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INTERNATIONAL INSTITUTE OF REFRIGERATION

SOLAR COOLING

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“ In countries with good insolation, photovoltaic solar cooling can compete directly with conventional cooling systems. ”

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Summary

Solar cooling is a promising and environmentally friendly technology that can help meet the growing global demand for space cooling.

Solar cooling can be achieved by various technologies. The two main commercial options are photovoltaic (PV)-driven vapour compression chillers and heat-driven cooling machines powered by solar collectors.

Thermal cooling equipment can be coupled with various types of solar collectors with different efficiencies and costs.

Overall system efficiencies of PV-driven and solar thermal-driven plants may not have such different values.

Economic analysis indicates that the investment cost for the PV solution is at least half that of other systems.

Solar cooling may have a very positive environmental impact by reducing the use of fossil fuels, and the technology may be considered mature to compete with conventional cooling equipment.

This Informatory Note is an update of a previous version published in April 2017. It was prepared by Renato Lazzarin (President of IIR

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Introduction

Space heating and cooling account for a large proportion of global energy demand. While the energy demand for space heating is currently greater than the energy required for space cooling, there are several reasons to expect a decrease in the heating demand and an increase in space cooling demand:

- Economic growth in developing countries results in higher comfort standards and an increased demand for space cooling.
- It is easier to insulate a building from outside cold conditions, while it is more difficult to limit incoming solar radiation, particularly for a building largely made of glass.
- The increasing use of electrical appliances in homes and offices and other plug loads increase internal gains.
- Global warming must also be considered.

The IEA predicts that energy consumption for space cooling will increase threefold over the next 30 years, "requiring new electrical capacity equal to the combined electrical capacity of the US, EU and Japan today" by 2050 [1]. In fact, the global electrical capacity needed to meet these space cooling demands is expected to increase from 850 GW in 2016 to 3350 GW in 2050.

Since cooling demand depends on the intensity of solar radiation, it is not surprising that many studies have been devoted to solar cooling since the first energy crisis in 1973. Some pilot plants were quickly built and tested, and various solar cooling technologies were developed.

A solar cooling system consists of a part devoted to collecting solar radiation (the solar section) and converting it into heat or electricity, and equipment that uses heat or electricity to produce cooling. Thus, the development of solar cooling systems is strictly linked to improving the efficiency and reducing the costs of the solar section. The rapid improvement of solar thermal collectors initially favoured heat-driven cooling equipment, whereas the enhanced efficiency and impressive cost reduction of photovoltaic cells now tend to favour electrically driven cooling equipment.

For a good understanding of the current situation and prospects, a review of the main alternative routes from solar energy to cooling is presented.

Passive solar cooling technologies are not included in this presentation. These technologies include the effects of evaporative cooling, natural ventilation, and other heat dissipation techniques, as well as solar and thermal control and heat damping.

Passive solar cooling should always be considered when designing or refurbishing a building.

The solar section

The solar section, often referred to as solar array, consists of various solar panels, and is composed of either photovoltaic (PV) panels or thermal solar collectors.

PV PANELS

Today, PV modules are mainly based on mono-crystalline or multi-crystalline silicon cells. A small niche market is served by the so-called "second" and "third generation" systems, which respectively use a thin film (mainly amorphous silicon) and advanced thin-film technologies such as CIS (copper indium selenide) or CdTe (cadmium telluride). These are certainly potential applications in the near future.

A PV module is made of various PV cells connected in series. Its efficiency is defined as the ratio between the electrical energy produced and the impinging solar radiation in the same period of time, so that either instantaneous, daily, monthly or even longer-term efficiency may be calculated. The efficiency of PV modules ranges between 13 and 17% under standard conditions (1000 Wm^{-2} solar radiation intensity, 25°C cell temperature). The cell temperature must be specified because the efficiency is negatively influenced by higher temperatures, particularly for silicon cells, i.e. the efficiency decreases on hot, sunny days.

Over the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from around 12% to 17%, even reaching 21% for the most efficient modules. Monocrystalline silicon modules have reached a laboratory efficiency of over 24%, which is the likely target for commercial PV in the coming years [2] while their cost has been steadily decreasing, with a dramatic reduction over the last ten years. The cost is usually formulated in € or $ Wp^{-1}, where Wp stands for watt of peak power, i.e. the peak radiation intensity of 1000 Wm^{-2} under standard conditions. The coupling of increased efficiency and cost reduction has decreased the cost from about €5 Wp^{-1} in 2005 to €3 in 2010, €1.5 in 2015 and €1.0 in 2020. A PV plant requires other components than solar panels: the most important is the Balance of System (BOS), which comprises an inverter whose main task is to convert the variable direct current (DC) output of the panels into alternate current (AC). The cost of the BOS can reach approximately 10-20% of the cost of the PV modules, a larger fraction for smaller plants.

SOLAR THERMAL COLLECTORS

The solar collector is the device that converts solar radiation into thermal energy. We will only deal here with liquid solar collectors, i.e. collectors that heat water, which is often mixed with an antifreeze additive.

Solar collectors can be either fixed (these are the most common) or tracking, i.e. collectors that follow the sun in order to optimise the angle of the sun's rays with the collector and that usually concentrate the sun's rays on a focal point or line.

The most widespread type of fixed collector is the flat plate collector, in which solar energy is absorbed by a channelled metal plate (Figure 1). Thermal energy is produced at temperatures that can exceed 80-90°C. The difference in temperature with the ambient gives rise to thermal losses tempered by one or more transparent shields usually made of glass, by a reasonable insulant thickness at the back and side of the collector (7-10 cm) and using a selective coating on the absorbing plate (selective here means that the surface is highly absorbent for low wavelengths, i.e. where most solar radiation is found, and highly reflective, then low emissive, in the infrared, i.e. wavelengths of most radiation of thermal losses.

Figure 1:

A picture of plate collectors (FTP)

For higher operating temperatures, Evacuated Tubular Collectors (ETCs) have been designed, in which convective losses are eliminated by the vacuum between the plate (selective coating) and the glass whose specific tubular shape can withstand the atmospheric pressure (Figure 2).

Figure 2

A picture of an evacuated tubular collector (ETC)

All these collectors are installed at a fixed tilt that optimises performance for a specified period: for summer use, a tilt equal to latitude Φ minus 10° can be considered optimal.

The performance of solar collectors depends on:

- Average temperature t_m of the fluid inside the collector [°C];
- Outside air temperature t_a [°C];
- Solar radiation intensity, I_β [W m^{-2}].

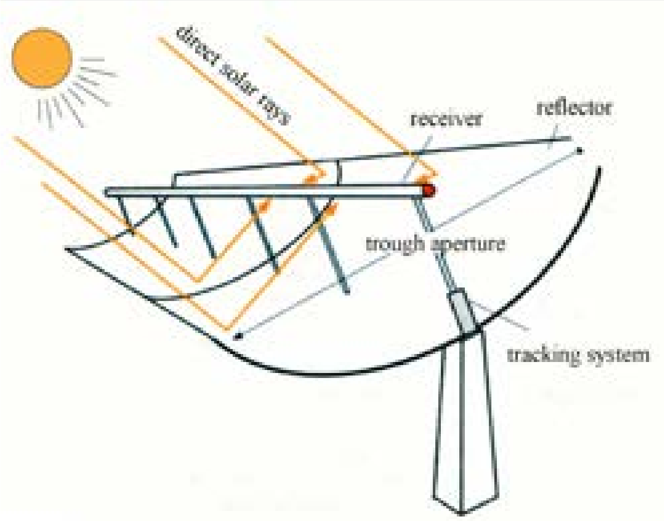
The thermal efficiency of the collector is defined as the ratio between the collected useful thermal power Qu and the impinging solar radiation in the same time period (Ac is the area of the collector):

$$\eta = \frac{\int \frac{Q_u}{A_c} \mathrm{d}t}{\int I_\beta \mathrm{d}t}$$

Although other technologies for fixed solar collectors are available, such as honeycomb or Compound Parabolic Concentrators (CPC), only selective flat-plate (FPC) and ETC will be considered, as they are by far the most common. Similarly, various tracking collectors might be considered, but the most common technology at present is the Parabolic Trough Concentrator (PTC). In a PTC, a reflector focuses direct solar radiation parallel to the collector axis onto the receiver placed on the focal line (Figure 3). The collector is equipped with a single-axis solar tracking system, usually with E-W tracking.

Figure 3

A shematic of a parabolic trough collector (PTC)



A technology based on Fresnel's reflective optics has recently become available on the market. These special reflectors concentrate sunlight into a common focal point where a receiver heats a fluid to a temperature of up to 200°C. This collector mainly exploits direct solar radiation, just as the PTC, with similar collector efficiency and costs; it can then share the PTC evaluation.

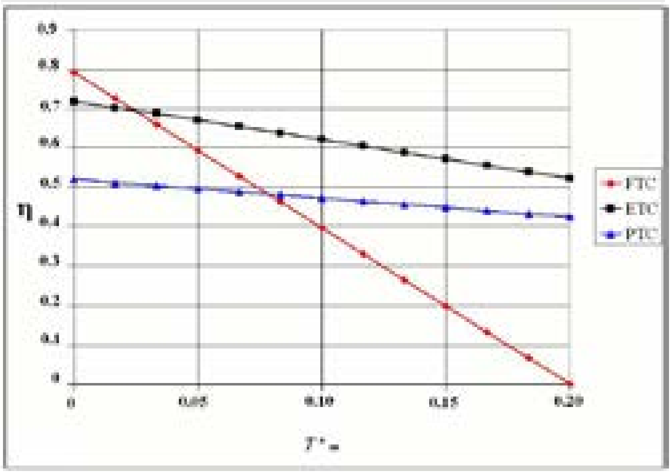
Equations are available to describe the behaviour of the above collectors, but for our purposes it is preferable to represent the efficiency as a function of a variable T_m*, which comprises the difference between the average temperature of the fluid in the collector and the ambient temperature divided by the solar radiation intensity [3]:

$$T^*_m = \frac{t_m - t_a}{I_\beta} \qquad t_m = t_{in} + \frac{\Delta T}{2}$$

Three possible efficiency curves are presented in Figure 4 for FPC, ETC and PTC. The figure assumes a 25% fraction of diffuse radiation (diffuse radiation is solar radiation not coming directly from the sun; it can be a 15% fraction of the total solar radiation for a very clear sky, even reaching 100% on extremely overcast days). The diffuse fraction of solar radiation is frequently evaluated as a function of the clearness index K_h, i.e. the ratio between the daily solar radiation impinging onto a horizontal surface and the corresponding radiation out of the atmosphere. The clearness index on a daily basis can range from 0.25 (overcast sky) to 0.75 (very clear sky).

Figure 4

Efficiency curves of the three typologies of considered solar collectors:
FPC- Flat Plate (selective) Collector,
ETC - Evacuated Tube Collector,
PTC- Parabolic Trough Collector.



It can be observed that FPCs are more influenced by the operating temperature, while ETCs and PTCs have a lower slope, so that they retain appreciable efficiency even when FPC is no longer able to collect useful energy. The starting efficiency at zero abscissa (e.g. for an operating temperature equal to ambient) shows a lower transparency of the ETC and the inability of the PTC to make full use of diffuse radiation.

The costs of solar thermal collectors vary greatly, not only in terms of technology, but also in terms of size of the plant or the purchaser negotiation power. Another influential parameter is the cost of the installation. An approximate cost can reach €200 m^{-2} for FPC, 450 for ETC and 350 for PTC. The above costs were found in list prices at 40% discount and for collectors installed in developed countries. Costs up to 50% lower or even more can be encountered in developing countries. However, the Purchasing Power Parity (PPP) criterion should be used, i.e. the cost should be compared with the per capita income in these countries. More than instantaneous efficiency, daily efficiency is an appropriate parameter for a technological comparison.

As regards PV systems, the most widespread technology on the market is the mono or polycrystalline silicon cell with a reference efficiency of 15%. The instantaneous efficiency depends mainly on the cell temperature, so the cell temperature must be evaluated at various times of the day. The inverter efficiency must also be considered when estimating the electricity produced on a typical summer day. A 90% inverter efficiency value is probably a conservative evaluation, as a reliable forecast for the near future is at levels above 95%. The actual cost is estimated at around 1,100 €/kWp for rooftop systems in Germany in the range of 10 to 100 kWp. The cost also includes the BOS [2].

On a sunny day with a solar radiation of 7.6 $kWhm^{-2}$ on a horizontal surface, the electricity produced may exceed 0.90 $kWhm^{-2}day^{-1}$ with a daily efficiency of about 12%, which is lower than the reference efficiency of 15% due to inverter losses and the reduction in the hottest hours when solar radiation intensity is higher.

To evaluate the useful energy collected by the solar thermal panels, the operating temperatures must be specified because of their strong influence on the efficiency. Three operating temperatures have been selected, that is 70°C, 90°C and 160°C. Table I reports the daily useful energy collected by the

Table 1

Daily useful energy collected ($kWhm^{-2}day^{-1}$) by the different collectors at the three considered working temperatures; inside brackets daily efficiency.

Operating temperature	Flat -plate Collector	Evacuated Tubular Collector	Parabolic Trough Collector
70°C	*3.59 (47%)*	*4.47 (59%)*	*2.99 (39%)*
90°C	*2.88 (38%)*	*4.26 (56%)*	*2.89 (38%)*
160°C	*0.86 (11%)*	*3.51 (46%)*	*2.52 (33%)*

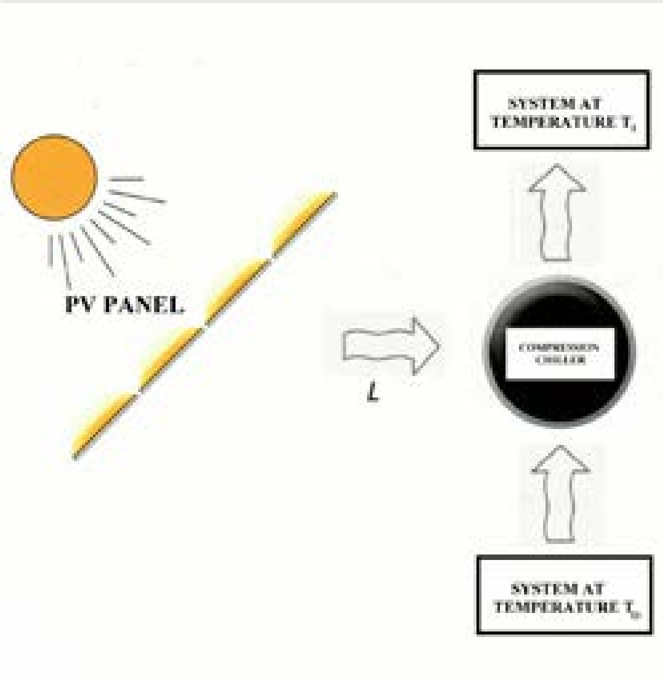
three different collectors at the three operating temperatures on the previously considered sunny day for the PV panels (in brackets, the daily efficiency).

PV-Driven cooling equipment

A wide variety of solar-powered cooling techniques are available. The most obvious option for PV-driven systems is vapour compression, which is very similar to conventional refrigeration equipment, with the compression eventually driven by a DC motor (Figure 5). As it is well known, in a vapour compression system, a refrigerant evaporates at a pressure allowing to produce the cooling effect, then a compressor brings the vapour to a higher pressure so that it can condense at a higher temperature than that of an ambient sink, and finally the condensate returns to the evaporator through a throttling valve.

Figure 5

Schematic of a PV panel that drives a compression chiller



The performance of the system is usually given by the COP (Coefficient of Performance), calculated as follows:

$$\mathrm{COP} = \frac{q_0}{E}$$

where q_0 is the usable cooling energy and E is the energy (electricity) consumed by the system.

The COP depends on many variables such as the characteristics of the equipment, the temperature of the produced cold and that of the heat sink (evaporator and condenser temperatures). Nowadays, air-conditioning equipment can have a COP of 3 if air-cooled and 4 if cooled by a cooling tower. Enhanced performance can be achieved through newly developed machines, but their cost is now much higher than the conventional option. These high-performance machines can exceed a COP of 4 (air-cooled) and 5-6 (water-cooled) respectively.

Solar thermal-driven equipment

Solar thermal-driven equipment offers a wide variety of options. Apart from the fact that solar heat can power direct cycle machines such as Stirling or Rankine engines, which in turn drive a vapour compression cycle, many different systems exploit the ability of a substance to extract refrigerant vapour from an evaporator, where the cooling effect is produced just as in the conventional vapour compression cycle. The direct cycle option turned out to be expensive and inefficient for plants of suitable size for building air conditioning, as it requires the concentration of solar collectors and high temperatures (up to 400°C or more) to achieve acceptable efficiency.

Most studies and experiments are devoted to sorption refrigeration. Sorption refrigeration uses the physical or chemical attraction between a pair of substances to produce a refrigeration effect. Two types of sorption processes exist. Adsorption and absorption: adsorption is the bonding of a gas or other material on the surface of a solid; in the absorption process, a liquid solution is formed from the absorbent and working fluids.

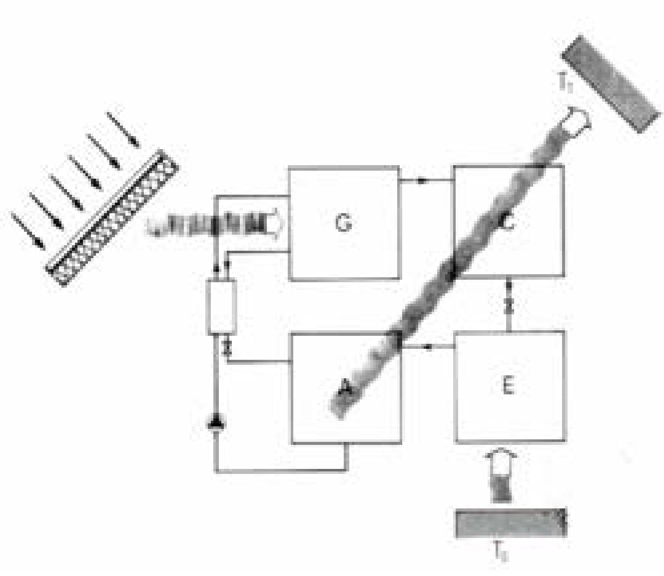
The sorption process can operate in a closed cycle where a thermally driven chiller produces chilled water for use in space-conditioning equipment, but also in open cycles where dehumidification of recirculated or outside air by a desiccant in a sorption process is followed by an evaporative cooling that allows for direct treatment of air in a ventilation system.

CLOSED-CYCLE SORPTION EQUIPMENT

Many years before the 1973 energy crisis, thermally driven cooling equipment (directly fired or using hot water or steam) was commercially available, working with the H_2O - lithium bromide (LiBr) and NH_3 - H_2O pairs. In the first pair, the refrigerant is water, and the sorbent is an aqueous solution of LiBr, while in the second pair, ammonia is the refrigerant, and the aqueous ammonia solution is the sorbent. The operating principle is the sorption of the refrigerant out of the evaporator into a vessel called absorber. A low power pump transports the refrigerant and sorbent mixture into a vessel at a higher pressure (generator). Here, heat separates some of the refrigerant from the mixture, so that the mixture can return regenerated to the absorber, thus closing the cycle of the sorbent. The refrigerant vapour from the generator is condensed in a heat exchanger cooled by ambient air or tower water, so that the liquid refrigerant can return to the evaporator, closing the refrigerant cycle (Figure 6). The absorber-pump-generator combination works as a thermally driven compressor since the low-pressure refrigerant vapour is finally desorbed at the higher pressure of the generator. In this process, cooling must be supplied to the condenser as in conventional cooling equipment, but also to the absorber where the sorption process is exothermic with a heat development slightly higher than the heat of vaporisation of the absorbed refrigerant.

Figure 6

Schematic of a thermal solar collector that drives a sorption chiller



Later, the adsorption process was also used in thermally driven cooling equipment. Adsorbents (zeolite, silica gel, activated carbon or alumina) can capture and retain refrigerants coming from an evaporator. The process terminates when the adsorbent is saturated; it must then be regenerated by heating. Vapour desorbed at a higher pressure can be condensed as in the above-mentioned process, by returning to the evaporator. For continuous operation, as opposed to intermittent apparatus, at least two adsorbent beds must be provided.

The performances of all these thermally driven machines are expressed by a COP, which this time is the ratio between the cooling effect and the heat supplied to the generator (the work of the pump is often neglected as it usually represents only a small fraction of the energy supplied to the generator):

$$COP_{th} = \frac{q_0}{q_g}$$

COP_{th} depends on the equipment, the temperature of the heat supplied to the generator, the temperature of the absorber and condenser and of course, the temperature of the chilled water produced. Solar cooling plants usually produce chilled water at 7-10°C, suitable for normal use in buildings, using fan-coils. However, it is also possible to produce chilled water at higher temperatures (e.g. 12 or 15°C), which increases not only the efficiency (COP) but also the cooling capacity of the sorption chiller. This choice can make air dehumidification difficult.

For air conditioning applications, H_2O - LiBr and adsorption equipment should be cooled by tower water: air cooling might prevent the equipment from operating at outside temperatures above 35°C. H_2O - LiBr machines require a generator temperature of 85-90°C, which gives a COP of about 0.8, whereas adsorption chillers can operate even at only 70°C but with a COP as low as 0.4. Double-effect H_2O - LiBr chillers are available where the heat of condensation at a higher temperature can be used for a further desorption of the mixture. The COP can reach 1.2, but the heat supplied to the high-pressure generator must be at a temperature of about 160°C.

NH_3 - H_2O equipment has the advantage that it can be air cooled and can produce a cooling effect below 0°C. However, even in the most efficient version (GAX), the COP is as low as 0.6 and the heat must be supplied at 140-160°C.

Recent developments and advances in com--mercially available absorption chiller technologies have been presented and discussed[4]. Regarding solar cooling, a small capacity absorption chiller has recently been commercialised. The novelty is that the chiller is air-cooled even if it operates with the H_2O - LiBr mixture. The cooling capacity is only 2.5 kW at a 35°C outside temperature (chilled water at 13°C). However, not enough reliable information on the operations and performance are at the moment available.

As regards the equipment cost for cooling capacity in the range of air conditioning in small buildings (10-50 kW), a specific value of €300 kW^{-1} can be assumed for a conventional vapour compression chiller, 400 for a single-effect absorption chiller (LiBr-H_2O or H_2O-NH_3), 500 for an adsorption chiller and 550 for a double-effect absorption chiller [5].

OPEN CYCLE SORPTION EQUIPMENT

Open-cycle sorption cooling can operate with a liquid or solid phase desiccant. The most commonly used operating mode is the so-called ventilation mode, where only fresh air is treated by the plant. An air stream from the outside is dehumidified by a desiccant: the stream is now hot and dry and is cooled down by the return air from the conditioned space, which is first cooled by direct evaporation of water. The return air, now warm and humid, is further heated by solar heat so that it can regenerate the desiccant. The outside air, cooled down in the heat exchanger by the return air, can be supplied directly to the conditioned space as dry air, or can be cooled down by suitable evaporative cooling. There are many different schemes, and some systems are commercially available.

Figure 7 illustrates a possible scheme operating with a solid-desiccant dehumidification wheel, a rotary heat exchanger and evaporative coolers; desiccant regeneration is produced by a heating coil powered by a solar collector.

It is difficult to compare the performance of these systems with that of closed-cycle equipment. Open-cycle sorption does not produce chilled water but treats ventilation air directly. It requires an all-air system and usually cannot be applied in the refurbishment of existing buildings unless they are equipped with an all-air system. As such, it will not be compared to the technologies described above.

In new buildings with a high ventilation or dehumidification demand, open-cycle sorption cooling powered by solar thermal collectors should be considered as a possible option, with performances close to those of closed-cycle equipment but with the advantage of providing a direct treatment of the ventilation air.

Other physical principles can be exploited to produce solar cooling using either PV electricity such as thermoelectric, thermoacoustic or magnetic refrigeration, or solar thermal such as

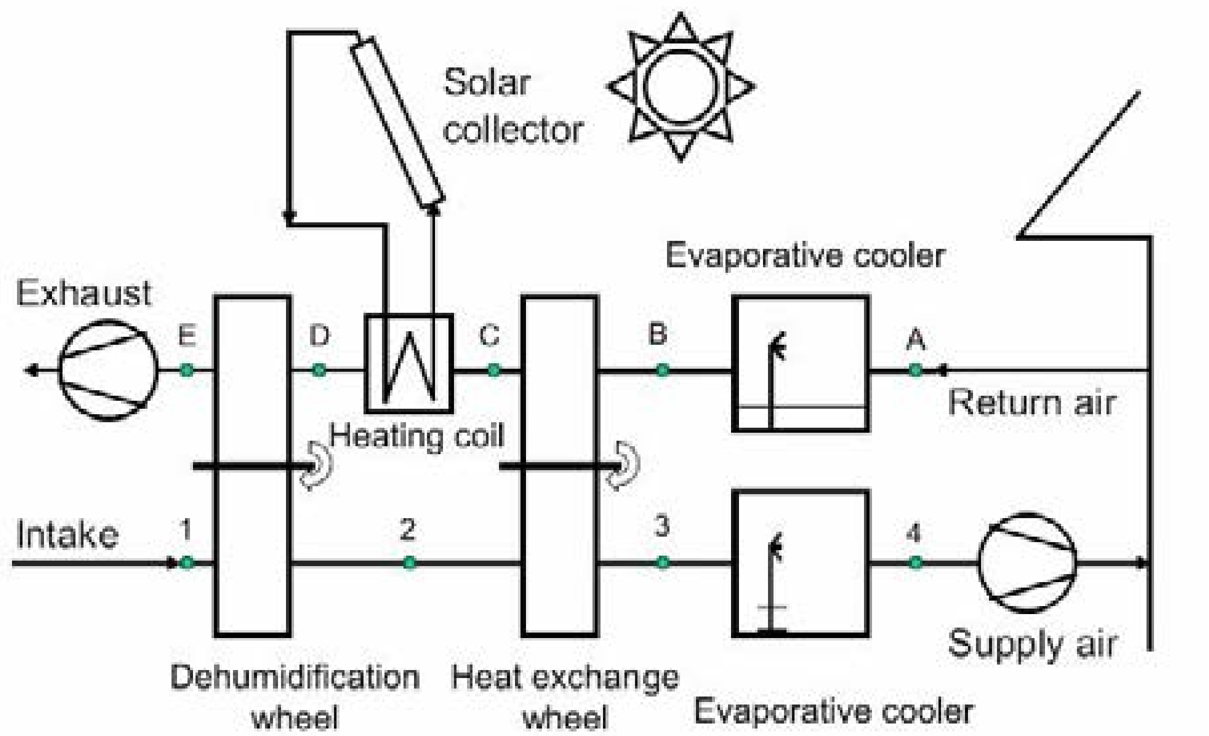
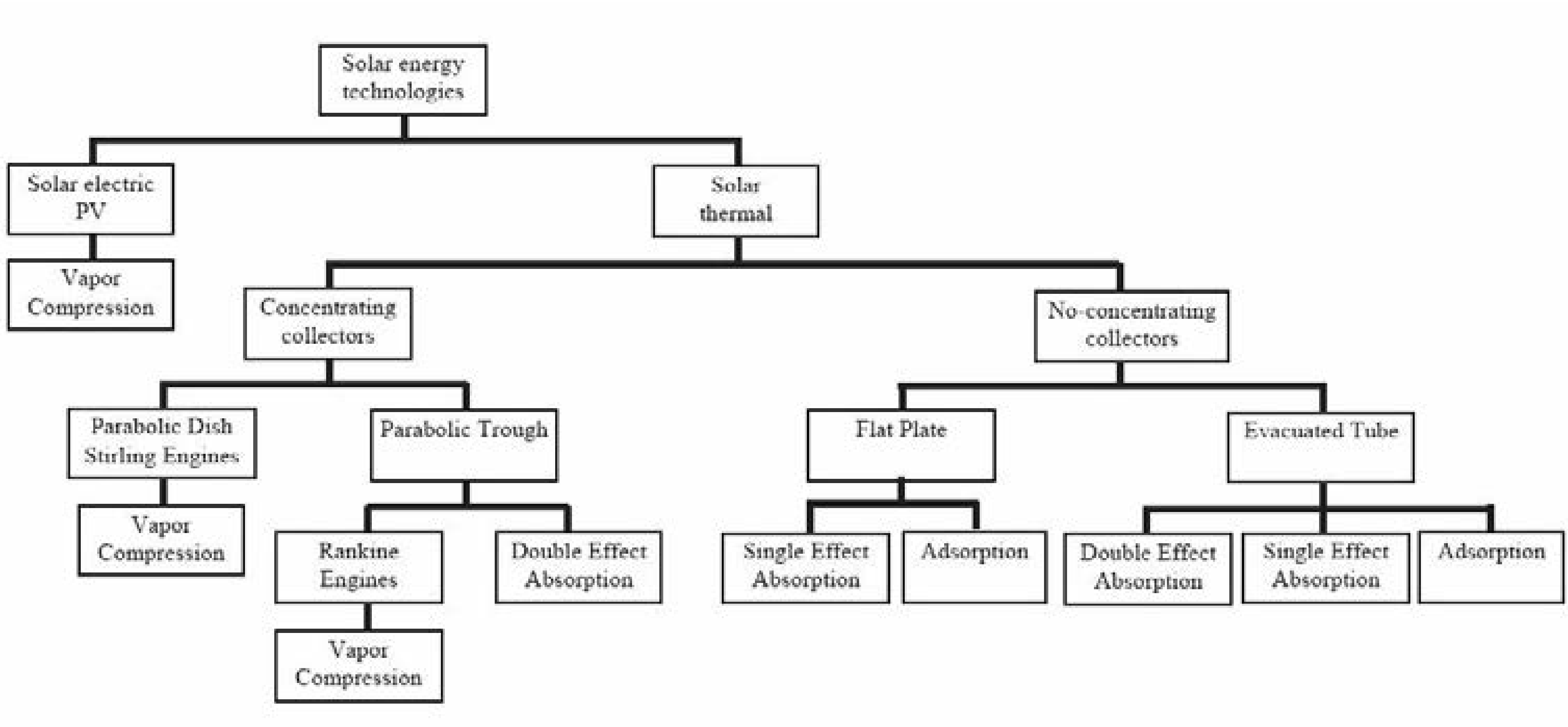


Figure 7

Schematic of a solid desiccantSchematic of a solid desiccant cooling system with solar collectors for dessiccant wheel regeneration

Figure 8

Alternatiive routes from solar energy into cooling effect



ejector systems. All these technologies are under development and very few or no equipment is commercially available.

The previously described alternative routes from solar energy to cooling effect are shown in Figure 8, where only open-cycle sorption is missing.

The overall efficiency

A thermodynamic evaluation of a solar cooling system can be obtained through the Overall System Efficiency (OSE), defined as the ratio between the specific cooling effect (q_o) and the incident solar radiation intensity (I_β) integrated over an appropriate period of time, e.g. one day or one month or the entire air-conditioning season.

For solar thermal cooling, the ratio can be correlated with the performance of the sorption chiller, characterised by the thermal COP_{th}, i.e. the ratio between the cooling effect and the thermal input to drive the chiller such that:

$$\mathrm{OSE} = \frac{q_0}{I_\beta} = \frac{q_0}{q_g}\frac{q_g}{I_\beta} = \mathrm{COP}_{th} \cdot \eta$$

For the PV solar cooling systems:

$$\mathrm{OSE} = \frac{q_0}{I_\beta} = \frac{q_0}{E}\frac{E}{I_\beta} = \mathrm{COP} \cdot \eta$$

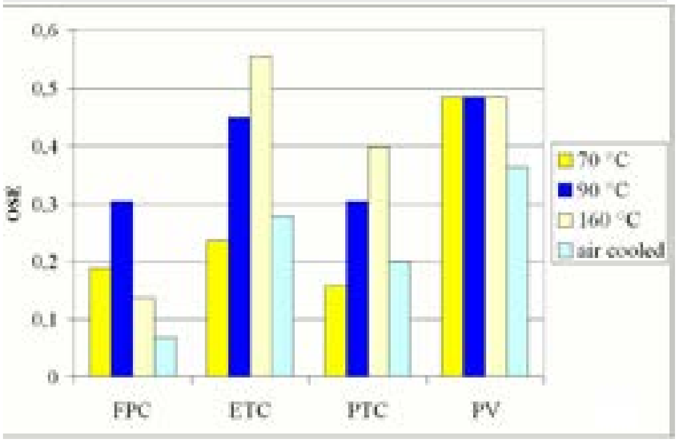
The subscript on COP is here to emphasise that it refers to thermal input while the latter refers to electricity. η is the efficiency of the thermal solar collector or that of the PV panel.

A first meaningful comparison can be made by evaluating the OSE of the various systems for an average summer day, which can be representative of the monthly performance. The insolation in the selected day can be characterised by the clearness index K_h, i.e., as indicated above, the ratio between the daily solar radiation impinging onto a horizontal surface and the corresponding radiation outside the atmosphere. Some numerical analyses have been carried out for a 0.65 clearness index K_h that can be representative of the climate of Rome in July. Let us consider that the index K_h is almost never higher than 0.75.

Figure 9 reports a selection of results for different systems (thermally or electrically driven), also including water- and air-cooled chillers. As far as air cooling of the condenser/absorber is considered, solar thermal only concerns ammonia-water GAX-cycle chillers, because most LiBr - H_2O systems require a water-cooling tower, as mentioned above.

Figure 9

Overall daily efficiency of the cooling system at the three temperatures of 70°C, 90°C, 160°C (adsorption, single effect absorption, double effect water-cooled) and 160°C air-cooled (ammonia water GAX) for the three considered solar collectors compared with traditional compression chiller driven by PV

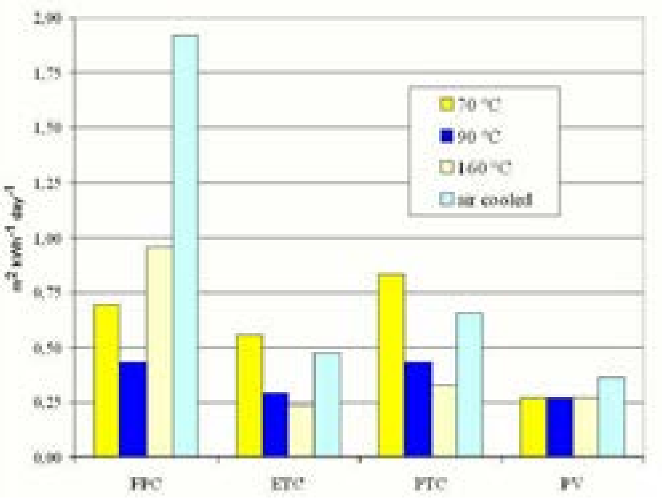


The highest OSE is achieved by ETC-driven double-effect systems; it can reach 55%, immediately followed by the PV-driven system which, if water-cooled, approaches 50%. According to the proposed evaluation, the low-temperature adsorption system offers a much lower OSE than the absorption system, as the improvement in solar collector efficiency due to the lower temperature does not compensate for the lower COP. Good performances are allowed by the ETC-driven single effect (45%) and the PTC-driven double effect (40%). While the OSE of thermally driven systems can be slightly higher than that of PV systems with water cooling, the air-cooled thermal systems are well below due to the combined effect of lower solar collector efficiency and low chiller COP. The OSE remains below 28% while PV systems can reach 36%.

Another possible comparison, similar to the one considered above, but more tangible, derives from the evaluation of the collecting surface area required to obtain 1 kWh of cooling on a summer day. The comparison is shown in Figure 10. A rough estimate for the best thermal systems is approximately 0.24-0.33 m^2 kWh^{-1} day-1 and 0.27-0.36 for the PV system.

Figure 10

Collecting area [m²] to produce 1kWh cooling effect on a sunny day (K_h=0.6) for the various considered systems



The parasitic energy that must be supplemented to the solar thermal systems is not included in the comparison. A very rough estimate is that the required collecting area should be increased by about 10% to account for the excess parasitic energy with respect to the PV system, with the penalty assessed in terms of primary energy. The pumps of the absorption chiller should also be taken into account for a correct comparison. Pumps are required not only to circulate the solution to be regenerated from the absorber to the generator, but also to circulate hot water to heat the generator and cooling water to cool down the absorber and the condenser. In principle, for small capacity machines (say up to 20 kW), no less than 300-900 W electricity should be considered with higher values for the double-effect and for the ammonia-water chiller. Careful design of the hydronic circuits is of paramount importance, as a poor sizing of tubes and fittings (e.g. valves) could give rise to an electricity demand of the same order as that of a conventional chiller, just to drive the pumps, as was recorded in some early pilot plants. In the case of a reasonable design, 3-7 kWh of electricity per day must be added to the electricity required for the solar collector circuit for a small cooling plant with a maximum capacity of 20 kW.

An economic analysis

High initial costs are common to many renewable energy installations. This is particularly the case of solar cooling plants. A full comparison of costs (investment and operating costs over the lifetime of the plant) would require specifying climate, utilisation and characteristics of the building, plant management, etc. A simplified economic analysis is here conducted only based on the investment cost for a solar air-conditioning installation for a small office building (10-50 kW cooling load).

An average clear summer day is considered (as before, a representative day of July in Rome with a clearness index of 0.65). To allow the results to be easily extended to different cooling capacity of the plant, the investment costs are evaluated in specific terms: an average cooling capacity of 1 kW is considered in operation for the 10 hours of opening of the commercial sectors (shops or offices). Then, a daily cooling production of 10 kWh is supplied. The computation can be extended by simply multiplying the values provided here by the desired capacity.

With the appropriate sizing of the storage, the plant can supply the nominal engine capacity for 10 hours. In other words, the collecting area can provide the chiller with the energy required that day to produce 10 kWh of cooling.

Figure 11

Estimate of investment cost for a plant that offers 10kWh cooling on a sunny day for the difeerent considered technologies

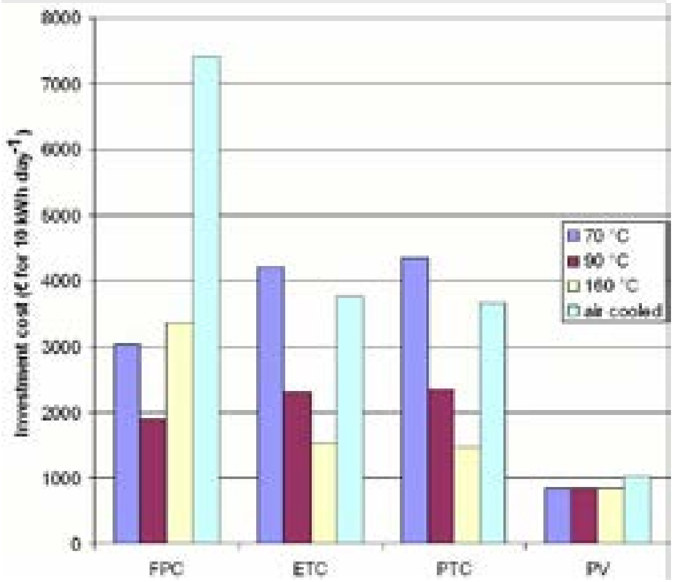


Figure 11 presents the evaluation taking into account the different computations that have just been developed. The figure shows the investment cost of the required collecting area and the chiller for a cooling of 10 kWh per summer day for the three different solar collectors and the four cooling technologies considered (adsorption at 70°C, single-effect absorption at 90°C, double-effect absorption at 160°C, GAX ammonia absorption at 160°C, (water-cooled – the first three values – and air cooled) and for PV solar cooling (water-cooled – the first bars – and air cooled – the other bar)(*)

The comparison with PV solar cooling is complicated by the need for storage for solar thermal systems. Indeed, not only hot storage must be provided, but even cold storage is suggested to limit the engine ON-OFF switching when the building cooling demand changes. In fact, many ON-OFF cycles can even halve the daily COP of small capacity absorption chillers. Moreover, for an absorption chiller with a COP inferior to 1, a cold storage for a similar temperature drop (usually in the range of 5 K) has proven to be smaller than a hot water storage and probably with less heat losses (in the case heat gains). The cost of a thermal storage can vary from 20 to 100 € kWh^{-1} [6]. The storage capacity to supply 1 kWh of cooling depends on the chiller's COP. For a single-effect absorption chiller, the capacity could be 1.25 kWh. As the useful temperature drop at the generator is about 5 K, the water content of the storage can be about 200 L kWh^{-1} of cooling. A smaller volume and higher performance can be achieved with Phase Change Material (PCM) storage, but the cost is also higher.

The dramatic reduction in the cost of PV panels over the last three years seems to eliminate any possibility of competition between solar thermal cooling and PV powered systems. The best alternatives to PV are double-effect chillers with ETC or PTC. However, the investment cost is about twice as high as for PV (€1064 or €1149 vs €746). Air-cooled chillers are too expensive if thermally driven, whereas an additional cost of 20% should be attributed to air coolers when PV driven.

Furthermore, to take into account the storage cost, an indicative additional cost of about €500 should be considered.

(*)To better clarify how the computation is carried out, let us consider a single-effect chiller, driven at 90°C by an ETC whose specific cost is estimated at 450 €m^{-2}. The specific cost of the chiller capacity is estimated at 400 € kW^{-1}. To obtain 10 kWh, 2.92 m^2 of collectors are required. In fact, for the average sunny day considered, the daily solar radiation on the collector is 7.6 $kWhm^{-2}day^{-1}$, the daily efficiency of such collectors being 56% and the OSE 45% (estimated COP=0.8), so that the specific area required is 0.292 $m^2kWh^{-1}day^{-1}$. The investment cost is therefore estimated at:2.92x450 + 400 = 1,714 € per 10 kWh day-1

The analysis for a PV-driven plant is quite similar. Its daily efficiency is estimated at 12%. Each kWh of electricity produces 4 kWh of cooling effect (COP = 4). The daily electrical energy can be evaluated at 7.6x0.12 = 0.91 $kWhm^{-2}day^{-1}$ with a cooling effect 4 times higher (3.65 $kWhm^{-2}day^{-1}$). Then the required PV area required is 10/3.65=2.74 m^2. The cost of the chiller cost is evaluated estimated at 300 €kW^{-1} and the total investment is (PV panel with inverter at 165 €m^{-2} – a PV area from 6 to 7 m^2 to reach 1 kWp): 2.7x165+300=746 € per 10 kWh day^{-1}

A careful comparison should also consider the need to equip the PV solar cooling system with a suitable battery storage, which is much more expensive than thermal storage. An estimate is of about 120 € kWh^{-1}. However, considering that 1 kWh of storage can produce about 3 kWh of cooling, the total cost would be of the same order as for a corresponding thermal storage. Another important fact to be considered is that PV systems are usually grid connected, so the grid usually supplies the storage service. To complete the picture, even solar thermal cooling is frequently grid connected, as it requires electricity for the various pumps (sometimes more than 1 kW). Of course, this electricity could be supplied by PV, but the analysis then turns out to be very complicated.

A fundamental parameter that must be carefully considered when planning a solar cooling plant is the f-fraction. This parameter is frequently used for other solar installations, such as solar heating of buildings or domestic water heating. The letter f stands for "free", i.e. the fraction of the cooling demand met by solar energy. In the usual design, the solar plant does not satisfy the whole demand. The plant is equipped with an auxiliary system, usually a conventional vapour compression chiller, or a boiler that feeds the absorption chiller for thermally driven systems, which operates when solar energy is insufficient due to low or no insolation and low storage capacity.

The choice of the right f-fraction depends on numerous parameters such as meteorological ones (solar radiation, temperatures during the cooling season), trend and amount of the building cooling demand, cost of conventional energy (grid electricity, natural gas or other fuels), cost of the solar section and storage, not forgetting economic parameters such as the discount rate.

Solar cooling development data

By the end of 2018, an estimated 1,800 solar cooling systems were installed worldwide. Most of them (around 70%) are located in Europe [7], mainly in Spain, Germany, Italy and Greece. The majority of installed solar thermal cooling systems is equipped with high-performance flat plate or evacuated tube collectors. The most commonly used solar thermal cooling technology in the world is by far absorption technology (72%), followed by adsorption (17%) and solid desiccant (10%) technologies. Liquid desiccant technology accounts for only 1% of total installations. Surprisingly, few PV-driven applications are now reported in the literature. The first combination of PV and air-conditioning dates back to 1993 [8], but the few studies carried out in the following years concerned only low-capacity stand-alone installations. An extensive literature research carried out in 2018 resulted in only two experimental works dealing with PV-powered air-conditioning devices tested for one year [9]. The very recent drop in the cost of PV cells suggests a rapid increase in these applications in the years to come. Recent studies evaluate the payback period of a PV-driven air conditioner to be less than 4 years in a favourable climate (hot summer and warm winter) [10]. The result is strongly bound to the electricity tariff with a convenience threshold set by some authors [9] at 0.15 €kWh^{-1}.

Environmental aspects

Solar cooling can have a very positive environmental impact by reducing the use of fossil fuels. The benefit can be assessed by the amount of CO_2 emissions avoided, which can reach about 0.5-1.0 kg CO_2 kWh^{-1} for grid electricity according to different mixes in electricity production for various countries. Then, for each kWh of cooling (COP=3) by solar, the amount of CO_2 avoided is in the range of 160-330 gCO_2. However, thermally driven solar cooling plants need to be supplemented by parasitic energy (pumps and fans). Parasitic energy could account for 10% of the renewable energy supplied, so that the cost of parasitic energy could be estimated at 50-100 gCO_2 per kWh for a single-effect absorption chiller. Moreover, the energy payback period (the time required to recover the energy needed to manufacture a device) should be evaluated both for PV panels and solar collectors. There has been much debate on these issues and no general agreement. However, to clarify expectations, the energy payback of PV panels is estimated between 1.5 and 3 years for silicon cells and less than 1 year for thin-film cells, depending on the climate (the greater the solar radiation, the shorter the payback period). Similar values can be considered for solar thermal collectors. Then the benefits must be evaluated over the lifetime of the plant, which can be in the order of 20 years.

An estimate depends on many variables such as the climate or the utilisation of the plant. A rough estimate could attribute between 100 and 200 $kWhm^{-2}$ of electricity production per year to a silicon PV panel. Then, over the lifetime, 2000 to 4000 $kWhm^{-2}$ would be produced at an energy cost of 150-300 kWh, i.e. with a net gain of 1700-3850 kWh, which means that 850 to 3850 $kgCO_2m^{-2}$ of CO_2 emissions would be avoided.

Conclusions

Several solar cooling technologies were discussed among the commercially available systems. Two main families were compared: solar thermal and PV driven.

A first comparison focuses on overall efficiency where, in some cases, thermally driven systems may be better than PV systems. In fact, ETC driving a double-effect absorption chiller allows an OSE of 55% while PV systems reach 48%. However, when the comparison focuses on investment costs, thermally driven systems are no longer competitive as the investment cost of a PV system is about half that of the best solar thermally driven alternative. The transition from quasi-parity of costs between the two system families in recent years [11] to the present situation can be attributed to the huge economies of scale for PV panels. So far, thermal solar panels have not benefitted from a similarly significant cost reduction in spite of a strong increase in production, although not to the same extent as that of PV panels.

The present update of the Informatory Note dated April 2017 records a cost reduction of 20% - 40% for solar collectors. The reduction in the cost of PV has been around 20% over the same period. For countries with good insolation, PV solar cooling can compete directly with conventional cooling systems. This result, coupled with a possible increase in the COP of vapour compression chillers with a COP as high as 5 or 6, seems to put an end to any competition with thermally driven solar cooling for good. However, mass production of ETC or PTC could reduce the cost to levels not far from that of FPC. Quasi-parity with current PV systems would then be possible, better if a similar cost reduction and/or performance improvement is achieved for absorption machinery.

Desiccant cooling was not included in the comparison. As mentioned above, this technology is suitable in buildings with an all-air system. In such buildings, desiccant cooling can offer excellent results both in terms of performance and cost when high ventilation rate and/or high latent loads are present, particularly in hot and dry climates.

Finally, solar thermal technology should be valued for the service provided throughout the year and also when cooling is not required. In fact, the solar thermal system can provide building heating and hot water. Similarly, PV systems should be evaluated when coupled with a heat pump for winter heating. The development and mass production of PV/T collectors, i.e. PV panels that provide electricity and heat at the same time, may offer entirely new and unexpected possibilities [12].

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IIR recommendations

Solar cooling can have a very positive environmental impact by reducing the use of fossil fuels and can be considered mature to compete with the conventional cooling equipment. Thus, the IIR emphasises the need to:

- Develop strong worldwide campaigns on the economic and environmental benefits of implementing solar cooling to raise awareness among potential users, policy makers and industry representatives.
- Train refrigeration professionals on solar cooling technologies by including specific courses in training programs and developing advanced modeling and simulation tools for designers and installers.
- Promote research on solar cooling technologies through funding.
- Support implementation of solar cooling at the national and international levels by providing subsidies to interested users, particularly those in developing countries.
- Set up incentive schemes to promote the use of solar cooling, e.g. tax exemptions for users of solar assisted cooling systems.

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