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Review article

A review on solar-powered cooling and air-conditioning systems for building applications

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ABSTRACT

Cooling and air-conditioning systems are the primary consumers of building energy in hot and mixed climate locations. The reliance on traditional systems, driven electrically, is the main reason behind the deterioration and ever-increasing demand for energy in buildings. This is also associated with a vast amount of CO_2 emissions and other environmental concerns. Solar energy has been introduced as a crucial alternative for many applications, including cooling and air-conditioning, which has been proven to be a reliable and excellent energy source. This paper presents and discusses a general overview of solar cooling and air-conditioning systems (SCACSs) used for building applications. The popular SCACSs driven by solar thermal energy are elaborated in detail, considering their operation and development aspects. A comparison among solar thermal SCACSs is performed, taking into account several technical, operational, economic and environmental indicators. Some research gaps, recommendations, and conclusions are derived from the reviewed literature to understand and further develop this essential research domain.

Contents

1. Introduction

Building sector is the major consumer of final energy use worldwide by up to 40%. Statistics of responsible organisations and parties evident that most of this percentage is consumed

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Nomenclature

Abbreviations

AC	Air-conditioning
COP	Coefficient of performance
DC	Direct current
DX	Direct expansion
ECC	Ejector cooling cycle
ECS	Ejector cooling system
ETSC	Evacuated tube solar collector
FPSC	Flat plate solar collector
H_2O/LiBr	Water/lithium bromide
HVAC	Heating, ventilating and air-conditioning
IEA	International Energy Agency
IEC	Indirect evaporative cooler
NH_3/H_2O	Ammonia/water
PP	Payback period
PTSC	Parabolic trough solar collector
PV	Photovoltaic
SABSs	Solar absorption systems
SADSs	Solar adsorption systems
SCACSs	solar cooling and air-conditioning systems
SCOP	Seasonal coefficient of performance
SDSs	Solid desiccant systems
SE-VCR	Solar electric/vapour compression refrigeration

for cooling and air-conditioning purposes (IEA, 2013; IEA and UN Environment Programme, 2019). It is commonly known that most of the electric energy is spent on heating, ventilating and air-conditioning (HVAC) systems in hot regions. For instance, it has been reported that 32% of end-use electrical energy is consumed by household cooling systems in Egypt, and as high as 38%–60% of the electrical power is used for cooling devices in the commercial buildings of Saudi Arabia (El-Sharkawy et al., 2014). In this regard, the International Energy Agency (IEA) reported that the cooling market is growing drastically and improved by 10% between 2018 and 2019 only (China dominates about 40% of total equipment) (IEA, 2020). IEA also reported that around 2/3 of the world's buildings would have air-conditioning (AC) systems by 2050, and as shown in Fig. 1, China, India, and Indonesia will account for half of the world demand (IEA, 2018).

Building energy performance can be achieved by thermally enhancing the building envelop elements or developing the HVAC systems. For building envelope scope, different passive and active techniques are implemented, such as the double skin technique (Zingre et al., 2017), insulation applications (Tükel et al., 2021), thermally activated systems, incorporation of phase change materials (Al-Yasiri and Szabó, 2021), Trombe walls (Hong et al., 2019; Yu et al., 2016), and others (Algburi and Behan, 2019; Azmi et al., 2021). On the other hand, HVAC systems have also been developed considering different design measures (Berardi and Filippi, 2020), control strategies (Franco et al., 2021; Özbek and Uslu, 2019) and integration of renewable resources (Hussein et al., 2020).

At present, the world's attention is directed towards renewable energy of various sources and forms (especially solar energy) to replace the conventional energy produced from coal, oil, natural gas etc. This is mainly because of the environmental impact and also their limited resources. Some statistics claimed that the conventional oil and natural gas sources would run out within the next 50 years as the world's population would reach almost nine billion people (IEA, 2021). Utilising renewable energy sources for cooling systems, predominantly powered by solar energy, has become one of the forefront technologies that attracted engineers and responsible authorities as such systems associated with the shining sun period. In this regard, cooling technologies driven by solar energy have many advantages, including cutting CO_2 emissions to decrease global warming (Al-Yasiri and Géczi, 2021), saving heating and cooling bills, reducing the dependency on fossil resources, and reducing imported fuels (Kalkan et al., 2012). Nevertheless, SCACSs are still not penetrating the market due to several concerns that can be summarised as follows:

i. High initial and installation costs of SCSCSs compared with the traditional ones driven by electric power (primarily work based on vapour compression cycles) (Al-Yasiri and Szabó, 2016; Gao et al., 2018; Otanicar et al., 2012).
ii. Technical considerations in which the traditional systems have a much higher coefficient of performance (COP) than SCACSs (Albatayneh et al., 2021; Meron Mulatu Mengistu, 2011).
iii. SCACSs are complex (for both the chiller and solar system parts), and experts are required for periodic maintenance and sudden operations (Palomba et al., 2019).
iv. The limited number of manufacturers and suppliers for SCACSs minimises the competitiveness with the traditional systems.
v. Intermittent availability of solar energy daily and annually requires supplementary storage devices and auxiliary energy systems.

The development of SCACSs is in progress since 1959, in which the overall number of articles up to date is 22718 (Scopus database, 2022). However, the rapid development research has started since 2005 and still been growing drastically (Saikia et al., 2020). The top ten countries, journals and research institutions are shown in Fig. 2, which indicates that China, ELSEVIER and Chinese academic institutions are the leading in this regard.

This paper aimed to shed light on SCACSs that have developed over this century. The paper consists of three main chapters in which Section 2 gives a general overview of the main systems driven by solar energy as an electrical or thermal energy source. Section 3 summarises the main advanced systems driven by solar thermal energy in detail. Section 4 compares SCACSs considering several technical, operational, environmental and economic aspects. Research gaps and recommendations for future studies are highlighted in Section 5. Finally, some conclusions are raised from the reviewed literature studies, which are believed to provide a clear overview of this research area.

2. Overview of SCACSs

Solar energy can be utilised to power cooling and air-conditioning systems by two methods: electrically and thermally. In the electrical form, photovoltaic (PV) panels convert the sunlight directly into electricity to run conventional cooling systems. These systems are typically referred to as solar electric/vapour compression refrigeration (SE-VCR) systems and are sometimes called solar PV assisted cooling systems. Fig. 3 shows the main parts of SE-VCR. The PV panel generates direct current (DC), which requires an inverter to run the traditional AC compressor (DC compressors also can be used to eliminate the inverter). In addition, other elements such as batteries to cope with intermitted electricity, voltage regulator and electrical connections are needed to support the system. These systems could save

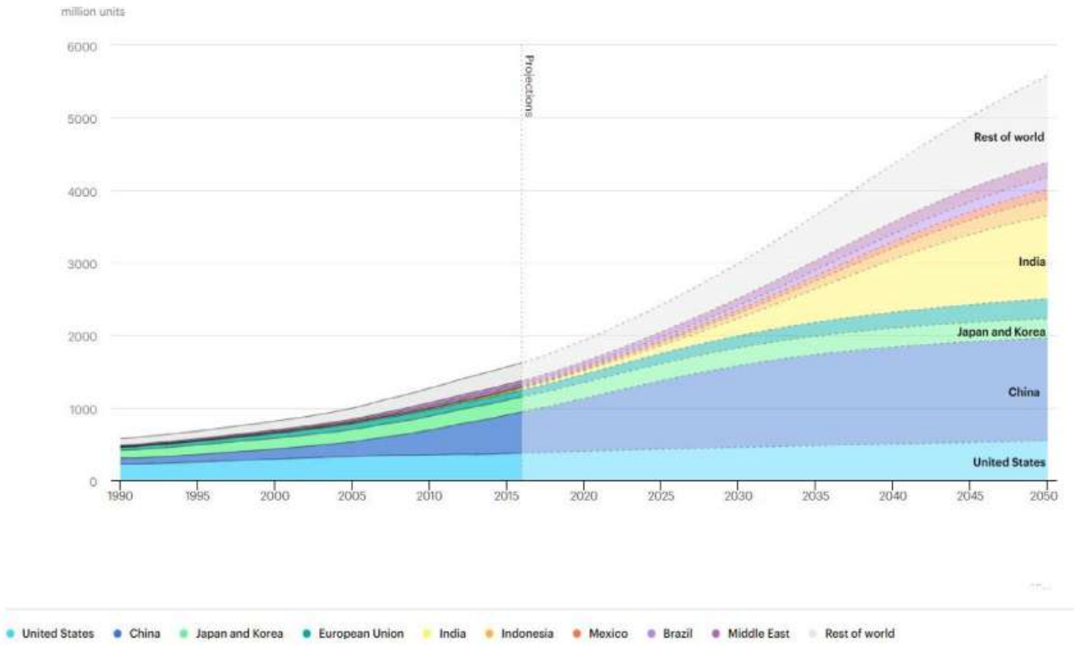


Fig. 1. Global air-conditioning stock in the period 1990–2050 (IEA, 2018).

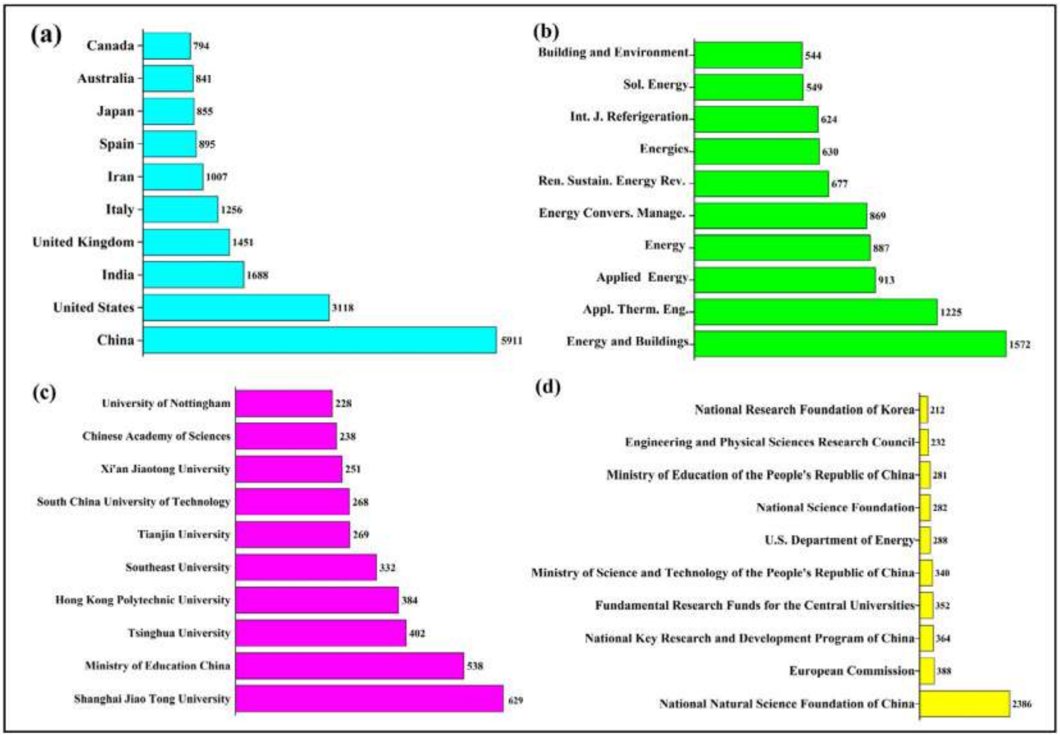


Fig. 2. Top ten statistics for SCACSs by (a) countries, (b) journals, (c) research institutions, (d) funding sponsors (Scopus database, 2022).

the primary electrical energy by 39%–100% depending on the building location (Ayadi and Al-Dahidi, 2019) and reduce the cost of traditional systems by 12.3% (Song et al., 2017).

In this regard, Bilgili (2011) analysed the performance of a SE-VCR system applied for a building located in the south of Turkey during the 23rd day of cooling months, i.e. from May to September. The experimental results showed that at 0 °C evaporating temperature, the maximum compressor power consumption was 2.53 kW at 3:00 PM on August 23, and the required PV panel surface area should be 31.26 m^2, which showed that the SE-VCR systems could be used efficiently under these conditions. A year-round dynamic simulation was conducted by Fong et al. (2011) under subtropical climate where an ejector design was incorporated to improve the SE-VCR system. The results demonstrated that the system coefficient of performance (COP) increased, and the total primary energy consumption decreased for all three different refrigerants (R22, R134a and R410 A) analysed within the study. Furthermore, the study reported that the year-round immediate energy use could be reduced by more than 5% using a suitable ejector design and refrigerant for the SE-VCR system.

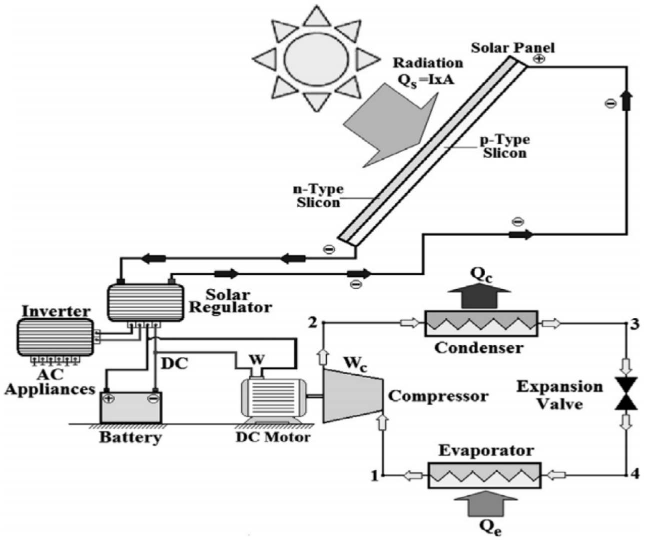


Fig. 3. Typical parts of SE-VCR system (Bilgili, 2011).

In systems based on thermal solar energy, the solar radiation can be collected and used to minimise the electric power consumption in small scale systems, as in the hybrid solar AC system shown in Fig. 4. The system combines a traditional split-type air conditioner and a vacuum tube solar collector. The solar radiation absorbed by solar collectors is utilised to heat the water inside the collector tank fixed on the top. Evaporator tubes of the outdoor split unit pass through the tank before entering the compressor. The refrigerant inside the tubes gains heat from the water tank and enters the compressor at a higher temperature. Accordingly, the required compressor size reduces, and therefore, the electricity consumption declines by up to 60% (IMM FTUI Science and Technology, 2013).

Solar thermal energy also can be used to power higher capacities and more advanced SCACSs, as detailed in the next section.

3. Solar thermal powered cooling and air-conditioning systems

Solar thermal energy is typically used as a driving temperature in the SCACSs. These systems are generally classified as open, closed, and thermo-mechanical cycles, as shown in Fig. 5.

In open cycles, the air inside the built environment is processed directly by treating the temperature and humidity ratio. In contrast, the chilled water circulated in closed loops in the closed cycle (Ghafoor and Munir, 2015). Those two cycles will be discussed in detail in the following sub-sections. On the other hand, the thermo-mechanical cycle utilises thermal energy rather than mechanical energy to produce a cooling effect through special devices such as an ejector system (Sarbu and Sebarchievici, 2013). Ejector cooling systems (ECS) is a novel cooling device that could use solar thermal energy for cooling applications (Elbarghthi et al., 2021; Khalid Shaker Al-Sayyab et al., 2021). The ECS consists of two ports in the inlet (one for the primary fluid flow known as motive flow and the other for the secondary flow or the entrained flow) and one in the outlet. In addition to these ports, the typical ECS consists of a convergence–divergence nozzle, a suction chamber, a mixing chamber (constant area section), and a diffuser (shown in Fig. 6).

The main objective of ECS is to accelerate the low-pressure stream coming through the secondary inlet port when mixed with the primary flow and discharged through the outlet port with intermediate pressure. In the ECS integrated solar energy, the compressor in the VCR system is replaced by the ejector cooling cycle (ECC), as indicated in Fig. 7. More details about the step-by-step working procedure of this cycle with possible modifications and combinations with different solar applications, including solar cooling, are presented by (Bechir et al., 2021; Braimakis, 2021; Eveloy and Alkendi, 2021; Ghodbane and Husseín, 2021; Peris Pérez et al., 2022).

This article mainly focuses on solar absorption systems (SABSs), solar adsorption systems (SADSs) and solar desiccant systems (SDSs), the widely used systems in building applications. The thermal energy is extracted from fallen solar radiation by employing different solar collectors; each has its temperature range depending on how the heat is extracted. Although, in general, solar flat plate collectors (FPSCs) are employed for SCACSs, they have a wide range of applications, such as solar heating and cooling (Boyaghchi and Montazerinejad, 2016; Ge et al., 2018), domestic hot water (Al-Yasiri and Szabó, 2019), solar drying (Benhamza et al., 2021; Fudholi and Sopian, 2019), solar desalination (Ghorbani and Ebadi, 2020), solar cooking applications (Kumaresan et al., 2018). Fig. 8 shows typical solar collectors and their temperature ranges suitable for SCACSs.

Among others, parabolic trough collectors (PTSCs) were the most investigated type for solar cooling systems by up to 60% in the literature studies (Alsagri et al., 2020) and generally showed better performance than FPSCs (Altun and Kilic, 2020). However, solar thermal collectors generally have a thermal efficiency in the range of 0.06–0.64 (Alobaid et al., 2017). Therefore, they have been developed remarkably in the last century, and many advanced techniques have implemented, which are highly developed for the associated applications. Some of these developments are dealt with the design aspects and collecting methods, whereas the others applied different enhancers to augment the thermal performance and prolong the availability of driving temperature (Evangelisti et al., 2019; Senthil and Cheralathan, 2019).

The main SCACSs, namely solar absorption, solar adsorption and solar desiccant systems, will be discussed in the following subsections.

3.1. Absorption systems

Absorption systems are one of the oldest systems that have been used in cooling and air-conditioning for buildings (Sokhansefat et al., 2017) and other industrial applications (Darwish Ahmad et al., 2020). They work based on the same principle as vapour compression systems, except that this system utilises a thermal compressor instead of the mechanical compressor in the vapour compression systems. Moreover, these systems can save up to 88% of energy and CO_2 emissions compared to traditional vapour compression systems (Al-Yasiri and Szabó, 2016).

The typical SABS consists of a thermal compressor (an absorber, a generator (desorber) and a solution pump), a condenser, an expansion valve and an evaporator (Patel et al., 2017). Commonly, water/lithium bromide (H_2O/LiBr) and ammonia/water (NH_3/H_2O), whose advantages and drawbacks are listed in Table 1 are used as refrigerant/absorbent pairs in the absorption cycle. H_2O/LiBr systems are more appropriate for cooling and air-conditioning purposes, whereas NH_3–H_2O absorption systems are mostly utilised for industrial and refrigerating applications (Fan et al., 2007).

The operation steps of the H_2O/LiBr SABS can be detailed as follows:

i. Applying heat by any heat source to the generator where the solution fluids (LiBr-H_2O) will separate, generating water vapour. Due to high pressure, the vapour moves to the condenser, resulting from a continuous heating process, while the absorbent (LiBr) will be sent to the absorber.

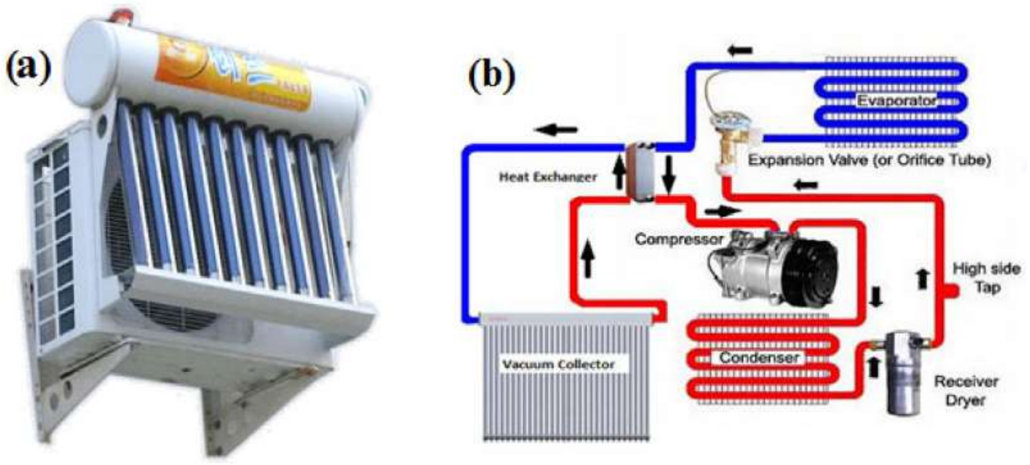


Fig. 4. (a) Outdoor hybrid solar air-conditioner (Ningbo Yoton Industrial & Trade Co., 2021), (b) Schematic drawing of the system loops.

Table 1
A comparison between working pairs in absorption systems.

Working pair	Advantages	Drawbacks
NH_3–H_2O	• Evaporation at temperatures below 0 °C.	• NH_3 is toxic and unsafe for human health. • A rectifier is needed to minimise H_2O vapour generation. • Operate under high pressure.
H_2O/LiBr	• High COP. • Work under low operational pressure. • Non-toxic pair. • Environmentally friendly. • Large latent heat of vaporisation	• Risk of congelation (anti-crystallisation devices is required). • LiBr is expensive

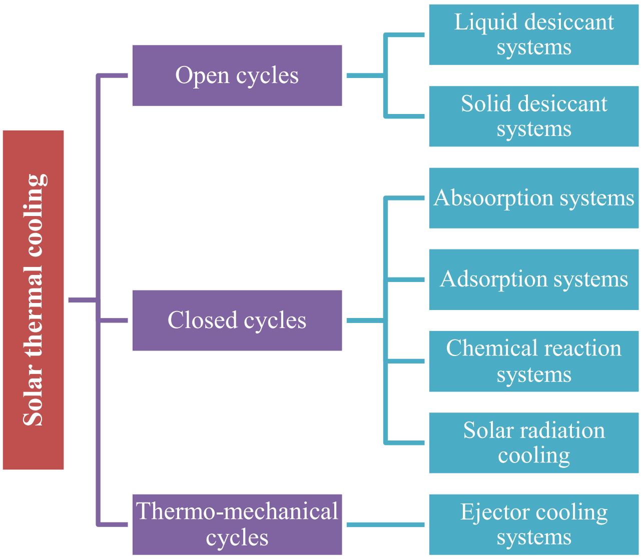


Fig. 5. Cooling systems powered by solar thermal energy (Rafique, 2020).

ii. The refrigerant condenses within the condenser using the ambient air in the small systems or water for better COP in large-scale chillers, which needs to be provided with a cooling tower.
iii. The pressured and high-temperature refrigerant moves through the expansion valve, and its pressure and temperature decrease, moving to the evaporator.
iv. The coolant with a low temperature in the evaporator is used for space cooling through different methods (direct expansion or chilled water system).

Table 2
Typical performance of SABSs (Hwang et al., 2008).

Chiller type	Possible solar collectors used	Source temperature (°C)	COP
Single effect	FPSC	85	0.7
Double effect	FPSC/compound PTSC	130	1.2
Triple effect	ETSC/ concentrating collectors	220	1.7

v. Finally, the gaseous refrigerant out from the evaporator moves to the absorber. It meets the absorbent to form a pumped solution to the generator via a pump, and then, the cycle is repeated.

Although many renewable and traditional heat sources can be utilised to provide the driving temperature for SABSs (Nikbakhti et al., 2020; Sadi et al., 2021), solar thermal energy can be used in this system as a heat source. The solar radiation is extracted by thermal collectors and stored in a special thermal storage tank for prolonged usage, as illustrated in Fig. 9.

The absorption systems require a minimum temperature of 80 °C (Macía et al., 2013). This magnitude can be obtained via a FPSC used with single-effect chillers of 0.7 COP (COP is the ratio of cooling capacity/effect earned from the systems to the thermal energy supplied to the system) (Modi et al., 2017). On the other hand, the double-effect chiller (two generators are used and have COP ranged from 1–1.5 Duffie and Beckman, 2013) requires a higher temperature range that can be attained by evacuated tube collectors (ETSCs) or even concentrating collectors (Maryami and Dehghan, 2017). Likewise, a triple-effect absorption chiller requires a higher generator temperature and produces higher COP (Azhar and Siddiqui, 2019). Table 2 shows the characteristics of designing single, double and triple-effect solar absorption chillers.

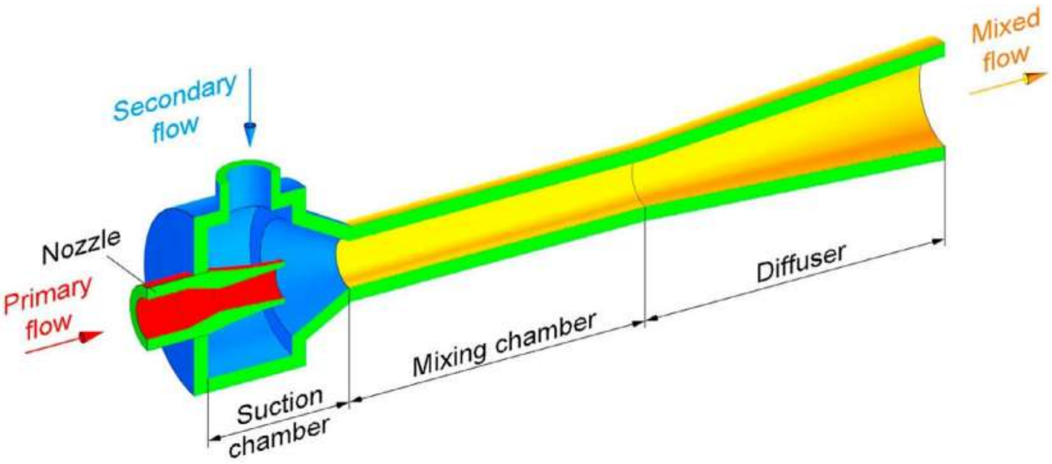


Fig. 6. Schematic of ECS parts (Tashtoush et al., 2019).

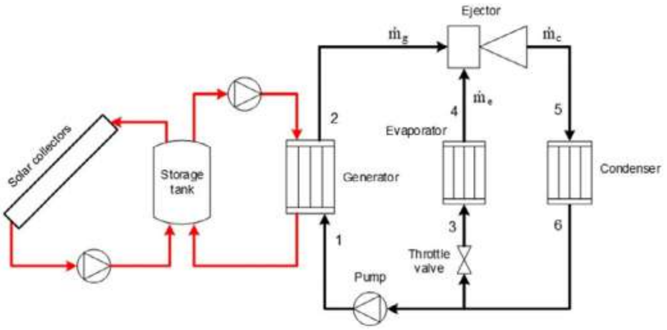


Fig. 7. Schematic diagram of ECC (Braimakis, 2021).

Several studies were conducted to develop the performance of SABSs by different methods, such as operation optimisation (Alghool et al., 2020; Sharifi et al., 2020; Xu et al., 2020), modified heat exchanger cycles (Kholghi and S. Mahmoudi, 2019), series and parallel flow cycles (Chahartaghi et al., 2019), optimal control (Sabbagh and Gómez, 2018), multi heat sources (Yang et al., 2017), hybrid with a traditional compression cycle (Dixit et al., 2017), and others (Almasri et al., 2022; Chen et al., 2017; Jiang et al., 2019; Ventas et al., 2016). Zhai et al. (2011) compared theoretical and experimental investigations of single-effect SABS, considering novel design options taking into account the solar collector and auxiliary energy systems. They summarised the other main types of SCACSs based on double-effect absorption systems, half-effect and two-stage absorption chiller, and found that a solar-driven double-effect absorption cooling system at high direct radiation is sufficient to maintain buildings with huge cooling load and limited collectors installation area. The study also reported that the half-effect and the two-stage absorption chillers are appropriate systems for air cooling in hot and dry areas that suffer from water shortages.

In the study by Fathi and Ouaskit (2001), a function of temperature in different cycle components is considered to evaluate the performance of a solar single-stage absorption refrigerator. Furthermore, the refrigerator dimensions were also changed by introducing a double-line heat exchanger (placed between the generator and the condenser and between the evaporator and the generator) to recover a part of the condenser heat. The study concluded that using such a method improved the COP of both cycles by up to 4%. Another numerical study investigated the optimum system design of the solar thermal system for a solar absorption chiller based H_2O–LiBr under the climate of Malaysia and alike regions (Assilzadeh et al., 2005). The TRNSYS software was used for modelling and simulation for long term operation. The study found that the best solar thermal consists of 35 m^2 ETSCs with a 20° slope. Suárez López et al. (2020) evaluated the performance of a laboratory manufactured absorption chiller derived by FPSCs. The chiller was tested and evaluated under a range of temperatures and powers for several charging and discharging cycles. The study showed that the COP ranged between 0.4 and 0.65, which is in the range of typical SABSs. However, the authors revealed that the system has operational issues when the driving temperature drops below 75 °C, which increases the auxiliary energy consumption. Xu and Wang (2017) numerically tested the performance of single-effect, double-effect and a novel variable-effect SABS based H_2O–Li–Br, driven by concentrated solar collectors as a cost-saving option. The developed variable-effect absorption system had an extra resorption-generation heat exchange compared to the double-effect system. This resorption allowed the chiller to change the flow rate and hence, different driving temperatures. The variable effect chiller worked at high and medium temperatures in which the higher driving temperatures resulted in higher COP. Using MATLAB and TRNSYS tools, the performance was evaluated considering solar collector, driving temperature, the volume of storage tank on the solar cooling fraction impact, auxiliary heat requirements, solar efficiency and COP. Findings showed that variable-effect and double-effect systems had a higher average solar efficiency than the single effect chiller, and the larger area of collector resulted in a better cooling fraction. The authors concluded that the variable effect chiller has the best performance considering all studied parameters. Bilardo et al. (2020) numerically evaluated the energy performance of SABS proposed for a multi-family building demand in a Mediterranean area. The study also proposed an optimisation framework to improve the system design and maximise the energy benefits. The main findings showed that the optimal design could reduce the primary energy demand by up to 48%, increasing renewable energy usage by 83%. Moreover, the study emphasised the potential of such systems to meet future zero energy buildings considering climate change and modern building developments. All in all, other numerical studies that investigated SABSs from the technical point of view are presented in Table 3.

3.2. Adsorption systems

Adsorption systems use solid or liquid sorption materials to produce a cooling effect. In the solid adsorption systems (popularly based on silica gel and salt), interaction takes place between

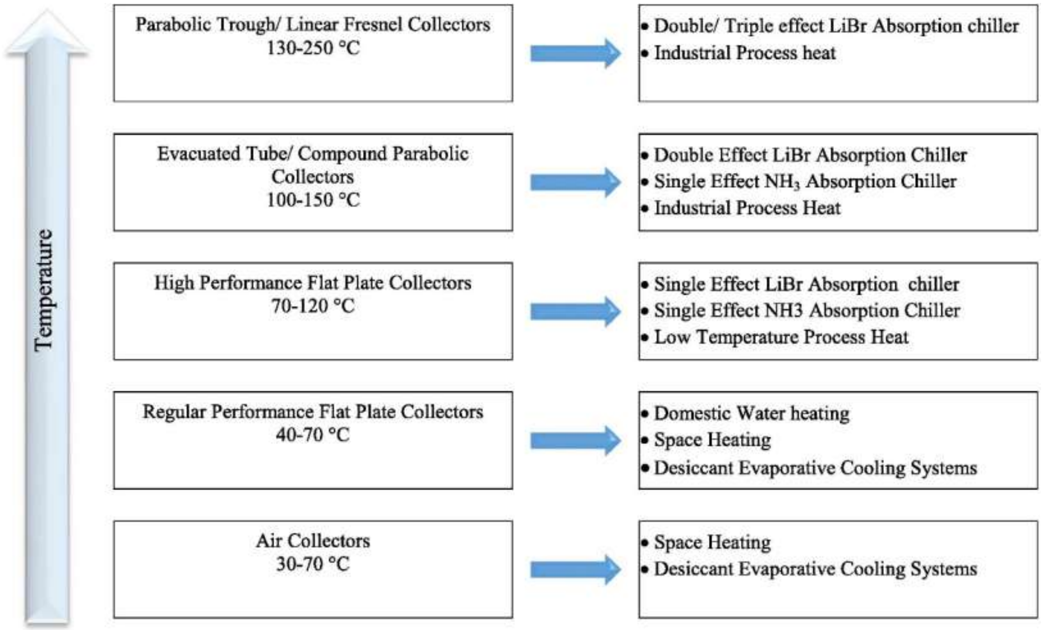


Fig. 8. Temperature range of solar collectors appropriate for SCACSs (Alahmer and Ajib, 2020).

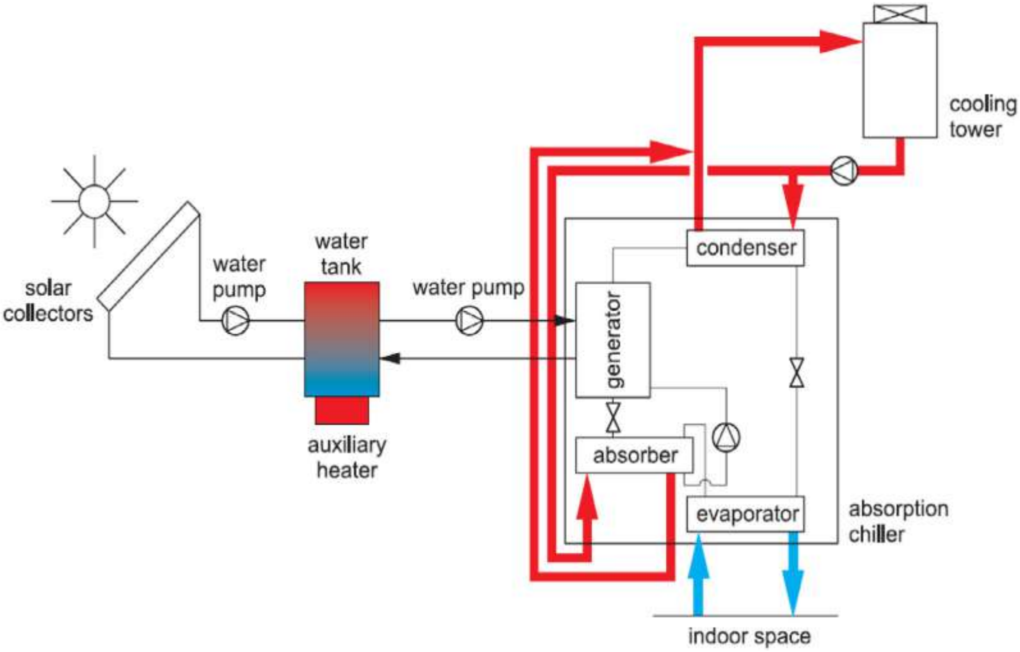


Fig. 9. Schematic of typical SABS (Chwieduk and Andrzej Grzebielec, 2014).

a gas (refrigerant/adsorbate) and a solid (adsorbent) based on physical or chemical processes. The adsorption system works based on the physical adsorption between the adsorbate and the solid adsorbent. The adsorbate molecules form on the adsorbent's surface via Van der Waals connections (Wang et al., 2008). These systems work at low temperatures and use refrigerants with zero influence on the ozone layer and global warming potential, attracting the growing interest of researchers and workers in cooling and air-conditioning for buildings and industrial sectors (Abakouy et al., 2018; Sah et al., 2017, 2016; Sur et al., 2020; Sur and Das, 2017). However, this type of SCACSs is more complex, expensive, heavier and has lower COP than SABS (Mugagga and Chamdimba, 2020).

Generally, the SADS consists of an adsorber/s, condenser and evaporator. The basic SADS work according to the following four phases:

i. Heating and pressurisation: In this phase, the adsorber is heated by a heat source (such as solar energy), increasing the adsorbent pressure from the evaporating pressure up to the condensing pressure. This phase is equivalent to the compression process in the mechanical vapour-compression cycle.
ii. Desorption and condensation: The temperature of the adsorbent keeps increasing due to continued supplied heat, resulting in desorption of the refrigerant vapour from the

Table 3
Summary of recent studies deal with SABSs for buildings (limited to numerical studies using TRNSYS and LiBr-H_2O as a working pair).

Building type (Location)	Chiller type	Chiller		Solar collectors			Remarks	Reference
		Capacity (kW)	COP	Type	Area (m^2)	Temperature range (°C)		
School (Mexico)	Single-effect	35	0.7	ETSC	110.25	75–95	- Storage tank is essential to meet the required load and time.	(Aguilar-Jiménez et al., 2020)
Hospital (Denmark)	Single-effect	NA	0.715	PTSC	39	397–541	- The chiller is used to produce hot water as well.	(Arabkoohsar and Sadi, 2020a)
NA (Turkey)	Single-effect	10	0.76	ETSC	30	90–105	- Cooling capacity can be ranged between 0.12 and 0.22 kW/m^2 when optimising solar collectors	(Altun and Kilic, 2020)
NA (Abu Dhabi in UAE, Almeria in Spain, Athens in Greece, Cairo in Egypt, Istanbul in Turkey, Madrid in Spain, Phoenix in the USA, Rome in Italy, Teheran in Iran and Thessaloniki in Greece)	Single-effect	10	0.7	ETSC	10–60	130	- The best performance of the chiller was under Abu Dhabi and Phoenix weather conditions	(Bellos and Tzivanidis, 2017)
Hospital (Aarhus in Denmark)	Single, double and triple-effect	NA	0.75, 1.40 and 1.75	PTSC	39	86–108 °C, 108–128 °C and 122–176 °C	- Annual power production was 780 kW for a single-effect absorption chiller. Moreover, double- and triple-effect chillers reduced 45% and 50% of the system price compared with the single-effect machine.	(Arabkoohsar and Sadi, 2020b)
Residential (Australia)	Single-effect	7.1–8.9	0.65	ETSC	4.15	70–95	- Thermal comfort was maintained within 20 °C–24 °C and a solar fraction of 0.91.	(Narayanan et al., 2021)
NA (Australia)	Single-effect	16	0.32–0.37	FPSC	34	60	- High cooling capacity was obtained even in the late afternoon.	(Nikbakhti and Iranmanesh, 2021)
University building (Sabzevar in Iran)	Single-effect	NA	0.8078	ETSC	100	50–150	- Solar fraction of 59.81% was reached at a maximum generator temperature of 97 °C.	(Amiri Rad and Davoodi, 2021)
5-star hotel (Changle, Shandong in China)	Single-effect	NA	0.75	ETSC	1020	84–90	- The system saved 49.7% of the gas consumption of the hotel.	(Sun et al., 2015)

adsorbent in the adsorber. The desorbed vapour becomes liquid in the condenser employing a cooling medium (cooling towers are required for large-scale systems). This phase is equivalent to the condensation process in the vapour compression cycle.

iii. Cooling and depressurisation: At the beginning of this phase, the adsorber is disconnected from the condenser, the refrigerant is cooled down, whose pressure declines from the condensing pressure to the evaporating pressure as a result of the decreased adsorber temperature. This phase is similar to the expansion process in the vapour-compression cycle.

iv. Adsorption and evaporation: This is the last phase where the refrigerant vapour temperature keeps decreasing in the evaporator, providing the desired cooling effect. This is equivalent to the evaporation process in the traditional cycle.

The basic adsorption refrigeration cycle gives an intermittent cooling effect because the adsorbent regenerates when it is saturated. Therefore, maintaining a continuous cooling effect requires two or more adsorbers (The second adsorber is in the desorption phase when the first one is in the adsorption phase). These adsorbers sequentially execute the adsorption–desorption process.

Fig. 10 shows the typical SADS, consisting of a basic adsorption cycle with two adsorbers receiving heat energy stored inside a hot water buffer tank connected to a thermal collector system.

In SADSs, activated carbon, silica gel and zeolite are the most widely utilised adsorbent materials, while water, methanol

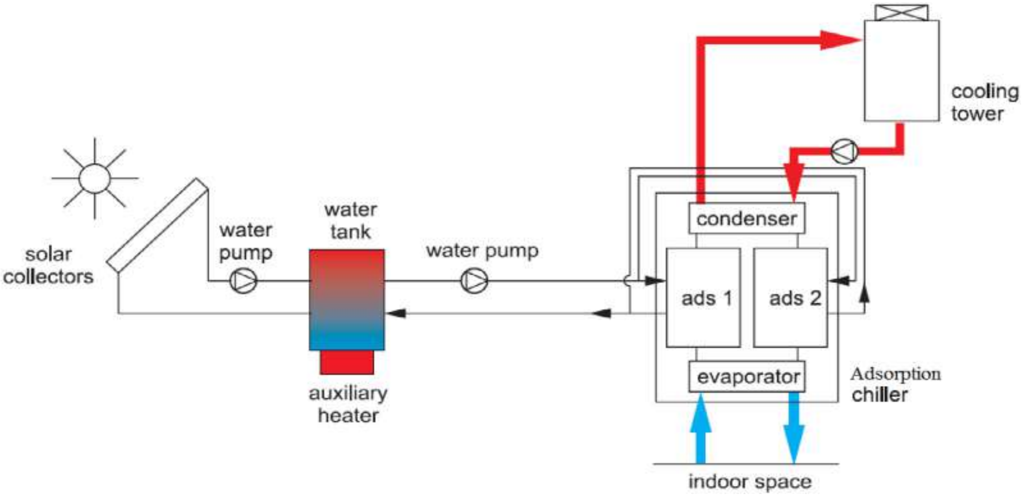


Fig. 10. Schematic diagram of the typical SADS (Chwieduk and Andrzej Grzebielec, 2014).

(ethanol) and ammonia are the most commonly used adsorbates (refrigerants) (Cherrad and Benchabane, 2018). Anyanwu and Ogueke (2005) studied a thermodynamic design procedure applied to SADSs based on activated carbon/methanol, activated carbon/ammonia, and zeolite/water (adsorbent/adsorbate pairs). The study aimed to choose the best pair for cooling applications. The results indicated that the zeolite/water is the most suitable pair for an AC application, while the activated carbon/ammonia is preferable for deep freezing, food preservation, and ice making. They used a conventional FPSC and found that the maximum possible net COP was 0.16, 0.19 and 0.3, respectively, for the activated carbon/methanol, activated carbon/ammonia, and zeolite/water.

Several advanced designs (such as implementing heat or mass recovery cycles, multi-bed and multi-stage technologies (Chan et al., 2018; Sah et al., 2015; Sur and Das, 2016) have been investigated on the basic adsorption cooling cycle to improve efficiency and address intermittent cooling effect issues. The heat recovery cycle was utilised in a system with two or more adsorbers. The working principle of the process is that when the adsorption and desorption phases are complete in each adsorber, a heat transfer fluid in a closed-loop is circulated to transfer the heat generated from the hot adsorber to the cold adsorber. Some experimental results showed that the COP of the adsorption system increased with the heat recovery cycle by 25% (Wang et al., 2010). On the other hand, to improve the cooling production and the system COP, the refrigerant mass recovery between two adsorbers is integrated with the mass recovery cycle. A closed-loop channel connects the high-pressure adsorber with the low-pressure desorber. Due to the pressure difference between the two adsorbers, the high-pressure adsorber refrigerant is re-adsorbed by the adsorbent of the low-pressure adsorber, which increases the adsorption quantity of the adsorber adsorbent, and thus increments the cooling capacity and COP. Based on this method, a study calculated the cooling capacity and COP by a cycle simulation computer program for silica gel/water adsorption refrigeration cycle compared with a single-stage adsorption cycle (Akahira et al., 2004). The results showed that the cooling effect of the mass recovery cycle is better than that of the conventional cycle and the effectiveness of the mass recovery process is more profound at low regenerating temperatures. Nasruddin and Alhamid (2015) numerically modelled and tested a two-bed silica gel-water SADS under climate conditions of Indonesia using MATLAB®. The authors considered the effect of the country's highest and lowest solar radiation on the chiller performance. Besides, mass recovery and heat recovery were used to enhance the cycle performance. Research outputs indicated that during the highest radiation values, the COP reached 0.26, while it was around 0.15 during the lowest radiation conditions. The results further demonstrated that the cooling capacity reached 37.8 kW and 5.3 kW in the highest and lowest solar radiation period, respectively. Marlinda Uyun et al. (2010) investigated a modified double-effect adsorption chiller concerning cascading adsorption cycle. The heat generated from the condenser of the top cycle is used as a driving temperature in the bottom cycle. Findings generally showed that the double-effect cycle had a better COP than the single-effect one at 100 °C–150 °C driving temperature and 9 °C chilled water temperature. Furthermore, the COP was doubled when the driving temperature reached 130 °C. The authors also concluded that the double-effect chiller performance is highly influenced by the adsorbent mass ratio of the high-temperature cycle to the low-temperature one. Khan et al. (2011) experimentally examined a mass recovery process for a three-bed adsorption system based silica gel-water cycle compared with the one without mass recovery. The chiller was composed of three beds, one condenser and one evaporator in which the mass recovery cycle is applied between the first and second beds only, under from 55 to 80 °C driving temperature range, 30 °C coolant temperature and 14 °C fixed chilled water temperature. It was found that the modified chiller with mass recovery had improved the cooling effect, and the best COP values were obtained for 65 °C–75 °C driving temperature range. Other numerical and experimental studies and their main findings are summarised in Table 4.

3.3. Desiccant systems

SABSs and SADSs discussed earlier are called closed cooling cycles because the whole process occurs in closed loops. The resulted cooling effect is exploited for producing chilled water for space cooling by different cooling equipment. On the contrary, desiccant systems are usually called open cooling cycles. These systems provide direct air cooling by combining dehumidification and evaporative air cooling.

Solar energy can be utilised in these systems to regenerate the desiccant material. The system deals with outside air or the return air from the building. The SDSs use solid desiccant materials to dehumidify the air and then cool it with sensible heat exchange and evaporation. SDSs components include heat exchangers, evaporative coolers, and heat and mass exchangers for dehumidification (Duffie and Beckman, 2013).

Table 4
Summary of recent studies dealing with SADS performance.

Adsorbent/adsorbate pair	Collector type	SADS cooling effect (capacity)	COP	Remarks	Reference
Silica gel/water	ETSC	220 kW/kg of Silica gel	0.63	- The best performance is at 85 °C driving temperature, and above this limit, the improvement is marginal.	(Almohammadi and Harby, 2020)
Activated carbon/ethanol	PTSC	500 W	0.68	- Activated carbon/ethanol is the best pair for the continuous SADS cooling cycle. - The temperature of chilled water decreases when the maximum adsorption temperature increases.	(Sha and Baiju, 2021)
Activated carbon (Maxsorb III)/CO_2	NA	2 kW	0.1	- Heat and mass recovery techniques are necessary to improve the system performance.	(Jribi et al., 2014)
SAPO-34 zeolite/water	PTSC	181.3–298.9 kJ	0.112–0.13	- The adsorption capacity is changing nonlinearly with the adsorption time. - The system COP and the specific cooling power did not have the same optimal time for adsorption.	(Chen et al., 2018)
Silica gel/water	PTSC	11 kW	0.5	- COP in the range of 0.4 to 0.55 was obtained in the daytime between 10:00 to 17:00, indicating efficient cooling for commercial or residential buildings.	(Alahmer et al., 2020)
Activated Carbon/methanol	ETSC	35 kW	0.403	- The collector area was reduced by 63% and 33% when using 20 kW and 40 kW auxiliary heater, respectively. - Increasing the solar loop mass flow rate increases the solar fraction. However, a higher flow rate (≥ 0.2 kg/s) showed no effect on the solar fraction.	(Ahmed et al., 2018)
Silica gel/water Zeolite (SAPO-34)/water	Tracked PTSC	548.8 kJ 284.2 kJ	0.258 0.133	- Silica gel showed better performance than the zeolite-based on the COP and cooling power. - The zeolite-based SADS was less sensitive to the adsorption time changing as compared to the silica gel-based SADS.	(Liu et al., 2021)
Zeolite 13X/CaCl2)/water	NA	371 W	0.16	- The heat and mass recovery cycle have a huge improvement on the COP of the SADS, which improved by about 125%. - The mass recovery, together with the pre-heating and pre-cooling cycles, achieved a 100% increase in the COP compared with the basic cycle based Zeolite 13X/water.	(Tso et al., 2015)
Zeolite (SAPO-34)/water	ETSC	10 kW	0.575	- The best performance of the SADS was reported at 75 °C, in which the cooling load of the building was satisfactorily met with a mean energy efficiency ratio (EER) of 5.8.	(Roumpedakis et al., 2020)
Activated carbon–ammonia	ETSC	25 to 80 W/kg	0.12–0.24	Using thermally activated controls to adjust the heating/cooling of the adsorbent bed gave better thermal performance than relying on the solar cycle.	(Robbins and Garimella, 2020)

Nowadays, the most applicable standard cycle is the rotating desiccant wheel cycle, in which the silica gel or lithium-chloride applies as the sorption material, in addition to other investigated materials. Bareschino et al. (2019) tested three different materials for a desiccant wheel for classroom air-conditioning in southern Italy. The tested materials were silica-gel, MIL101@GO-6 (MILGO) (a composite material made of graphite oxide dispersed in a MIL101 metal–organic framework) and Campanian Ignimbrite (a naturally occurring tuff, rich in phillipsite and chabazite zeolites), analysed using TRNSYS software. The numerical results revealed that the primary energy saving of about 20%, 29%, and 15% was obtained using silica-gel, MILGO and zeolite-rich tuff, respectively.

The typical desiccant wheel cycle used for AC applications is displayed in Fig. 11, which operates according to the following steps (Kim and Infante Ferreira, 2008):
1–2: Drying and heating the ambient air by the dehumidifier (desiccant wheel).
2–3: Pre-cooling the ambient air with the counter-flow stream from the building by the heat recovery wheel.
3–4: Cool the ambient air evaporatively using a humidifier and control the desired temperature and humidity.

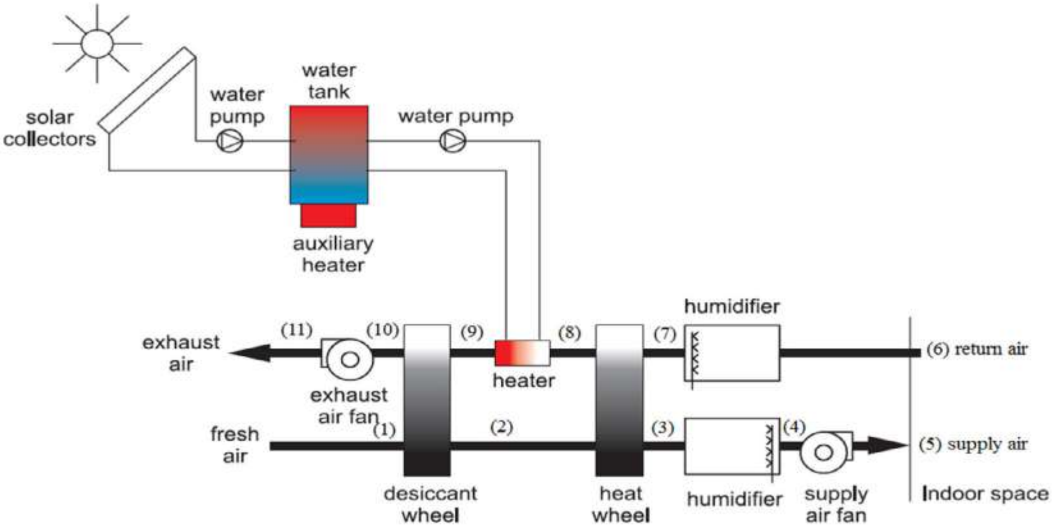


Fig. 11. Schematic diagram of a typical SDS (Chwieduk and Andrzej Grzebielec, 2014).

4–5: Blowing the cooled air into the building using an air supply fan (a slight increase in the air temperature would occur due to the fan).
5–6: Increasing the temperature and humidity of the supplied air due to the internal loads inside the building.
6–7: The return air from the building is cooled evaporatively using a humidifier.
7–8: The return air in the counter-flow stream into the supply air is pre-heated by a heat recovery wheel.
8–9: Regeneration heat is transferred to the return air from the solar thermal collector system.
9–10: Drying the desiccant wheel utilising the hot return air.
10–11: Blowing the exhaust air to the outdoor environment via an exhaust air fan.

Applications of such systems are limited to temperate regions, where there is no need for high cooling levels or removing large proportions of moisture (Kim et al., 2016). The desiccant part may not be required in hot/dry climates. The system could combine two cooling coils in the return air stream (could be supplied with well or river cold water or even a conventional chiller (Pillai et al., 2018)). Although the system configuration, geometry of dehumidifiers, properties of the desiccant material, and so on affects the energy performance of these systems, the COP of this technology is generally around 1.0 (Florides et al., 2002).

Several studies have been conducted to improve the solid desiccant system performance. A study (Jia et al., 2007) utilised a new compound desiccant wheel to augment the performance of rotary solid desiccant systems. The new compound desiccant materials are characterised by their ability to work under higher dehumidification capacity and lower regeneration temperature. Hence, low-grade thermal energy resources such as solar energy can be exploited effectively. A mathematical model was established to estimate the system performance. The simulation results demonstrated that the new wheel could remove about 20%–40% more moisture from the processed air over the desiccant wheel employing regular silica gel. Moreover, the system COP was increased relatively. Zendehboudi and Esmaeili (2016) studied the performance of desiccant wheel based silica gel and molecular Sieve desiccants considering the influence of regeneration area ratio under a fixed driving temperature (80 °C), different humidity ratios and wheel rotational speed between 4–12 revolution per hour. Several parameters, including outlet humidity ratio, processed outlet temperature, removed moisture mass, reactivation outlet temperature and moisture, were examined under the ratio of 1:3, 1:2 and 1:1 of the wheel rotational speed to the inlet air humidity. The main findings indicated that the increase in wheels' area ratio increased the moisture removal, reactivated outlet temperature, and decreased the reactivation outlet moisture and humidity ratio of the outlet air (processed air). In the same path, Alahmer et al. (2019) developed a mathematical model to numerically investigate the desiccant wheel performance considering the process inlet humidity ratio, inlet volumetric flow rate, reactivation/process airflow ratio (R/P), regenerative temperature and rotational speed under hot and humid climates. In this study, silica gel and molecular sieve served as desiccants in which the wheel operated in two modes (90° for reactivation and 270° for process, and 180° for activation and 180° for process). Findings showed that higher regeneration air temperature improved dehumidification and reduced the thermal COP. Besides, increasing inlet volume flow rate reduced the moisture removal, and greater R/P ratio removed more moisture, whereas low R/P ratio lowered the power consumed for regeneration. The study also concluded that the silica gel is more effective at high inlet relative humidities, whereas the molecular sieve can be preferred at low inlet relative humidities. Fong and Lee (2020) have conducted a year-round evaluation of a SDS using TRNSYS simulation tool for office zone under humid and hot weather conditions of Hong Kong. The authors suggested a controlled combination of SDS (based silica gel) with a SABS to overcome cooling requirements for such weather conditions. The outcomes indicated that such a combination was not a good option without mandatory humidity control. However, the SDS improved the solar fraction and primary energy usage by 9.5% and 11.5% respectively, when working as a heat recovery at high speed and without heat generation. Farooq et al. (2020) numerically evaluated the performance of SDS coupled with a photovoltaic-thermal solar collector for a building cooling load requirements of 2.5 TR under weather conditions of Lahore, Pakistan. The authors considered three cases; C-1, when an auxiliary heat source is used to heat the return air; C-2, when the auxiliary heat source is placed in the solar hot water loop; and C-3, similar to C-2 but without an evaporative cooler. The simulation results showed that C-1 has the maximum energy saving and solar fraction, whereas C-3 showed the least performance and non-feasible option. Jani et al. (2016) fabricated and experimentally studied the performance of a SDS coupled with a traditional vapour compression air-conditioner under hot and humid weather conditions of Roorkee, India. The study aimed to evaluate the whole system considering the outdoor temperature

Table 5
Recent studies discuss the performance of SDSs (rotating wheel based Silica gel as a sorption material).

Study location	Study objectives	Main findings	Reference
Martos (Jaen) in Spain	Seasonal COP (SCOP), COP dependency on outdoor conditions, and percentage of solar energy used.	- SCOP of 2 was reached, and 75% of renewable energy was used. - Higher outdoor temperatures resulted in higher instantaneous COP	(Comino et al., 2020)
Babol, Abadan and Bushehr in Iran	Monthly supply air temperature and humidity ratio under different climate regions.	- Low supply air temperature (below 16 °C) was achieved. - The cooling effect and COP were reduced in Hot and Humid climate due to the high humidity ratio. - The highest COP obtained was 0.728	(Delfani and Karami, 2020)
Spain	Study the moisture removal capacity and sensible heat ratio under variable airflow rate and air regeneration temperature (lower than 60 °C)	- A maximum of 14 kg/h moisture removal capacity and 0.62 sensible heat ratio were obtained.	(Comino and Ruiz de Adana, 2016)
Taxila in Pakistan	Study the effectiveness of dehumidification, dew point, COP, and cooling capacity	-Average cooling capacity of 3.78 kW and COP of 0.91 were obtained at a solar fraction of 70%	(Qadar Chaudhary et al., 2018)
Matrouh Governorate in Egypt	Improve the air-conditioning of an intensive care unit of a hospital.	- Saving of power consumption by 87.15% in winter (February) and 13.53% in summer (August).	(El-Maghlany et al., 2017)
Singapore in Singapore, Taipei in Taiwan, Tunis in Tunisia, Barcelona in Spain, Budapest in Hungary and Ottawa in Canada.	Compare the annual energy consumption of a hybrid SDS coupled with an indirect evaporative cooler (IEC) against a direct expansion (DX) conventional system in a small building for six different regions.	- SDS-IEC achieved annual energy saving of 46.8% compared with the DX system. - Up to SCOP=2.8 was obtained for the proposed SDS-IEC. However, all SCOP were greater than 0.25 difference in all studied regions.	(Comino et al., 2018)

and humidity variations when the processed humid air passes through the desiccant wheel. The study outcomes showed that the humidity of processed air was reduced from 18.5 g/kg dry air to 7.10 g/kg dry air, and such a hybrid system can work more efficiently than traditional air-conditioners. A summary of some recent publications that studied the performance of SDS and their findings are presented in Table 5.

4. Comparison of SABSs, SADSs and SDSs

IEA has reported that SCACSs among solar technologies are forecasted to progress rapidly in the future, compared with other thermally driven applications (IEA, 2018). A brief comparison has been conducted in this section to shed light on the progress level of each SCACSs type discussed in the previous section (Section 3). Fig. 12 displays the progress of SCACSs over the last ten years (including 2022).

It is evident that the solar systems based absorption cycle is the most developed technology during the last decade. This might indicate the rapid development of such systems, which may compete with the traditional systems in the near future.

Some indicators have been presented and discussed in the following subsections to make a fair comparison among SCACSs highlighted in the previous section (Section 3), considering the main influential aspects of these technologies.

4.1. System COP

The most significant indicator to compare the SCACSs is the COP, which measures the system efficiency depending upon the input and output energy sources. A high COP indicates a better system efficiency. This indicator is also a helpful index for comparisons among different systems driven by the same energy source.

4.2. Driving temperature

The input driving temperature is another essential indicator to compare among solar systems as it controls the performance of SCACSs (Cherrad et al., 2018). Solar thermal energy is harvested by employing the solar thermal system consisting of FPSC or ETSCs connected to the hot storage tank. The level of driving temperature contributes to the system's total cost and affects total system COP, as shown in Fig. 13.

4.3. Overall collector area

Collector area is not directly comparable for different SCACSs because the collected solar thermal energy in some installations is used for other purposes such as domestic hot water and space heating, besides air-conditioning. Therefore, the designed collector area can be larger. Thus, the installed collector area per each kW cooling capacity for SCACSs should be compared (Fig. 14).

4.4. Overall installations

The number of installed SCACSs indicates the development level of a particular system and affects the overall system cost. It is reported that the SABSs are the most commercially installed systems worldwide, where they represent around 59% of the total installed SCACSs in Europe, mainly in Germany (Balaras et al., 2007). Fig. 15 shows the number of SCACSs installations in Europe compared with the world installations.

The variety in the cooling capacity of solar systems is necessary to give flexibility and easy selection of the proper system and fit it to different types of applications. Fig. 16 shows the relation of installed SCACSs, used collector area and their cooling capacity.

Considering the large-scale SCACSs, Table 6 summarises some installed SCACSs worldwide as presented by the European Commission (Delorme et al., 2004).

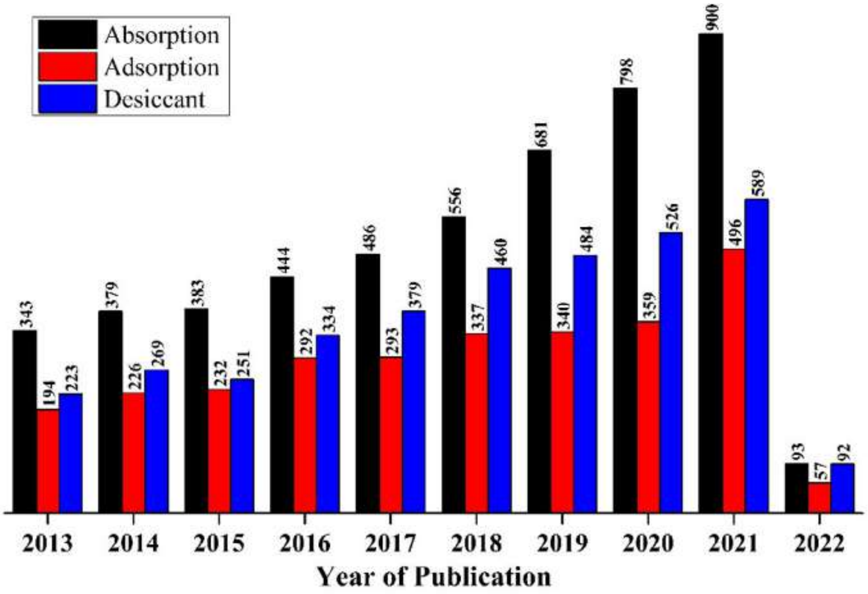


Fig. 12. Number of publications of SCACSs in the last ten years (according to Scopus database, accessed 4 January 2022).

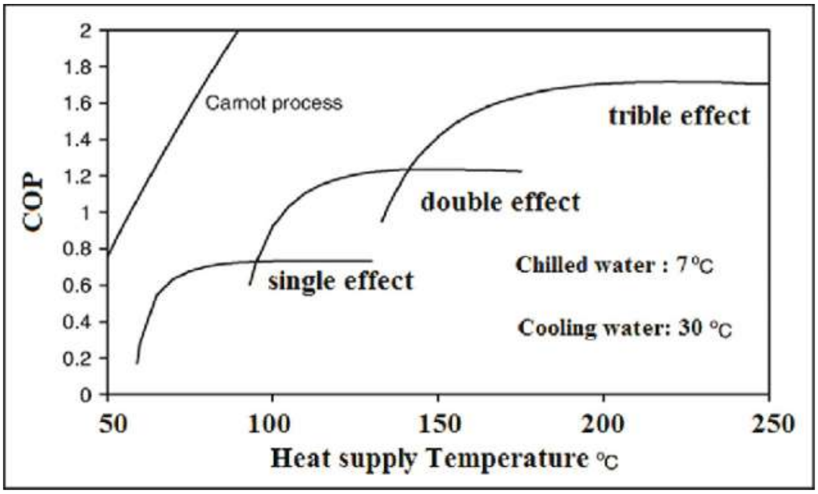


Fig. 13. COP curves of SCACSs based driving temperature (Henning et al., 2006)(Bataineh and Alrifai, 2015).

4.5. Economic indicator

System feasibility is an essential aspect (in addition to the technical ones) to be considered when discussing the appropriate SCACS for buildings. The market share of solar systems is remarkably increased in the last century, and four countries, namely China, Germany, Denmark and Austria, showed the highest share by up to 81% (Tschopp et al., 2020). Accordingly, investments in SCACSs has been developed in these countries, and many manufacturers and suppliers have grown in the market (Otanicar et al., 2012). However, the initial investments in SCACSs are much higher than the investment in traditional technologies, as mentioned earlier. The cost of each kW cooling depends highly on two main aspects: technical (such as SCACS type and building operation) and geographical aspect (such as location and availability of solar radiation, length of cooling period and volume of cooling loads to be processed) (Montagnino, 2017). The payback period (PP) of SCACSs investment is relatively high compared with other solar thermal technologies, which is the leading cause of the technology deterioration (ESTTP, 2009). It has been reported that PP could range from 7–10 years (Tsoutsos et al., 2003) up to 24 years, exceeding the building operation lifetime (Fasfous et al., 2013). Therefore, the PP of SCACSs is influenced by several aspects that must be considered, such as (i) initial cost (cost of chiller and solar thermal parts) and maintenance costs, (ii) building cooling and heating loads, (iii) quality and availability of solar radiation, (iv) electric power tariff and local policy, and (v) integration with conventional technologies (Montagnino, 2017).

Based on the above-discussed indicators and other literature studies, a brief comparison among the investigated SCACSs is shown in Table 7, considering different Technical, operational, environmental and economic indicators, which may facilitate selecting appropriate systems for various buildings.

It can be realised from the table above that SABSs have the majority of advantages compared with the adsorption and solid desiccant systems. This is also supported by many literature studies (Han et al., 2020; Rahman et al., 2020).

5. Research gaps and recommendations for future studies

The SCACSs are still under development, and researchers are paying extensive efforts on the technical and economic points

Table 6
Existing SCACS installations worldwide.

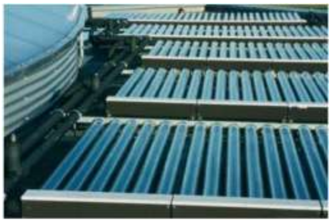
Location	SCACS type (Cooling capacity, kW)	Collector type (area, m^2)	Building type	Working time	Photo of installation
Austria (Hartberg in Stryria)	SDS (30)	ETSC (12)	Research house	Since 2000	
Spain (Arteixo- A Coruña)	SABS (170)	FPSC (1626)	Offices and stores for Inditex	Since 2003	
Greece (Crete, Rethimno)	SABS (105)	FPSC (448)	Hotel	Since 2000	
Greece (Oinofyta, Viotia)	SADS (700)	FPSC (2700)	Warehouse of cosmetic Company Gr. Sarantis S.A.	Since 1999	
Germany (Freiburg)	SADS (70)	ETSC (230)	Laboratories	Since 1999	
Germany (Freiburg)	SDS (60)	FPSC (100)	Offices	Since 2001	

(*continued on next page*)

of view towards commercialisation. However, several research gaps could be noticed from the reviewed articles that need more attention in future studies. These gaps are listed as follows:

- Although SCACSs have grown and developed rapidly during recent years, their performance still lags compared with the traditional systems driven by electricity. This is a crucial issue to be considered for hot weather locations that require thermal comfort to last for a longer time. Therefore, new numerical and experimental studies considering novel advances to improve the solar collectors, creating new sorption materials, developing hybrid cycles and heat transfer components need further effort.
- Following the above point and considering the locations that suffer from high ambient temperatures for long hours, the envelope techniques are required to minimise the reliance on SCACSs. However, no studies consider the development

Table 6 (*continued*).

Location	SCACS type (Cooling capacity, kW)	Collector type (area, m^2)	Building type	Working time	Photo of installation
Germany (Langenau)	SABS (35)	ETSC (45)	Offices	Since 1997	
France (Banyuls/Mer)	SABS (52)	ETSC (215)	Wine cellar	Since 1991	
Italy (Pergine Valsugana-Trento)	SABS (108)	FPSC (265)	Business Innovation Centre	Since 2004	
Portugal (Lisbon)	SDS (36)	PTSC (48)	offices	Since 1999	

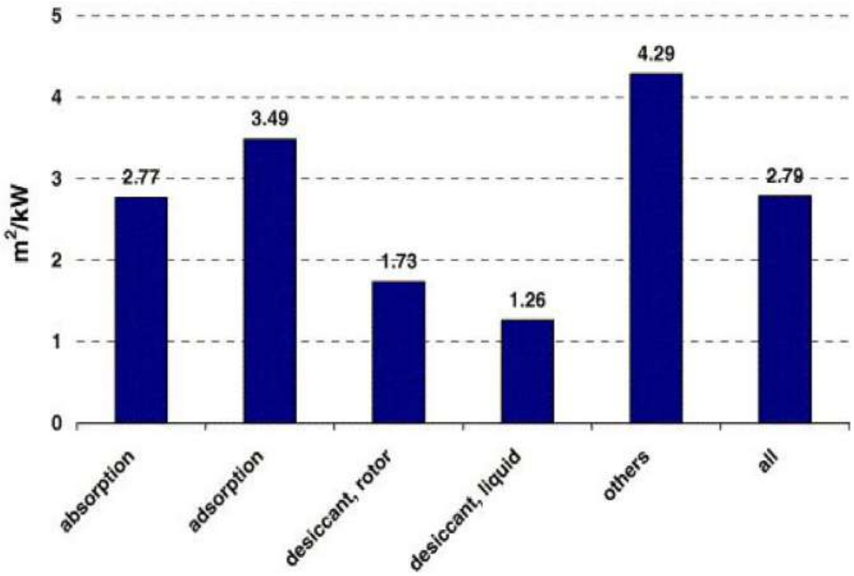


Fig. 14. Collector area per kW for different SCACSs (Henning, 2007).

of SCACS and improving the building envelope performance according to the authors' best knowledge. Such coupled trends are highly encouraged to move towards zero energy and efficient buildings.

- The intermittent nature of solar energy requires the dependency on thermal energy storage technologies, which are generally costly and increase the initial cost of these systems.

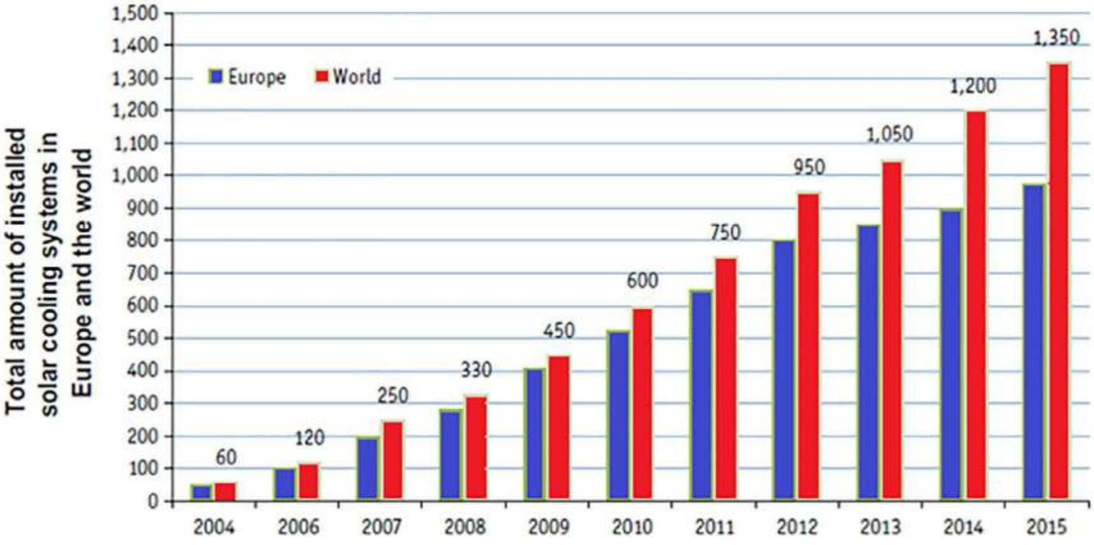


Fig. 15. Number of SCACSs installations in Europe vs the world (Weiss and Mauthner, 2018).

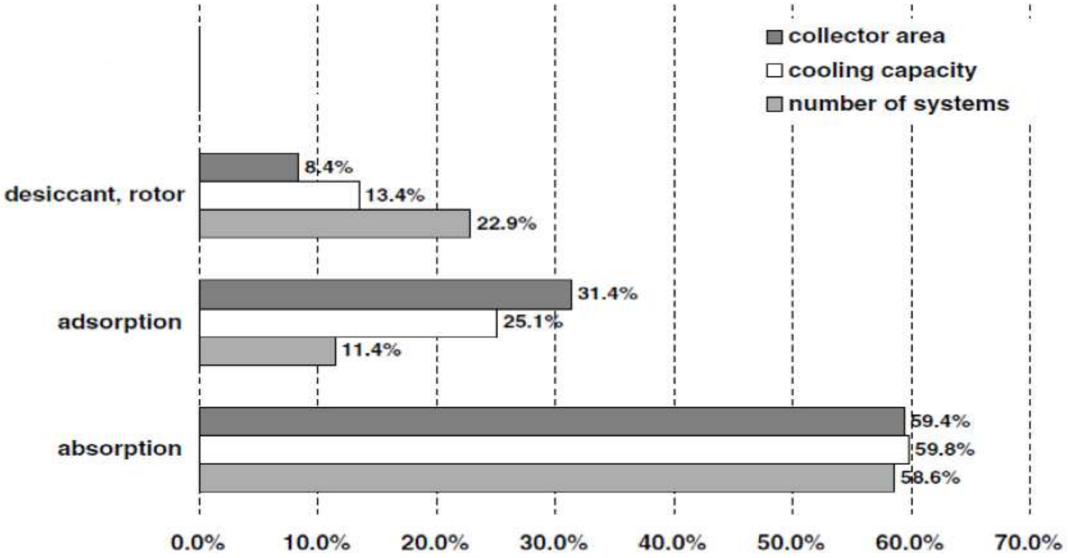


Fig. 16. SCACSs distribution based on the number of installed systems, cooling capacity and collector area (Henning, 2007).

- Combining different energy technologies, such as solid oxide fuel cells and bio-mass hydrogen production systems, could be a promising endorsement for future studies.
- Several aspects need to be considered (and developed) all together to make SCACSs more competitive in building applications, such as (i) improving the COP of systems; (ii) developing driving temperature strategies and performance of SCACSs; (iii) improving the control and operation strategies for both the SCACSs and buildings; (iv) applying passive and active strategies on the building envelope to support the performance of SCACSs; and (v) providing governmental support to encourage utilisation of green and renewable energy sources and technologies.

6. Conclusions

This paper discussed the main SCACSs, driven by solar thermal energy, such as absorption, adsorption, and solid desiccant systems. The primary operation method for each type is discussed, and some recent developments are highlighted. Furthermore, a brief comparison among them is performed considering several intrinsic indicators. Several conclusions can be derived from the summarised literature studies, as below:

- The number of numerical studies (conducted mainly by TRNSYS dynamic tool) is much higher than that of experimental studies due to the complexity of such systems and their limited numbers worldwide.
- LiBr/water is the most discussed working pair in the SABSs in the literature. Whereas, Silica gel is the most considered for SADSs and SDSs.
- In real case studies, SCACSs (SABSs in particular) are installed for commercial buildings more than residential ones with high capacities. However, most of them are provided with auxiliary energy systems, especially for those who continually need cooling, such as hospitals, airport lounges, etc.
- ETSCs and PTSCs are mainly discussed as efficient collectors for double and triple-effect SABSs and two-bed and three-bed SADSs. On the other hand, FPSCs are suitable for SDSs in most cases.

Table 7
Comparison of solar absorption, adsorption and solid desiccant systems.

Comparative Indicator	SABS ($LiBr/H_20$)	SADS (Silica gel/H_20)	SDS (Silica gel/H_20)
COP range	0.7 (single effect), 1–1.5 (double) (Duffie and Beckman, 2013)	0.40–0.61(Gordon and Choon Ng, 2000)	1.0 (Florides et al., 2002)
Driving temperature range (°C) (Wang et al., 2009)	70–150	60–85	50–80
Cooling capacity range (Gupta et al., 2008)	Commercial units available 5–2500 tons, but sales are primarily in >100 tons	>20 tons	140–280 mm^3
Number of installed systems worldwide until 2012 (Chwieduk and Andrzej Grzebielec, 2014)	13,100	3,222	746
Cost (5-tons unit) ($/ W_{th})	1.14 (Yazaki Energy Systems, 2011)	1.14 (Wang et al., 2010)	1.42 (Camargo et al., 2003)
Indirect environmental impact[a] (g CO_2/kWh cooling) (Otanicar et al., 2012)	263	323	444
Safe operation (Gupta et al., 2008)	LiBr is hazardous for health and complex to dispose	Safe	Safe
Cooling distribution system method[b]	Piping system	Piping system	Ducting system

[a] Resulting from CO_2 emissions released from backup energy used during low daytime solar irradiance (electricity or natural gas consumption).
[b] Reflects the suitability of the cooling system for existing or newly constructed buildings.

- Most developing strategies considered using heat and/or mass recovery processes, multi-stage and/or multi-bed techniques.
- Optimisation approaches and control strategies are the newest trends adopted by researchers.
- Referring to the literature progress shown in Fig. 12, SABSs are more advanced than the other types (i.e., SADSs and SDSs), and much focus is paid to develop them.

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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