector. It was found that the optimum values of the adsorbent mass and collector area are 30 kg and 5 m^2, respectively to maximize a SCP of 150 W/m. Fasfous et al. [16] found experimentally that the area of the flat plate solar collector of 40 m^2 could provide solar heat for an 8 kW zeolite–water adsorption chiller under the climatic condition of Amman, Jordan. Ghoneim and Abdullah [84] stated that the modified FPC through transparent insulation material could reduce the energy cost for solar cooling and heating system by 64% compared with the corresponding cost of the conventional fuel at a current price.

3.2. Evacuated tube collector

The average efficiency of the evacuated tube solar collectors (ETC) is about 36%, if the hot water supplied to the chiller reaches approximately 85 °C [89]. Zhai et al. [90] installed a solar-powered, silica gel-water, heat and mass recovery, two adsorption bed air conditioning system. The solar collectors consisted of 150 m^2 of U-type evacuated tubular solar collectors incorporating with compound parabolic collectors and heat pipe evacuated tubular solar collectors. The results showed that the daily average solar COP, the daily average of the entire system, and the daily average electric COP were 0.15, 0.38 and 8.19 respectively under the climatic weather condition of Shanghai, China. The average cooling capacity of the solar-powered adsorption air conditioning system was 15.3 kW for 8 h. Mahesh [91] investigated theoretically and experimentally a performance of a solar powered adsorption refrigerator with an ETC solar collector area of 2 m^2 which could be produced COP in ranges 0.15–0.23 and the adsorption bed reached the temperature of 90–110 °C. The author developed a mathematical model and solved numerically by employing the fourth-order Runge-Kutta Method to the ordinary differential equations and then solving the resulting set of nonlinear algebraic equations using an iterative approach. The novelty of the proposed system was the adsorption bed immersed into a water bath and then powered by vacuum tube solar collectors. Habib et al. [92] investigated numerically a solar thermal driven evacuated tube solar collectors combined with an adsorption refrigeration system suitable for tropical climates such as Singapore and Malaysia.

This analysis was carried out by the TRNSYS software and a cycle to investigate simulation computer program the cooling capacity, COP and chiller efficiency variations by varying adsorption/desorption cycle times and regeneration temperatures. The evacuated tube solar collectors were used to operate the 8.0 kW adsorption cooling system in a non-residential building under the climatic condition of Vilnius, Lithuania by Januševičius et al. [93]. A TRNSYS V17 simulation was used to show the effect of different operating parameters on the adsorption system performance. The simulation showed that the maximum COP and solar fraction could be obtained if the tilting angle of the collector was 30° with the absorber area of 16 m^2. The optimization of the collector area and cycle time for a single-stage, two-bed, silica gel - water adsorption chiller operating driven by an evacuated tube solar collector under the climatic condition of Bangalore, India was analyzed by Jaiswal et al. [94]. The author reported that the optimized collector size and cycle time could operate a solar adsorption chiller directly without the need of a thermal storage. Mateus and Oliveira [95] evaluated the potential of integrated solar absorption for cooling and heating purposes for domestic applications using TRNSYS software under there climatic conditions of Berlin (Germany), Lisbon (Portugal), and Rome (Italy). The results showed that a reduction of solar collector area in a range of 15–50% in the case of using vacuum tube collectors compared to flat-plate collectors despite the higher initial cost of vacuum tube collectors leads to lower economic viability.

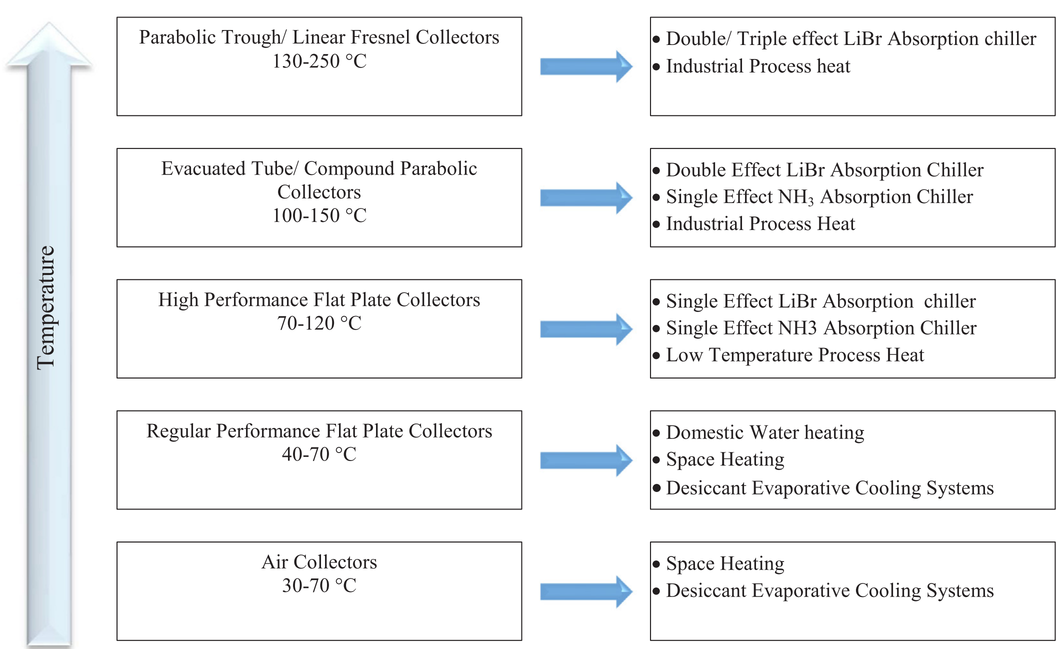

Fig. 4. Solar collector types with the temperature variation and their applications.

3.3. Compound parabolic collector

Normally, solar collectors are straight, facing south. The compound parabolic collector (CPC) has a good performance when direct solar radiation is available, its efficiency drops rapidly when only diffuse radiation is available. On the contrary, flat panels have good performances with diffuse solar radiation, but the output hot water temperature remains below 100 °C, which will have an impact on the adsorption unit performances [96]. To improve the performance of the linear CPC, Umair et al. [97,98] used a wing type of CPC. The novel CPC solar collector could increase the system performance by up to 2% in winter and up to 6% in summer, compared to a conventional CPC with the same dimension. González and Rodríguez [99] investigated experimentally the performance of a solar thermal driven adsorption chiller using CPC solar collector and the activated carbon–methanol as working pair. Tubular of receiver CPC contained the sorption bed, part of the receiver was exposed to sunlight. The total collection area was 0.55 m^2. The minimum and maximum bed temperatures achieved 38 °C and 116 °C, respectively, and the COP was measured in a range of 0.078–0.096. To overcome gap loss issues, Oommen and Jayaraman [100,101] developed a CPC reflector with a V-groove at a half acceptance angle of 23.5 for a tubular absorber with an outer diameter of 19 mm. The efficiency of the CPC module was higher than that of the FPC and could obtain an operating temperature higher than the boiling pint of water. Lu [102] reported that the use of CPC collectors could produce the chilled water at a temperature of 16 °C with 55 °C heat source temperature under the climatic conditions of Dezhou city, China, resulting in an average solar COP of 0.16. El-Sharkawy et al. [103] presented a theoretical study based on a mathematical lumped parameter model coded into MATLAB for the performance of a conventional two-bed silica gel/water compound parabolic concentrator (CPC) solar powered adsorption chiller under the weather condition of different cities in Egypt. The system could achieve a maximum cycle COP, solar COP and maximum cyclic cooling capacity about 0.48, 0.28 and 14.8 kW, respectively in Cairo, Egypt.

4. Solar cooling optimization approaches

There are many methods of optimization to maximize the specific cooling power (SCP) and improved the performance of the adsorption system. Therefore, any optimization method aims to find the variable values that maximize or minimize the main objective function and at the same time satisfying its constraints. The framework of any optimization approaches should include the following terms: (i) objective function: to maximize or minimize the objective function as maximize the specific cooling power (SCP) or minimize the cost; (ii) variables as cycle time, flow rate…etc; (iii) boundary conditions as chilled water outlet temperature; and finally (iv) input parameters as cooling of water inlet temperature, mass flow rates of cold or hot water…etc. The optimization methods can be summarized below:

4.1. Particle swarm optimization

The particle swarm optimization method (PSO) is usually used to obtain the maximum specific cooling power by optimizing cycle time under standard working conditions. This is a stochastic population and computational method based on optimization techniques. PSO is used to optimize the nonlinear function based on a swarm of particles [104,105]. Let particle swarm (PS) consists of 'n' particles. The dimension or number of variables is indicated by z. The particles of the swarm are represented by x_{z1}, x_{z2}, x_{z3}, …, x_{zn} and the best particle of the swarm, i.e. the particle with the maximum function value, is denoted by index g. The best previous position (i.e. the position giving the maximum function value) of the i-th particle is recorded and represented as p_{z1}, p_{z2}, p_{z3}, …, p_{zn} and the position change (velocity) of the particles is represented as v_{z1}, v_{z2}, v_{z3}, …, v_{zn}. The position of particle move rule is shown as follows:

$$v_{zi}^{k+1} = \omega.\ v_{zi}^{k} + C_1.\ r_1(P_{zi}^{k} - x_{zi}^{k}) + C_2.\ r_2(P_{zg}^{k} - x_{zi}^{k}) \quad (1)$$

$$x_{zi}^{k+1} = x_{zi}^{k} + v_{zi}^{k+1} \quad (2)$$

where; *xi* and *vi* are the position and velocity vectors of the ith particle. *pi* is the personal best position that the ith particle, *pzg*, best position of the particle found at present. *k* represents the number of iteration. ω is the inertia weight; C_1 and C_2 are two positive constant, called the cognitive and social parameters, respectively; and r_1 and r_2 are two random numbers in the range (0, 1).

Rahman et al. [106,107] optimized the cycle time and performance for two types of a silica gel-water three-bed adsorption chiller with mass and heat recovery. The results showed that the proposed adsorption chiller had relatively higher COP at a low heat source temperature of 50 °C than the conventional single-stage adsorption cooling cycle. In general, a three-bed mass recovery was applicable for a heat source with a temperature between 50 °C and 90 °C and it reached a maximum performance at the heat source temperature of 70 °C.

4.2. Genetic algorithm optimization

To solve multi-objective optimization problems, there are many optimization algorithms available as Genetic Algorithm (GA) which is based on an analogy with Darwin's [108]. For any multi-objective optimization problems, it can be defined as the minimization or maximization of the vector function below, which has (m) objectives and (n) variables $F(x) = F(f_1(x), f_2(x), \cdots f_m(x))$

where; F(x) is the function of variable space as x = x(x_1, x_2,…,x_n) to the points of objective function space.

Maximize or Minimize $f_1(x), f_2(x), \cdots f_m(x)$ which subjected to

$$g_j(x) \geq 0; =1, 2, \cdots, j$$

$$h_k(x) \geq 0; k = 1, 2, \cdots, k$$

$$x_i(lower) \leq x_i \leq x_i(upper) i = 1, 2, \cdots, n \quad (3)$$

The basic idea of the genetic algorithm is to generate a new set of population (design variables) from a current set to improve fitness (objectives). A flow chart of the main representation for all various stages of the genetic algorithm is depicted in Fig. 5. Abdullah [109] used a genetic algorithm technique to optimize the two objective functions in terms of maximization of the exergy efficiency and minimization of the total cost rate. The author used the genetic algorithm

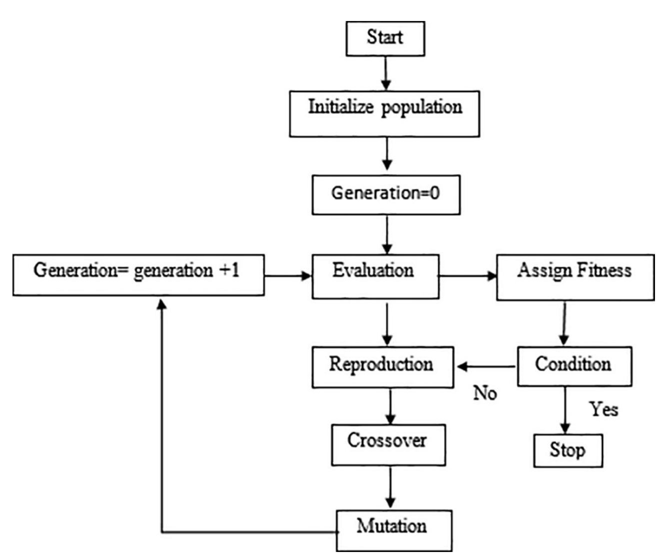

Fig. 5. A flow chart of the genetic algorithm principal.

toolbox of MATLAB with the following assumptions of 400 generations, the population size of 50 individuals, crossover probability 0.8 and mutation probability 0.2.

4.3. Artificial neural network

Artificial Neural Network (ANN) is a non-algorithmic, black-box computational strategy technique concentrates on describing the system inputs-outputs relationship, and is extremely useful to predict the system behaviour without tracing hard the underlying physical laws. ANN composed of interconnected artificial neurons; each has an input/output (I/O) characteristic and implements a local computation. Fig. 6 shows an artificial neuron with r number of inputs. For each input u, a weight w is assigned to describe its influence. The sum of the weighted inputs and then bias b forms the input to the activation function f. The output a is given by

$$a = f\left(\sum_{i=1}^{r} w_{1,i}u_i + b\right) \tag{4}$$

Chow et al. [110] used an artificial neural network model to optimize the performance of a direct-fired double-effect absorption chiller system. Aisyah et al. [30] developed the artificial neural network (ANN) based on experimental data to predict the performance of the solar absorption chiller system at Indonesian Universities. A Principle Component Analysis (PCA) was used in this study to reduce the number of input variables for performance prediction. The ANN & PCA model of this study showed good accuracy of the prediction model.

4.4. Integration of genetic algorithm and artificial neural network

Fig. 7 represents the outline of the integration optimization plan based on GA and ANN techniques. The process begins with input variables, their constraints, control variables, and uncontrolled variables and integrated GA and ANN to achieve finally the main objective of a fitness function as minimize the energy cost and running cost. Krzywanski et al. [111] optimized the cooling capacity of a tri-bed, dual evaporator adsorption chiller based on integrated genetic algorithms and artificial neural networks. The results showed that the optimization model has a good agreement with the experimental data with a maximum relative error of less than ± 10%.

4.5. A statistical approach

In general, statistical methods are used to describe or understand a variability, which means successive observations of a system do not produce the same result. Therefore, a statistical method is considered as a useful way to incorporate this variability into decision-making processes. For example, consider a solar adsorption system that has a lot of factors or variables affecting his performance (mass flow rates, condenser, and generator temperature …etc). These factors represent potential sources of variability in the system. Statistics gives us a structure for describing this variability and give us the most important potential sources of variability. Therefore, a statistical approach will be used to optimize of solar air conditioning unit using the Analysis of Variance (ANOVA) test. The ANOVA test takes place when the factors that affect the experiment have no interaction between each other so the analysis takes only the main effect of each factor on the process response and giving us a primary conclusion about the most important effective factors. But in case, there is an interaction between the factors of the process the factorial design takes its place and the analysis becomes more complicated. Tashtoush [112] used ANOVA analysis to evaluate the most important factors affect the Solar Adsorption Refrigeration System (SAR). The results showed that the COP of a SAR system does not depend sharply on the evaporator temperature and it depends significantly on both condenser temperature and adsorption material in the refrigeration system.

4.6. Control strategy approach

The cooling capacity of the adsorption chiller can be modified effectively by adjusting and controlling both the mass flow rate and the temperature set point. This strategy will use the optimization algorithms to control both the flow rate and temperature simultaneously to match the cooling load and to minimize electricity consumption. Dalibard et al. [113] developed an optimization algorithm combined within the controller to evaluate the set points that minimize the consumption of the system electricity. The authors focused on the control of the cooling tower fan and cooling water pump. The experimental results indicated that the electricity savings in a range of 20% to 60% could be achieved based on weather conditions compared to other control approaches. Shirazi et al. [26] employed different control strategies for the solar collector output including a variable versus constant speed pump, and the use of an auxiliary heater in series and parallel with the storage tank. The results indicated that an improvement in system performance up to 20% when using a variable speed pump combined with a parallel auxiliary heater and a variable temperature set point linked to the instantaneous cooling load.

5. Industrial solar cooling barriers and challenges

Some many challenges and barriers face of solar cooling for adopting in the industrial sector, which are [3,17,114]:

- There are no international ISO/EN guidelines or standards relating to solar cooling.
- There are no incentives for executing solar cooling technology in the industrial sector compared to solar photovoltaic (PV). Therefore, rewards for constructing or decreasing energy during times of peak load should be applied.
- A cooling process is needed for a long time in a day and night. Therefore, availability, reliability, and quality of the cooling process remain the critical barriers.
- In the industrial sector, it is unnecessarily the cooling demand coincidence with the availability of solar irradiation.
- Highly dependency on the backup heat source in case of using low efficiencies parts like pumps, fans and solar collectors, using insufficient solar collectors, or high energy losses to poor pipe insulation and indigent collectors' fluid flow design.

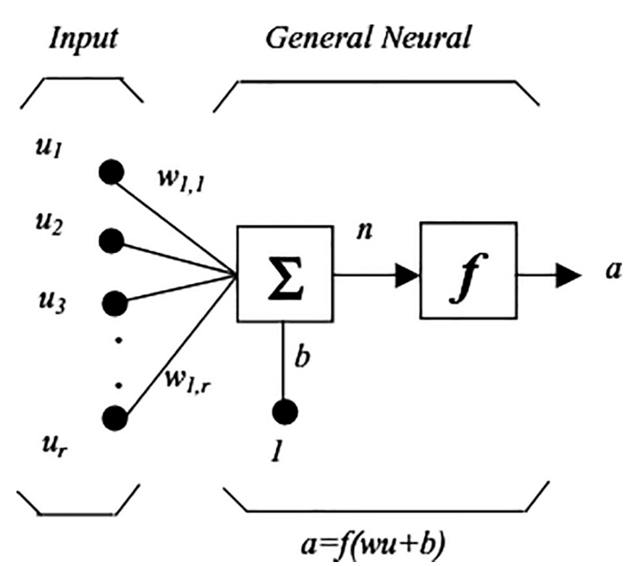

Fig. 6. Schematic diagram of the artificial neural network (ANN) model.

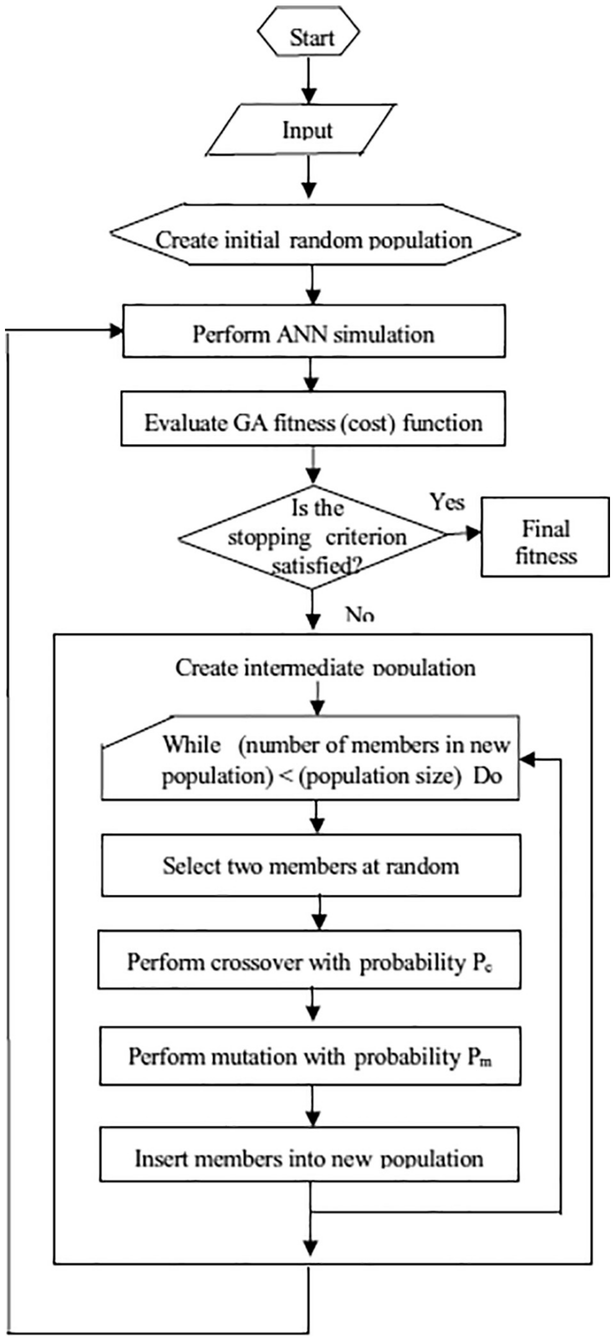

Fig. 7. Flow chart of the combined GA with ANN optimizations.

- The increase in the cost of improving the performance.
- High investment cost due to the numerous parts involved in this technology as a solar collector, storage tank and, cooling tower… etc.
- Most of the solar cooling technologies have been unadapted to work with the sun oriented.
- Most of the solar cooling systems are added to buildings after the building was built, so the absence of a building integration. Therefore, all solar cooling components as solar collectors, energy storages and heat sink must be integrated into buildings.
- The relatively high price of the solar collector, therefore the increase of production volumes will reduce the cost of the system.

6. Solar cooling current status, markets and perspectives

Solar Heating and Cooling Program reported that at the end of 2015 more than 1350 solar cooling systems were installed in Europe and diverse countries as displayed in Fig. 8 [115]. In the last 10 years, the solar cooling market was growing dramatically in the range of 40–70% per year [10]. Compared to vapor compression cooling systems, the initial costs for solar cooling technology are about 2–2.5 times higher depending on system size, building stipulations and weather conditions. According to the cost analysis, the total system expense in the range from 2000 per kWcold to 5000 per kWcold and much higher in some specific cases [116,117].

More progress and developments were developed in the small capacity of solar cooling chillers up to 35 kW cold. The prices were dropping dramatically from 6000 EUR/kWr in 2007 to about 4500 EUR/kWr in 2013 for a small scale (excepting the installation cost and distribution system to the building) and 2250 EUR/kWr for large scale as outlined in Fig. 9. The target price is for solar cooling system in the range of 1000 and 1500 EUR/kWr (medium/high cooling size) and 3000 EUR/kWr (low cooling size) [10,118,119]. In general, a payback period of solar cooling system investment is about 10–15 years. It is expected in 2050; solar cooling will have a potential market of 417 TWh/a as display in Fig. 10, which represents about 17% of energy used for cooling purpose assigning to the International Energy Agency (IEA) [120].

Fig. 11 demonstrates various solar cooling systems installed in Europe and the world [121]. As appeared in Fig. 11 about 59% of solar cooling systems use absorption chillers, 12% of the establishments use an adsorption chiller and in about 23% of the establishments a desiccant cooling framework utilizing a sorption wheel. Just about 4% of all solar cooling systems utilize liquid desiccant innovation, which demonstrates this technology is still less produced on a business level. On the other hand, about 25% of all the installed solar cooling systems utilize adsorption chillers especially for large cooling capacity [121]. Table 4 displays a solar cooling supplier with a cooling capacity of up to 200 kW [17,119,121].

7. Sample of solar cooling existing projects

There are many solar cooling projects were established around the world. In Canada, the absorption cooling framework was installed in 2010 and finished in 2011 at the Shouldice Hospital in Thornhill, Ontario [122]. The absorption project incorporates 10 kW ClimateWell chillers, 131 Thermomax Collectors, a 4364 L thermal storage and a cooling tower. Energy demonstrating predicts the absorption project will probably counter balance 36% of the cooling load, 44% of the heating load and 91% of the household hot water load. Taking into account a 56% of the expected energy required was gathered from the sun. This system has the ability to decrease the amount of CO_2 discharged every year by the health care by 100 metric tons and will carry out an 80% decrease in the peak power use because of cooling [5,123].

In Italy, a single stage of the H_2O–LiBr absorption system was installed in Vallo della Lucania to cooling the restaurant of the Curia seminar. The absorption system consists of 42 vacuum tubes with a total surface of 139 m^2. The absorption unit is YAZAKI WFC 10 (35 kWcold) [124].

In Germany, 70 kW of adsorption chiller to provide the laboratory of University hospital in Freiburg by air-conditioning. The system was operated by utilizing evacuated tube collectors with a total surface area of 170 m^2. Another system was developed in Freiburg/Germany is a desiccant cooling system to cool the seminar room and the cafeteria in the chamber of trade and commerce building. The system is composed of a silica gel desiccant wheel. To perform a regeneration for desiccant material, an air volume flow rate of 10,200 m^3/h and 100 m^2 of a surface area of the solar collector were used [125].

Table 5 demonstrates some of the solar cooling systems installed

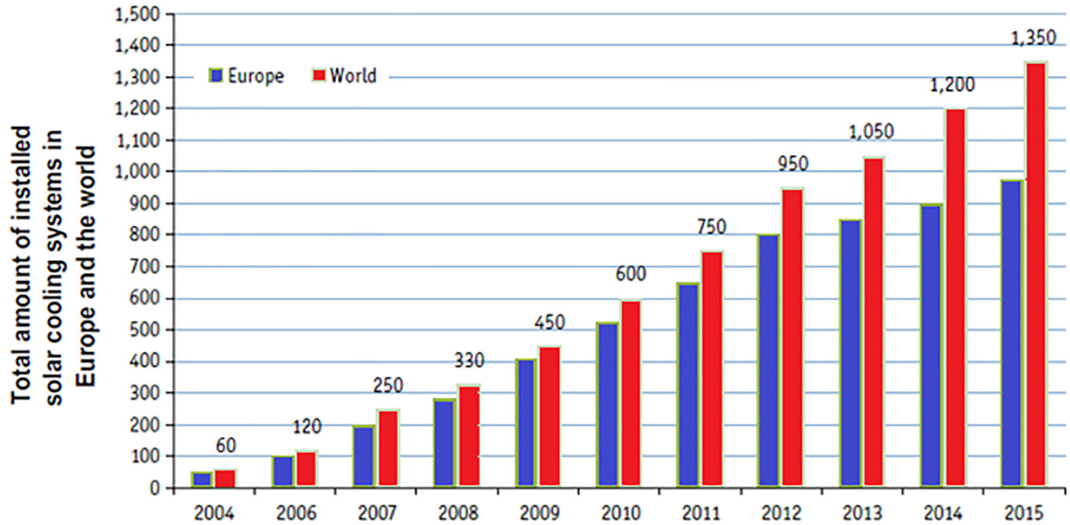

Fig. 8. Total number of solar cooling system installations in Europe and worldwide [115].

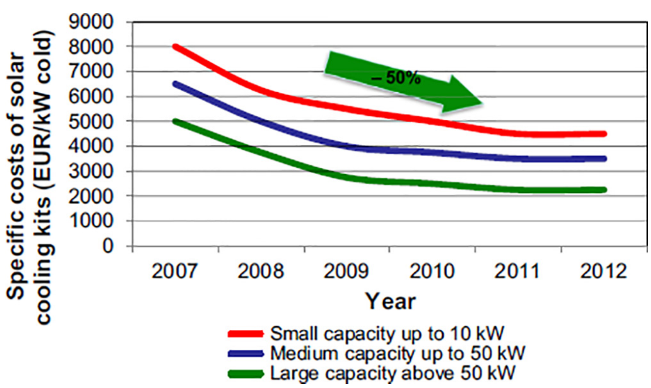

Fig. 9. Different solar cooling capacities cost [118].

after 2001 around the world [82,90,126–131]. The technical information about these systems was mostly accessed from scientific articles, websites, journals and direct contact with manufacturers.

8. Solar cooling research area and trend

According to research areas and previous studies for solar cooling systems design, the following topics deserve more investigation to enable the solar cooling systems operating at a lower temperature driven and compete with a conventional cooling technique [3,23,125]:

- Developed new working pairs with the high porous sorption material.
- Improving the performance of heat exchangers by (i) development of new Nano coating sorption materials to minimize the friction losses during fluid flow; (ii) micro-fluid systems for compact; and (iii) develop new matrices for sorption heat exchanger as metal foams.
- Develop new thermodynamic cycles based on heat and mass transfer criteria. Optimized switching time, optimized internal heat recovery to make the system more compact, cheap and achieves a higher COP.
- Developing a new material with high density for the cold storage tank by the use of phase change materials (PCM) and thermo-chemical reactions at different temperatures.
- Conduct transient, exergy analysis and life cycle analysis of system performance to adopt a current concept to classify the unchanging to solar cooling chiller applications.
- Using advanced optimization methods and simulation tools at various scales and strategies starting from sorption phenomena end to the system scale.
- Developing hybrid systems as adsorption with ejector, adsorption with desiccant.
- Investigating the triple effect of absorption systems.

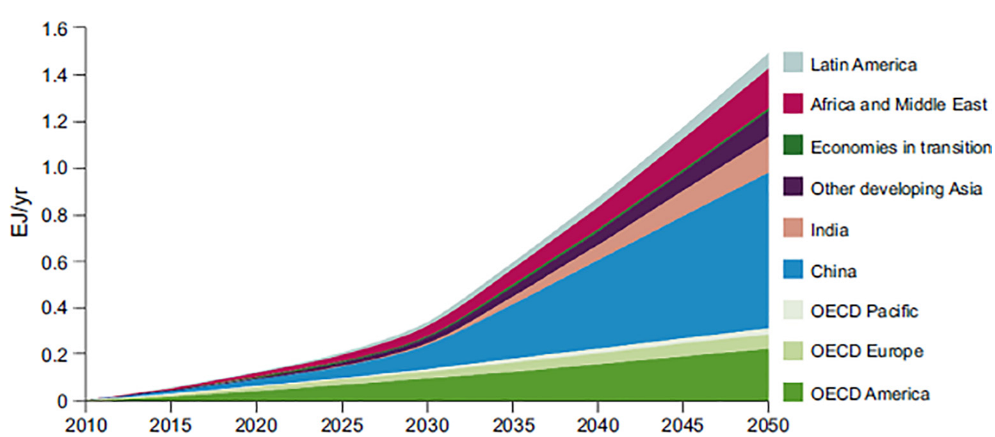

Fig. 10. Solar cooling road market according to the International Energy Agency (IEA) [120].

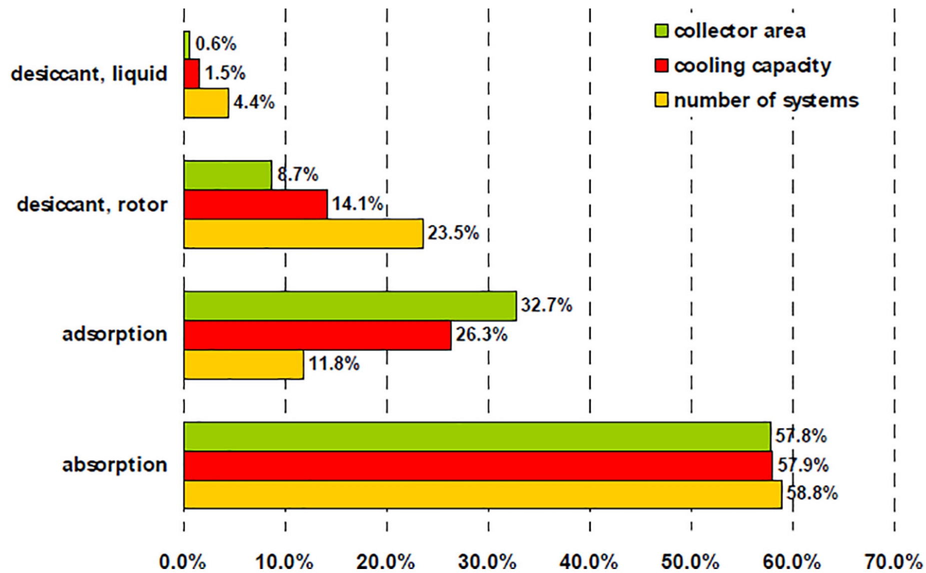

Fig. 11. Distribution of different solar cooling systems installed in Europe [121].

9. Conclusion and recommendation

This manuscript performed a summarized review for solar cooling technologies in terms of absorption, adsorption and desiccant cooling systems. Furthermore, this article highlights the essential attributes of solar cooling technology to identify the main advantages, challenges, shortcomings, feasibility analysis, and mention some techniques to improve the COP and SCP. The most significant outcomes derived from the literature review can be summarized as below:

- Although the solar cooling reduces the high costly peak loads in the electricity grid and avoid greenhouse gases (GHG) emissions, but it has been suffering from low COP, low SCP and high initial investment compared to conventional refrigeration technologies.
- There are many strategies to improve the performance of solar cooling technologies by employing a heat recovery, mass recovery, multi-bed and multi-stage technologies.
- These technologies need more governmental support to make the share of solar cooling at the market higher and competitive.
- The desiccant cooling system can represent a suitable selection to improve indoor air quality with low operating costs.
- Artificial neural networks and genetic algorithms are optimization methods to develop a non-iterative model permitting to conduct optimization study of the adsorption chiller based on a cooling capacity.
- The execution of such optimization approaches as control strategies in real systems only requires modification of the control algorithm without any additional costs.
- The particle swarm optimization (PSO) is a very useful method to optimize the cycle time of adsorption chiller which allows us to

Table 4
Solar cooling supplier with cooling capacity of up to 200 kW [17,119,121].

Supplier	Country	Cooling capacity (kW)	Working pairs	Remarks
EAW	Germany	15–200	Absorption (H_2O/LiBr)	T_{cold} = 11 °C; T_{reject} = 30 °C; T_{gen}:70–90 °C; COP: 0.75
Yazaki	Japan	17.5–175	Absorption (H_2O/LiBr)	T_{cold} = 12.5/7 °C; T_{reject} = 31/35 °C T_{gen}: 88/83 °C; COP: 0.70
Pink	Austria	19	Absorption (NH_3/H_2O)	T_{cold} = 12/6 °C; T_{reject}: 24/31 °C; T_{gen}:85/75 °C; COP:0.63
Sakura	Japan	10.5–316	Absorption (H2O/LiBr)	–
AGO	Germany	50–500	Absorption (NH_3/H_2O)	–
Tranter Solarice	Germany	30 and 50	Absorption (NH_3/H_2O)	–
Thermax	India	17.5–352	Absorption (H_2O/LiBr)	T_{cold} = 12.5/7°C; T_{reject} = 29/36.5 °C; COP: 0.70; T_{gen}: 91/85 °C
Jiangsu Huineng	China	11–350	Absorption (H_2O/LiBr)	T_{cold} = 15/10 °C; T_{reject} = 30 °C; T_{gen}: 90/85 °C
Gasokol	Austria	15, 30, 54, 83, 150, 200	Absorption (H_2O/LiBr)	–
Schüco	Germany	15, 30	Absorption (H_2O/LiBr)	–
Kloben	Italy	17.5, 35, 70, 105	Absorption (H_2O/LiBr)	–
Köhler	Germany	40–250	Absorption	–
Solution	Austria	15, 30, 54Absorption Water/ LiBr	Absorption (H_2O/LiBr	–
Solution	Austria	8, 15	Adsorption Water/ silica gel	–
InvenSor	Germany	10 and 18	Adsorption water/ zeolite	For 18 kW: High T_{amb} above 40 °C; COP: 0.5; For 10 kW: T_{gen}: 45 °C; COP of 0.6
Mayekawa	Japan	105–430	Adsorption water/ zeolite	T_{cold} = 16/9°C; T_{reject} = 29/34 °C; T_{gen}: 75/67 °C
SolabCool	Netherland	4.5 kW with integrated heat rejection	Adsorption Water/ silica gel	–
SorTech	Germany	8 and 15	Adsorption Water/ silica gel	T_{cold} = 18/15 °C; COP: 0.60For wet cooling tower: T_{reject} = 27/33 °C; T_{gen}: 72/ 65 °CFor dry cooler: T_{reject} = 33/38 °C; T_{gen}: 85/75∘C
Mitsubishi Plastics	Japan	10	Adsorption water/ zeolite	–

T_{cold}: Cold Water Temperature; T_{reject}: Heat Rejection Temperature; COP: Coefficient of Performance; T_{gen}: generator temperatures; T_{amb}: ambient temperature

Table 5
Some of the solar cooling systems installed around the world [82,90,126–131].

Building type, Location	Cooling system type	Application	Capacity	Remarks
Open system				
Center for Renewable Energy Sources in Koropi, Greece (2007)	A desiccant evaporative cooling systemLithium Chloride	Heat and cool solar thermal building for demonstration and research purposes for air conditioned area 84 m^2.	–	10 m^2 area of flat plate is employed; Nominal air volume flow rate = 1100 m^3/h; Typical operation temperature = 60 °C; Heat storage = 0.5 m^3 water
Solar Info Center SIC in Freiburg, Germany (2004)	Liquid desiccant evaporative cooling systemLithium Chloride	To ensure the air-conditioning of a chain of offices and a seminar room for air-conditioned area 300 m^2	10 kW	16.8 m^2 flat plate collectors are usedNominal air volume flow rate: 1500 m^3/h; 55–70 °C regeneration temperature; 1.5 m^3 Heat storage
Chamber of Commerce 'Südlicher Oberrhein' (IHK-SO) in Freiburg, Germany (2001)	Desiccant type Silica Gel	Air-conditioning of a seminar room and a cafeteria area of the building for air conditioned area 213 m^2	60 kW	Nominal air volume flow rate: 10,200 m^3/h; 92 m^2 aperture of flat-plate 70 °C regeneration temperature of sorption wheel
'Pompeu Fabra' Library in Mataró, Spain (2002)	Desiccant type Silica Gel	Desiccant cooling system with PV/solar air collectors for air conditioning for library for air conditioned area 471 m^2	81 kW	Nominal air volume flow rate: 12,000 m^3/h; 88 m^2 aperture of air collector was used; 65 °C driving temperature for chiller operation
Town Hall and Service Center in Gleisdorf, Austria (2008)	Desiccant type Silica Gel	The system is supplying two office buildings with space cooling and space heating energy for air-conditioned area 2000 m^2	35 kW	Nominal air volume flow rate: 6180 m^3/h; high temperature flat plate (Teflon foil between glass and absorber 302 m^2 gross (134 m^2 flat roof, 168 m^2 solar trees); 4600 L heat storage, 1000 L Cold storage
Closed cycle adsorption				
Fraunhofer ISE, Freiburg, Germany (2007)	Adsorption	Solar air-conditioning with adsorption chiller of the kitchen for air-conditioned area 42 m^2	5.5 kWcold	22 m^2 aperture of flat plate 75 °C driving temperature for chiller operation; 2 m^3 water heat storage
Residential building in Thening, Austria (2007)	Adsorption Silica gel/Water	Residential building with a heat load of 7 kW and adsorption machine without auxiliary cooling for air-conditioned area 177 m^2	5.5 kWcold	40 m^2 gross area of flat plate; 75 °C driving temperature for chiller operation; 6 m^3 water split into three tanks of heat storage
CNRS PROMES Research Center Office, Perpignan, France (2008)	Adsorption	Air conditioning of research center office for air-conditioned area 180 m^2	7.5 kW	25 m^2 absorber area of double glazed flat plat collectors; 75 °C driving temperature for chiller operation; 0.3 m^3 water heat storage.
Shanghai Research Institute of Building Science (2005)	adsorption chillers Silica gel/Water	Solar cooling system for public buildings for air-conditioned area 460 m^2	15 kW	150 m^2 aperture solar collectors; two adsorption chiller based on silica gel and water
Closed cycle absorption				
Echuca Regional Health, Australia (2011)	absorption chiller	Provide cooling to three hospital buildings, including operating theatres and hospital wards	500 kW	largest solar cooling plant in Australia102 vacuum tube collectors; Collectors used to heat water to 95 °C
industrial building, France (2008)	H_2O-LiBr single-effect absorption chiller	Air conditioning of 3700 m^2 office area	105 kW	Absorption chiller cooled by a 256 kW wet open tower, and supplied by 300 m^2 of evacuated tube collectors.
Technological Institute of Canary Islands	H_2O-LiBr single-effect absorption chiller	Air conditioning of an office building of 400 m^2	35.2 kW	68,4m^2 flat plate collectors; Two tanks, a 3,000 L hot water and a 1,000 L chilled water storage tanks
L' Amor Rouge Bakery, Nicosia, Cyprus (2006)	absorption chiller (H_2O-LiBr)	Air conditioning of an bakery offices with total surface of 627 m^2	70,3kW	system consists of 120 m^2 vacuum tube collectors; 6,8m^3 hot water storage tank212 kW nominal power cooling tower
Kota, Rajasthan, India (2013)	Triple effect vapour absorption chiller	NPCIL (Nuclear Power Corporation of India Limited),	100 TR	manufacturers: Thermax, Pune
German Jordanian University, Jordan (2015)	Absorption chiller, type Bumblebee	Building air conditioning	160 kW	Gross collector area of solar field: 480 m^2Temperature of chilled water supply:6–8 °C; Operating period: 6 to 10 h per day
Petra Guest House, Jordan (2016)	one-stage absorption chiller, type Bumblebee	Building air conditioning	160 kW	Gross collector area of solar field: 388 m^2Temperature of chilled water supply: 9–11 °C; Operating period: 24/7
Royal Cultural Center, Jordan (2016)	Absorption chiller, type Bumblebee	Building air conditioning	160 kW	Gross collector area of solar field: 449 m^2Temperature of chilled water supply: 8–10 °C; Operating period: 8 to 16 h per day
Irbid Chamber of Commerce, Jordan (2016)	Absorption chiller, type Bee/50 kW	Building air conditioning	50 kW	Gross collector area of solar field: 140 m^2Temperature of chilled water supply: 8–10 °C; Operating period: 6 to 12 h per day
Pretoria, Gauteng South Africa (2009)	Absorption chiller	Netcare Moot Hospital Air-conditioning System	35 kWth/48 kWth	consists of 52 evacuated tube collectors
Office building of S.O.L.I.D., Graz, Austria(2008)	Absorption (H_2O-LiBr)	Air conditioning for office building for air-conditioned area 435 m^2	17.5 kWcold, 21 kW peak	60 m^2 gross high temperature flat plate;88 °C driving temperature for chiller operation; 2000 L heat storage, 200 L cold storage
Résidence du Lac, Maclas, France (2007)	Absorption	Solar air conditioning system of a building to retired people for air-conditioned area 210 m^2	10 kWcold	24 m^2 absorber area of evacuated tube 75 °C driving temperature for chiller operation
Office building of IBA AG in Fürth, Germany (2007)	Absorption (H_2O-LiBr)	Air conditioning of Office building for air-conditioned area 920 m^2	30 kWcold	87.7 m^2 aperture of flat plate; 86 °C driving temperature for chiller operation3.7 m^3 water heat storage; 1.4 m^3 water of cold storage
Office Building Vajra in Loulé, Portugal (2005)	Absorption (H_2O-LiBr)	Solar heating and cooling of the head office building of Vajra with air-conditioned area 670 m^2	35 kWcold	128.8 m^2 aperture of flat-plate; 88 °C driving temperature for chiller operation 12 m^3 water of heat storage

(*continued on next page*)

Table 5 (*continued*)

Building type, Location	Cooling system type	Application	Capacity	Remarks
Promitheus Building, Sol Energy Offices in Palaio Faliro, Greece (2007)	Absorption	Used to heat and cool the offices with air-conditioned area 360 m^2Capacity 63 kW cooling, 14 kW heating	35 kWcold	78.6 m^2 gross of flat-plate; 83 °C (driving heat for cooling application); 2 × 180 m^3 water heat storage; 1 × 180 m^3 water cold storage
Manufacturing area in Bolzano, Italy (2005)	absorption	Research institute for renewable energy with air-conditioned area 400 m^2	15 kWcold	150 m^2 of flat plate collectors are connected with 15 kW absorption chiller; 3 tanks are installed in the system; 90 °C (driving heat for cooling application)17.6 m^3 water heat storage
Technical College for Engineering in Butzbach, Germany (2008)	Absorption	Summer air conditioning due to high occupation rates and frequent use of computer equipment with air-conditioned area 335 m^2	20 kWcold	60 m2 aperture of evacuated tube with CPC-mirror; 80 °C driving temperature for chiller operation; 3 m^3 water of Heat storage, 1 m^3 water of Cold storage
Chhatrapati Shivaji, India (2011)	Absorption + desiccant	Building air conditioning of hospital, Thane	212 TR Capacity	160 TR vapour absorption cooling and 52 TR desiccant cooling manufacturers: Sharda Inventions Pvt. Ltd., Nashik
Swiss Embassy in India, New Delhi (2017)	Double stage absorption system (H2O-LiBr)	Building air conditioning of Swiss Embassy in India with air-conditioned area 630 m^2	60 TR	The CPC solar collectors was used; 88 °C driving temperature for chiller operation; Temperature of chilled water supply: 7–10 °C; 40% of electricity was saved

identify the best performance of the adsorption cooling system with different configurations.
- The optimization methods are not limited to solar cooling systems, it can be also used to other conventional air conditioning systems.
- There are some efforts for solar cooling of small scale cooling capacity systems around the world, but the share of the market is still extremely low.
- To achieve a high energy saving from solar cooling systems, the following things are needed to develop: (i) solar cooling system should be simple; (ii) the system should be in the optimum size of all components and including for the efficient backup auxiliaries when the sun is unavailable; (iii) all auxiliary segments, including fans and pumps should be working in high efficiency; (iv) control and operation planning strategies should be working to achieve high superior performance under both part and full load conditions; and finally (v) continuous monitoring to ensure all system parts operate at energy efficiently as planned.

Therefore, the obtained information would provide valuable information about the current status of solar cooling technologies and the ways to improve its performance.

CRediT authorship contribution statement

Ali Alahmer: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing. **Salman Ajib:** Conceptualization, Formal analysis, Data curation, Supervision, Project administration, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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