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Solar Air-Conditioning Systems

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Additional information is available at the end of the chapter

Abstract

The chapter presents the recent studies focusing on optimizing the efficiency of air-conditioning (AC) systems using solar energy. For this purpose, several advanced AC plants (absorption, adsorption, and desiccant) are designed. Their technology and components are described in this chapter. It also discusses the energy intake of the solar energy use in air-conditioning, especially in rural regions where the electricity shortage is frequent, as well as the reduction of the energy costs and the pollution rate. A comparison between solar AC systems and traditional AC systems at the level of the designs, costs, and effectiveness is made at the end of the chapter.

Keywords: solar energy, air-conditioning systems, energy savings, absorption systems, desiccant systems, adsorption systems

1. Introduction

In recent years, the demand for comfort has been accentuated due to the earth's changing climate. Therefore, the use of air-conditioning systems is increased, which leads to higher costs and consumption of energy. It also significantly contributes to the global warming. For instance, in the United States, air conditioners use about 6% of the entire electricity produced, at an annual cost of about $ 29 billion to homeowners. Consequently, roughly 117 million metric tons of CO_2, per year, are released into the atmosphere. On the other hand, 40% of energy consumption and 36% of CO_2 emissions in the EU are caused by buildings, according to United Nations Environment Programme (UNEP). As a result, an increasing interest has been concentrated on the design of modern sustainable AC systems powered by renewables, especially the solar energy that is a universally inexhaustible natural and clean resource [1]. Hence, it can offer a reduction of the consumption, the demand, and the costs of energy, without decreasing the desired comfort. These systems allow converting the solar thermal energy (in the form of

heat) into conditioned air and sometimes chilling storage water. They are outstandingly used in residential and other sectors (offices, hotels, restaurants, storage warehouses, schools, hospitals, etc.) [2], what makes them classified among the most energy consumers.

The present chapter reviews recent studies focusing on three technologies of solar AC systems: absorption, adsorption, and desiccant systems.

2. Solar absorption systems

The harmful effects of conventional AC systems (use of environmentally unfriendly refrigerants; CO_2 emission) and their high primary energy consumption lead scientists to invest in clean energy resources, especially the solar energy [3]. The absorption technology is the most used in air-conditioning [4–6]. It uses an absorber and a generator instead of the compressor. Therefore, no electrical power is needed to pressurize the refrigerant (water or ammonia) [7]. In fact, the refrigerant is first absorbed in an absorbing material and then pressurized in the absorbed liquid phase. The pressurized absorption mixture is then reheated in a solar-powered generator to regenerate the pressurized refrigerant vapor. After that, it is deliquesced in the condenser in order to become liquid, which is then expanded through an expansion valve. The chilled refrigerant causes the cooling effect in the evaporator. Finally, the refrigerant is transferred to the absorber and a new cycle is beginning. Thereby, absorption systems contribute to reducing the greenhouse gas emissions to the atmosphere and the energy costs. Nonetheless, they have a low coefficient of performance (COP) (between about 0.3 and 0.75 according to the cooling capacity) compared with the electrical vapor compression AC systems that their COP can reach up to 3 [7].

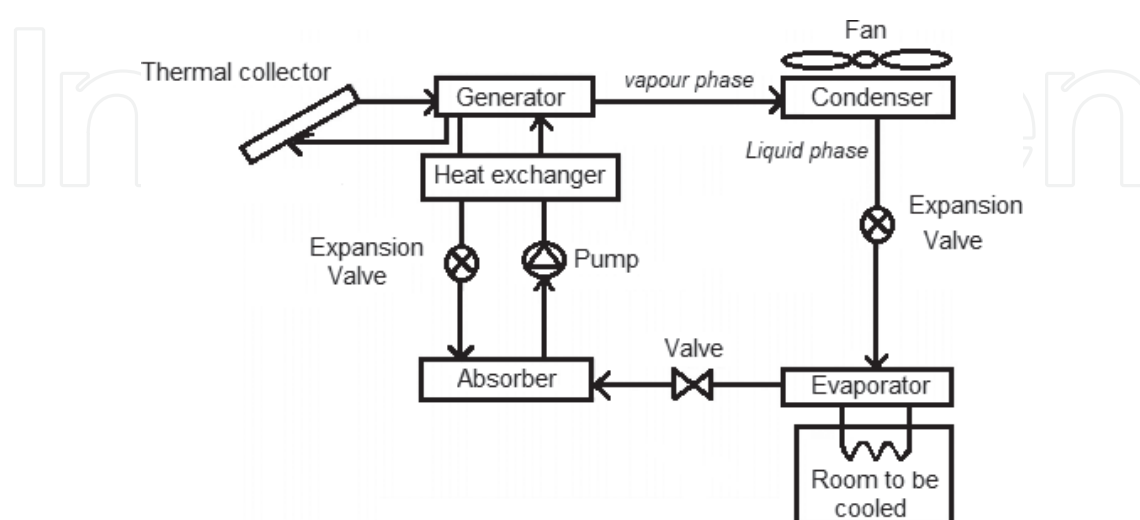The operating principle of a solar air-conditioning system is illustrated in **Figure 1**.

Figure 1. Absorption solar air-conditioning system.

Several research studies around the world aimed to design various modern solar-powered plants with energy storage. They allow minimizing the environmental effects and satisfying the energy demand [4, 8, 9]. We find single-stage or double-stage absorption systems with and without crystallization [4]. The single-stage systems are equipped with two heat exchangers and two or three storage tanks. However, the double-stage systems are different from the preview systems by adding the two pairs of absorber/generator and evaporator/condenser. In addition, the crystallization process occurs that the refrigerant undergoes three-phase transformation (solid: usually crystallized salt, liquid, and vapor) [4]. Furthermore, these plants and their performance are closely linked to the climatic conditions (especially solar irradiance) of the regions where they are installed. For instance, Mediterranean countries are characterized by a hot climate, which encourages the use of solar air-conditioning systems [5]. In fact, Tunisia widely invests in solar energy that this country is characterized by a sunny climate over long periods of the year [10]. In this reference, an absorption solar installation is applied to a room of 150 m^2 to minimize the energy consumption during the summer. It consists of a water-lithium bromide absorption chiller having a capacity of 11 kW, a flat-plate solar collector having an area of 30 m^2, and a hot water storage tank having a volume of 0.8 m^3. The simulation results showed that the COP reached 0.725 for a cooling capacity of 16.5 kW as long as the heat source temperature increases, which causes the growth of the heat transfer between the system exchangers and then the quantity of heat distributed in the surroundings [11]. Moreover, another study analyzed the energy performance of a solar air-conditioning office building that maximum monthly consumes about 380 kWh [12]. It consists of insulating the walls and cooling the roof. Hence, it allows reaching an energy saving of 46 and 80% in winter and summer, respectively, as well as, reducing the cooling load from 14.09 to 8.68 kW. In the same framework, the studies [13, 14] aimed to improve the efficiency of a solar installation equipped with parabolic solar collectors (having an area of 39 m^2), an absorption chiller associated with a cooling tower, a backup heater, two tanks for storage and drain-back storage, and a set of fan coils installed in the building to be cooled [14]. The synoptic scheme presenting the main components of the proposed cooling system is illustrated in **Figure 2**, according to Ref. [14].
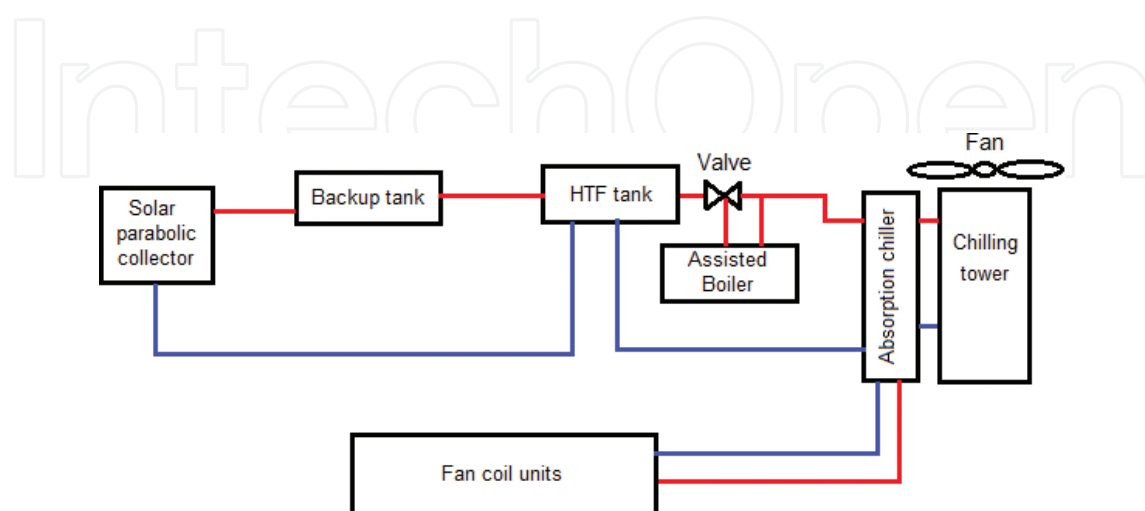

Figure 2. Synoptic schema of the solar cooling system using parabolic collectors.

The analysis of the system performance showed that the absorption chiller output could reach up to about 12 kW. Also, its COP is ranged between about 0.8 and 0.9 [15]. Furthermore, it allowed reducing the CO_2 emission of about 3000 kg during hot seasons and reaching an energy saving of 1154 l of gasoil. This type of solar air-conditioning plants was reviewed in Ref. [16] and performed in the investigation [17] for cooling and heating office buildings in Greece. It is characterized by lower thermal losses, high efficiency, and a small collecting surface of about 14 m². An energy saving of up to 50% can be obtained [17]. Nonetheless, the installation costs are higher (about 924 €/m² of the solar collector), especially for large areas [17]. Moreover, the maintenance is frequent and also expensive. Reference 18 reports the performance statistics of a solar AC system constituted by thermal parabolic collectors (having an area of 588 m²) and a double-effect absorption chiller. The system has an annual average efficiency of 40% and a peak efficiency of 58% [18]. It also allows chilling water contained in a storage tank of 23.000 l that is used as a buffer tank. The annual average COP of the absorption chiller, which is a water-cooled double-effect chiller, can reach 1.1. Nonetheless, its costs are very high and reach up to $ 680.000 that can be paid after about 21 years [18].

In Algeria, the solar energy was also harnessed to cool houses in hot climates [19]. In this investigation, the authors developed a model of the air conditioner and the absorption cooling system of 10 kW, which is constituted by solar collectors (having a surface of 28 m²) and a 900-l hot storage tank, as well as a cooling tower and a thermally driven chiller. The results obtained showed that the solar system with a thermal COP equal to 0.73 can satisfy the required conditioned air of a house having a surface of 120 m² [20]. The study [21] proposed a very efficient hybrid combined cooling, heating, and power system driven by solar energy and biomass applied to a building with a 100-kW electricity load. It consists of a biomass gasification subsystem, solar evacuated collector (having an area of 96 m² for an 800 W/m² solar irradiance), internal combustion engine, and dual-source powered mixed-effect absorption water chiller. In fact, the system allowed an energy saving of about 57%, a reduction of the carbon emission ratio of about 95%, and providing about 200 kW of cooling power. In addition, the COP of the system is high (1.1) [21].

Furthermore, the high ambient temperatures in Gulf countries cause a ceaseless demand for cooling, which allows achieving a significant scientific development in the solar AC field. For instance, in Saudi Arabia, the investigation [22] focused on optimizing the performance of a solar-powered LiBr-water absorption AC system. It is equipped with a flat-plate collector and storage tanks of cold and refrigerant, which ensure a continuous operation of 24 h/7 days. The chiller has a cooling capacity of 5 kW. The authors also give its complete mathematical model using unsteady time-dependent values of the solar intensity and the ambient temperature that are assumed to be constant over given small time intervals Δt. In fact, the generalized energy equation over each Δt, assuming uniform flow processes, is given by Eq. 1 [22].

$$Q - W = \left(\sum m \cdot h \right)_{out} - \left(\sum m \cdot h \right)_{in} + m \left(u_f - u_i \right)_{system} \tag{1}$$

where Q and W are the net thermal and mechanical energies, m is the mass inside the volume (V) of each system component, and $(u_f - u_i)$ is the change in internal energy per unit mass inside the volume (V) during the time Δt (u_f is the final internal energy per unit mass inside the volume (V) at the end of the time step (Δt), while u_i is the initial value).

Moreover, the governing equations of the mass flow rates of the weak and strong refrigerant-absorbent solutions (ws and ss, respectively) for lithium bromide-water are given by Eq. (2) [22].

$$\dot{m}_{ss} = X_{ws}/(X_{ss} - X_{ws}) \cdot \dot{m}_r$$
$$\dot{m}_{ws} = X_{ss}/(X_{ss} - X_{ws}) \cdot \dot{m}_r$$

(2)

where X_{ws} and X_{ss} are the mass concentrations for weak and strong solutions.

The generator and evaporator heat and pump work are written in Eq. (3) [22].

$$Q_G = (\dot{m}_r h_1 + \dot{m}_{ws} h_8 - m_{ss} h_7) \cdot \Delta t$$
$$Q_E = (\dot{m}_r (h_4 - h_3)) \cdot \Delta t$$
$$W_P = (m_{ss} (h_6 - h_5)) \cdot \Delta t$$

(3)

where Δt is a 1-h time-step interval and the enthalpy h(1 to 10) is based on the thermodynamic state shown in **Figure 3**, according to Ref. [22].

For a collector area of 48 m², a hot storage mass of 1500 kg, and a constant load, the simulation results using Engineering Equation Solver (EES) software indicated that the COP of the system is about 0.85. However, the experimental results showed that it can reach 0.9 [22]. At the level of the size of system components (collector and tanks), they become smaller in summer that the solar intensity is high. Thus, the required mass storage will be reduced and the COP will be enhanced.

In the same context, many related studies were carried out in Australia. For example, in Ref. [23], the author modeled a building (having a volume of 60 m³) equipped with an autonomous solar photovoltaic-battery air conditioner in order to satisfy the desired comfort with the minimum energy consumption. The conditioned supply air temperature T_s and the humidity ratio HR_s are computed using Eq. (4) [23].

$$T_s = T_b - \frac{Q_s}{\dot{m} c_p}$$
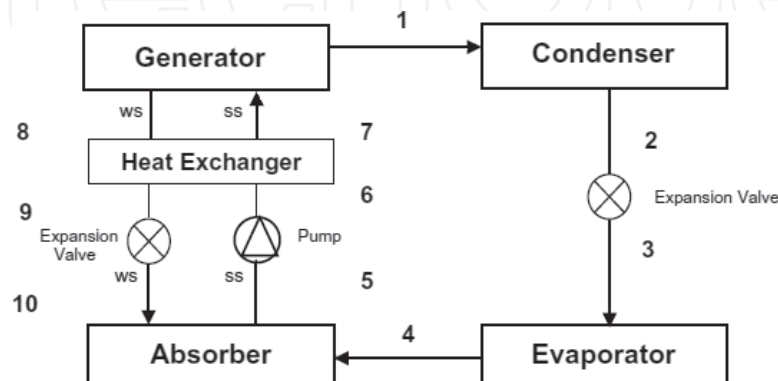$$HR_s = HR_b - (Q_t - Q_s)/\dot{m} h_{fg}$$

(4)

Figure 3. Thermodynamic state of the LiBr-H₂O absorption system.

where Q_s and Q_t are, respectively, the sensible and total cooling power, h_{fg} is the heat of vaporization of water, T_b is the building air temperature (it must be higher than 25°C to activate the air-conditioning process), and $\dot{m}$ is the supply air flow rate (0.275 kg/s) [23].

Thanks to the presence of the battery, the system can be used during peak times to provide the energy required. Indeed, the energy stored in the battery $E_{battery}$ is determined using Eq. (5) [23].

$$\frac{dE_{battery}}{dt} = \eta_c P_c - \frac{1}{\eta_d P_d} \tag{5}$$

where P_c is the battery charging power, P_d is the battery discharging power, η_c is the charge efficiency, and η_d is the discharge efficiency.

The simulation results of the internal temperature and humidity were carried out for different types of buildings and climates using TRNSYS software. The system increased the solar fraction of 30% [23]. Moreover, medium-temperature, concentrated solar thermal collectors are used in an air-conditioning system with an auxiliary heater (used to compensate for a lack of energy) and a double-effect absorption chiller [24] to cool a building. The main components of the proposed AC system are shown in **Figure 4**, according to Ref. [24].

For a collector area of 2.4 m²/kW of cooling capacity and a storage tank volume of 40 L/m², the simulation results using TRNSYS software show that the system is able to cover 50% of the load needs of the building [24]. In addition, the COP system is 1.4, which reveals the system efficiency.

On the other hand, the investigation [25] couples the solar energy to a traditional vapor compression air conditioner to perform a new hybrid solar-driven AC system. The proposed system was modeled and controlled using TRNSYS software in order to improve its energy efficiency. It is constituted of three main parts (a vapor compression system, a solar vacuum collector, and a solar storage tank). At steady-state conditions, the compressor power consumption was decreased from 1.45 to 1.24 kW, which is traduced by a global energy saving of about 14 and 7.1% for only the compressor. Likewise, an energy saving achieved by the condenser fan is about 2.6% [25], which allows increasing the COP. Hence, the authors reported that the system is able to satisfy efficiently the cooling requirements.
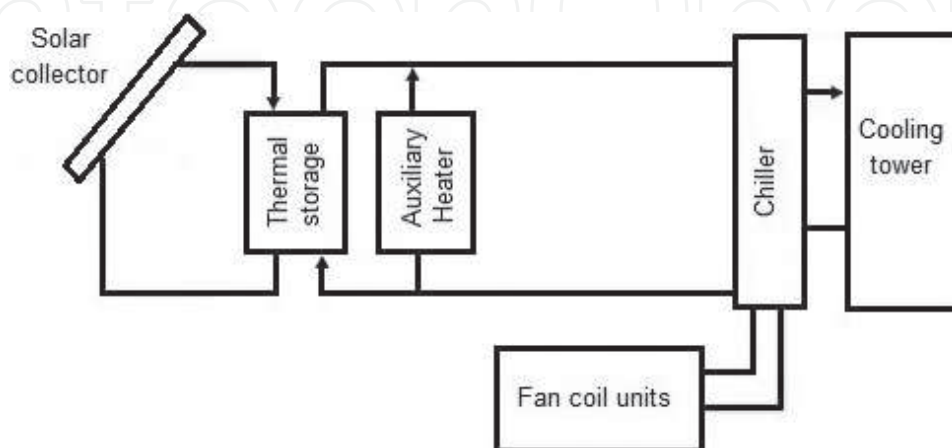

Figure 4. General scheme of the components constituting the solar AC system.

3. Solar adsorption systems

These systems have long-term environmental benefits and significant energy efficiency like the absorption AC systems [26]. In fact, they use natural refrigerants such as the water [27] and can be driven by a low-temperature heat source [28].

Several studies have been focused on the design of solar adsorption AC systems. Nonetheless, their design is complex and some parameters, like the heat rejection, are not easy to be determined using classical tools [27]. In this investigation, the authors developed a dynamic model to simulate a solar cooling system equipped with a backup unit, a heat rejection unit (having a thermal capacity of 35 kW), and adsorption chillers, which are driven by solar collectors distributed over an area of 27.52 m^2 to cool a flat building area of 130 m^2 in Italy.

The authors expressed the thermal performance of the solar collectors as [27]:

$$\frac{Q}{A} = G\left(\eta_0 - 1.485\frac{(T_m - T_a)}{G} - 0.002\frac{(T_m - T_a)^2}{G}\right)$$ (6)

where Q is the power of solar collectors, A is their area, G is the intensity of the solar radiation, η_0 is the ratio of the efficiency measured at actual admitted irradiance to vertical admitted irradiance, T_m is the collector average temperature, and T_a is the ambient temperature.

The system also cooled about 1000 l of water that can be used in numerous activities. However, the COP of the chiller is much low compared with the electric one: 0.35 and 2.5, respectively. They are computed using Eq. (7) [27].

$$COP_{chiller} = \frac{Q_{ev}}{Q_s + Q_{heater}}$$

$$COP_{electric} = \frac{Q_{ev}}{E_{el,tot}}$$ (7)

where Q_{ev} is the evaporation energy representing the useful effect of the chiller, Q_s is the energy supplied by the solar collectors, Q_{heater} is the energy supplied by the backup unit, and $E_{el,tot}$ is the total electric consumption of all the system components.

The ratio between the energy supplied by the thermal collectors and the total energy required by the complete system, called solar fraction, is given by Eq. (8) [27].

$$SF = \frac{Q_s}{Q_s + Q_{heater}}$$ (8)

In addition, the installation costs are very high, about $ 29.022. They can be paid back after about 13 years. In fact, about $ 1085 and 3942.45 kWh of electric energy are saved per year. Another adsorption cooling system using a tubular solar 1-m^2 double-glazed collector/adsorber was designed, as shown in **Figure 5**, according to Ref. [28]. The main objective is to decrease the energy consumption of cooling systems in the sub-Sahara regions in Algeria. Indeed, an energy saving of about 28.3 MWh could be reached during August [28]. However, the solar COP is too low (about 0.21).
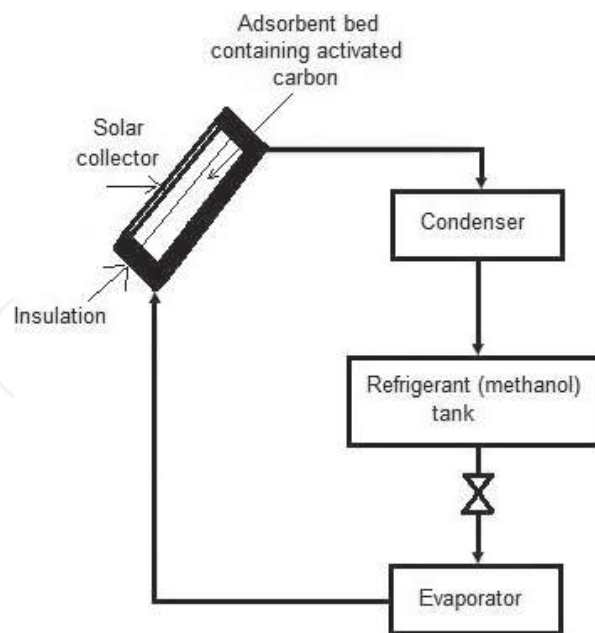
Figure 5. Synoptic schema of the adsorption solar cooling system.

In the investigation [29], a reduction of the energy consumption of about 50% was achieved, especially in hot and wet climates due to the use of solar energy for the production of cold. The authors used a traditional cooling system with a dehydrating cooling cycle that can be adapted to the fixed solar cells to air-condition a housing volume of 330 m³ using 20 m² flat-plate collector and 2 m³ hot water tank [30], which can be employed in household activities. However, the COP of the cooling system is low (about 0.6) and the indoor climate does not fulfill standard comfort criteria for few hours during the cooling season. A new water/air-conditioning system for buildings is presented in Ref. [31]. It is constituted by a solar-driven adsorption chiller, a solar chimney (having 12 m² of area), and a cooling channel (having 24 m² of area), through which the hot air is cooled and distributed in the test room (having 200 m³ of volume) under hot and humid, and hot and arid climate. The cyclic cooling capacity and the COP of the chiller reached their maximum values (about 16 kW and 0.71, respectively) during the day (between 15 and 16 h). This allowed decreasing the room temperature by 26.8%. Furthermore, the electric energy consumed by the system is 37% less than that consumed by a split inverter air conditioner having the same cooling power [31].

Absorption and adsorption technologies can be combined in the same AC system in order to further improve its performance. This is the subject of [32] in which the authors proposed novel solar poly-generation systems, based on both adsorption and absorption chiller technologies fed by dish-shaped concentrating and flat photovoltaic/thermal collectors instead of conventional solar collectors. They developed a computer code to determine the optimal system configurations taking into account the operating parameters and the climatic conditions. The systems are applied to buildings (office and residential spaces) located in different climatic European regions. They provided electricity and hot water, as well as they ensured the heating and cooling of the air-conditioned spaces.

4. Solar desiccant systems

On the environmental front, desiccant systems rank among the top efficient cooling systems [33]. In fact, they can decrease the greenhouse gas emissions and improve the energy savings given that they do not use any ozone-depleting refrigerants and consume less energy as compared with the vapor compression systems [34–36]. Their benefits are meaningful when they interact with renewable energy technologies, such as solar collectors [37, 38]. They also reduce moisture from the indoor air and enhance its quality [39–41]. For instance, liquid desiccant dehumidification solar systems are used to supply fresh air in humid climate locations using the calcium chloride liquid and a flat-plate solar collector (having an area of 86.16 m^2). It allows reducing their latent heat load and then enhancing their efficiency [42, 43]. During the entire cooling season, the proposed system in this study provides 10 [44] and 40 kW for cooling a typical house and a small restaurant, respectively. However, the COP of the desiccant unit is too low (0.41 for the house and 0.45 for the restaurant). The costs of the installation powered by natural gas can be paid back after 11 years if the gas price is 0.5638 \$/kg [43]. In addition, this kind of system (having 1 m^2 of dehumidifier area and 80 m^2 of solar collector area) has been tested under hot and dry climate conditions, and a Multi-Population Genetic Algorithm (MPGA) is developed to optimize the system parameters to reach a maximum energy saving and a minimum payback period. It is shown in **Figure 6** according to Ref. [45].

In fact, 38% of electricity saving and a payback period of 14 years are achieved [45]. Furthermore, a solar desiccant cooling unit equipped with evacuated solar collectors (having 16 m^2 of area), in which the regeneration thermal energy is supplied by a natural gas boiler, and with a conventional air-handling device is enough to obtain a reduction of primary energy consumption and CO_2 emissions of 50.2% and 49.8%, respectively. Moreover, the system costs can be paid back after 17 years [36]. A liquid desiccant solar system is combined with two evaporative coolers (a regenerative indirect evaporative cooler and a direct evaporative cooler with an adjustable bypass flow) [46]. This has the objective to improve the performance of the desiccant system by using low-grade heat for air-conditioning [46]. The liquid desiccant system is characterized by a self-cycle solution at dehumidification. Its performance was analyzed through a mathematical model that studies the impact of varying five parameters (solution self-cycle ratio, working to intake air flow ratio, regeneration temperature, ambient air temperature, and humidity ratio). The system can decrease the air temperature of the cooled space to 17.9°C. Nonetheless, the obtained thermal COP is low (0.5) for the design conditions [46]. In addition, the system has the advantage of using lower temperature heat source compared with a conventional AC system. The same technology was also invested for hot climates in Saudi Arabia [47]. The investigation shows that the desiccant evaporative AC system presents a modest performance in dry climates and does not operate in very wet conditions.

On the other hand, three models of solar solid desiccant AC system were performed in Ref. [48] under cold, humid, hot, and dry climates in Tunisia and applied to a building having a volume of 48 m^3. The authors used a fixed solid desiccant bed in place of a rotary desiccant wheel. The solar flat-plate collectors (having an area of 2 m^2) consist mainly of a transparent cover, a plate absorber, tubes fixed and set under the absorber plate, and insulation on the back side of them.
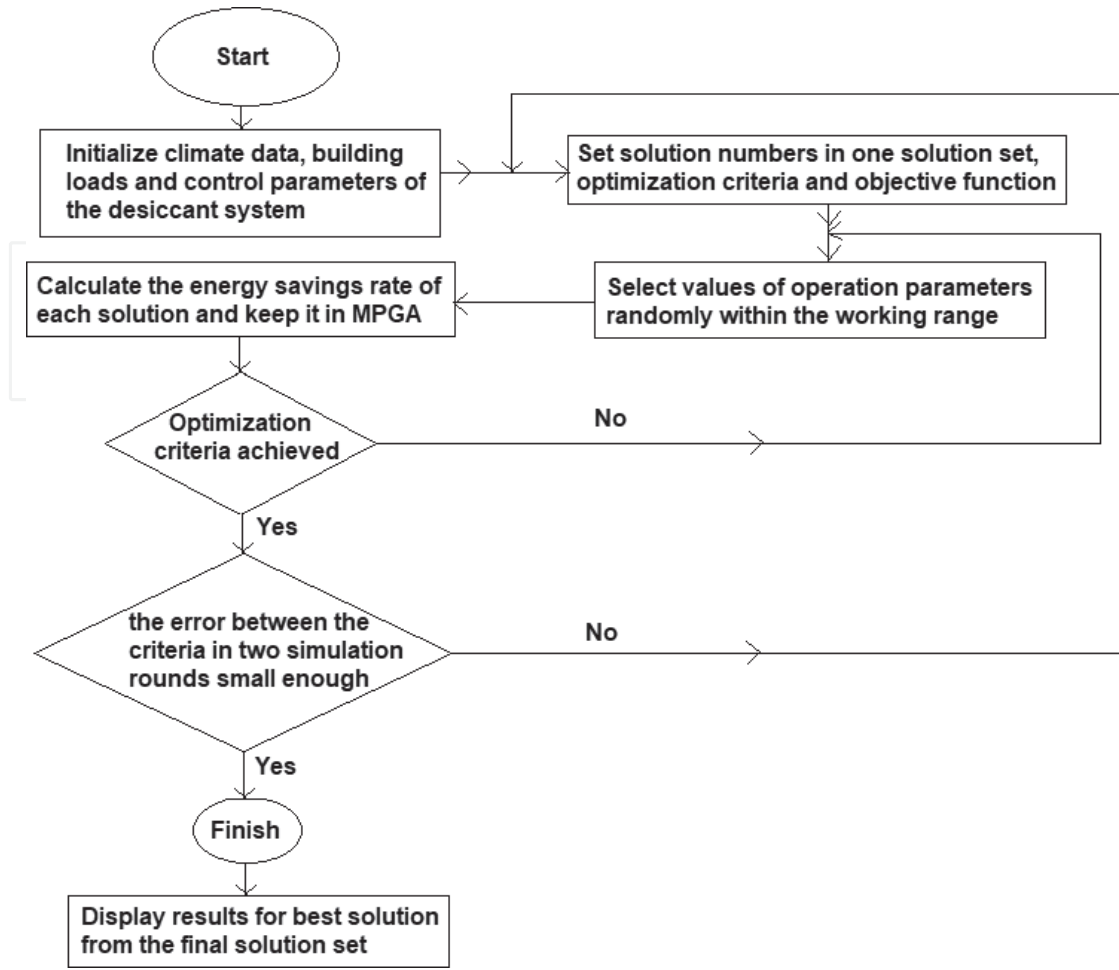
Figure 6. Multi-population genetic algorithm (MPGA) to optimize the desiccant AC system.

They are made of copper. Water circulates into the tubes in order to be heated. The solar collectors are coupled to the desiccant system (it consists of a desiccant dehumidifier, an air–air heat exchanger, a water-air heat exchanger, and a humidifier). This provides the heat required to regenerate it, precisely the desiccant dehumidifier. The coupling is ensured by a water storage tank and a heating coil inserted in the return air stream of the desiccant system [48].

The authors expressed the thermal balance for the absorber as follows [48]:

$$
\begin{aligned}
\rho_{abs}\,\delta_{abs}\,C_{abs}\,\frac{dT_{abs}}{dt} &= G\,\tau_{abs}\,\alpha_{abs} + h_{r_{abs\_tc}}\left(T_{tc} - T_{abs}\right) + h_{conv_{a-abs}}\left(T_a - T_{abs}\right) \\
&+ \left(\frac{S_{abs-tube}}{S_{abs}}\right)h_{cond_{abs-tub}}\left(T_{tube} - T_{abs}\right) + \left(\frac{S_{abs-insulation}}{S_{abs}}\right)h_{cond_{abs-insulation}}\left(T_{insulation} - T_{abs}\right) \quad (9) \\
&+ \lambda_{abs}\,\delta_{abs}\left(\frac{\partial^2 T_{abs}}{\partial x^2} + \frac{\partial^2 T_{abs}}{\partial y^2}\right)
\end{aligned}
$$

where 'abs' refers to absorber, ρ is the intrinsic average density, σ is the thickness, C is the specific heat, G is the solar global radiation, τ is the transmission coefficient, α is the absorption coefficient, $hr.$ is the radiation heat transfer coefficient, T_{tc} is the temperature of the transparent cover, T_a is the air temperature, S is the surface area, and λ is the conductivity.

Solar air-conditioning systems			
	Absorption systems [3–25]	**Adsorption systems [26–32]**	**Desiccant systems [33–48]**
Design values	*Small storage water volume:* minimum 0.8 m³	*Small storage water volume:* up to 2 m³	*Small storage water volume:* up to 2 m³
	Collector area: 14–96 m²	*Collector area:* 1–20 m²	*Collector area:* 2–80 m²
	Building volume (or surface): up to 150 m²	*Building volume (or surface):* minimum 130 m², up to 330 m³	*Building volume (or surface):* minimum 48 m³
Design optimization	• Insulating the walls and cooling the roof of the building. • Using parabolic and concentrated thermal collectors. • Combining solar energy and biomass. • Small size of collectors and tanks • Adding batteries	• Using low-temperature heat source. • Using sustainable adsorption chillers. • Using tubular solar double-glazed collector/adsorber.	• Using dehumidifier to reduce moisture from the cooled air. • Using multi-population genetic algorithm to optimize the system parameters. • Using a natural gas boiler to regenerate thermal energy.
Cooling capacity	From 5 to 16.5 kW	About 16 kW	About 40 kW
Effectiveness COP	From 0.3 to 0.75 and sometimes up to 1.4	From 0.2 to 0.7	From 0.41 to 0.5
Environmental benefits	Reduction of the energy consumption up to 80% (especially during the summer). Reduction of the CO_2 emissions up to 95% (up to 3000 kg).	Energy saving: up to 28.3 MWh. Up to 50%.	Reduction of the energy consumption up to 52%. Reduction of the CO_2 emissions up to 49.8%.

Table 1. Design values and effectiveness of absorption, adsorption, and desiccant solar AC systems.

$$h_{cond_{abs-tube}} = \frac{1}{\frac{\delta_{abs}}{\lambda_{abs}} + \frac{\delta_{tube}}{\lambda_{tube}}} : \text{conductive heat transfer coefficient between absorber plate and tube}$$

$$h_{cond_{abs-insulation}} = \frac{1}{\frac{\delta_{abs}}{\lambda_{abs}} + \frac{\delta_{insulation}}{\lambda_{insulation}}} : \text{conductive heat transfer coefficient between absorber plate and insulation}$$

$$h_{conv_{a-abs}} = \frac{Nu_a \lambda_a}{\delta_a} : \text{the convective heat transfer coefficient between air gap and the absorber}$$

For the tube, the thermal balance is written as [48]:

$$\rho_{tube} S_{tube} C_{tube} \frac{dT_{tube}}{dt} = Sc_{abs-tube} h_{cond_{abs-tub}} (T_{abs} - T_{tube}) + P_{tube} h_{conv_{tube-insulation}} (T_{insulation} - T_{tube})$$
$$+ Sc_{tube-insulation} h_{cond_{tub-insulation}} (T_{insulation} - T_{tube}) + \lambda_{tube} S_{tube} \frac{\partial^2 T_{tube}}{\partial y^2}$$

(10)

where P is the perimeter.

$h_{conv_{a-abs}} = \dfrac{Nu_{tube} \lambda_f}{D_{h,tube}}$: the convective heat transfer coefficient between tube and circulating fluid (water)

$h_{cond_{tube-insulation}} = \dfrac{1}{\dfrac{\delta_{tube}}{\lambda_{tube}} + \dfrac{\delta_{insulation}}{\lambda_{insulation}}}$: conductive heat transfer coefficient between tube and insulation

The value of the Nusselt number Nu_{tube} depends on the Reynolds number Re as follows [48]:

$$Re < 2300 \Rightarrow Nu_{tube} = 4.364$$
$$Re > 2300 \Rightarrow Nu_{tube} = 0.023 \, Re^{0.8} \, Pr^{0.4}$$

The numerical values of the temperature and humidity show that the desired comfort is reached by the three proposed models under different climatic conditions.

Table 1 summarizes the design values and the effectiveness of the three technologies of solar AC systems investigated in the present chapter.

5. Comparative study of solar air-conditioning systems vs. traditional ones

From research studies reviewed in this chapter, we conclude that whatever the technology, solar AC systems have many environmental benefits compared with those that are driven by conventional vapor compression cycles. In fact, traditional AC systems operate with chlorofluorocarbons and hydrofluorocarbon refrigerants that impact on ozone depletion [49]. Hence, solar AC systems present an interesting solution to inhibit the harmful effects on the environment. It is observed that they significantly lower the emission of greenhouse gases into the atmosphere, achieve the desired comfort, and reach a considerable saving of energy of up to 80%. They also can be installed in all regions and operating under all climatic conditions. On the other hand, the solar air-conditioning can effectively mitigate peak load pressures occurred with the use of conventional air conditioners, thanks to the heat storage process. Indeed, the heat is especially stored when the solar irradiance is high and can be after harnessed when the solar radiation becomes deficient [50]. This fact ensures the continuous operation of the solar AC systems. In terms of COP, the thermal COP of a solar AC system is generally lower than those of a conventional AC system without decreasing the solar system performance. All these benefits make solar AC systems attractive and extensively integrated into modern buildings. This comparative study is illustrated in the following **Table 2**.

		Solar air-conditioning systems	Conventional air-conditioning systems
Designs of installations		Complex installations and new components are added to them according to the technology adopted (solar collectors, boiler, absorber, adsorber, generator, desiccant bed, rotary wheel and so on).	Simple installations based on the vapor compression cycles
Costs		Maintenance is frequent and expensive, especially for the desiccant AC systems. - 924 €/m² of the solar collector (for solar absorption AC systems). - Up to $ 29.022 that can be paid back after 13 years (for solar adsorption AC systems). - Gas price up to 0.5638 $/kg can be paid after 11–17 years (for solar desiccant AC systems).	Low costs
Effectiveness	COP	Low COP (according to the technology of the solar AC system)	High COP
	Environmental benefits	Use lower temperature heat source	Use harmful refrigerants
		Continuous operation of the solar AC systems	Depend on a supply of electricity
		Driven by an exhausted clean energy resource (solar)	Driven by a vapor compression cycle
		Reduce the CO_2 emissions into the atmosphere	Contribute to the global warming
		Can be installed in regions where the electricity is unavailable (desert, etc.)	Impact on ozone depletion
		Reduce the energy consumption	High energy consumption

Table 2. Advantages and disadvantages of solar AC systems compared with conventional AC ones.

6. Conclusions

The solar AC systems reported in this chapter present an interesting worldwide solution to reduce the harmful effects (high energy consumption and pollution) of traditional AC systems. In fact, research studies revealed that absorption, adsorption, and desiccant systems allowed saving energy up to 80, 50, and 52%, respectively, thanks to the optimization of their designs at the level of using environmentally unfriendly refrigerants, investing in the free and clean solar energy to power them, as well as at the level of the choice of the components that comprise them. Therefore, these systems also reduced the pollution rate

up to 95% (about 3000 kg of CO_2), especially the absorption systems. In addition, their use is remarkably suitable in rural regions where the electricity is not available or its shortage is frequent. Some solar AC systems are also equipped with chilled or hot water tanks, which can be used in various activities (household, agricultural, and so on). However, their coefficient of performance is lower than 1 in most cases compared with the traditional AC systems that their coefficient can reach the value 3. Moreover, the installation and maintenance costs of the most solar AC systems are relatively high. They can reach up to $ 29.000 and be paid back after at least 9 years. Hence, we can reach a long-term sustainability. Nonetheless, the design of these systems, especially adsorption and desiccant AC systems, is complex.

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