34th Informatory Note on Refrigeration Technologies / April 2017

Solar cooling

The IIR publishes Informatory Notes designed to meet the needs of decision-makers worldwide, on a regular basis. These notes summarize knowledge in key refrigeration-technology and refrigeration-application domains. Each note puts forward future priority developmental axes and provides IIR recommendations in this context.

Solar cooling is a promising, environmentally friendly technology that can help satisfy the increasing world demand for space cooling.

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

Thermally driven 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 have not so different values. The economic analysis indicates the investment cost for the PV solution to be at least half of the other systems.

Solar cooling may have a very positive environmental impact reducing the usage of fossil fuel, and the technology is almost mature to compete with conventional cooling equipment.

This Informatory Note was prepared by Renato Lazzarin, President of IIR Section E, with the assistance of the IIR head office, and was reviewed by several experts from the IIR network.

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Introduction

A large proportion of global energy demand is represented by space heating and cooling. Whereas the energy demand for space heating is currently greater than the energy required by space cooling, a number of reasons suggest a forecast of a decreasing demand for space heating and increasing for space cooling:

- the economic growth in developing countries results in higher comfort standards and a higher demand for space cooling;
- it is easier to insulate a building from outside cold conditions, while it is more difficult to limit the incoming solar radiation particularly for a building largely using glass;
- the increasing use of electric appliances in homes and offices and other plug loads increase internal gains;
- global warming must also be considered.
- IEA gives an energy use for space cooling of 3.5 EJ /y (exajoules, 10^{18}J) and forecasts a more than twice as high demand of 9 EJy^{-1} in 2050[1].

As the demand for cooling depends on solar radiation intensity, it is not surprising that many studies have been devoted to solar cooling since the first energy crisis of 1973. Some pilot plants were soon built and experimented with[2,3,4,5,6,7], and a variety of solar cooling technologies was developed.

A solar cooling system features a part devoted to collecting solar radiation (the solar section) and turning it into heat or electricity, and equipment that uses heat or electricity to produce cooling. Thus solar cooling systems development is strictly linked to the efficiency improvement and cost reduction of the solar section. The rapid improvement of thermal solar 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 proper 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 comprise cooling effects by evaporation, natural ventilation and other heat dissipation techniques together with solar and heat control and heat amortisation[8].

Passive solar cooling should always be considered in the design or in the refurbishment of 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

Nowadays PV modules are mainly based on single-crystalline or multi-crystalline silicon cells. A small niche market is served by the so called “second” and “third generation” systems, which use, respectively, 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 series connected together. Its efficiency is defined as the ratio of the electrical energy produced and the impinging solar radiation in the same period of time, so that an instantaneous efficiency may be calculated as well as a daily efficiency, or a monthly efficiency, and so on. The efficiency of PV modules ranges between 13 and 17% at 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.

PV module efficiency has been steadily increasing, and it is forecast to reach about 19% in 2020 and 21% in 2030[9]. At the same time, its cost has been continuously decreasing with a dramatic reduction in the last ten years. The cost is usually formulated in € or $ Wp^{-1}, where Wp stands for watt of peak power, that is for peak radiation intensity of 1000 Wm^{-2} at standard conditions. The coupling of increased efficiency and decreasing cost led from a cost of about 5€ Wp^{-1} in 2005 to 3€ in 2010 and 1.5€ in 2015. A PV plant requires some other components besides solar panels: the most important is the Balance of System (BOS) that 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 higher fraction for smaller plants.

Solar thermal collectors

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

Solar collectors can be fixed (they are the most common) or tracking, i.e. collectors that follow the sun so to optimise the angle of the solar ray with the collector and usually concentrate solar rays on a focus.

Figure 1: *A picture of flat plate collectors (FTP)*

The most widespread fixed collector is the flat-plate, in which solar energy is absorbed by a channelled metallic plate (figure 1). Thermal energy is produced at temperatures that can exceed 80-90 °C. The temperature difference 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 at the side of the collector (7-10 cm) and using a selective coating on the absorbing plate[10] (selective here means that the surface is strongly absorbent for low wavelength, i.e. where most solar energy radiation is, and highly reflective, and then low emissive, in the infrared, i.e. wavelengths of most radiation of thermal losses). For higher operative temperatures, Evacuated Tubular Collectors (ETC) were conceived where the convective losses are eliminated by vacuum between the plate (selective coated) and the glass with the characteristic tubular shape to withstand the pressure[11,12] (figure 2).

Figure 2: *A picture of an evacuated tubular collector (ETC)*

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

Solar collector performance 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}].

Thermal collector efficiency is defined as the ratio of useful thermal energy collected Q^u and impinging solar radiation in the same time period (A_c is the area of the collector):

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

Though 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. Likewise various tracking collectors might be considered, but actually the most common technology is the Parabolic Trough Concentrator (PTC)[13]. In a PTC a reflector focuses the direct solar radiation parallel to the collector axis onto the receiver placed on the focal line[14,15.16] (figure 3). The collector is equipped with a one-axis solar tracking system, usually with E-W tracking.

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

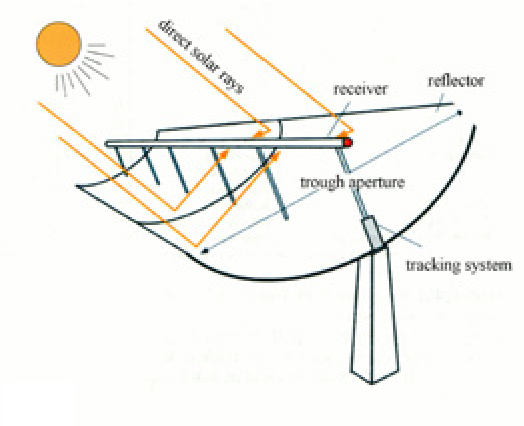

Figure 3: *A schematic of a parabolic trough collector (PTC)*

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^* that comprises the difference between the average temperature of the fluid in the collector and the ambient temperature divided by the solar radiation intensity[17]:

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

Three possible efficiency curves are presented in figure 4 for FPC, ETC and PTC. The figure assumes a 25% diffuse radiation fraction (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, reaching even 100% on extremely overcast days)[18]. 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 correspondent 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).

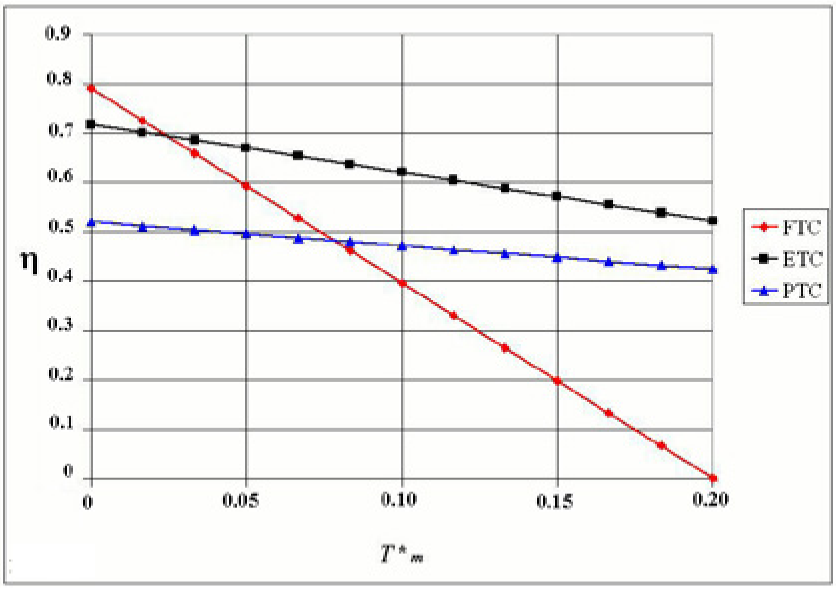

Figure 4: *Efficiency curves of the three typologies of considered solar collectors (FPC – Flat Plate (selective) Collector, ETC – Evacuated Tube Collector, PTC – Parabolic Trough Collector)*

It can be observed that FPC are more influenced by the operative temperature, while ETC and PTC have a lower slope of the efficiency curve, so that they keep an appreciable efficiency even when FPC is no longer able to collect useful energy. The starting efficiency at zero abscissa (say for an operative temperature equal to ambient) shows a lower transparency of ETC and the inability of PTC to exploit the most of diffuse radiation.

Solar thermal collectors have quite different costs, not only regarding the technology, but also the size of the plant or the purchaser negotiation strength. An approximate cost can reach 350€ m^{-2} for FPC, 650 for ETC and 450 for PTC. The above costs were found in list prices at 40% discount and for installed collectors in developed countries. Costs 50% lower can be encountered in developing countries. However, the Purchase Parity Power (PPP) criterion should be used, i.e. the cost should be compared with the per capita income in those countries. More than the instantaneous efficiency, a daily efficiency is a suitable parameter for a technology comparison.

As regards a PV system, the most widespread technology on the market is mono or polycrystalline silicon cell with a reference efficiency of 15%. The instantaneous efficiency is mainly dependent on the cell temperature so that at various times of a day the cell temperature must be evaluated. The inverter efficiency must also be considered to estimate the electricity produced on a typical summer day. A 90% inverter efficiency value is probably a conservative evaluation as a reliable forecasting for the near future is at levels higher than 95%.

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 around 12%, lower than the reference efficiency of 15% due to the 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 working temperatures must be specified because of their strong influence on the efficiency. Three working temperatures have been selected, that is 70 °C, 90 °C and 160 °C. Table 1 reports daily useful energy collected by the three different collectors at the three working temperatures on the sunny day previously considered for the PV panels (in brackets daily efficiency).

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

Working 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%)

PV driven cooling equipment

A wide variety of cooling techniques driven by solar energy are at hand[19,20,21]. The most obvious option for PV driven system is the vapour compression, 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 which allows to produce the cooling effect, then a compressor takes the vapour to a higher pressure so that it can condense at a temperature above that of an ambient sink, and finally the condensate returns to the evaporator through a throttling valve.

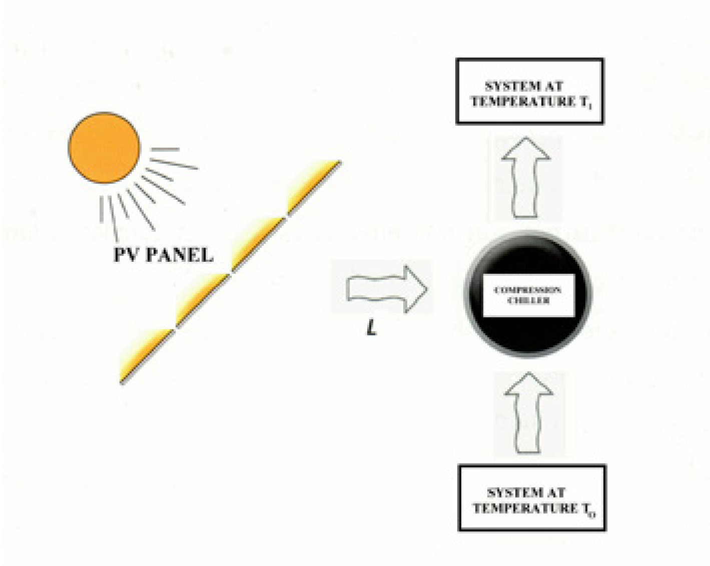

Figure 5: *Schematic of a PV panel that drives a compression chiller*

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

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

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

The COP depends on many variables such as characteristics of the equipment, temperature of the produced cold and that of the heat sink (evaporator and condenser temperatures). Nowadays, air conditioning equipment may have a COP of 3 if air-cooled and 4 if cooled by a cooling tower. Enhanced performance can be obtained by newly developed machines, but their cost is nowadays well higher than the conventional option. These high performance machines may exceed a COP respectively of 4 (air-cooled) and 5-6 (water-cooled)[22].

Solar thermal driven equipment

Solar thermal driven equipment offers a wide variety of possible 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 the 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 not particularly efficient for plant size suitable for building air conditioning, as it requires concentrating solar collectors and high temperatures (up to 400°C or more) to reach an acceptable efficiency[23].

The bulk of studies and experiments are devoted to the above mentioned effect, i.e. the extraction ability, designated as sorption refrigeration. Sorption refrigeration uses physical or chemical attraction between a pair of substances to produce refrigeration effect. Two types of sorption processes exist: adsorption and absorptio. 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.

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 a direct treatment of air in a ventilation system.

Closed cycle sorption equipment

Many years before the 1973 energy crisis thermally driven (directly fired or using hot water or steam) cooling equipment was commercially available, working with the two pairs H_2O-LiBr (lithium bromide) and NH_3-H_2O. In the former couple the refrigerant is water and the sorbent is an aqueous solution of LiBr whereas in the latter ammonia is the refrigerant and the aqueous solution of ammonia the sorbent. The operating principle is the sorption of the refrigerant out of the evaporator in a vessel called absorber. A pump with a small work takes the mixture of refrigerant and sorbent to a vessel at a higher pressure (generator). Here heat separates some refrigerant from the mixture, so that the mixture can go back regenerated to the absorber, closing the cycle of the sorbent. Refrigerant vapour from the generator is condensed in a heat exchanger cooled by ambient air or tower water, so that liquid refrigerant can go back to the evaporator closing the cycle of refrigerant (figure 6). The ensemble absorber-pump-generator functions 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 provided to the condenser as in the conventional cooling equipment, but also to the absorber where the process of sorption is exothermic with a heat development a bit greater than the heat of vaporisation of the absorbed refrigerant.

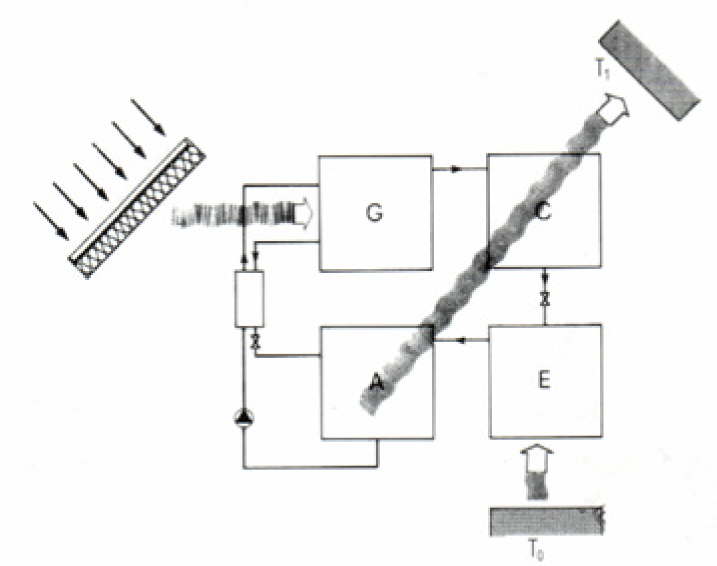

Figure 6: *Schematic of a thermal solar collector that drives a sorption chiller*

Later on also, the adsorption process was used in thermally driven cooling equipment[24,25,26,27]. Adsorbents (zeolite, silica gel, activated carbon or alumina) can catch and hold refrigerants coming from an evaporator. The process terminates when the adsorbent is saturated; then it must be regenerated by heating. The desorbed vapour at a higher pressure can be condensed as in the above mentioned process returning to the evaporator. For continuous operation, in the otherwise intermittent apparatus, at least two adsorbent beds must be provided.

Performances of all these thermally driven machines are expressed by a COP which this time is the ratio of the cooling effect (q_o) and the heat provided to the generator (q_g) (the work of the pump is often neglected as it is usually 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 usage in buildings through fan-coils. However, it is also possible to produce chilled water at higher temperatures (e.g. 12 or 15 °C) increasing 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 equipment operation at the outside air temperature over 35 °C. H_2O- LiBr machines need a generator temperature of 85-90 °C, giving a COP of about 0.8[28,29], when adsorption chillers can operate even at only 70 °C but with a COP as low as 0.4[30,31]. 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 arrive at 1.2 but the heat supplied to the high pressure generator must be at a temperature of about 160 °C.

NH3 - H2O equipment has the advantage that it can be air cooled and can produce a cooling effect below 0 °C. However, even in the highest efficient version (GAX) the COP is as low as 0.6 and heat must be supplied at 140-160 °C[32].

As far as the equipment cost is concerned for cooling capacity in the range of air conditioning of 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), 600 for an adsorption chiller and 700 for a double-effect absorption chiller.

Open cycle sorption equipment

Open cycle sorption cooling can operate either with a desiccant in liquid[33-44] or solid phase[45-49]. The most used operative mode is the so called ventilation mode that works with all fresh air. An air stream from the outside is dehumidified by a desiccant: the stream is now hot and dry and it is cooled down by the return air from the conditioned space that 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 directly supplied to the conditioned space as dry air or can be cooled down by a suitable evaporative cooling. Many different schemes are available 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.

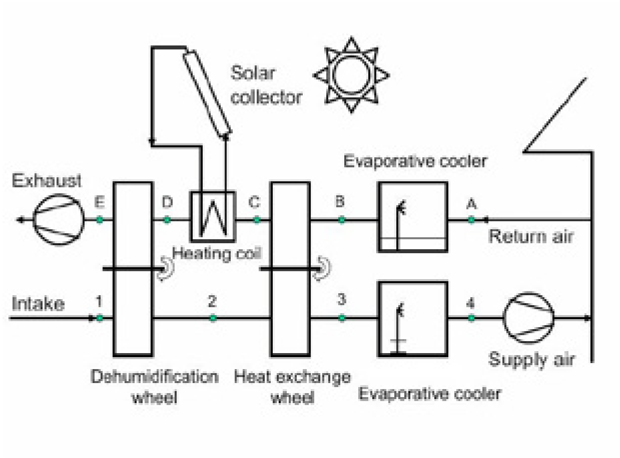

Figure 7: *Schematic of a solid desiccant cooling system with solar collectors for desiccant wheel regeneration*

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

In new buildings with a large ventilation or dehumidification demand, open cycle sorption cooling powered by thermal solar collectors should be considered as a possible option, with performance not far from closed cycle equipment but with the advantage of 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 thermal solar such as ejector systems[50]. All these technologies are under development and very few products or no equipment at all are commercially available.

The previously described alternative routes from solar energy into cooling effect are represented in figure 8 where only open cycle sorption is missing.

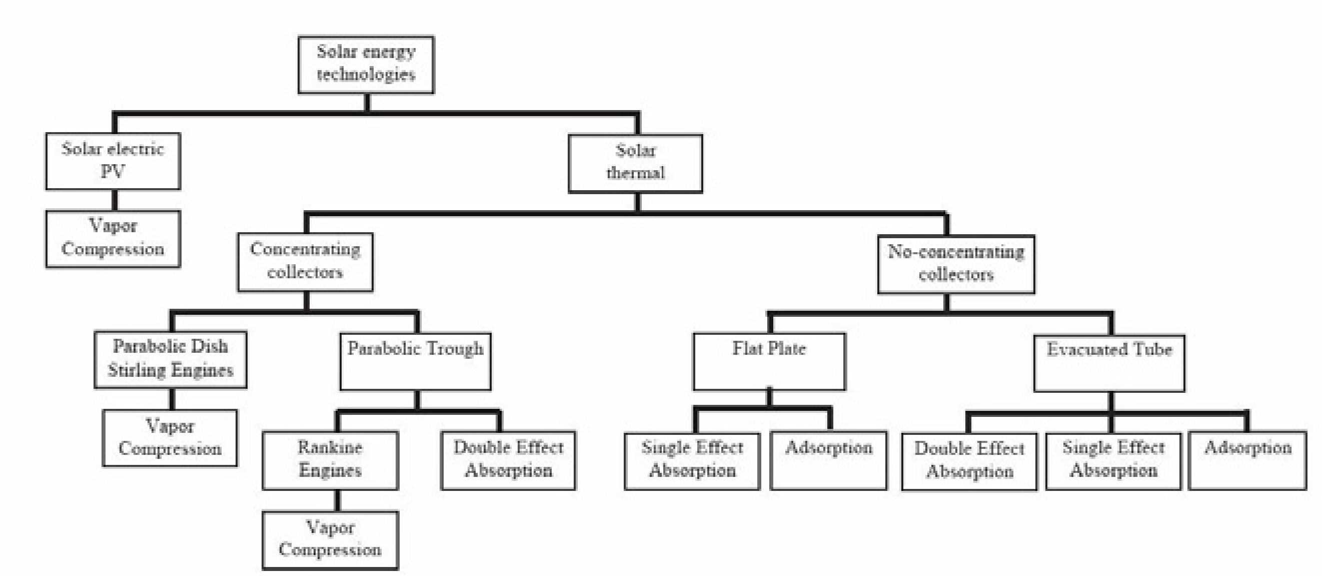

Figure 8: *Alternative routes from solar energy into cooling effect*

The overall efficiency

A thermodynamic evaluation of a solar cooling system can be obtained through the Overall System Efficiency (OSE), defined as the ratio of the specific cooling effect (q_o, i.e. the cooling effect produced by an unit area of solar section,) and the incident solar radiation intensity (I_β, i.e the solar radiation impinging on a unit area of solar section) integrated for a suitable time period, for example one day or one month or the whole air conditioning season.

For solar thermal cooling the ratio can be correlated with the sorption chiller performance, characterised by the thermal COP_{th}, i.e. the ratio between the cooling effect and the thermal input to drive the chiller (q_g, that is the thermal energy supplied by the solar section), so 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 wants to emphasise that it refers to a thermal input whereas the latter to electricity. η is respectively the efficiency of the thermal solar collector or of the PV panel.

A first significant comparison can be carried out by evaluating the OSE for the various systems on an average summer day that can be representative of monthly performance. The insolation in the selected day can be characterised by the clearness index K_h, i.e., as above specified, the ratio between the daily solar radiation impinging onto a horizontal surface and the correspondent radiation out of the atmosphere. Some numerical analyses were carried out for a 0.65 clearness index K_h that can be representative for the climate of Rome in July. Consider that the index K_h is almost never higher than 0.75.

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

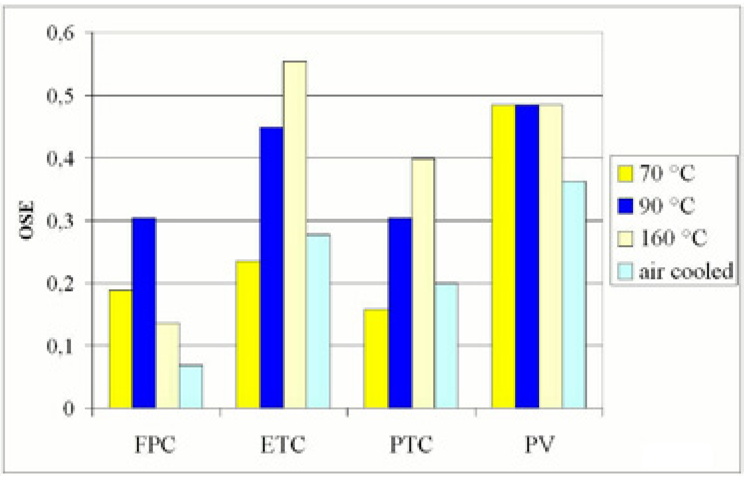

Figure 9: *Overall daily efficiency of the cooling system at the three temperatures of 70 °C, 90 °C 160 °C (adsorption, single effect absorption, double effect water-cooled) and 160 °C air-cooled (ammonia water GAX) for the three considered solar collectors compared with traditional compression chiller driven by PV*

The highest OSE is reached by ETC driven double effect systems which reaches 55% immediately followed by the PV driven, system which, if water-cooled, approaches 50%. According to the proposed evaluation, the adsorption low temperature driven system offers an OSE well below the absorption system, as the improvement of solar collector efficiency due to the lower temperature does not balance the lower COP. Good performances are allowed by ETC driven single effect (45%) and PTC driven double effect (40%). While the thermal driven systems OSE manages to overcome the PV systems with water cooling, the air cooled thermal systems are well below due to the combined effect of a lower solar collector efficiency and low chiller COP. The OSE remains below 28% with a 36% of PV.

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

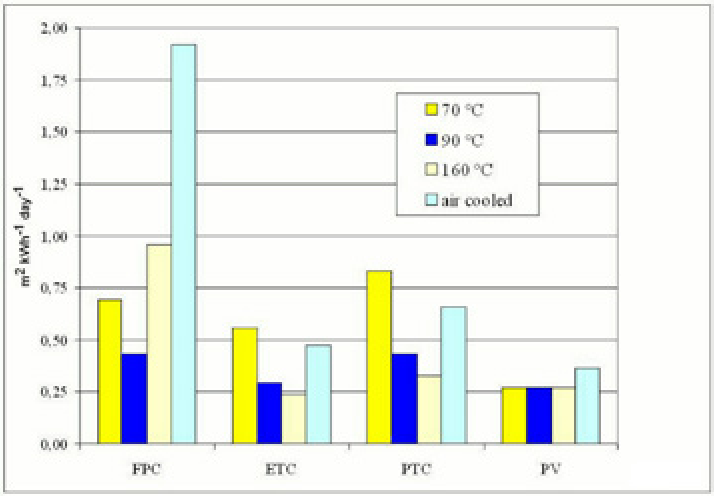

Figure 10: *Collecting area [m^2] to produce 1 kWh cooling effect on a sunny day (K_h=0.6) for the various considered systems*

The parasitic energy that must be supplemented to the solar thermal systems has not entered the comparison. A very rough estimate is that the required collecting area should be increased of about 10% for accounting the surplus parasitic energy with respect to the PV system, with the penalisation evaluated in terms of primary energy[51]. The pumps of the absorption chiller should also be taken into account for a correct comparison. Pumps are needed 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 absorber and condenser. In principle for low 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. A careful design of the hydronic circuits is of paramount importance, as a poor sizing of tubes and fittings (e.g. valves) might give rise to an electricity demand of the same order of a conventional chiller just to drive the pumps, as was recorded in some first pilot plants. In the case of a reasonable design, additional 3-7 kWh electricity per day must be added to the electricity required for the solar collectors circuit.

An economic analysis

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

A clear average summer day is considered (as before a representative day of July in Rome with a clearness index of 0.65). To allow to easily extend the results to different plant cooling capacity, the investment costs are evaluated in specific terms: an average cooling capacity of 1 kW is considered in operation for the 10 h of opening of the commercial sectors (shops or offices). Then a daily cooling production of 10 kWh is supplied.

A suitable storage sizing allows the plant to supply the nominal engine capacity for 10 h. In other words, the collecting area is able to provide the chiller with the required energy on that day to produce 10 kWh cooling.

Figure 11 presents the evaluation that accounts for the different computations just 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 air cooled at 160 °C) and for PV solar cooling (water- the first three values and air cooled) *.

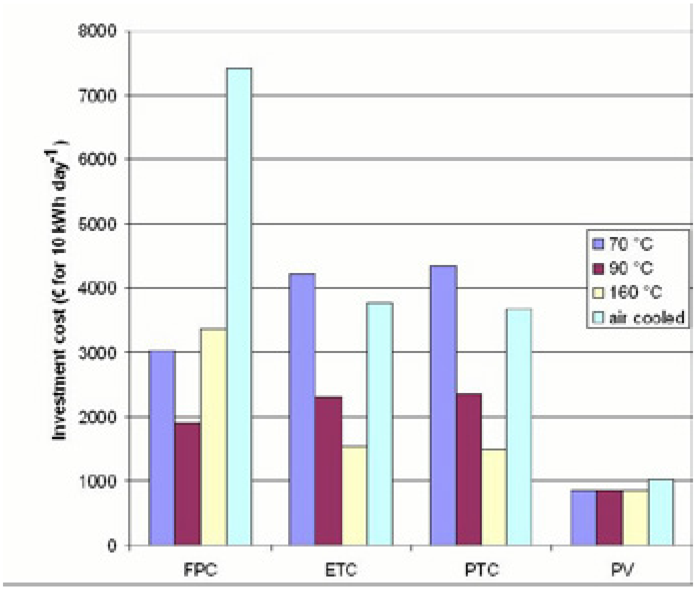

Figure 11: *Estimate of investment cost for a plant that offers 10 kWh cooling on a sunny day for the different considered technologies*

* *To better clarify how the computation is carried out, consider a single effect chiller, driven at 90 °C by an ETC whose specific cost is evaluated in 650 € m^{-2}. The specific cost of chiller capacity is evaluated to be 400€ kW^{-1}. To obtain 10 kWh, 2.92 m^2 of collectors are required. In fact, for the average considered sunny day, the daily solar radiation on the collector is 7.6 $kWhm^{-2}day^{-1}$, the daily efficiency of such collectors is 56% and the OSE 45% (estimated COP=0.8), so that the specific requested area is 0.292 $m^2kWh^{-1}d^{-1}$.*

The investment cost is therefore estimated at:

2.92x650 + 400 = 2,298€ per 10 kWh day^{-1}

The analysis for a PV driven plant is quite similar. Its daily efficiency is evaluated at 12%. Every kWh of electricity gives 4 kWh cooling effect (COP=4). The daily electric energy can be evaluated at 7.6x0.12=0.91 $kWhm^{-2}d^{-1}$ with a cooling effect 4 times higher (3.65 $kWhm^{-2}d^{-1}$). Then the required PV area is 10/3.65=2.74 m^2. The chiller cost is evaluated at 300€ kW^{-1} and the total investment is (PV panel with inverter at 200€ m^{-2}):

2.74x200+300=843€ per 10 $kWhday^{-1}$

The comparison with PV solar cooling is complicated by the need of storage for solar thermal systems[52]. Indeed, not only a hot storage must be provided, but even a cold storage is suggested to limit the engine ON-OFF when the building cooling demand changes[53,54]. In fact many ON-OFF cycles can even halve the daily COP for small capacity absorption chillers[55]. Moreover, for an absorption chiller with a COP less than 1, a cold storage for a similar temperature drop (usually in the range of 5 K) has proven smaller than a hot water storage and likely with less heat losses (in the case gains). The cost of a thermal storage can vary from 20 to 100€ kWh^{-1}[56]. The storage capacity to supply 1 kWh cooling depends on the chiller 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 of about 200 l kWh^{-1} of cooling. A smaller volume and higher performance is obtainable with Phase Change Material (PCM) storage, but the cost is also higher[57].

The dramatic cost reduction of PV panels over the last three years seem to eliminate any possibility of competition of thermal driven solar cooling with PV powered systems. The best alternative options to PV are double effect chillers with ETC or PTC. However, the investment cost is about twice as much as for PV (1536 or 1478 € against 843). Air cooled chillers are too expensive if thermally driven, whereas an additional cost of 20% shall be attributed to air cooled chillers when PV driven.

Furthermore to account for the storage cost, an indicative supplementary cost of about 500 € should be considered.

A careful comparison should also consider the need of equipping the PV solar cooling system with a suitable battery storage, whose cost is much higher than for a thermal storage. An estimate is of about 120 € kWh^{-1}[58]. However, considering that 1 kWh storage can produce around 3 kWh cooling, the total cost would be in the same range as for a correspondent 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 PV provided, but then the analysis turns out to be very complicated.

A fundamental parameter that must be carefully regarded when planning a solar cooling plant is the ***f***-fraction. This parameter is frequently used for other solar installations, such as building solar heating or domestic hot water heating. The letter ***f*** stands for free, i.e. the fraction of the cooling demand satisfied 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 that operates when solar energy is insufficient due to low or no insolation and low storage capacity.

The proper ***f***-fraction selection depends on many parameters, meteorological parameters (solar radiation, temperatures during the cooling season), shape and amount of the building cooling demand, cost of conventional energy (grid electricity, natural gas or other fuels), cost of solar section and storage, without forgetting economic parameters such as the discount rate.

Solar cooling development data

By the end of 2014, an estimated 1,175 solar cooling systems were installed worldwide[59].

The market showed a very rapid pace of growth between 2004 and 2014, even if the growth rates tended to decrease from 32% in 2007-2008 to 12% in 2013-2014. Approximately three quarters of the solar cooling installations worldwide are installed in Europe, most notably 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%) then adsorption (17%) and solid desiccant (10%) technologies[60, 61]. The liquid desiccant technology shares only 1% of total installations. Surprisingly, few PV-driven applications are reported in literature. The very recent cost drop in PV cells suggests a rapid increase of these applications in the years to come.

Environmental aspects

Solar cooling may have a very positive environmental impact reducing the usage of fossil fuel. The benefit can be evaluated by the avoided amount of CO_2 emission, which can reach about 0.5-1.0 kg CO_2 kWh^{-1} for the grid electricity according to different mixing in electricity production for various countries. Then for every kWh of cooling (COP=3) by solar, an amount of CO_2 that is avoided is in the range of 160-330 g CO_2. However, thermally driven solar cooling plants must be supplemented by parasitic energy (pumps and fans). Parasitic energy might account for 10% of the supplied renewable energy, so that it could be evaluated at 50-100 g CO_2 per kWh for a single effect absorption chiller. Moreover, the energy payback (the time necessary to recover the energy needed to manufacture a device) should be evaluated both for PV panels and solar collectors. Many debates have taken place on these topics and no general agreement exists. However, to clarify expectations the energy payback of PV panels is estimated to be between 1.5 and 3 years for silicon cells and less than 1 year for thin film cells, depending on the climate (the more solar radiation the shorter the payback time). Similar values can be considered for thermal solar collectors. Then the benefits must be evaluated in the lifetime of the plant, which can be in the range of 20 years.

An estimate depends on many variables such as the climate or the utilisation of the plant. A rough estimate could attribute from 100 to 200 $kWhm^{-2}$ of electricity production per year of a PV silicon panel. Then in the lifetime from 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 avoiding CO_2 emission from 850 to 3850 kg CO_2m^{-2}.

Conclusions

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

A first comparison considers the overall efficiency where in some cases thermally driven systems can 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 not competitive anymore as the investment cost of a PV system is about half of that of the best solar thermally driven alternative. The transition from a quasi-parity of cost between the two system families from recent years[59] to the present situation can be attributed to the huge savings of scale regarding PV panels. Until today, solar thermal panels did not benefit of a cost reduction of a similar importance in spite of a strong increase in production, even if of not same extent as PV panels.

A further reduction in the cost of PV panels is expected in the near future, both for a reduction of cost and an efficiency increase. Halving cost might take place in the ten coming years arriving to 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 definitely to close any competition with thermally-driven solar cooling. However, a mass production of ETC or PTC might reduce the cost at levels not far from that of FPC. Then a quasi-parity with the actual PV systems would be possible.

Desiccant cooling was not included in the comparison. As mentioned above, this technology is suitable in buildings with 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 strong latent loads are present, particularly in hot and dry climates.

A final consideration is that solar thermal technology must be appreciated for the service supplied during the whole year and also when cooling is not required. In fact, solar thermal system can supply heating of the building and hot water. Likewise, PV systems should be evaluated when coupled with a heat pump for winter heating.

Thus a payback estimation with respect to a conventional system should carefully analyse the yearly utilisation of the plant and the tariff levels.

Recommendations

Solar cooling may have a very positive environmental impact by reducing the usage of fossil fuel. It is mature to compete with the conventional cooling equipment. So the IIR emphasizes the need to:

- Develop strong worldwide campaigns on economic and environmental benefits of solar cooling implementation to raise awareness of 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 of solar cooling technologies by granting funding,
- Support implementation of solar cooling at national and international levels by granting subsidies to interested users and particularly those in developing countries,
- Set up incentive schemes to promote the use of solar cooling, for example by tax exemptions for users of solar assisted cooling systems.

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