Chapter

Renewable Energy Application for Solar Air Conditioning

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Abstract

This chapter presents an overview of various solar air conditioning technologies such as solar PV, absorption, desiccant, and adsorption cooling systems. It includes feasibility and comparative analysis of numerous standalone and hybrid configurations of solar cooling systems, which were investigated in past. In addition, recent developments in use of solar energy as a regeneration source to dehumidify desiccant wheel in different applications are also discussed. Details of system technologies and climate-based performance comparison in terms of various performance factors, for example, COP_{th}, Q_{latent}, $Q_{sensible}$, COP_{solar}, SF, PES, and $\eta_{collector}$ for solar-assisted configurations are highlighted. It is observed that hybridization of solar solid desiccant system results more efficient and cost-effective cooling system as latent and sensible loads are treated independently, especially when regeneration process of desiccant wheel is integrated with solar energy. This review will help to explore further improvements in solar-assisted cooling systems.

Keywords: cooling technologies, solar air conditioning, hybrid desiccant, solar collectors, separate load handling

1. Introduction

Earth has varying climates and environmental conditions depending upon the location and the time of the year. Air conditioning is meant to change the environmental conditions of a space by regulating its humidity, temperature, distribution, and cleanliness [1]. Whereas there are many objectives of developing the heating, ventilation, and air conditioning (HVAC) systems, the ultimate objective is to provide human comfort against extreme weather conditions. Various studies in literature report the fact that human performance is affected by extreme weather conditions. For example, Gagge et al. [2] studied subjects at different temperature ranges (12–48°C) and compared their physical response while concluding that the environmental conditions had drastic effects on the performance of human beings. Decreased performance could be resulted in humid and hot environments with more chances of illness and other health problems. Thus, in extreme environments, the need of efficient air conditioning becomes extremely important.

The air conditioning appliances have a fair amount of pollution effect as most of these systems use energy that is generated using fossil fuels [3]. The demand of electricity has an ever-increasing trend, as a result of which it has increased from 4661 MTOE in 1973 to 9384 MTOE in 2015 [4]. The availability of electricity as a source of energy has been strained due to ever increasing air conditioning demands. It has been reported that energy consumption for space conditioning will be increasing by up to 50% during next 15 years [5]. It is therefore the need of the time to evaluate alternate and renewable energy resources in all sectors, especially in air conditioning. Solar energy is one of the most efficient, clean, and affordable energy alternatives available today, and its use for space cooling and heating has proved to be feasible [6].

The utilization of renewable energy sources like solar energy is being given a serious consideration to meet the power requirements of the air-conditioning sector as energy demands drastic increase for air conditioning applications [7]. In addition, solar energy is both eco-friendly and energy efficient technology [8], which has motivated researchers toward development of hybrid air conditioning systems.

The air conditioning systems are classified into two main categories as shown in **Figure 1**.The first one is known as closed sorption technologies including absorption and adsorption systems, and second one is open sorption technologies including desiccant system. They are further classified as solid desiccant and liquid desiccant systems. However, these technologies are integrated with renewable energy sources especially solar energy source.

The energy saving potentials of absorption systems are more as compared with conventional systems for air conditioning and cooling applications [9]. These systems have main advantage of less moving parts [10]. To check the feasibility of solar-assisted absorption system under different climates was investigated by Baniyounes et al. [11], and results show that these systems have ability to save up to 80% when integrated with 50m^2 solar collector's area. Similarly, in another multi climate application study highlighted by Martínez et al. [12] of solar-assisted absorption system, it is shown that the system has ability to achieve 60–78% thermal comfort. In another study of two-stage solar absorption system, a maximum of 1.4 COP was reported [13].

Moreover, to improve the system performance, solar-assisted absorption system was coupled with fix speed and variable speed solar loop pump, and results showed that 11% increment was observed with variable speed pump [14]. The results of transient simulation-based parametric study of different configurations of solar-assisted absorption system show that reduced size system configuration gives 43% SF and 4.1 year payback period, which was found economically best among other configurations [15]. In another study, parabolic trough collector-assisted absorption system with a capacity of 16 kW was analyzed by simulations and experimentally. The results show that system achieves COP in the range of 0.65–1.29 with solar collector efficiency 26–35% and 82% PES when compared with conventional system [16]. Similarly, direct air cooled LiBr-H20 system integrated with solar collector was

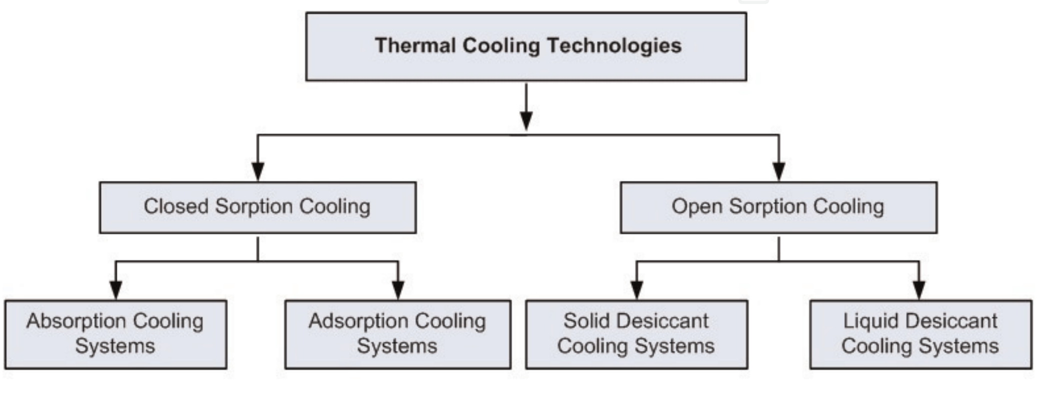

Figure 1.
Classification of thermal cooling technologies.

study experimentally for cooling season reported that 0.6 COP was achieved at 12.8° C temperature of chilled water [17].

The second type of closed sorption technique adsorption cooling systems is also evaluated by different researchers as solar-assisted adsorption cooling system was replaced by convention refrigeration system for the application of grain cooling and storage [18]. In another simulation study of solar-assisted adsorption system saves 23% primary energy as compared to conventional and achieves average COP in the range of 0.1–0.13 and provides 14-22oC chilled air temperature for domestic application [19]. Whereas the drawback of adsorption system was highlighted in [20] that these systems have complicated operating and maintenance mechanism with high cost and less efficient when used for cumulative loads [21, 22].

To avoid environmental hazards of absorption systems, desiccant systems are used as alternative for air conditioning purposes. Commercial conventional desiccant cooling systems are (1) liquid desiccant cooling system (LDCS) and (2) solid desiccant cooling system (SDCS). The liquid desiccant evaporative cooling system gives 68% of energy savings yearly compared to conventional system [23]. An experimental study show that average primary energy ratio was 1.6 and 30% of energy saving was achieved by liquid solar desiccant cooling system [24]. In another similar experimental study, results show that COP of the desiccant system increased about 54% over vapor compression system with reheat and achieved 33–60% energy savings [25]. In an economic comparison of proposed and conventional liquid desiccant system, results show that payback period of proposed system to return initial cost was 7 years and 8 months [26]. Significant energy savings were achieved in Hong Kong for three different commercial buildings where liquid desiccant system was deployed to handle latent and sensible loads [27].

However, performance of DCS can be improved by utilizing low grade renewable energy sources for regeneration purposes. Collector efficiency has been reported to increase further from 56% under hot and humid weather when desiccant system integrated with evacuated tube collectors was used [28]. PV panels have also been used for solar energy collection, which minimized the environmental pollution and maximized economic benefits [29].

Solar pond powered liquid desiccant evaporative cooling shows that indirect evaporator cooler was more effective than direct evaporative cooler [30]. However, the LDCS has disadvantages as crystallization risk and difficulty in design for small applications. Desiccant moves with supply air that is harmful for users. For large systems, cost of operating devices increased to handle large loads. To overcome these demerits, solar-assisted LDCS replaces by solar-assisted SDCS as SD cooling system has numerous advantages, for example, these systems are energy efficient, environment friendly with no contribution to ozone layer depletion, reduce electricity demands in hot and humid conditions and provide dry, clean, and comfortable environment, can handle latent and sensible loads separately, and cost effective as low grade energy can be used to remove moisture.

The SDCS has great potential to work efficiently in dry, humid, hot, and very hot climates, saves energy consumption, and provides clean environment. In humid climate, evaporative cooling has not been found efficient for greenhouses, poultries, vegetable, and fruits stores as compared to conventional vapor compression and vapor absorption systems [31]. Furthermore, studies show that solid desiccant cooling system provides CFCs free clean air conditioning [32–34]. Another feature of SDACS is that it can handle sensible and latent loads separately as compared to conventional systems [35, 36] and provides improved indoor air quality by controlling temperature and humidity. Desiccant systems have been reported to handle 51.7% humidity load. Conventional systems need more fossil fuel energy to control humidity and temperature, which pollute the environment [35, 37, 38], whereas desiccant system serves as an alternative to conventional systems for wet market applications, and results show that 1–13% less CO2 emissions can also be achieved by them [36]. In hot and humid climate, electric energy saving by desiccant system was found to be 24% [39], and 46.5% energy savings were achieved as compared to conventional systems [40]. It was predicted that desiccant system can efficiently use low grade renewable energy and increase COP as compared to conventional systems [35]. Furthermore, 50–120% increase has been reported in COP by utilizing solar energy, and reduced gas usage has also been achieved [41, 42]. Many experimental and simulation-based studies were carried out to make developments in standalone and hybrid desiccant air conditioning systems [43] as this technology development was started in 1979 by Shelpuk and Hooker [33], and its applications are expanding widely due to more efficient as compared with conventional systems [44].

2. Solar-assisted solid desiccant air conditioning

SASDAC system has four main components (1) desiccant dehumidifier, (2) sensible heat exchanger, (3) cooling unit, and (4) solar regeneration heat source. Main component of solid desiccant system basic working principle is elaborated below and pictorially presented in **Figure 2**. During process at stage (1–2) hot and humid air from outside enters in system and passed through desiccant wheel and becomes hot and dry as desiccant wheel absorbs moisture. This hot and dry air passes through heat recovery wheel (2–3) where heat exchange between return and primary air takes place. Then this air passes through humidifier at stage (3–5) moisture added to obtain desired cooling effect and enters in conditioned space. At stage (6–7), air returns from room and passed through humidifier where moisture added to reduce temperature. This moist air passes through heat recovery wheel at stage (7–8) and becomes hot. This hot air passes through heating coils at stage (8–10) and desiccant material regenerated by increasing the temperature using solar energy.

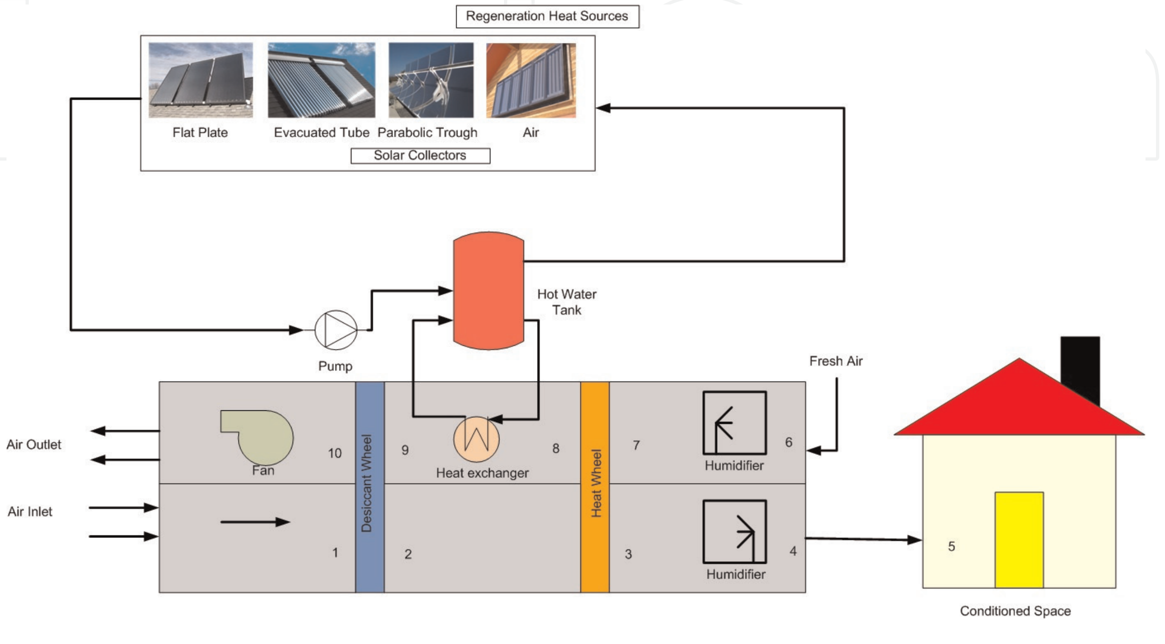

Figure 2.
Working principle of solar-assisted solid desiccant cooling system [20].

2.1 Classification of solar-assisted hybrid desiccant cooling system

The SAHSDCS is combined ability of air-conditioning system and cooling unit to remove latent and sensible loads separately by desiccant dehumidification process and cooling unit, respectively, while regeneration of solid desiccant is achieved by solar energy [45]. In other words, driving force for the process is water vapor pressure; moisture is transferred to the desiccant material from air when it is higher than on the desiccant surface, till an equilibrium is achieved. On the other side, desiccant material is regenerated by heating, and water vapor pressure increases on the surface of DW. When low vapor pressure air comes in contact, DW due to pressure gradient moisture transfers to the air, and desiccant material is regenerated.

The main classification of the hybrid solar-assisted solid desiccant cooling system is based on the cooling units used to reduce the temperature of dehumidified air and removes moisture to achieve comfort conditions. **Figure 3** presents a proposed classification for solar-assisted hybrid solid desiccant cooling system. Hybridization of SASDCS can be done with various conventional cooling technologies, which are DEC, VC, VA, and innovative modern evaporator cooler called Maisotsenko cycle (M-cycle).

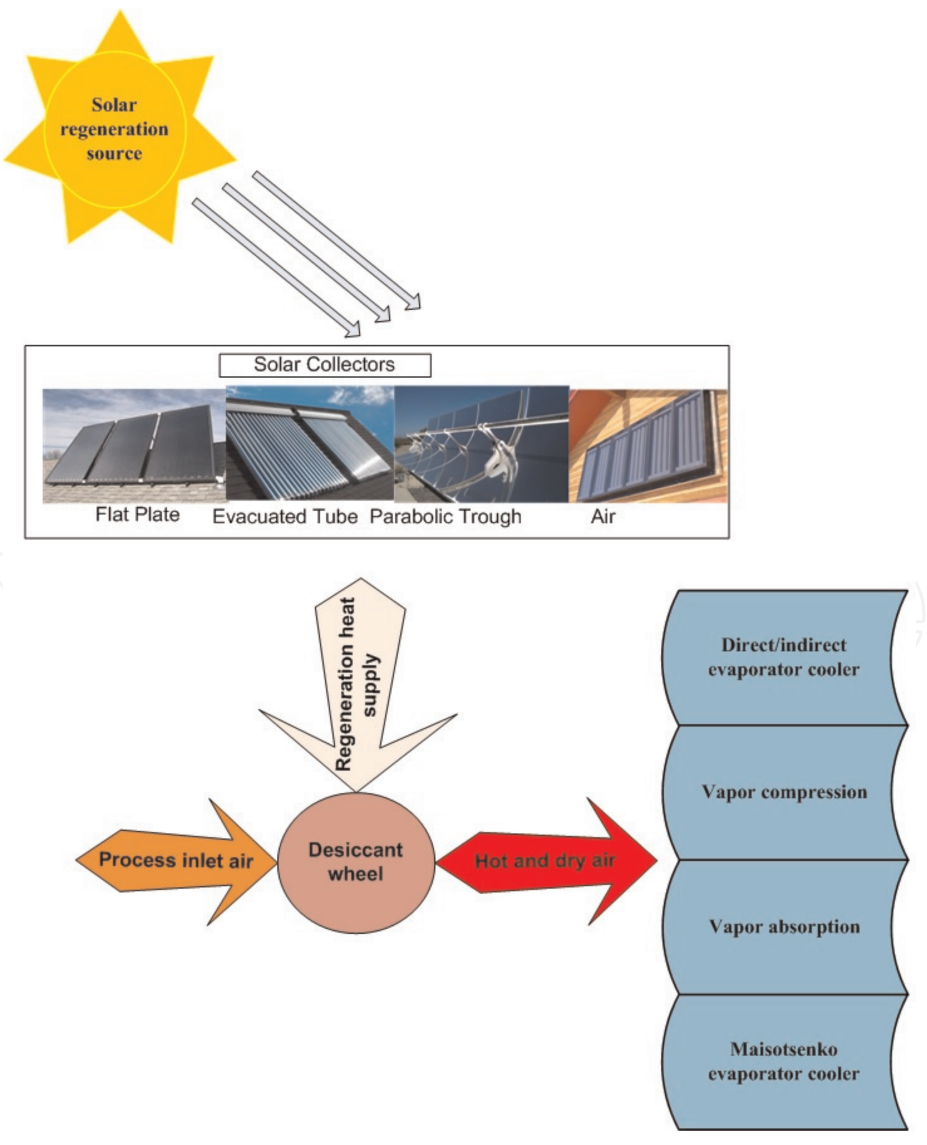

Figure 3.
Classification of solar-assisted hybrid desiccant cooling system.

2.2 Desiccant materials

Desiccant materials can be defined as materials that can adsorb water vapor from moist air and regenerated at low temperature [46]. Classification of desiccant materials is found in the literature as solid or liquid desiccant, natural or artificial desiccant, composite and polymer desiccant, bio or rock-based desiccant. **Figure 4** presents the classification of desiccant materials used in solid desiccant systems.

Silica gel is a granular or beaded form with amorphous microporous structure [47]. Large amount of water vapors can be adsorbed by desiccant material and can also be desorbed at low regeneration temperature. Similarly, composite desiccants are developed from synthetic zeolite and silica gel to achieve high dehumidification under different climatic conditions [43].

Studies have also shown that composite desiccants can give better results as compared to conventional silica gel, for example, [35]. Synthetic zeolite is suitable for different applications where dehumidification is required due to strong ability to adsorb moisture contents [48]. Water sorption analysis of clinoptilolite shows that less dehumidification capability is compared to silica gel and alumina [49]. Activated alumina has shown satisfactory results when used for desiccant dehumidification [50]. Furthermore, use of liquid desiccants, for example, lithium chloride, lithium bromide, and calcium chloride results in good COP of desiccant air conditioning because it regenerates at lower temperature [51]. Higher performance found at high humidity and low regeneration temperature [52].

As compared to silica gel, dry coconut performs better at low regeneration temperature [53]. Another naturally available porous adsorbent material is clay. The performance of this type of desiccant materials depends on their source and activation type. It was found that when bentonite clay was chemically treated with hygroscopic materials, their water vapor adsorption capacity increased by 20% [54].

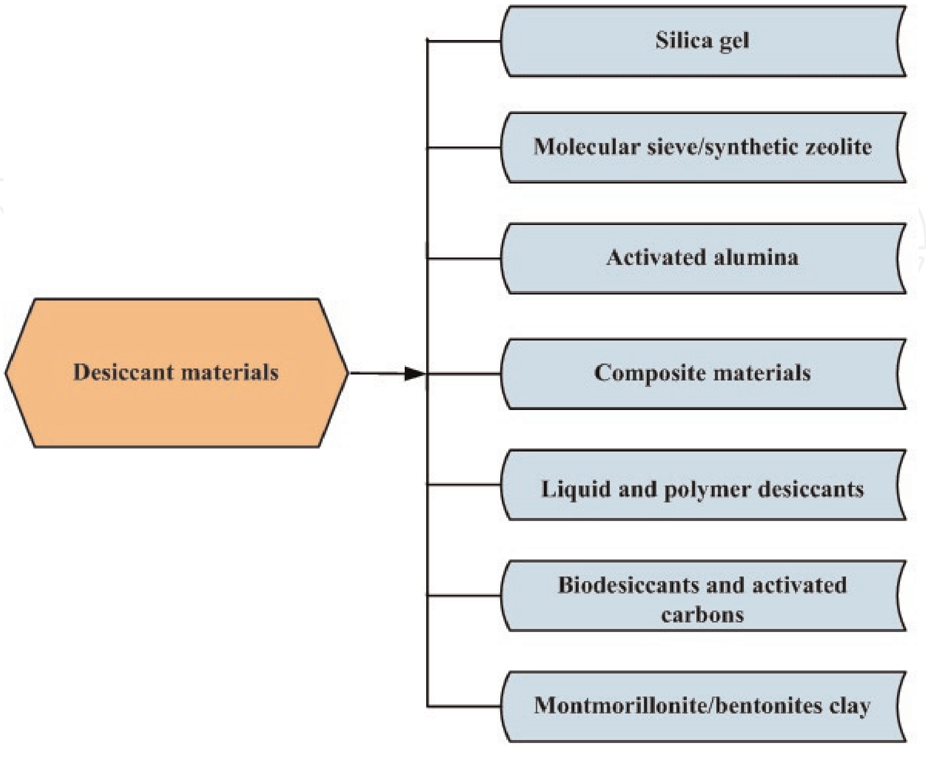

Figure 4.
Classification of desiccant materials.

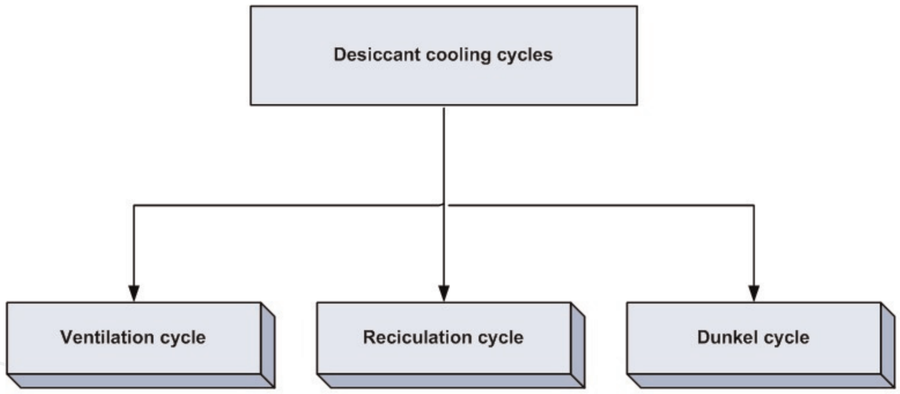

Figure 5.
Classification of desiccant cooling cycle.

2.3 Solid desiccant cooling cycles

Pennington [55] patented the earliest desiccant cooling mechanism in 1955. Since then many researchers have investigated the area. A desiccant can absorb water from its surrounding environment. The solid desiccant adsorbs moisture from air. Jain et al. [45] have classified the solid desiccant cooling cycles as shown in **Figure 5**.

Pingeton cycle is known as ventilation cycle in which air exhausted at the end of regeneration process and fresh air intake for further process. When building exhaust cannot be incorporated for coprocessing, a modified ventilation cycle also proposed but the drawback of this cycle is low cooling capacity and COP than standard cycle due to high temperature and humidity ratio. To increase the cooling capacity of the system, recirculation cycle was developed in which return air reused in process side and fresh air used for regeneration side but its COP not more than 0.8, the drawback of this cycle is lack of fresh air in conditioned space. Another cycle was developed by integrating an additional heat exchanger to take advantages of both ventilation and recirculation cycles named Dunkel cycle.

3. Hybridization of solar-assisted solid desiccant cooling system

This section presents recent research trends and literature review of SAHSDS. The major hybridization options for SADCS are already mentioned in Section 3.1.

Many research studies have shown that hybridization increases COP of SASDCS. An experimental investigation of SASDCS shows that COP of the system was increased due to solar energy utilization between 50 and 120% [41]. In another simulation study, the electrical COP of the system was found to be in the range of 1.22–4.07, and to regenerate desiccant, temperature range was 50–70°C, while at constant airflow rate, COP was found to be 3.2 [56]. Moisture control is an important aspect of the HVAC system. A two-stage air dehumidification system studied shows that this system has ability to remove moisture from incoming air by 8–10 g water per kg of dry air in tropical climate, and thermal COP of system was found to be 0.6 [57]. Similarly, in study of another two-stage SDACS COP was found 0.97 [58]. It was found that self-cooled solid desiccant coated heat exchanger system has higher thermal COP [59].

Use of solar energy reduced the 21% natural gas usage yearly, and experimental results showed that 35% of total cooling load was handled by solar energy [42]. Another simulation-based study reported that dehumidification decreased the latent load and provided humidity level for human comfort but increased the sensible load. It has also been observed that PV panels could easily meet the requirement of energy demand but they were unable to fulfill the air-conditioning demand [60]. For cooling and hot water production, it was reported that by using minimum backup electric energy, hybrid system performed better as SDCS reduced both the temperature and the moisture content of the incoming air using solar energy [61].

Bader et al. [62] presented their study for 17 cities in different regions of world and gave recommendations for the configurations and the design of solar desiccant system for different international regions. Impact of collectors on air conditioning system has also been studied. Evacuated tube collector was used to utilize 44% of solar energy, which achieved below 18% moisture content in 2 days [63]. Another study reported that solar air collector's efficiency was 50% when flat plate collector was used in Germany and Spain, whereas two-stage desiccant system provided 88% dehumidification efficiency in China [64].

System comparisons have been carried out along with financial analysis to assess the feasibility to show that SDACS performs more effectively than conventional systems with payback periods 4.7 years in Berlin and 7.2 years in Shanghai [65]. In experimental study, it was found that highest COP and exergy efficiency were achieved for Dunkel configuration in ventilation mode as 0.6 and 35%, respectively, while the Uckan and Dunkel configurations consumed 50% lower electrical energy [67].

3.1 Solar-assisted hybrid solid desiccant-based direct evaporator cooling system (SAHSD-EVC)

In SAHSD-EVC system, air passes through desiccant wheel where moisture is absorbed by desiccant material due to pressure difference, and temperature rises at the exit. This hot and dehumidified air then flows through heat recovery wheel and then DEC/IEC to cool the air at desired conditions for space. In regeneration side, return air flows through evaporator cooler, heat recovery wheel and then heating coil where temperature of air increases by using solar water heating system. This hot air passes through desiccant wheel and regenerates the desiccant material. A schematic diagram of such system is presented in **Figure 6**.

Literature reports various studies of these systems. Simulation results show that SAHDC-EVC for pre-cooling post-cooling of air achieved higher COP and payback period of about 14 years by economic assessment [68]. In other study, it was found that hybrid system provided comfort conditions in different climate zones and achieved highest and lowest COP values 1.03 and 0.15, respectively [69]. It has also been reported through simulation study that the cooling capacity of the system is increased by 40–60%, and energy consumption is reduced by 20–30% [70]. To achieve comfort conditions, SAHSD-EVC without thermal back up was analyzed for different cities of Australia, and it was found that ventilation cooling cycle-based desiccant system is not suitable for tropical climates [71]. SAHSD-EVC with active heat pump cooling and dehumidification can be achieved simultaneously by pre-heating regeneration air [72]. Full year performance with SAHSD-EVC was investigated under different climates, and primary energy savings were found up to 50% in south Europe and hot climatic conditions whereas in Frankfurt it was about 66% [73]. Furthermore, comparison between numerical and experimental results of SAHSD-EVC showed the latent load for 51.7% can be totally handled by the two-stage desiccant cooling unit [37]. Similarly, another SAHSD-EVC achieved a 0.7 COP with 22% of solar fraction during the cooling season, and COP can be increased by increasing collectors' area [74].

Seasonal analysis has predicted that 60% humidity load was efficiently handled by hybrid system and 70% of total cooling, and 40% heating load was handled by solar-assisted two-stage desiccant cooling system [75]. It has also been reported that air inlet velocity in regeneration side has strong effect on optimal rotational speed in case

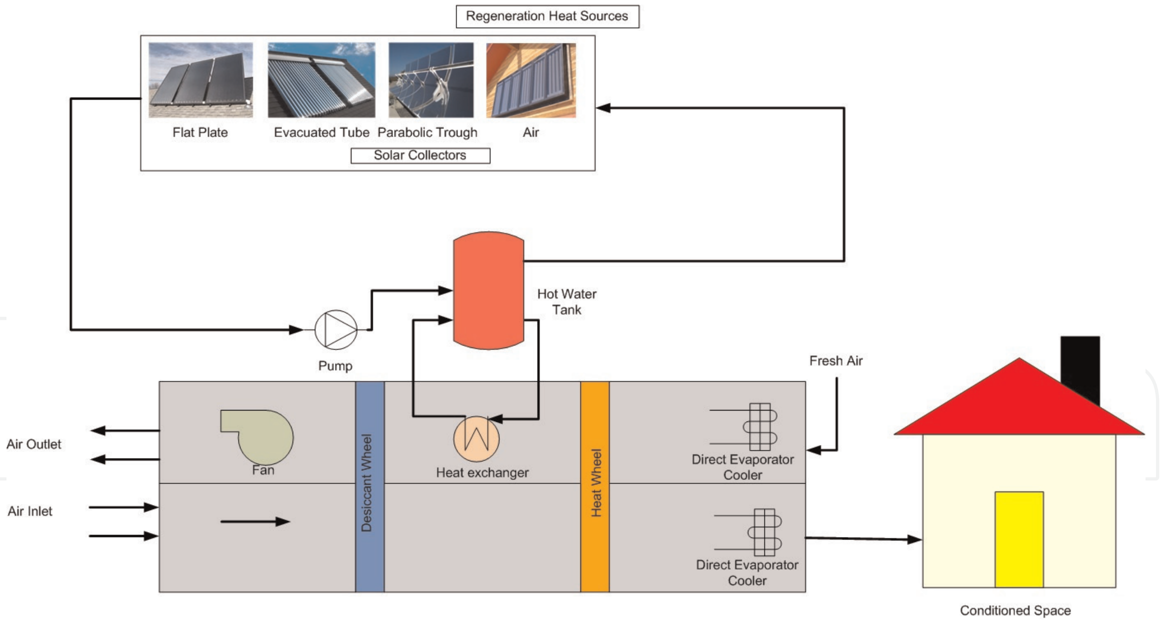

Figure 6.
Solar-assisted hybrid solid desiccant-based direct evaporator cooling system.

of one rotor six-stage solar desiccant cooling system [76]. Experimental investigation of SAHSD-EVC has revealed that thermal COP is strongly affected by optimal cycle time. System used 100% fresh air for mild conditions, and for high humidity, it was proposed to use primary return air with fresh to attain satisfactory supply air condition [77]. It was found that the energy performance of SAHSD-EVC system was more sensitive to outdoor humidity ratio as higher humidity ratio decreases the COP [78]. To investigate SAHSD-EVC by selecting optimum hot water and supply air conditions, system provides supply air 5.15 g/kg humidity ratio with supply air 28.3°C temperature and 1.78 COP [79].

3.2 Solar-assisted hybrid solid desiccant-based vapor compression cooling system (SAHSD-VC)

SAHSD-VC cooling system handles latent and sensible loads separately as desiccant wheel works to dehumidification of process air while vapor compression unit performs cooling operation as shown in **Figure 7**. In process side, ventilated or recirculated air first passes through desiccant wheel where moisture is absorbed due to pressure difference and dehumidifies the air. During this dehumidification process, temperature increases. This hot air passes through the heat recovery wheel where it is cooled and then passes through vapor compression unit to attain desired cooling and comfort conditions for selected space. In regeneration side sensibly, heated air from conditioned space passes through heat recovery wheel where it cools the air in process side, and temperature of the air rises at exit of heat wheel, but humidity remains constant. This hot air passes through heating coils of solar water heating system, which utilizes solar energy to elevate the temperature of water and transfers heat to regeneration air, and as result of it, desiccant material regenerated, so hot and humid air available at exit of desiccant dehumidifier.

In simulation-based study, it was found test control strategy for cooling season and compared with compression system that SAHSD-VC saves 40% energy in French climate [80]. Furthermore, another study results show that under Beijing, Shanghai, and Hong Kong, weather proposed system can remove 57, 69, and 55% moisture and reduce 32, 34, and 22% electric power. However, hybrid system is found feasible for humid, temperate, and extreme humid weather conditions.

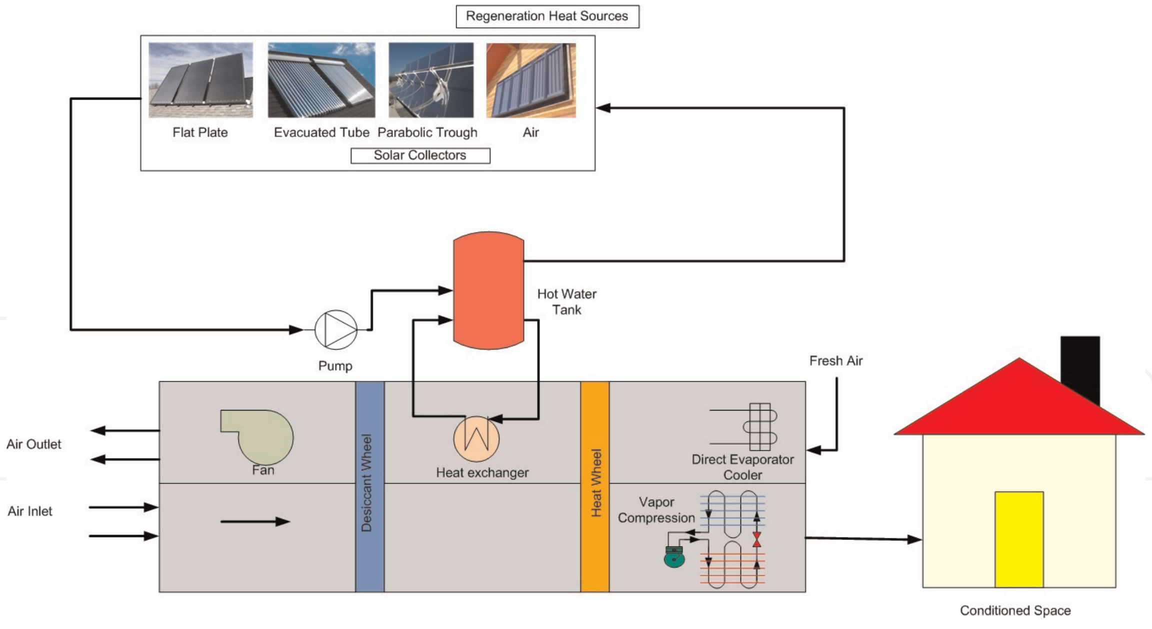

Figure 7.
Solar-assisted hybrid solid desiccant-based vapor compression cooling system.

In simulation-based study, it was found that SAHSD-VC operates under the condition with higher evaporation and condensation temperature to achieve COP of about 5.7 and adjustable MRC [81].

Another experimental study found that SAHSD-VC system performance increased as compared to VCS [82]. Similarly, in another study, SAHSD-VC is capable to handle high latent load and has energy saving potential than conventional system by 49.5% in the Chinese restaurant and 13.3% in the wet market [83]. In another study of two-hybrid cooling systems which were regenerated by solar and electric energy shows that solar SAHSD-VC saves more energy in humid climates than conventional vapor compression system [84]. It was reported in another study of SAHSD-VC that electric COP during summer operation was 2.4 and heat rejected by the chiller used for preheating airflow in regeneration side can reduce the collector area by about 30% [85]. Another experimental study conducted to examine the SAHSD-VC, 18% energy savings with 0.83 COP and 48% desiccant efficiency were achieved [86]. Similarly, experimental study shows that SAHSD-VC saves 46.5% energy than conventional system [39]. In experimental investigation of SAHSD-VC shows that process air humidity 61.7% reduces in hot and humid climates, and by varying the ambient conditions, results indicate that system performance is very sensitive to ambient conditions [87].

To predict the performance of rotary solid desiccant dehumidifier in SAHSD-VC using ANN shows that maximum percentage difference between the ANN predictions and the experimental values was found to be 7.27% for latent load handling and 3.22% for dehumidification effectiveness [88]. In another study, it was found that SAHSD-VC provides cold and dry supply air of 26°C, 8.9 g/kg and the corresponding COP reaches to 7.0 in summer, whereas in winter, supply air from the system is 26.6° C, 14.1 g/kg and the COP reaches up to 6.3 [89]. In another study, author reported that SAHSD-VC with solar panels having total collecting area of 102 m2 provides 77% of required regeneration heat to operate the system [90]. Similarly, SAHSD-VC using PV panels and PVT as power source, power consumption was 19.9 and 10.4% respectively. While in recirculation mode, 61.4 and 57.9% for ventilation and recirculation mode, respectively, less power as compared to reference system [91]. Furthermore, hybrid system was optimized by varying the temperature and humidity of the process air. Due to higher evaporation temperature, 75% share segment of the evaporator remains dry, therefore the consumption of electricity is reduced. The system required 37.5% lower energy as compared to standalone VCS [92]. In another SAHSD-VC study, capacity of VCS is reduced from 23 to 15 kW at the full demand, and the sensible capacity of the system is also improved from 0.47 to 0.73 with payback period is 5 years, and total savings for 20 years life cycle is 4295.19 USD [93]. In experimental comparison of VCS and SAHSD-VC by different operating parameters shows that at room temperature 26.7–10°C, the most suitable rotor speed is 40–50 rph, and moisture extraction ability of SAHSD-VC was improved by 17.6–27.1% as compared to the VCS [94].

3.3 Solar-assisted hybrid solid desiccant-based vapor absorption cooling system (SAHSD-VA)

SAHSD-VA cooling system as shown in **Figure 8** is designed to handle the latent load by desiccant and sensible cooling load by absorption, and the results show that proposed system feasible for high cooling demands with 36.5% lower energy consumption and reduces carbon emissions [95]. In an investigation of a SAHSD-VA shows that SAHSD-VA is environmental friendly and suitable for handling high latent loads. In comparison with other cooling technologies, SAHSD-VA with micro-generators reduces 34% emissions [96]. To improve the performance of solar-assisted absorption system by three integration strategies of components, they found that proposed strategies have less primary energy consumption and up to 50.6 and 25.5% year round energy savings than VCS and basic VA system, respectively [97]. In detail, a SAHSD-VA using six different configurations was investigated, and the results show that SAHSD-VA consumes 57.9% less power than SDCS [91].

3.4 Solar-assisted hybrid solid desiccant-based M-cycle cooling system (SAHSD-M)

SAHSD-M cycle cooling system has been schematically presented in **Figure 9**. The process side air flows through desiccant wheel where moisture is absorbed and its temperature increases. Hot and dry air then passes through heat exchanger and

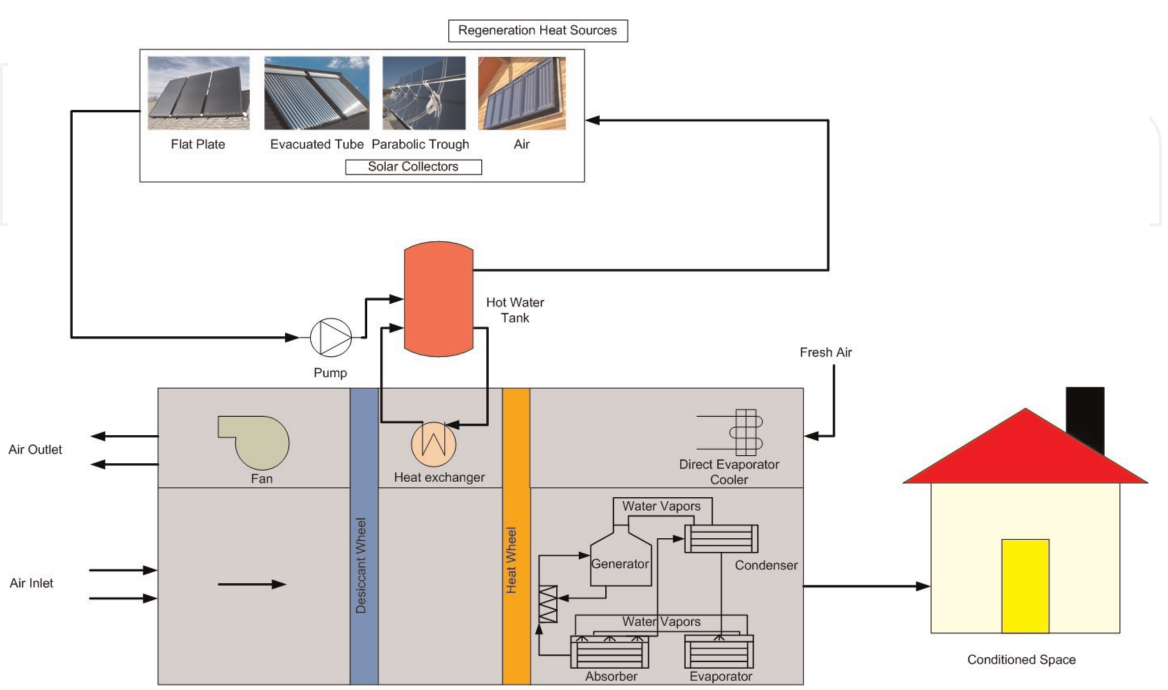

Figure 8.
Solar-assisted hybrid solid desiccant-based vapor absorption cooling system.

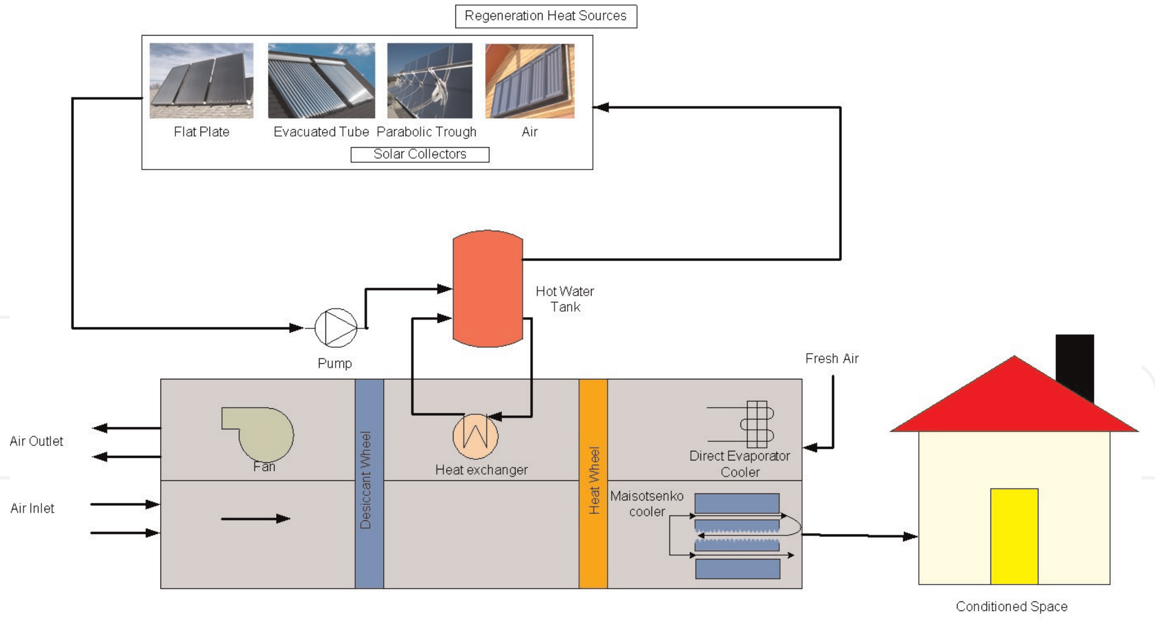

Figure 9.
Solar-assisted hybrid solid desiccant-based M-cycle cooling system.

M-cycle where air is divided in parts. Working air flows in wet channels, whereas product air travels through dry channels and gets moisturized, and sensible heat transfer takes place. As a result, this air becomes warm and saturated and discharges to atmosphere while remaining part of air moves in dry channels and cooled below the wet bulb temperature and delivered to conditioned space. In regeneration side, air passes through heat wheel and then through solar heating system and becomes hot and moves to desiccant wheel where desiccant material is regenerated.

The SAHSD-M is suitable for hot and dry climate and less suitable for hot and humid climate of Guangzhou and Shanghai [98]. To analyze proposed SAHSD-M, at low regeneration temperature 50–60°C, SAHSD-M provides comfort conditions for moderate climate [99]. Similarly in another numerical study, SAHSD-M with cross flow Maisotsenko cycle heat and mass exchanger was compared with a conventional system, and it was found that SAHSD-M system performance was in comfort zone in typical moderate climate conditions [100]. Furthermore, two-stage SAHSD-M for hot and humid climate and transient analysis show that system average COP was 0.46 [101]. Another study of SAHSD-M was designed to assess the solar energy utilization for two different configurations in humid climate. Average COP for two configurations is 0.2495 and 0.2713 and with solar shares 32.2 and 36.5%, respectively [102]. A numerical study of the different arrangements of the SAHSD-M under different inlet air conditions was carried out, and then based on results modified, the third configuration that provides thermal comfort regardless of the outdoor conditions [103]. Similarly, a hybrid system was compared with DAC under different operating parameters. It was found that Maisotsenko evaporative coolers are 16% more efficient than indirect evaporative coolers, and hybrid system has 62.96% higher value of COP than DAC [104].

4. Analysis and discussion

As noticeable from the data presented in Section 3, SASDAC systems are an important research area which is highly published, and efforts are still being made to attain good solutions to utilize freely available solar energy to develop systems which can perform efficiently in different climatic zones.

4.1 Performance-based studies on SAHSDCS

Table 1 presents performance-based studies conducted in past by different researchers to highlight different SAHSDCS in terms of COP, cooling capacity, energy savings, moisture removal, etc.

References	Research type	Climate	Desiccant wheel	System description	Findings
[71]	Experimental, simulation	Hot	Two stage	D + EV	Ventilation cooling cycle is not suitable for tropical climates
[77]	Experimental	Hot and humid	Single stage	D + EV	COP increases
[105]	Simulation	Humid	Single stage	D + EV	Energy saving high moisture removal
[106]	Experimental	Hot and humid	Single stage	D + EV	The COP was found 0.46 with a CC of 353.8 W
[78]	Experimental, simulation	Tropical climate	Single stage	D + EV	Comparative difference of experimental and simulation results varies from 0.2 to 3%, and the humidity ratio varies from 9 to 14%
[79]	Experimental	—	Single stage	D + EV	System supply air at 28.3°C, 5.15 g/kg with 1.78 COP
[73]	Simulation	Multiple climates	Single stage	D + EV	Save 50% primary energy
[74]	Simulation	Subtropical	Single stage	D + EV	Achieved 0.7 COP with 22% of solar fraction
[107]	Simulation	Multi climates	Single stage	D + EV	The maximum system COP is 7
[86]	Experimental, simulation	Hot and humid	Single stage	D + VC	18% energy savings with a COP of 0.83 and 48% efficiency
[108]	Experimental	Multi climate	Two stage	D + VC	35.7% of the CC provided by the SAHSD-VC
[84]	Numerical	Hot and humid, hot and dry	—	D + VC	SAHSD-VC saved more energy than VCS
[90]	Experimental	South European	—	D + VC	Innovative system is still very efficient as its PER is twice as high as the one of the considered reference systems
[100]	Numerical		Two stage	D + M	Higher temperature effectiveness than the traditional solution
[102]	Experimental	Humid	Two stage	D + M	COP for two configurations are 0.2495 and 0.2713, and solar shares are 32.2 and 36.5%, respectively
[103]	Simulation, modeling	Moderate climate	Single stage	D + M	Provide comfort conditions and desiccant wheel regenerated at low temperature

Table 1.
Performance-based studies on SAHSDCS.

Köppen climate classification	Average COP summer	Average COP winter
Csa (subtropical)	>2	≈0
Cfa (semiarid)	2.6	0.55
Aw (Tropical wet)	7	2
Cfb (oceanic climate)	>2	≈0

Table 2.
Performance comparison of SADCS for different climates [107].

Table 2 presents performance of SDEC system that was compared with conventional VAV system for office building for different climates. Solar collector area was taken 760m^2, 3 kg/s volume flow rate, and 3.5m^3 storage tank volume. A simulation model of the building is developed using Energy Plus software. Simulation results show that if economic factors are considered, the application of the SDEC technology would be more beneficial in Aw climate zone applications with an annual energy savings of 557 GJ and CO2 emission reduction of 121 tones. The maximum system COP is 7. For Cfb climate, the SDEC system is not as energy

References	Working fluid	Research type	Climate	System description	Findings
[80]	Silica gel	Experimental, simulation	Hot and humid	D + EV	Saves 40% energy for French climate.
[61]	Silica gel, titanium dioxide	Numerical, experimental	Multiple climates	D + EV	Titanium dioxide is more efficient than silica gel
[109]	Lithium chloride	Modeling, experimental		D + EV	A comparison of experimental and simulation results shows good compliance for wheel operation after adjusting relevant model parameters
[67]	—	Simulation	Hot and humid	D + EV	Dunckle cooling cycle has higher COP
[37]	—	Simulation	Hot and humid	D + EV	51.7% latent load totally handled by hybrid system, 49% solar energy used for heating
[83]	Silica gel	Experimental	Hot and humid	D + VC	Save energy consumption by 49.5% in the Chinese restaurant and 13.3% in the wet market
[39]	Silica gel	Numerical, experimental	Hot and humid	D + VC	20% energy consumption reduces at high humidity
[85]	Silica gel	Experimental	Humid	D + VC	Primary energy savings 50% achieved
[88]	Synthesized metal silicate	Simulation, experimental	Hot and humid	D + VC	Hybrid system saves primary energy
[110]	Silica gel	Experimental	Hot	D + AB	47.3% primary energy consumption lower than conventional

Table 3.
Comparison-based studies on SAHDAC.

efficient as the conventional VAV system. SDEC system is technically and environmentally more feasible for high cooling demand in hot and humid climates.

4.2 Comparison-based studies on SAHDAC

Literature survey shows that SAHDAC system performs efficiently as compared to conventional systems as listed in **Table 3** in different climatic conditions.

Table 4 presents a feasibility study of three different solar-assisted cooling technologies including SDEC system, SDCC system, and SAC system that was carried by [111]. These systems then compared to conventional VCS. Performance of each system was measured in terms of SF, COP, PBP, and annual energy savings. It was found that SDEC performs efficiently in hot and humid climate as it is most economical and environment friendly.

Different configurations of DEC based on operating cycle were investigated by Ali et al. [112] in different Köppen climate zones, and results show that performance of ventilated cycle is more suitable in BWh(arid) and Cfa (semiarid), while ventilated Dunkel cycle for Dfb (temperate), Cwa (dry summer), and Csa (subtropical) are weather conditions as shown in **Table 5**.

4.3 Economic and optimization-based studies

To evaluate the economic and optimal SAHSDCS, many researchers work in this area and find payback period of solar thermal source as well as cooling and dehumidification system, and also parametric analysis was performed to find optimal system for different climates and applications as shown in **Table 6**.

4.4 Effect of solar collector on SAHDCS

Table 7 presents summary of performance of solar collectors used in SAHSDC. It is based on the previous research work carried out in various climates in the world by researchers. The efficient utilization of solar energy for system performance is very encouraging to use solar energy.

Köppen climate classification	SF			COP			Annual energy savings (GJ)		
	SDEC	SDCC	SAC	SDEC	SDCC	SAC	SDEC	SDCC	SAC
Csa (subtropical)	0.68	0.45	0.6	2.9	1.9	2.9	196.88	34.14	211.22
Cfa (semiarid)	0.79	0.62	0.7	8.8	2.98	3.4	349.77	25.51	261.5
Cfb (oceanic climate)	0.55	0.4	0.43	2.1	1.8	1.9	141.52	11.75	158.03
Aw (Tropical wet)	0.81	0.6	0.68	25.5	6.2	3.6	855.88	384.34	277.64

Table 4.
Comparison of cooling technologies in different climates [111].

Configuration	Climate zones with Köppen climate classification				
	(Dfb)	(Cwa)	(Csa)	(BWh)	(Cfa)
Ventilation	0.19	0.76	0.65	2.46	3.03
Ventilated Dunkel	0.4	0.89	1.01	1.66	1.75

Table 5.
Operating cycle-based performance of DEC in different climate zones.

References	Research type	Climate	System description	Findings
[68]	Experimental, simulation	Hot and humid	D + EV	Payback period of solar collector 14 years and system 1 and 1.5 years, uncertainty in the COP was 11.76%
[113]	Numerical, experimental	Hot and humid	D + EV	4.86 years for the energy cost 0.45 LE/kW h
[101]	Experimental	Hot and humid	D + M	System average COP was found 0.46
[114]	Experimental	Hot and humid	D + EV	21–22°C temperature can be achieved with standalone optimized system
[75]	Numerical, experimental	Hot and humid	D + EV	60% of the humidity load can be handled by desiccant system and 40% of the heating load can be handled by collectors
[72]	Simulation	Hot and humid	D + EV	Hybrid system saves 45.5 MWh
[76]	Numerical	—	D + EV	Velocity of regeneration side air affects the moisture removal ability

Table 6.
Economic and optimization-based studies of SAHSDCS with findings.

Ref	Year	Collector type	Collector area	Outcomes
[68]	2009	FPC	12m^2	Payback period of solar collector 14 years
[80]	2008	FPC	100 m^2	40% energy saving for French climate
[75]	2014	ETC	15 m^2	Collectors contribute to handle 40% load
[61]	2012	FPC	12, 14 m^2	Collector efficiency varies 50–70% for different locations
[106]	2016	ETC	14 m^2	64.3°C attained by solar collectors for regeneration
[73]	2012	FPC	285 m^2	Saves 60.5% primary energy
[37]	2013	ETC	92.4 m^2	49% of total heating load handled by solar collectors
[74]	2012	FPC	10 m^2	22% solar fraction during cooling season
[86]	2013	FPC	10 m^2	Coefficient of performance of 0.83
[108]	2011	FPC	90 m^2	Average efficiency of solar heating subsystem 0.32
[85]	2012	FPC	22.5 m^2	Summer and winter collector efficiency 38 and 30%, respectively
[90]	2018	FPC	102 m^2	Primary energy ratio improved
[110]	2010	ETC	100 m^2	High solar thermal gain in cooling season
[66]	2016	ETC	100 m^2	SF for Abu-Dhabi lower than Riyadh
[102]	2016	PV/T	681, 656 m^2	Solar shares are 32.2 and 36.5% for proposed configurations

Table 7.
Performance of solar collectors used in SAHSDCS.

4.5 Applications of solar-assisted solid desiccant system

Fast technical developments in HVAC systems during last few years have produced severed environmental problems as these systems contribute to human comfort with harmful effects on environment through ozone depletion and global

Applications	References
Commercial	[42, 56, 58, 64, 65, 95–98, 101, 107, 108, 115, 116]
Residential, office, hospital buildings	[73, 89, 91, 94, 105, 117, 118]
Automobile, marine, and museum air conditioning	[119–123]
Storing food and fiber drying	[44, 63]
Hot water production	[115, 124]

Table 8.
Applications of SASDCS.

warming. So, some serious efforts put to develop ecofriendly and economic systems for different applications, and solar-assisted hybrid solid desiccant systems were found feasible where cooling and dehumidification required. **Table 8** shows the potential applications of SASDAC systems in different areas like commercial, domestic, and industry.

5. Conclusion

Performance of air conditioning systems can be enhanced by hybridization in terms of coefficient of performance, cooling capacity, and solar fraction as well as economically more feasible specially when integrated with renewable energy resources such as solar energy for regeneration purposes which cut down the peak electricity energy demand in hot and humid weather as compared to conventional systems.

As dehumidification in desiccant wheel results conversion of latent loads to sensible load and to remove this sensible load evaporator coolers are used to meet required cooling comfort conditions in hot and humid climates. When solar energy used as regeneration source of desiccant, it reduces the electricity cost, and these systems are environment friendly.

Hybridization of conventional vapor compression with solar-assisted solid desiccant results reduction in cost and improves the performance of system under various climatic conditions having high humidity and becomes environment friendly when freely available cheap solar energy uses to regenerate the desiccant wheel and auxiliary thermal energy requirement decreases.

Hybridization of solar-assisted solid desiccant with vapor absorption system results in reduction in source temperature as conventional vapor absorption system required high source temperature and system performance improved, and it became suitable for hot and humid climates.

Hybridization of solar-assisted solid desiccant system with Maisotsenko cooler results no moisture addition in process air, so more comfort conditions achieved easily as compared to simple evaporator cooler and solar-assisted solid desiccant-integrated Maisotsenko cooling systems are sensitive to environment, airflow rate, and rotational speed of desiccant wheel than humidity ratio change.

For right selection of solar-assisted hybrid cooling system in any climate, dry bulb temperature, relative humidity, and availability of solar energy are very important factors that should be considered.

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Abbreviations

AHU	air handling unit
ANN	artificial neural network
CFC	chloro fluoro carbon
COP	coefficient of performance
D	desiccant
D + AB	desiccant absorption
D + EV	desiccant evaporative
D + M	desiccant Maisotsenko
D + VC	desiccant vapor compression
DAC	desiccant air conditioning
DEC	direct evaporator cooler
DINC	direct/indirect
ETC	evacuated tube collector
FPC	flat plate collector
GJ	giga joules
HD	hybrid desiccant
kW	kilo watt
m/s	meter/sec
MRR	moisture removal rate
MRC	moisture removal capacity
MWh	mega-watt hour
PBP	payback period
PES	primary energy saving
PV	photovoltaic
rph	revolution per hour
SAC	solar air conditioning
SAHSDCS	solar-assisted hybrid solid desiccant cooling system
SASDCS	solar-assisted solid desiccant cooling system
SCOP	system coefficient of performance
SDACS	solid desiccant air conditioning system
SDCC	solar desiccant compression cooling
SDEC	solar desiccant evaporative cooling
SF	solar fraction
USD	united states dollar
VAC	vapor absorption cooling
VAV	variable air volume
VCS	vapor compression system
W	watts

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