COOLING BUILDINGS THROUGH SOLAR ENERGY

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Abstract

This project is about solar cooling. Solar heating is also examined, because the solar cooling systems can produce both heat and cold (but not vice versa). There are two basic categories of solar systems, photovoltaic and solar thermal systems. This project is more about the latter because they are more environmentally friendly. The project begins with a retrospect of the first, primitive solar cooling systems and how they evolved to the sophisticated systems that are used today. All the types of chillers, solar collectors and heat rejection systems are thoroughly examined and their advantages and disadvantages are pointed out as well as their possible combinations. Economic data and payback time for the solar cooling systems are studied and some notable appliances, both in Greece and abroad practically show the benefits of solar cooling even in generally cold countries. Then, there's part 2, which is the practical part of the project. Real data is used in order to pre-design a solar heating and cooling system for the students' residence in the technical university of Crete with the help of Pistache software. Weather data is the input of Pistache and many possible combinations of chillers/collectors/heat rejection systems are examined to design an inexpensive yet efficient and hygienic solar cooling system, capable of covering the needs of around seventy five students. The output of Pistache software is cooling/heating demands and production and an important analysis report that essentially states how efficient the system's pre-design is. Finally, the economic savings and fast payback time as well as the harmful emissions reduction with the help of solar cooling systems are emphasized in the conclusion.

Περίληψη

Η παρούσα διπλωματική εργασία σχετίζεται με την ηλιακή ψύξη. Εξετάζεται επίσης και η ηλιακή θέρμανση γιατί τα ηλιακά συστήματα ψύξης μπορούν να παράγουν και θέρμανση (όχι το αντίθετο). Υπάρχουν δύο βασικές κατηγορίες ηλιακών συστημάτων, τα φωτοβολταϊκά και τα ηλιακά θερμικά συστήματα, από τα οποία μελετώνται κυρίως τα δεύτερα, όντας πιο φιλικά προς το περιβάλλον. Αρχικά γίνεται μια αναδρομή των πρώιμων εφαρμογών ηλιακής ψύξης, φτάνοντας στα εξελιγμένα ηλιακά συστήματα που χρησιμοποιούνται σήμερα. Όλοι οι τύποι ψυκτών, ηλιακών συλλεκτών και συστημάτων αποβολής θερμότητας περιγράφονται αναλυτικά, τα πλεονεκτήματα και μειονεκτήματά τους καθώς και οι δυνατοί συνδυασμοί τους. Με τη χρήση οικονομικών δεδομένων υπολογίζονται οι χρόνοι απόσβεσης και μερικές αξιοσημείωτες εφαρμογές ηλιακής ψύξης αναλύονται τόσο της Ελλάδας όσο και του εξωτερικού για να δείξουν τα πολλαπλά οφέλη της ηλιακής ψύξης. Στο δεύτερο και πρακτικό μέρος της διπλωματικής, χρησιμοποιούνται αληθινά δεδομένα για να μοντελοποιηθεί ένα σύστημα ηλιακής θέρμανσης και ψύξης για την εστία φοιτητών στο Πολυτεχνείο Κρήτης, με τη βοήθεια του λογισμικού Pistache. Το πρόγραμμα έχει σαν είσοδο αναλυτικά δεδομένα καιρού για την περιοχή και μαζί με διάφορους συνδυασμούς ψυκτών/συλλεκτών κτλ γίνεται μια προσπάθεια προσχεδιασμού ενός οικονομικού αλλά και αποτελεσματικού συστήματος ψύξης/θέρμανσης για τους περίπου εβδομήντα πέντε κατοίκους των εστιών. Τα αποτελέσματα του Pistache είναι η παραγώμενη θέρμανση και ψύξη και η ζήτηση αυτών καθώς και μια σημαντική αναφορά που δείχνει πόσο αποτελεσματικός και δυνατός να πραγματοποιηθεί είναι ο προσχεδιασμός που εκπονήθηκε. Στο τέλος, τονίζονται τα οικονομικά οφέλη, η γρήγορη απόσβεση και ο σημαντικός περιορισμός εκπομπών επικίνδυνων αερίων με τη χρήση των συστημάτων ηλιακής ψύξης και θέρμανσης.

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Chapter 1

In Chapter 1 the importance of solar cooling is emphasized and after a short chronology of the solar cooling installations from centuries ago till today, all the types of chillers, solar collectors and heat rejection systems are explained and some notable installations (both in Greece and abroad) are looked in detail.

1.1 Introduction

Solar energy is the result of electromagnetic radiation released from the sun by the thermonuclear reactions occurring inside its core. The properties of this light radiation are visible, infrared or ultraviolet and the sun transmits a vast amount of solar energy to the surface of the earth most part of which is not used in any way.

The increasing demand of energy and the effort, at the same time, to reduce the concentration of greenhouse gases in the atmosphere leads to the search not only of new environmental friendly technologies but also of ways to improve the already existing clean technologies, so that they are made more economically competitive.

Our joint concern regarding the global warming is slowly but steadily changing the way we behave and act in different aspects of our lives in order to reduce our CO_2 footprints. Governments have begun dynamically encouraging communities and companies to implement green technologies at different sectors, including the building industry. The use of solar energy in buildings greatly reduces the consumption of fossil fuel and harmful emissions to the environment. As a promising technology, solar cooling systems have been paid more and more attention to. In countries with a large amount of sunshine throughout the year, such as the Mediterranean or the Middle Eastern countries, using solar energy for heating or cooling can easily cover over 40% of the annual energy demand and attenuation comes fast, in some cases in less than ten years.

Notably, after the 1973 energy (petroleum) crisis not only studies were published regarding solar cooling, but just in the following months the first pilot plants were put in use and the scientific community began talking about environmental sustainability, whose common perception back then was mostly associated to the choice of natural and ecological materials.

The European Union has recognized the high potential for energy savings from buildings and actively promotes the installation of solar thermal systems in the building sector. Nowadays many countries are starting to accept that solar energy has enormous potential because of its cleanliness, low price and infinite natural availability. Conventional solar cooling systems are also getting cheaper and new and more efficient ones are slowly introduced in the market.

Along with photovoltaic systems, solar thermal energy has been used over the last few decades at a growing rate to meet the cooling needs of both domestic and industrial purposes. It contributes to the reduction of fossil fuel demand with the use of solar heat and by this, contributes to the reduction of indirect greenhouse gas emissions. Generally speaking solar energy contribution for space heating, although it varies from winter to summer, has been observed to contribute in some cases more than 50% of the total energy requirements. Under suitable ambient conditions, approximately 35% of total building cooling load can be met by a solar driven cooling system. This rate can be viable even in countries with limited sunshine, like Germany. In Europe solar annual radiation is between 500 (in a country like Denmark) and 1800 kWh/m^2 (for a Mediterranean country) [13, 19, 22, 25, 34].

1.2 What is solar cooling and why it is important

Solar cooling is the kind of technology that converts heat collected from the sun into building cooling. The process works by making use of solar heat, which is collected and supplied to a thermally driven cooling process, something that is thermodynamically possible, in order to generate chilled water or conditioned air for use in buildings. It can also be used to control the building's humidity, especially in humid environments.

Solar collectors transform solar radiation into heat and transfer that heat to a medium (water, solar fluid, or air). Then solar heat can be used for heating water, to heating or cooling buildings depending on the season, or for heating swimming pools if the installation is not big enough. Solar cooling technologies demand very high temperatures and not all the type of solar collectors are capable of producing them such as the thermosiphon used mainly in Greece and Cyprus, a system that is only able to heat water.

However, solar systems will always require some kind of energy storage and backup system. Solar electric systems can make use of batteries or be connected to the electric net so that electricity can be imported or exported from the system. They can also be connected with the boiler room, where natural gas or petroleum is used or with a conventional ac, so that the system can automatically switch back and forth, depending on the amount of sunshine and the energy demand.

Solar cooling in not yet in a very mature state as systems are constantly being updated, initial cost is high and maintenance can be an issue as few mechanics will undertake the responsibility of repairing one. Even with that in mind, the simple thermodynamics behind solar cooling operating principle (theory behind it is some 150 years old) and the fact that we only make use of only 0.0007% of the solar energy reaching the earth, an infinite and green form of energy, solar cooling is gathering quite a lot of attention towards buildings solar heating and cooling [13, 22, 25, 34].

1.3 Solar cooling installations chronology

The heat pump is one of the few devices conceived in theory before practice. Sadi Carnot's analysis back in 1824 primarily applies to the steam engine, but a fundamental role in his *Réfl exions* is played by the concept of a reversible cycle that implies a possible working cooling machine. Passing from cooling machine to heat pump is rather simple for the modern scientific world: changing the roles of cold source and heat sink is enough. The useful effect of the heat pump's cycle is the heat that the cooling machine must dissipate. However, theoretical passing required almost 30 years. William Thompson, known as Lord Kelvin, wrote a report on the economy of the heating and cooling of buildings by means of currents of air.

Meanwhile practical knowledge was also developed later on. In 1851 John Gorrie, a doctor and amateur technician, patented the first compression cooling machine, which was actually used for curing his patients suffering in Florida's hot and humid climate. The very first heat pump was built in 1855 by Peter Ritter von Rittinger who installed an open-cycle mechanical vapor recompression unit, directly driven by hydro energy, in Austria. The vapor developed in the aqueous solution concentrators at a temperature of 117ºC and a pressure of 170 kPa was compressed till 300 kPa. The condensation temperature at that pressure is 138ºC. Therefore vapor condensation allowed the development of a vapor quantity at a COP higher than 10. The condensate before discharging, preheated the salt diluted solution at the inlet of the concentrators. During the 19th century the heat pump was not considered a useful device both because of the high cost of the equipment and the lack of suitable refrigerants. What's more, direct combustion either of wood or coal was considerably cheaper. Even the cooling equipment had difficulty in its competition with natural ice that was stored in winter for the following summer over the centuries. Organic refrigerants were first developed in the 1930s with a following development of cooling equipment. Apart from isolated installations (most of them in Switzerland and Scotland and one, well known in Milan, Italy), the first commercial heat pump spread took place in US during the 1950s. The utilization of this equipment in North America's icy winters suddenly evidenced the weak points (Figure 1). The much higher pressure ratio gave rise to frequent compressor failures as this device was conceived for lower ratios. Other problems (defrosting, compressor slugging and lack of lubrication) gave a low reliability reputation to heat pumps and produced a selling stagnation for a 10 year period. The main factor, however, holding back the heat pump's everyday use was the high initial cost of the PV modules.

The heat pump rediscovery in the US happened during the first energy crisis when the various design and constructive faults were faced and eventually solved. However, the two energy crises in 1973 and in 1979 were not conclusive in promoting heat pump selling in spite of very favourable conditions, with regard to the relative cost of electricity and fossil fuels. During the last ten years the heat pump market has spread greatly in the world. After developing in the US, it has spread towards new markets like Japan where 95% of the air conditioners can operate as heat pumps, and unexpected ones, like China, where about 60% of the 11 million heat pumps are reversible. Only recently public opinion and government politics began to accept the high initial costs for heating devices against lower working costs and reduced pollution. This allowed not only technological progress in the classical electric heat pumps but also the growing and technological development of somewhat niche products such as gas heat pumps. A recent evaluation gives an estimate of around 135 million of heat pumps in the world with an annual thermal production estimated at 1300 TWh as for 2001, so today the number should be considerably bigger. This energy is used for 57% in residential heating, 27% in commercial applications and 16% in industry. In the last 20 years the heat pump has been greatly improved regarding the thermal exchange surfaces, the compressor, as well as the control and defrosting systems. Thus not only was the COP strongly improved but also the gap in performance between different seasons. Further equipment improvements are aimed to better exploit the properties of new refrigerants, utilising even the pressure drop between the condenser and the evaporator. Gas driven heat pumps were also improved with higher efficiency and much longer maintenance intervals. Absorption heat pumps are now available in many different models suitable for different applications. Most improvements took place with lower heating temperatures and the use of cold sources more suitable than the outside air, mainly surface and underground water. The market growth is particularly important in Europe where the annual increment even has two digits in recent years, such as in Germany, Austria, Switzerland and Sweden. Heat pump applications like ground heat pumps can be favourably used even in cold climates and they are used increasingly in Northern countries such as Canada and Sweden. Other heat pump developing fields are in heat recovery in building mechanical ventilation and in sanitary water heating.

The first evolution of the absorption system began back in the 1700s. It was observed that in the presence of H_2SO_4 (sulfuric acid), ice can be made by evaporating pure water within an evacuated container. In 1810, it was found that ice could be produced from water in a couple of vessels connected together in the presence of sulfuric acid. As the sulfuric acid absorbed water vapor (to reduce heat), ice formed on the surface of water. However, difficulties emerged with leakage and corrosion from air. In 1859, a French engineer named Ferdinand Carre designed a machine that used a working fluid pair of water and ammonia (NH_3). This machine was used for making ice as well as for storing food, and he filed for a US patent in 1860. In 1950, a new system was introduced with a water/lithium bromide pairing as working fluids for commercial purposes. The primary advantage of the absorption system was that it has a larger COP (coefficient of performance) than other thermally operated technologies. Faraday first introduced vapor adsorption technology in 1848, using a solid adsorbent. Adsorption cycles were first used in refrigeration and heat pumps in the early 1990s. The disadvantages of liquid–vapor systems were overcome by using solid–vapor cycle; this technology was first marketed in the 1920s. The Nishiyodo Kuchouki Company was the pioneer in bringing adsorption refrigeration technology to the US market in 1986. Adsorption refrigeration technology has been used for many specific applications, such as purification, separation and thermal refrigeration technologies [30-32, 37].

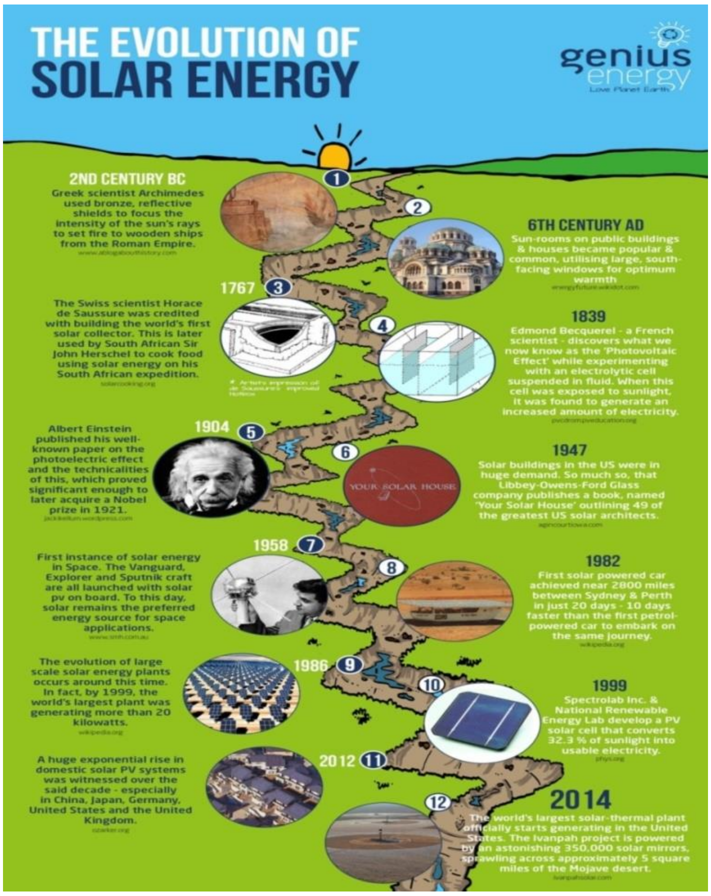


Figure 1: The evolution of solar energy appliances, starting from use in warfare and passive cooling to the large solar thermal plants and sophisticated domestic PV cells that are used today [www.pinterest.com/explore/solar-energy-system/, assessed on December 2016]

1.4 Photovoltaic and solar thermal systems

Before is extensively explained how a solar cooling system works and what parts is consisted of, the commonly used types of solar collectors need to be mentioned, starting by what exactly a photovoltaic system is. The photovoltaic is a power system designed to supply usable solar power. It consists of an arrangement of several components, including solar panels to absorb and convert sunlight into electricity, a solar inverter to change the electric current from DC to AC, as well as mounting and cabling and other electrical accessories to set up a properly working system.

A PV cell is basically a solid-state semiconductor device, much like any computer chip, that converts light energy into electrical energy. They come in all sizes and the small PV cells are typically used in wrist watches and calculators, whereas the larger ones are used for supplying power for industrial and domestic electrical appliances. The simplest and cheaper of the latter are thermosiphon systems that only heat up water, while the more complicated and expensive ones can be used for solar heating and cooling, too. The domestic or commercial energy demand is covered by the electricity obtained by the photovoltaic modules and if required from the electric net, wherewith the PV is connected. If the electricity produced by the PV is higher than the electricity demand, especially in the summer, the surplus can be fed into to electric net or simply be stored for later use.

There is one main difference between a photovoltaic system and a solar thermal system: the latter are not directly connected with the electric grid. They use air or water as heating/cooling means and the heat produced by the sun is not converted into electricity first. There is no way to benefit economically by providing electricity surplus to the net with the use of a solar thermal system, they only cover ones needs. For this reason mainly photovoltaics are more common than solar thermal systems. However the latter are more eficient, and thus more expensive. They are also more enviromentally friendly payment comes faster than photovoltaics if there’s no interest in providing a certain surplus to the electric net [13, 18, 23, 27, 32].

1.5 Types of solar collectors

Two are the main types of solar collectors used for solar cooling, the flat-plate collectors and the evacuated tube collectors, the latter being more complex and more expensive. There are also the solar air collectors and the stationary CPC collectors in use, but there are rarely used for solar cooling or are only used in large installations.

Flat-plate collectors (FPC)

They are the most widely used kind of collectors in the world for domestic water-heating systems and solar space heating or cooling. The first accurate model of flat plate solar collectors was developed by Hottel and Whillier in the 1950’s. A typical flat-plate collector consists of an absorber, transparent cover sheets, and an insulated box (Figure 2). The absorber is usually a sheet of high thermal conductivity metal such as copper or aluminum, with tubes either integral or attached. Its surface is specially coated to maximize radiant energy absorption and to minimize solar energy reflection. The insulated box reduces heat loss from the back or the sides of the collector. The cover sheets, called glazing, allow sunlight to pass through the absorber but also insulate the space above the absorber to prevent cool air to flow into this space. Flat-plate solar collectors have been widely in service for the last 30 years, without significant changes in their design or operating principles. The larger the demand, the bigger the size of the collector and this increases their manufacturing cost for extensive appliances. They are fairly effective, especially for small home appliances but they become less suitable if higher efficiency is required. Anti-freeze for use in northern countries is also necessary [8, 17, 21, 38, 41].

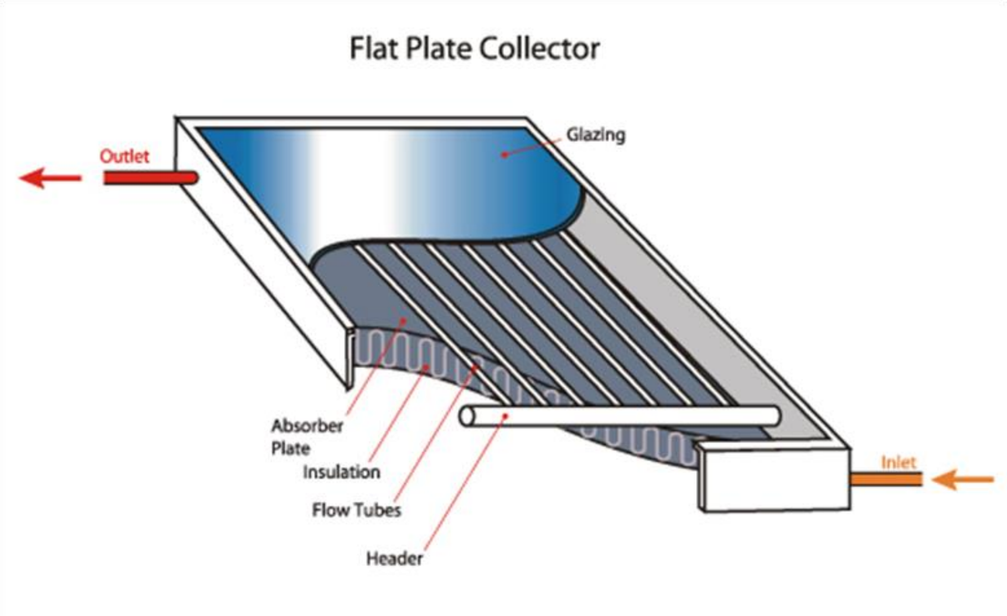


Figure 2: The simple but quite efficient flat plate collector, the most widely used type of collector in solar cooling [http://gogreenheatsolutions.co.za/?q=project-type/solar-water-heating/flat-plate-collector, assessed on December 2016]

Evacuated (or vacuum) tubes

They are solar panels built to minimize convective and heat conduction loss (vacuum is a heat insulator) compared to other solar panels. Different construction types are available in the market: heat pipes or direct flow, all glass tubes with or without concentrator. Each evacuated tube consists of two glass tubes. The outer tube is made of extremely strong transparent Pyrex glass that is able to resist strong impact. The inner tube is also made of Pyrex (borosilicate) glass, but coated with a special coating, which features excellent solar heat absorption and minimal heat reflection properties (Figure 3). The manifold is heavily insulated with a second level of coating to keep the heat in. Unlike flat plates, these headers are so well insulated that they should not require antifreeze in normal operation – the temperature of the header is unlikely to fall below 10° C even in very cold weather. Evacuated (or vacuum) tubes include a low temperature facility – should the temperature of the collector fall below a defined level, the pump will operate to allow the water at the bottom of the tank to heat the collector slightly. In normal conditions, this would never be necessary, but it acts as a good safety measure. In that way vacuum tubes can easily be used in Northern Europe.

The air is evacuated from the space between the two glass tubes to form a vacuum, which eliminates conductive and convective heat loss. The vacuum tube solar panel has been around for several years and has proved to be both reliable and dependable. The double wall glass tubes have a space in the centre which contains the heat pipe. The sun’s radiation is absorbed by the selective coating on the inner glass surface, but is prevented from re-radiating out by the silver-coated innermost lining which has been optimized for infrared radiation. This acts similarly as a one-way mirror. It proves to be very efficient since 93% of the sun light's energy hitting the tube's surface, is absorbed, whereas only 7% is lost through reflection and re-emission. The presence of the vacuum wall prevents any losses by conduction or convection – just like a thermos flask. Because of this, the system will work even in very low temperatures, unlike traditional flat plate collectors. The heat transferred to the tip of the heat pipe is in turn transferred to a copper manifold in which water circulates to heat the domestic hot water tank. If a tube is placed in direct sunlight on a summer day, the tip temperature can reach 250° C – so the system easily heats domestic hot water cylinders to 60° C even in cooler weather.

Replacing flat plate collectors with evacuated tube collectors can reduce the solar collector area by up to 50%, thus sparing a lot of space, although the installation cost is higher (efficiency too) [8, 17, 21, 38, 41].

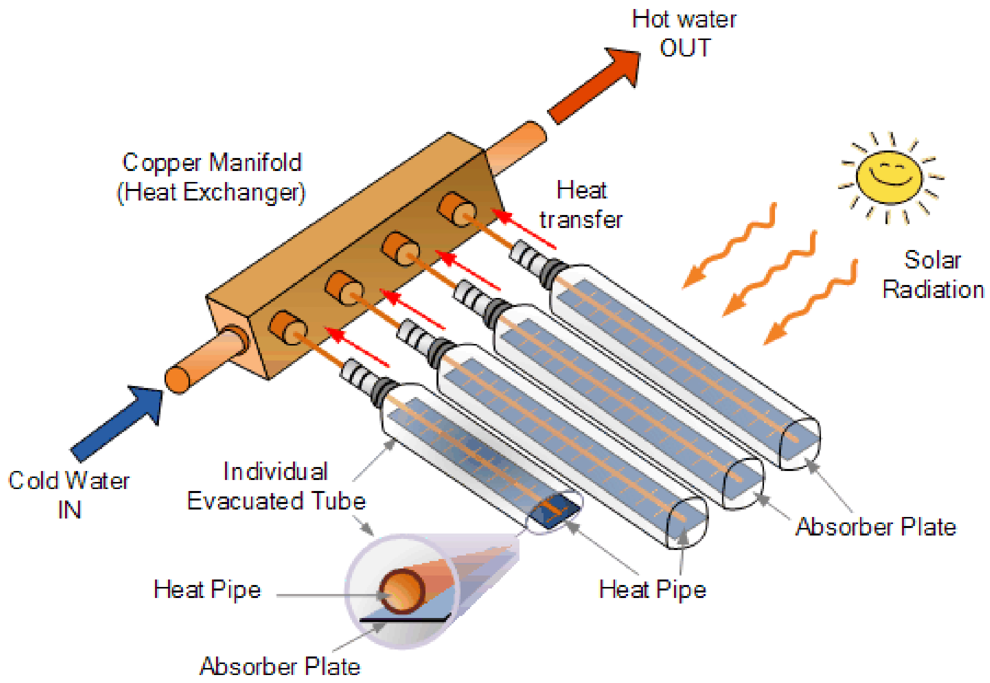


Figure 3: The sophisticated but pricey vacuum tube collector, one of the most efficient types of collectors, the design is much more complex than the flat plate collector but there is no need for anti-freeze [http://www.alternative-energy-tutorials.com/solar-hot-water/evacuated-tube-collector.html, assessed on December 2016]

Solar air collectors (SAC)

These collectors use air as fluid and heat directly it. They're usually employed for pre-heating air used for ventilation air (Figure 4). They are usually utilized in open cycle solar cooling technology. They are the least complex solar collector design. They too are often used in solar cooling systems, but in desiccant technology only (mostly supermarkets etc.). Solar air collectors can achieve temperatures of twenty degrees above that of the ambient temperature in a best case scenario and their output is about half that of flat plate collector. They are the cheapest type of solar collectors but the least efficient. Yet, they offer enough heat in simple tasks, like warming up pools a few degrees [8, 17, 21, 38, 41].

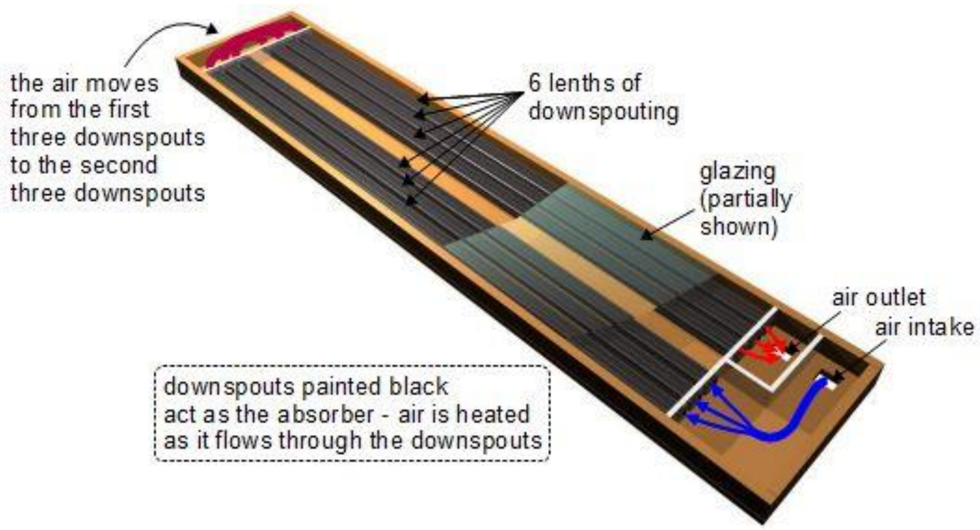


Figure 4: The simplest type of collector, the solar air collector consist of nothing more than an inlet/outlet and painted black downspouts for the heat transfer [http://rimstar.org/renewnrg/solar_air_heater_types_diy_homemade.htm, assessed on December 2016]

CPC collectors

CPC (concentrating parabolic compound collector) solar collectors use radiation concentration when fluid temperature won't reach more than 100°C. Radiation concentration can be static or dynamic (parabolic). It's usually used to heat liquid (oil, water or water with anti-freeze or diathermic fluid, usually glycol). It can be used for domestic hot water preparation and can also be used in solar cooling. In this panel there is a reduction of convective losses. Parabolic compound solar collectors differ in the way they work compared the other types of solar collectors. They make use of optics rules rather than heavy insulation in order to trap solar radiation. The exact way they work is subject of another project because some background about how optics work in general needs to be explained. They reflect and focus direct-beam radiation onto a central receiver to achieve the highest temperatures (Figure 5).

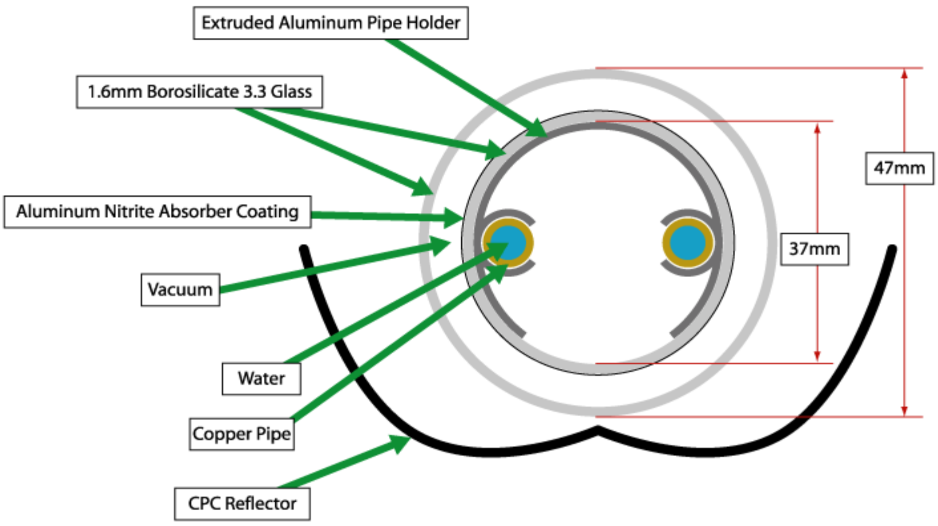


Figure 5: The compound parabolic collector, equal or even more efficient than the vacuum tube collectors, they make use of optics to gather more heat but their sophisticated design means that it's only logical to combine them with double-effect absorption chillers [http://andyschroder.com/CPCEvacuatedTube/AdditionalImages/, assessed on December 2016]

The higher temperatures achieved by concentrating solar collectors enable high efficiency two stage absorption chillers to be used. They are usually used on a large scale for professional use, not because they are not fit for a house but because their superiority and efficiency would probably be wasted on a small scale application [8, 17, 21, 38, 41].

1.6 Solar cooling with thermal systems: The Chiller

Sorption cooling is a technology that uses heat to generate cooling. Many technologies are available to produce solar cooling. The most widespread options are solar thermal driven sorption and photovoltaic driven compression chillers. Sorption chillers can be single or double effect (with the help of LiBr refrigerant) water cooled, or (NH_3) air cooled, but more on that later.

A typical solar cooling system consists of a common solar thermal system made up of solar collectors, a storage tank, a control unit, pipes and pumps for hot water or air flow and a thermally driven cooling machine, the chiller. The available solar energy, in the form of solar radiation flux, is utilised by a solar panel, in order to produce a high temperature fluid (generally water), usually helped by an auxiliary refrigerant, that is accumulated in a storage tank. If solar panels provide the necessary energy input to the plant, chillers are those machines that are able to produce cooling by utilising the hot water coming from the solar panels. The chiller, which is the core of solar cooling plants, uses the hot fluid of the storage tank to produce a cold fluid, by removing heat from a liquid via a vapor compression or absorption/adsorption refrigeration cycle. The cold fluid can then be used in the cooling plant, similar to a typical electric refrigerator. Cooling power production needs electrical or mechanical power, whereas chillers can produce chilled water from low temperature heat by utilising simple thermodynamic laws with the help of chemical solutions. The chiller is a complex machine, for instance in the absorption chillers (the most common type, will be explained in detail later) is constituted by four main components: generator, condenser, absorber and evaporator. For both the heat and cooling needs solar heating/cooling systems are usually backed by a conventional heat/cooling system (like a boiler/ac) for those occasions the performance is low [14, 19, 20, 23, 24, 32, 36].

Absorption and Adsorption cooling

Heat driven absorption or adsorption systems have been well studied and are widely available. They are the most complex but diverse types of solar cooling, although the first are more common. They are closed-cycle solar cooling systems where a refrigerant solution (usually with water) cools water in contrast with open-cycle systems (like desiccant cooling) where the water flowing in the pumps (and then rejected is the refrigerant itself.

1.6.1 Absorption Cooling

Absorption is the process in which a substance assimilates from one state into a different state. Absorption chillers' thermodynamic cycle is driven by the heat source. This heat is usually delivered to the chiller via steam, hot water, combustion or in the case of sunny climates (i.e. South Europe) solar energy can be used to operate absorption chillers. The chiller in the absorption cooling chillers consists of four main components (usually in a closed loop): the generator, the condenser, the absorber and the evaporator. Firstly, the solution used is heated and part of the water in it evaporates at low pressure. Therefore the concentration of the LiBr and water solution (absorbent dissolved in liquid refrigerant) increases (stronger solution). This strong solution is sent to the absorber, where it is absorbed with the help of the solution mentioned above. The absorption heat released during the absorption step is discharged by cooling water. By absorbing vaporous refrigerant, the absorber solution is diluted. The diluted absorber solution is subsequently directed to a regenerator where the solution is heated and concentrated by vaporising part of the refrigerant. The water vapor derived from the evaporation process flows to the condenser. Here it is put into contact with a heat exchanger fed by cooling water so that it is condensed and the heat is rejected to the ambient, using cooling tower water. The condensed water flows to the evaporator through an expansion device, where water evaporates in low pressure and low temperature surrounding environment. Since the liquid refrigerant extracts thermal energy from the surrounding during the vaporisation, the chilled liquid in the cooling pipes is further refrigerated. It takes heat from water in heat exchange tube, providing the desired cooling effect. In the condenser, the vaporised refrigerant is condensed to liquid and reinserted into the evaporator, which closes the loop (Figure 6).

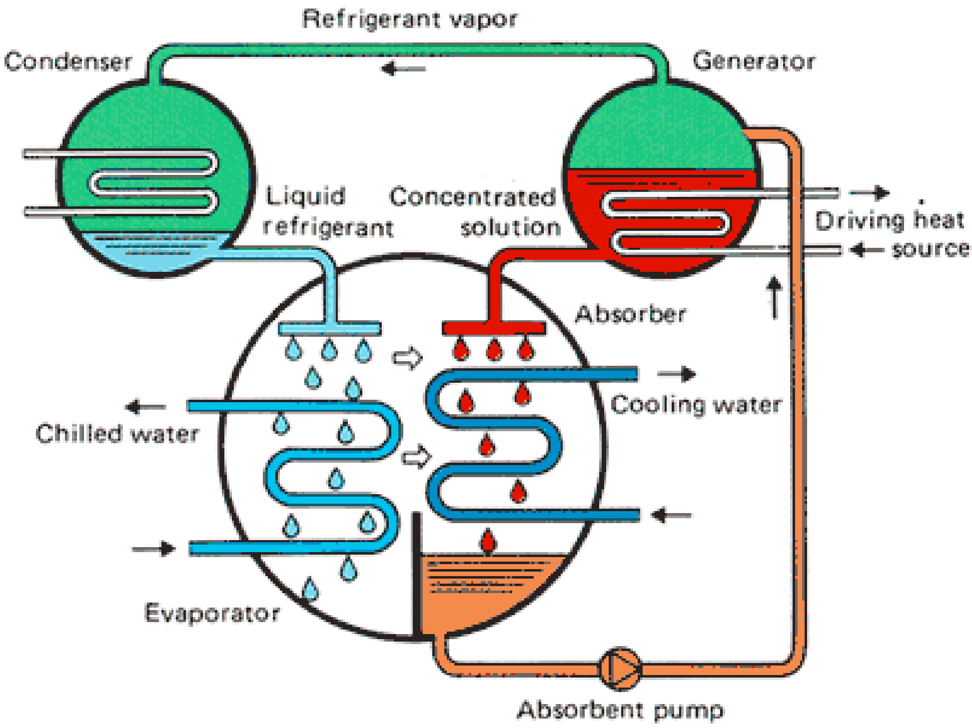


Figure 6: The widely used absorption cycle, consists of four main components: the generator, the condenser, the absorber and the evaporator, with the first one being the key component [http://www.midatlanticchptap.org/cleanenergy_chp_technologies-thermal.html, assessed on December 2016]

Compared to electrically powered chillers, they have very low electrical power requirements, very rarely above 15kW combined consumption for both the solution pump and the refrigerant. However, their heat input requirements are large, and their coefficients of performance (COP) are often 0.5 (single effect) to 1.0 (double effect). For the same tonnage capacity they require larger cooling towers than vapor compression chillers. However, absorption chillers, from an energy efficiency point of view, excel where cheap heat is readily available such as heat provided by solar thermal panels in sunny regions, like the Mediterranean countries. Absorption chillers are the most widely used chillers throughout the world. The thermal compression of the refrigerant is achieved by using both the liquid absorbent solution and the heat source, thereby replacing the electric power consumption of a mechanical compressor. For chilled water above 0°C, as is used in conventional air conditioning, a liquid H_2O/LiBr solution is typically applied with water as a refrigerant. The absorption chiller is a promising tool to refrigerate buildings by means of relatively low temperature heat, such as the one furnished by a solar panel.

However, the construction, installation and maintenance of these systems are rather expensive when compared to conventional vapor compression systems, which will also be explained in detail in the next chapter. In addition, because of the inherently intermittent nature of solar energy, systems driven by solar energy cannot stand alone. Additional heat sources, either from waste heat or from the burning of natural gas or petroleum are needed to keep the system working continuously. Considering the dominance of the vapor compression system in the air-conditioning and refrigeration market, it is highly promising to combine the solar energy-driven system with the vapor compression system to reduce energy consumption while providing a comfortable environment. However, their energy efficiency is very low, with a typical value of 0.2 or less. It is expected that combining the ejector cycle with other cycles (the so-called hybrid cycle) can facilitate higher system performance [9, 12, 23, 24, 28].

Single and double effect Absorption Cooling

The single effect cycle starts at the absorber. The absorber receives the vapor-refrigerant from the refrigerator and creates a rich-mixture. The pump forwards this mixture to the generator or the high pressure zone. In the generator, the refrigerant is then separated from the absorbent by the heat provided by the solar collector. Using a pressure-relief valve, the weak-solution then returns to the absorber. A SHX (solution heat-exchanger) is in place to recover the internal heat. It is also responsible for preheating the outgoing rich-solution from the absorber, improving the system's efficiency and resisting the irreversibility of the cycle. A 60% higher COP can be achieved by using the SHX. The refrigerant then follows the conventional cycle through the condenser, expansion valve and evaporator. A single-effect absorption cooling system is simpler than others when the design depends on the types of working fluids. The system shows better performance with non-volatile absorbents such as LiBr and water. If a volatile working pair such as ammonia/water is used, then an extra rectifier should be used before the condenser to provide pure refrigerant.

Double-effect absorption cooling technology was launched in 1956 for raising the system's performance within a heat-source to higher temperatures. The cycle begins with generator I providing heat to generator II. The condenser rejects the heat and passes the working fluid towards the evaporator, within this step, the required refrigeration occurs. Then, the fluids pass through the heat-exchangers (HX-I and HX-II) from the absorber to generator-I through the pump. Through this process, HX-II can pass the fluids to generator-II and then generator-II passes to HX-I (Figure 7). The complete cycle follows three different pressure levels: high, medium and low. Two single-effect systems effectively form a double-effect absorption cooling system; therefore the COP of a double-effect system is almost twice that of the single-effect absorption system. For example in an analysis conducted, it was found that the COP of a double-effect system is 0.96, whereas the single effect system has a COP of only 0.6. In the past few years, the COP of double-effect absorption systems has reached even higher values of 1.1–1.2 by using gas-fired absorption technology. The experiment mentioned above (they used a parabolic solar-collector of 52 m^2 with a heat-exchanger and pumps for circulation of the working fluids), implemented a double-effect absorption system with LiBr/water chillers of a total power of 16 kW, at the same time the single-effect absorption system was only capable of around 8.600kW. There was also a natural gas-burner used to supply heat in the absence of solar energy. On another experiment, with solar collectors covering an area of 230 m^2, the double-effect absorption cooling system showed to have the highest potential of savings, compared to other solar cooling systems, at an 86% rate, covering the demand of 50kW of power and reaching the temperature of just 90^{o}C [9, 12, 23, 24, 28].

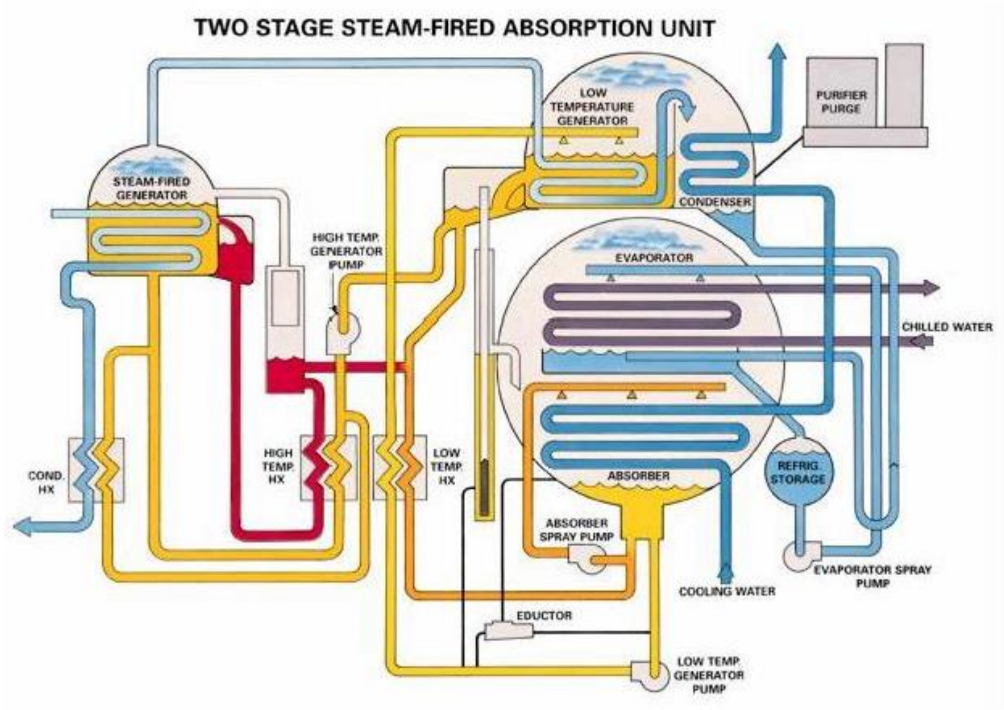


Figure 7: The double-effect absorption chiller is basically two single-effect absorption chillers merged together, as a result there two generators, two heat-exchangers etc. [http://www.enggcyclopedia.com/2012/01/absorption-chillers-refrigeration/, assessed on December 2016]

1.6.2 Adsorption Cooling

The adsorption process differs from the absorption process in that absorption is a volumetric phenomenon, whereas adsorption is a surface phenomenon. The primary component of an adsorption system is a solid porous surface with a large surface area and a large adsorptive capacity. Initially, this surface remains unsaturated. When a vapor molecule contacts the surface, an interaction occurs between the surface and the molecules and the molecules are adsorbed on to the surface. An adsorption cooling system is advantageous for its zero ODP (ozone depleting potential). Adsorption chillers perform a closed cycle adsorption / desorption process using a refrigerant and a solid adsorbent to achieve refrigeration. Refrigeration is used to cool down a secondary refrigerant circuit (chilled water or glycol) to enable the produced cold water/air to be distributed to where it is required. Adsorption chiller technology is able to operate with a lower temperature heat source than absorption systems and is more suitable for operation with a dry cooling tower (a device that rejects heat by heating the incoming air).

Adsorption cooling is a thermally driven refrigeration process, which can be powered by solar energy. Adsorption cooling is based on the evaporation and condensation of a refrigerant combined with adsorption. Adsorption refrigeration is mainly used for air-conditioning. Adsorption cooling machines are based on solid or liquid solvents, the adsorbents, which can bind gases or liquids to their surface. Adsorbed particles can be removed from the surface by heating the adsorbent. Unlike the closed loop in absorption cooling machines, the process in adsorption cooling machines is discontinuous. A supplementary step to regenerate or exchange the adsorbent is required. A solar collector containing an adsorbent is connected to a sealed circuit including a cooling chamber, an evaporator and a condenser. Water vapor is transported within the circuit. During the day, sunlight heats the solar energy collector and thus the adsorbent. The adsorbent thereby releases adsorbed water, producing water vapor which is directed to the condenser. Water vapor is precipitated in the condenser because pressure is much lower in this component than in the solar energy collector. The condensed water is subsequently directed towards the evaporator where it is collected. At night, as the solar energy collector cools down, the adsorbent becomes ready to adsorb water vapor again. A three-way valve is turned over so that the absorbent can adsorb water vapor evaporating in the evaporator. Since evaporation consumes thermal energy, the temperature in the cooling chamber drops. That way, the adsorption process allows cooling of the chilling chamber at night and during the day the adsorbent is regenerated by using solar radiation (Figure 8).

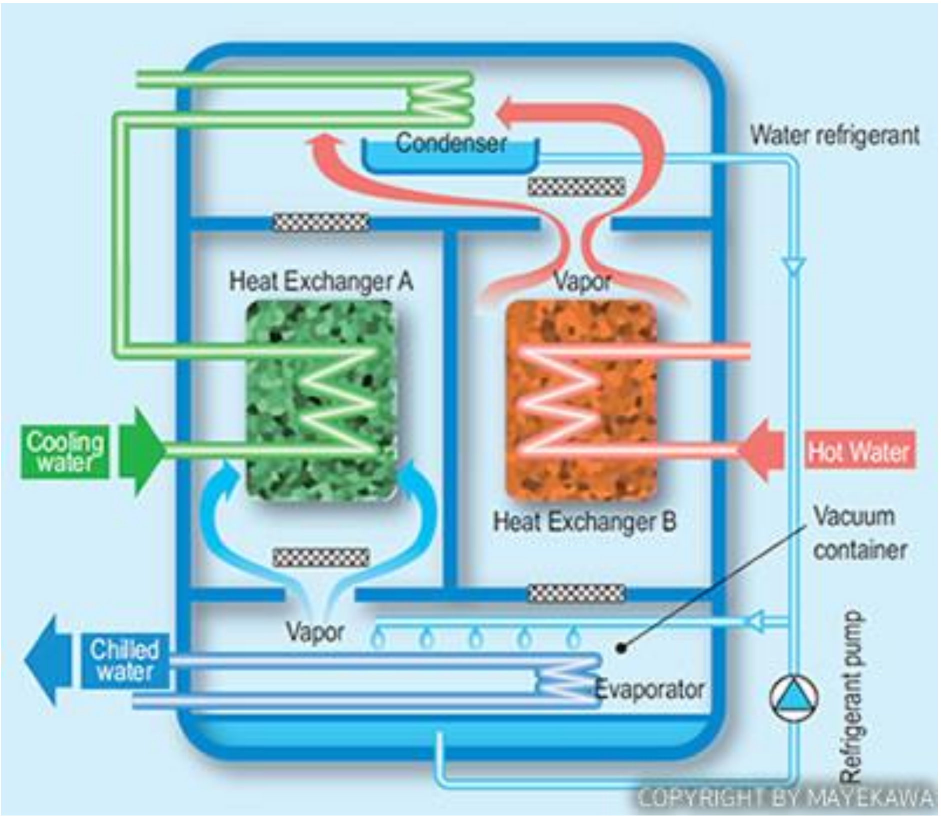


Figure 8: The adsorption cycle, a volumetric phenomenon, consists of two heat exchangers and its work is based on the condensation and evaporation of water [http://www.joules-project.eu/Joules/technologies/secondary_convertors, assessed on December 2016]

Adsorption chillers apply solid sorption materials instead of a liquid solution. Systems available in the market today use water as a refrigerant and silica gel as a sorption material. Under typical operating conditions, at about 80°C, the systems achieve a COP of about 0.6 but operation is possible even at heat source temperatures of approximately 60°C. The capacity of the chillers ranges from 50 to 500kW of chilling power.

Adsorption's technology advantage is that it can accommodate high temperature heat sources without corrosion, whereas corrosion occurs above 200° C in absorption technology. Adsorption technology is better equipped to handle vibration issues in a cooling system than absorption technology. Because of the liquid absorbent present in an absorption system, vibrations can cause serious problems, such as flows from the absorber to condenser or from the generator to evaporator, potentially polluting the refrigerant. Adsorption is immune to this condition. An adsorption system is also simpler to design than an absorption system. For example designing an absorption system with a H_2O/N_{H3} working pair, extra equipment is required because the boiling points of water and ammonia are very close [23, 24, 26, 28, 39].

1.6.3 Desiccant cooling

Desiccant cooling systems utilise a liquid or solid desiccant material to dehumidify air. After dehumidification, the air is dry enough to enable an evaporative cooling process to cool air well below ambient temperature conditions. This air is then supplied directly to the building. This is an open cycle process, in contrast with the absorption and adsorption cycle, where the cooling process makes use of water as the refrigerant and air as the delivery media. Desiccant cooling systems have been used extensively in certain applications (e.g. supermarkets) where the ability to independently control air humidity provides additional benefits.

The system is composed of three major components: the dehumidification unit, the regeneration unit and the cooling unit (heat exchanger evaporative coolers – will be explained below). The liquid desiccant is pumped into the dehumidification unit, where it is distributed over a large surface area and comes in contact with the humid air stream from which it absorbs moisture. The resulting diluted desiccant is fed to the regeneration unit to re-concentrate the diluted solution to an acceptable concentration for reuse, in order to maintain continual operation of the cycle. The cooling unit cools the dehumidified air, this could take the form of direct evaporative space. However, before being delivered to the room, a part of the mixed air was diverted as the secondary air to provide the evaporative cooling, and then released as exhaust (Figure 9).

The evaporative cooler can take the form of direct, indirect or semi-indirect. Relative to the direct type, the indirect type is generally less effective. Nonetheless, a certain variant of the indirect type – namely dew-point evaporative cooler – is found to be the most effective amongst all. Direct evaporative cooling is simply when water evaporates into the air to be cooled, simultaneously humidifying it, as it is being cooled. In contrast, for indirect evaporative cooling, the air to be cooled is separated from the evaporation process, by a heat exchange membrane, such that it is cooled without been humidified. Generally conventional desiccant cooling cycles require temperatures of around 80° C for adequate dehumidification.

Advantages of desiccant cooing systems are:

- Environment friendliness
- Significant potential for energy savings

- Electrical energy requirements are about 25% of a conventional vapor compression refrigeration system
- Source of input thermal energy are diverse and include solar energy, waste heat and natural gas
- IAQ is improved due to higher ventilation rates and the capability of desiccants to remove air pollutants
- Operation at near atmospheric pressures ensures their construction and maintenance cost to be relatively simple
- Desiccant systems can be used for summer/ monsoon air conditioner as well as winter heating when regeneration energy can be used for heating

A complete configuration of a desiccant evaporative cooling system was presented by Elsarrag. In their proposed system, a wide range of outdoor air flow rates were used (450 to 1000 m^3/h). In their configuration, the outside air was initially cooled and dehumidified by the desiccant and then cooled via a direct evaporative cooler. Supply of air with temperature as low as 19 °C was obtained in a hot, humid climate.

Means of heat recovery: Some heat recuperative configurations employ heat exchanger to use the return air from the indoor conditioned space to pre-cool the dehumidified air before it is cooled by evaporation. Another heat recuperative approach commonly encountered is the linking of the absorber and regenerator via a liquid-to-liquid heat exchanger to reduce the regenerator residual heat dumping back to the conditioner. Here, the cool dilute desiccant from the outlet conditioner was used to precool the warm concentrated solution transferred from the regenerator to the conditioner. This improved the dehumidifier performance and also reduces the heat input to the regenerator by 10–15% [15, 28, 33].

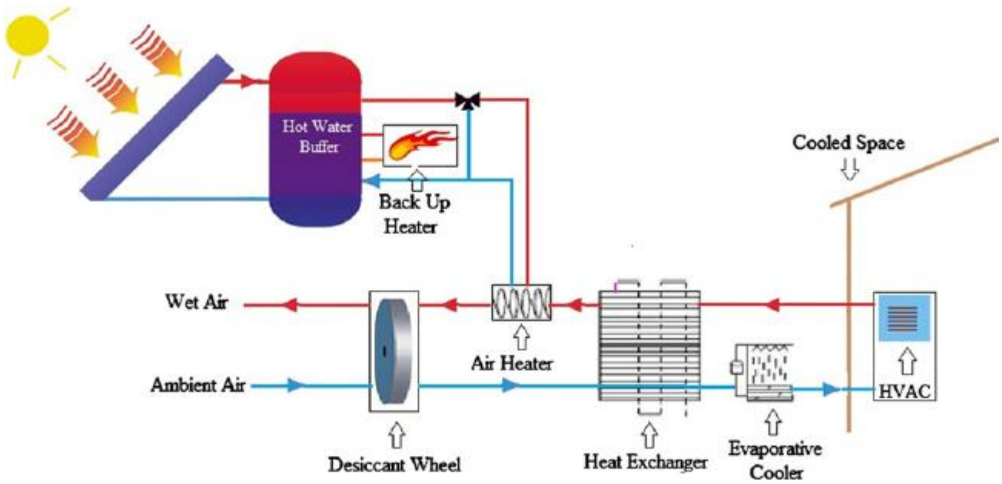


Figure 9: A desiccant cooling system, where the air is first dehumidified and then drived through an evaporative cooling process [https://www.researchgate.net/figure/257548531_fig2_Fig-2-A-schematic-of-solar-desiccant-cooling-system, assessed on December 2016]

1.6.4 Hybrid / Ejector cycle

The ejector cycle consists of an ejector, a condenser, an expansion valve, a circular pump, a generator, and an internal heat exchanger. The hybrid cycle is essentially an ejector cycle, as explained below, with an auxiliary condenser for the times solar energy is not enough. The collected solar energy is delivered to the refrigerant in the generator to evaporate the refrigerant into saturated or superheated vapor. The refrigerant vapor then flows into the ejector and is depressurized and accelerated inside the driving nozzle of the ejector. The high-speed, low-pressure driving flow is used to absorb the low-pressure suction flow from the internal heat exchanger. The driving flow and suction flow then mix with each other inside the mixing section of the ejector, and they are pressurized inside the diffuser of the ejector. The mixed flow enters the condenser and is condensed into saturated or sub cooled liquid. Finally, the condensed liquid is divided into two streams: one is pressurized and circulated back to the generator, and the other is depressurized by an expansion valve and delivered to the internal heat exchanger. Inside the internal heat exchanger, the refrigerant of the ejector cycle is used to cool the refrigerant of the vapor compression cycle, reduces the condensation temperature of the vapor compression cycle, and therefore reduces the energy consumption (Figure 10). When the ejector cycle is unable to provide enough cooling ability to the vapor compression cycle, the vapor compression cycle can release heat to the outside air through an auxiliary condenser. When there is no solar energy available, the hybrid cycle may reduce to a simple vapor compression cycle.

The COP of the hybrid cycle is the product of the *COPERC* and the *COPVCC*. However, for a given cooling load, the collected amount of solar heat may be higher or lower than that needed to provide sufficient cooling capacity for the internal heat exchanger. Usually, an auxiliary condenser is needed to release excessive heat to the environment. Considering the inherently variable nature of solar energy, such an auxiliary condenser is essential for a hybrid ejector-vapor compression system.

The advantage of the hybrid cycle is that in the heating mode, the collected solar heat is used to elevate the evaporation temperature, thereby enhancing the system performance The COP of the system increases with the evaporation temperature. If the hot water from the generator reaches 20~30 °C, the evaporator temperature could increase from 5 °C to 15~20 °C. This would result in an increase in the COP from 4 to 10, about 2.5 times that of the conventional cycle, and a reduction of about 50% to 60% in energy consumption in winter.

The COP of both the independent cycle and the hybrid cycle increases with an increase in collected heat. When there is no heat input, the two cycles take the same COP. For the independent cycle with higher solar heat, the cooling capacity provided by the ejector cycle increases, resulting in lower energy being consumed for the vapor compression cycle. Therefore, the COP increases steadily with the input heat. For the hybrid cycle, a similar increase in the COP versus the input heat can be seen. However, by increasing the evaporation temperature of the ejector cycle while decreasing the condensation temperature of the vapor compression cycle, the COPs of both cycles are enhanced, resulting in a higher system COP than that in the independent cycle.

The higher the solar heat input, the higher the system COP obtained. However, in practice, the cycle usually works with limited available solar heat. The temperature at the internal heat exchanger should be adjusted to obtain the maximum system performance according to the solar heat and required cooling capacity. The previous section demonstrated that the proposed hybrid cycle can provide higher energy efficiency than can a conventional cycle, thereby reducing the energy consumption.

For example in an office with a total floor area of 144 m^2, the collector area is assumed to be ½, 1/3, or 1/6 of the floor area. The solar collector is a vacuum-tube type solar collector. Standard annual climate data for Tokyo during the period 1991~2000 are used. When the installation area is half of the floor area, hybrid ejector cycle can provide sufficient cooling capacity at noon when the solar radiation intensity is high. The auxiliary cycle does not work under this condition. However, at earlier times or in the afternoon, the ejector cycle is unable to provide sufficient cooling capacity, and the auxiliary cycle must be operated [11, 31].

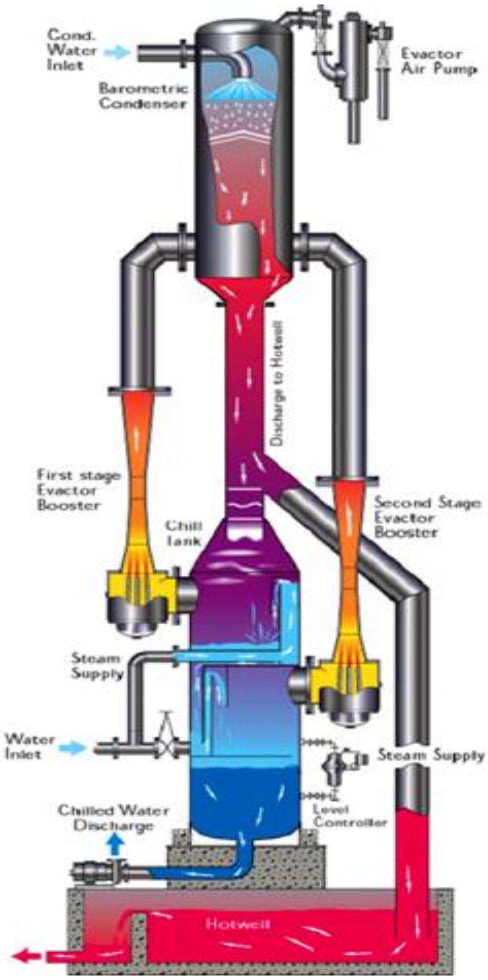


Figure 10: An Ejector cycle (Hybrid) consisting of an ejector, a condenser, an expansion valve, a circular pump and a generator, the hybrid nature is gained through the backup (auxiliary) generator [11]

1.7 Means of Phase Change in Photovoltaics

Vapor compression

Vapor compression machines generally comprise a mechanical compressor, a condenser, an expansion valve and an evaporator arranged in a closed loop, which transform the refrigerant into different thermodynamic states. First, vaporous refrigerant is compressed and heated in the compressor, transforming the refrigerant into a state at which it can subsequently be condensed to a liquid in the condenser. During the condensation process, the refrigerant yields thermal energy to the condenser, which is absorbed and removed by cooling water or cooling air. The condensed refrigerant is then directed to an expansion valve where it experiences a steep decrease in pressure, abruptly vaporising part of the liquid refrigerant and cooling the mixture of liquid and vaporous refrigerant. The cooled mixture is further directed to the evaporator where ambient air of the space to be cooled is routed through the evaporator in order to vaporise the liquid portion of the refrigerant. In doing so, thermal energy is extracted from the air which is chilled. Finally, the vaporous refrigerant is returned to the compressor and the loop is closed (Figure 11). The development of vapor compression technology essentially started in the 19th century [34].

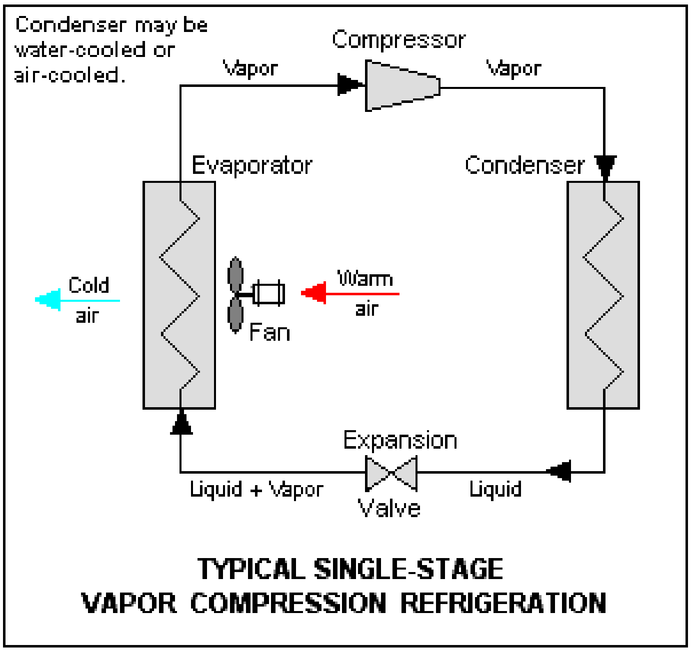


Figure 11: : The image above displays the steps of vapor compression of air, the process starts with the intake of warm air and proceeds clockwise until both air and water provide cold air [http://www.allsubjects4you.com/refrigeration-systems-and-cycles.htm, assessed on December 2016]

Evaporative cooling

In evaporative cooling devices, refrigeration is generally achieved by evaporating a liquid. Evaporation consumes thermal energy which lowers the temperature of the substrate on which evaporation takes place, and thereby also of the neighbouring material. The most common are evaporative systems where water is evaporated into air. Evaporative cooling devices are mainly used for air-conditioning. Evaporative cooling may be achieved by direct air-cooling, indirect air-cooling, a combination of both or combined with other refrigeration techniques. In direct evaporative cooling devices, water evaporates directly from an evaporative pad or from a water spray component into air. The evaporation extracts thermal energy from the environment, corresponding to a decrease in temperature. In addition, the evaporated water may humidify the environment. In indirect evaporative cooling devices, water evaporates into a so-called secondary air stream through the channels of a heat exchanger, which cools air flowing in a primary air stream (Figure 12). This two-stage process ensures that the evaporated water is never in direct contact with the space to be refrigerated. Evaporative cooling devices as such do not require solar energy; however, they may use solar energy for heating the surface of a substrate containing water in order to increase the evaporation rate. The evaporation rate increases because the air into which the water vaporizes is heated; which increases the capacity of the air to absorb water vapor [15].

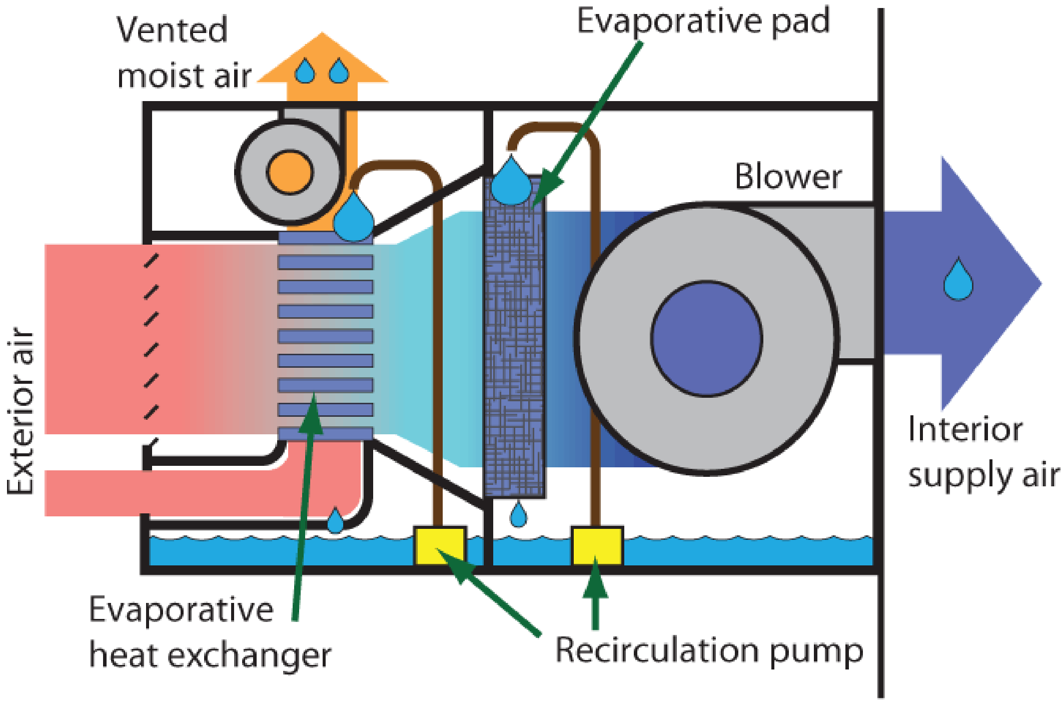


Figure 12: A guide through the evaporative cooling process of a liquid that produces chilled, humid air [https://www.pinterest.com/pin/134967320059243012/, assessed on December 2016]

Solar ejector cooling

Solar ejector cooling devices rely on so-called ejectors that use the "Venturi" effect and perform the task of a thermally-driven compressor in a heat pump refrigeration cycle. A fluid is directed through a nozzle type ejector, which narrows in a first section and widens in a second section. Accordingly, the velocity of the fluid increases in the first section while the pressure decreases, creating a low-pressure zone in the suction chamber where a second fluid can be drawn in. Both fluids mix and approach the exit of the nozzle in the second section where the mixture is slowed down and pressure increases again. In solar ejector cooling devices, the second fluid, mostly water vapor, is generally drawn in from an evaporator. As a consequence, additional water is vaporised in the evaporator and thermal energy is extracted from that component, chilling the component and its surroundings (Figure 13). Solar ejector cooling devices range from small and simple-to-use machines to complex devices for industrial applications [11, 31].

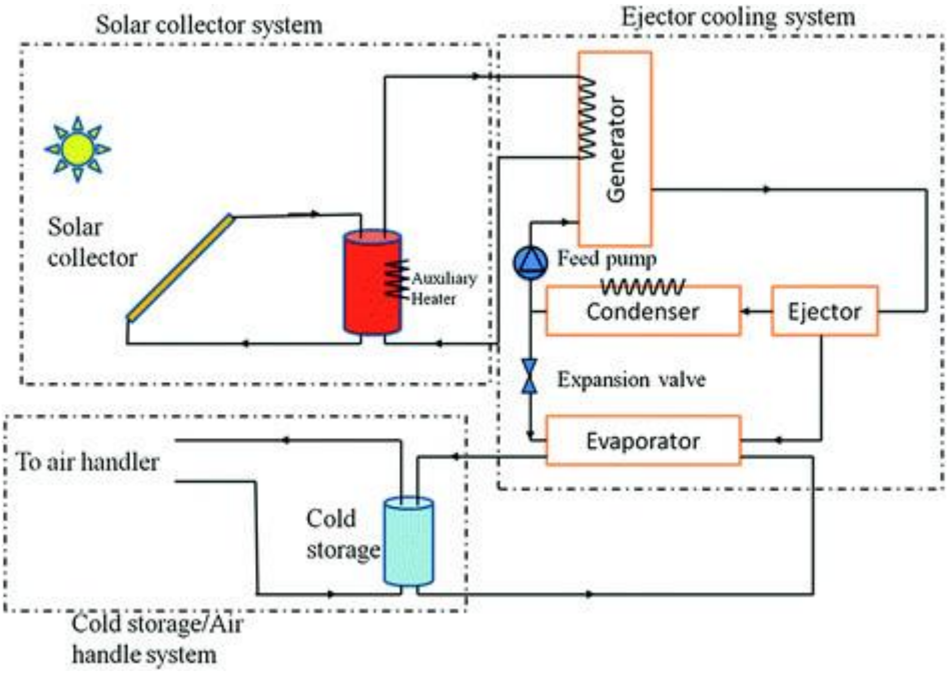


Figure 13: The ejector cooling system, a process that requires the change of the velocity and pressure of the fluid in use and acts like a thermally-driven compressor [https://www.researchgate.net/figure/278391855_fig3_Figure-1-91-A-preliminary-design-of-solar-driven-ejector-air-conditioning-system, assessed on December 2016]

1.8 Heat Rejection Systems

Heat rejection is the excess heat from a cooling system which is removed by the condenser/cooling tower. Heat rejection is the total amount of heat energy which is transferred from the cool side to the warm side, plus the work carried out by the compressor. A cooling system transfers an amount of energy from the cool side to the warm side, along with the power that is fed to the compressor in order to transfer that energy. Most of the added energy is transferred to the coolant via the work carried out by the compressor. Thus, the amount of energy to be removed from the warm side of the cooling system is the sum of the transferred energy and the added energy. This total amount of heat energy is called heat rejection and is removed by the condenser/cooling tower or other system which will be explained below in detail.

The choice of heat rejection solution is critical to the electrical power consumption of the thermally driven chiller. The possible lowering of the electrical consumption compared to traditional cooling solutions is in many cases the driving force towards utilizing the solar energy for cooling. Investigation of many installations shows that up to 50-60 % of the total electrical consumption is used in the heat rejection system, depending on the type and design of it. Therefore selecting the right heat rejection system is crucial to the economics of a solar cooling/heating system. .

Different heat sinks are possible to reject the excess heat, e.g. air, ground or water (river, lake, sea etc.). While the use of ground and water depends strongly on the local conditions, air is available for almost all applications and this is usually the preferable mean of heat exchange. For the rejection of heat to the ambient air, generally two types of systems are available: Cooling towers (open or wet cooling towers and closed cooling towers) and Dry coolers or a combination of those. Notable hybrid heat rejection solutions are the adiabatic pre-cooling of the air in a dry cooler and the hybrid cooling towers. The main difference between these technologies is that in the dry cooler the cooling water rejects the heat to the air via a heat exchanger whereas in wet cooling towers the cooling water is sprayed into the air and combined heat and mass transfer takes place. Thus in dry coolers only sensible heat and in cooling towers mainly latent heat is exchanged. A further option is to use ground coupled systems (geothermal probes) for heat rejection. These systems are well known as low temperature heat sources for ground coupled heat pumps and as heat sink for non-mechanical cooling systems. The performance strongly depends on the ground characteristics and an accurate dimensioning. They are complex systems and more details need to be taken into account during their design in comparison with the more standard cooling tower or dry cooler. What's more they are usually more useful in large installations [7, 21].

Dry Cooler

Dry coolers consist generally of finned heat exchangers (air to water), fans and a casing. The water circulates in a closed circuit and by passing ambient air over the finned surfaces the heat is rejected to the air. With air-cooled heat exchangers, it is not possible to cool the medium to below the ambient dry bulb temperature. In this case the approach temperature between the water outlet temperature and the inlet temperature of the dry air depends mainly on the size and capacity of the dry cooler – typical values of approach temperatures are 5 to 9 K (Figure 14). Dry coolers are often used for cooling refrigerants, oils or water/glycol mixtures. Compared to wet cooling towers they have lower operational and maintenance cost and because the cooling water does not come in direct contact to the air they have no hygienic problems or legionella risks. Further advantages are little noise, easy installation and a low profile. The main disadvantages compared to wet cooling towers are higher heat rejection temperatures, higher investment costs and parasitic energy consumption for the fan and space requirement.

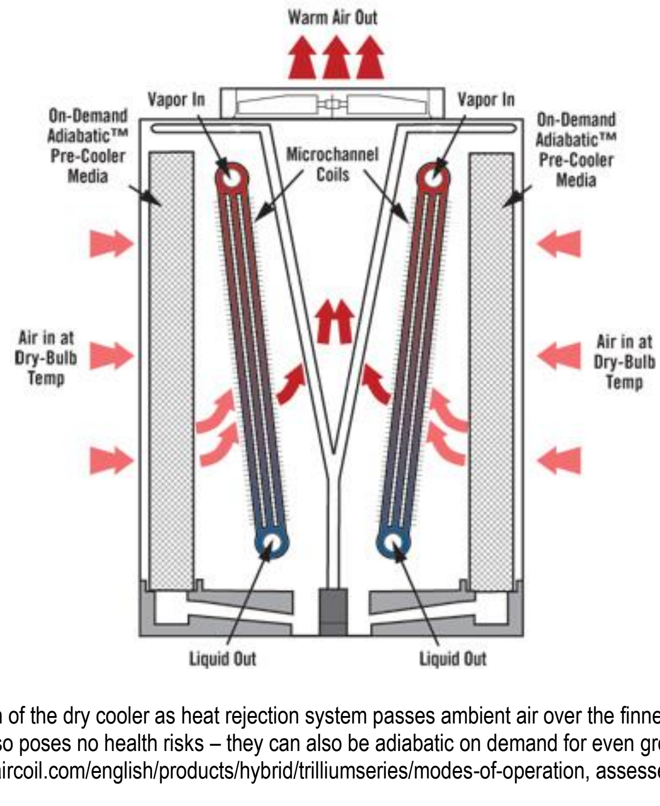


Figure 14: The simple solution of the dry cooler as heat rejection system passes ambient air over the finned surfaces and heat is rejected to the air, it also poses no health risks – they can also be adiabatic on demand for even greater efficiency [http://www.baltimoreaircoil.com/english/products/hybrid/trilliumseries/modes-of-operation, assessed on December 2016]

The performance of a dry cooler can be improved by pre cooling the air through the evaporation of water. The simplest way is to spray water into the intake air but caution is needed because solutes (for instance salts) will be deposited on the surface of the cooling coil and fins, even if all the water is evaporated before the air enters the cooling coil. Water treatment can reduce this, but further the risk of pollution from the ambient air (for instance acid) exists. Water usage also adds to both installation and operation cost. Different (but more or less the same) sophisticated systems exist but one has to be very careful concerning the drift of water into the cooling coil [7, 21].

Evaporative pre cooled dry coolers

Evaporative pre-cooled coolers are a subcategory of a regular dry cooler. It consists of a water wetted pad through which the ambient air is drawn before it enters the dry cooler. The cooler is not to be seen as a cooling tower: The air is evaporative cooled near the wet bulb temperature when passing through the pad after which the heat is rejected as sensible heating of the air in the dry cooler. Compared to the cooling tower where the whole heat is rejected through evaporation of water this reduces the water consumption down to less that 10% (depending on the ambient condition), but the efficiency is also lower that the cooling tower. If the air temperature is low enough, the cooler can operate as a dry cooler, although the pressure drop through the pads will cause a higher electrical consumption for the fan [7, 21].

Hybrid dry cooler

Another dry cooler subcategory is the hybrid dry cooler which combines dry cooling and evaporative cooling into the same heat exchanger. The cooling water is circulated by a pump in a closed primary cooling circuit from the heat source to cross current air to water heat exchanger. In cool weather conditions, this process cools down the cooling water sufficiently and the hybrid cooler operates like a dry cooler. At high air temperatures the hybrid cooler uses the principle of evaporative cooling in order to achieve lower cooling temperatures. Therefore, a pump circulates water from a basin to the cooling element where the water flows back via the finned surface of the air to water heat exchanger. The air flowing past the heat exchanger causes the water to evaporate on the fin surface, and takes the heat from the fins. Compared to common dry cooler a hybrid dry cooler has the advantage of using evaporative cooling at hot weather conditions and therefore cools down the cooling water below the dry bulb temperature, it also has a higher capacity and lower energy consumption. On the other hand the hybrid dry cooler has higher investment costs, maintenance effort and water consumption. Furthermore, hygienic measures have to be taken for the hybrid dry cooler to work properly [7, 21, 33]

Adiabatic dry cooler

An adiabatic dry cooler is somewhere between an evaporative and a hybrid dry cooler and is gradually gaining popularity. They are cost effective evaporative coolers, designed to operate at optimal efficiency in high ambient temperatures. The units use fans to operate the cooling for a high percentage of the year with a spray system which only activates during periods of high ambient temperatures. The spray activity is tightly monitored using a pulsing mechanism to ensure minimum adiabatic cooling is provided for any given load and ambient condition. This control reduces water consumption and running costs for a long, fault free lifespan. Adiabatic coolers are designed to pre-cool the air inlet stream into the heat exchange coils. By increasing the relative air humidity the temperature is lowered in order to achieve an effective air-on-temperature as low as 5^{o}C above the wet bulb temperature. The system operates by taking the heated fluid from a process through the condenser where for 95% of the year fans draw in cool air, reducing the fluid temperature and returning it at the required temperature to the rest of the process (Figure 15). Where the ambient temperature is high, adiabatic coolers utilise cold water (through a filter to kill any bacteria) by spraying a fine mist into the incoming fan-induced airflow. This creates a reduced air intake temperature, allowing greater efficiency and improved cooling. Proof of the adiabatic dry cooler's effectiveness is that it can easily achieve a 25^{o}C circulating air temperature while this ambient is 35-36^{o}C [7, 21, 33].

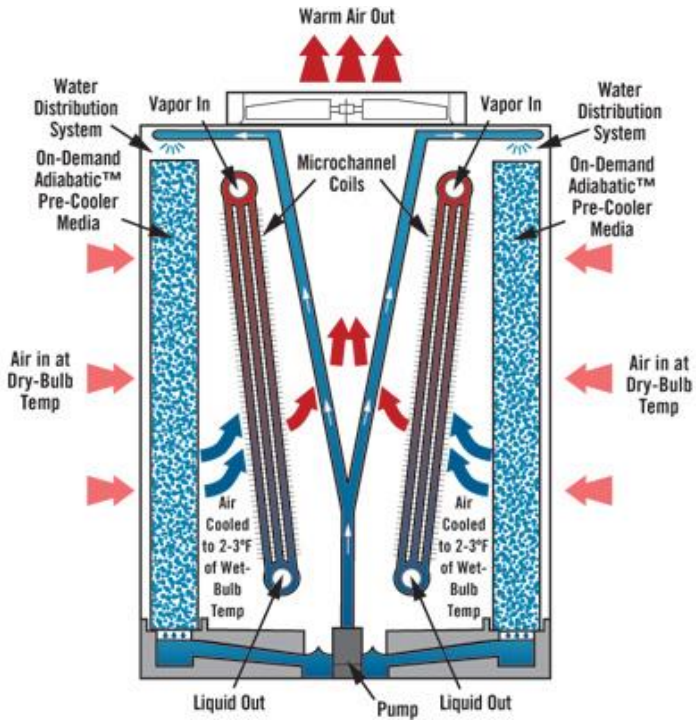


Figure 15: The difference compared to the conventional dry cooler is that the fluid is cooled adiabatically, with minimal to no heat loss [http://www.baltimoreaircoil.com/english/category/blog, assessed on December 2016]

Cooling tower

Cooling towers use the evaporation of water as a cooling method. The lowest achievable temperature is the wet bulb temperature of the ambient air. The wet bulb temperature is depending on both the dry bulb temperature and the moisture content of the air. Cooling towers can either be open type, where there is direct contact between cooling water and the air stream in the tower or closed type (the opposite). The open loop wet cooling tower consists of a shell containing fill material with a large surface area. Nozzles arranged above the packing, spray and distribute the cooling water. The water trickles through the packing into a basin from which it is pumped back to the chiller. The water is cooled by air which is drawn or blown through the packing with the use of a fan. The air flow, which is either in counter or cross flow to the water flow, causes some of the water to evaporate, thus latent heat is exchanged between the water and the air (Figure 16).

Evaporation also increases the concentration of the dissolved solids in the cooling water and blow down of the cooling water is therefore necessary. In wet cooling towers the wet-bulb temperature determines the degree of cooling and thus cooling below the ambient dry bulb temperature is possible. The characteristic approach temperature, which is the difference between the water outlet temperature and the ambient wet-bulb temperature, of open wet cooling towers lies between 4 to 8 K. Compared to dry coolers wet cooling towers are able to cool the cooling water to a lower temperature level, require less space and have lower investment costs. The open loop wet cooling tower has the risk of fouling the heat transfer surfaces with dirt and dust from the air. Biological material is usually used to rinse out the excess filth. This is eliminated in closed cycle wet cooling towers as the cooling water is cooled in pipes over which water is distributed and evaporates. Compared to open type wet cooling towers the approach temperature is higher but still lower than the dry coolers. Due to the more complex design the investment cost is higher, but the running cost is lower. In general, the main disadvantages of wet cooling towers are hygienic problems, water consumption and high maintenance effort. It's a classical, yet very effective solution but an expensive one on the long run [7, 21].

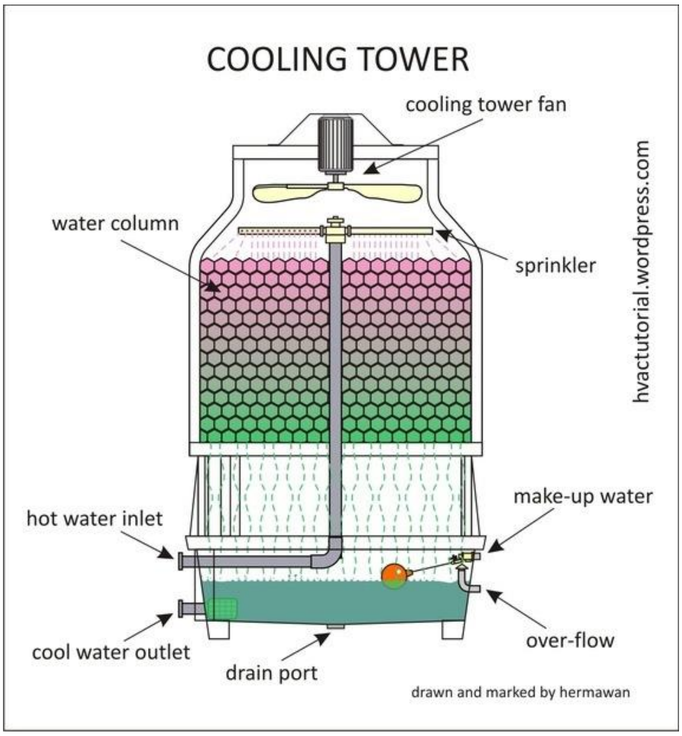


Figure 16: In a cooling tower water is the circulating fluid that evaporates and produces the desired cooling effect and are usually combined with absorption chillers [https://www.quora.com/How-do-cooling-towers-work, assessed on December 2016]

Dry cooler vs. cooling tower

The main difference between these technologies is that in the dry cooler the cooling water rejects the heat to the air via a heat exchanger and in wet cooling towers the cooling water is sprayed into the air and combined heat and mass transfer takes place. Thus in dry coolers only sensible heat and in wet cooling towers mainly latent heat is exchanged (Figure 17) [7, 21].

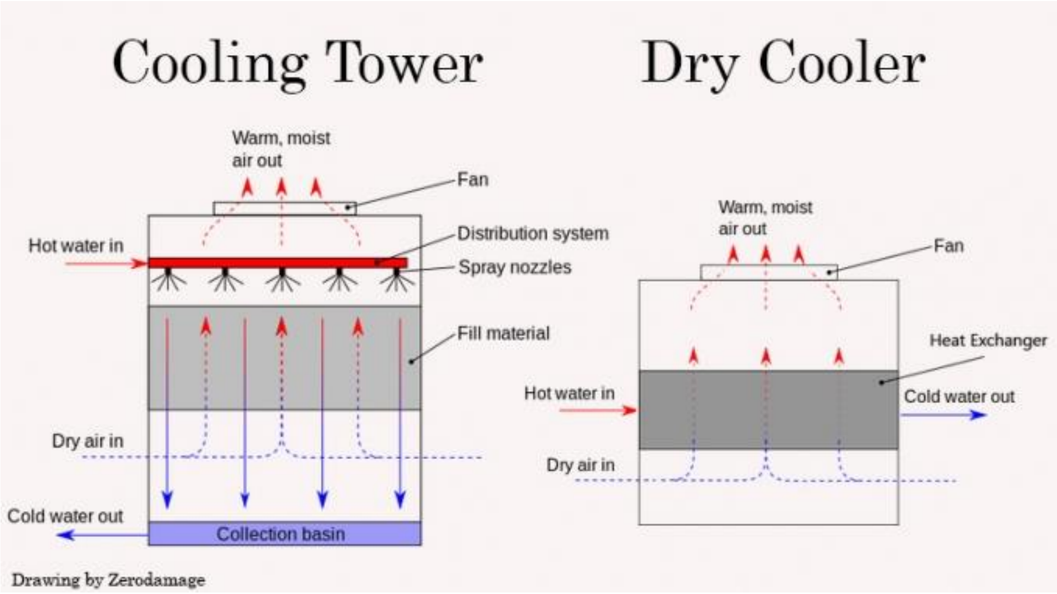


Figure 17: In the image above a graphic comparison between cooling towers and dry coolers is displayed, the cooling tower's design is more complex, because it uses water as a circulating means [http://surna.com/wp-content/uploads/2015/09/CoolingTowerDryCooler-680x380.jpg, assessed on December 2016]

Vertical and Horizontal Heat Exchangers

The horizontal ground heat exchanger is designed to be used as a cooling storage capacity in the ground. Heat exchanger made of polymer tubes is put at 0.5 to 2 m depth into the ground in order to reject heat. It is connected to the heat rejection circuit of a thermally driven chiller. This heat rejection technology is interesting for the following reasons: no need of any wet or dry cooling tower leading to far less electricity consumption, low heat rejection temperature (less than 30°C) if the geothermal heat exchanger is well designed, ease of implementation of the horizontal probe network for new buildings during the civil works phase, and the possibility to use these heat exchangers during winter in heat pump mode. The heat transfer in horizontal ground heat exchangers for heat rejection systems depends above all on the kind of soil. In all cases of applications the soil should be natural and not a man-made earth deposit. Regarding the guideline VDI 4640 [VDI 2001] the following specific heat transfer numbers can be expected: 10 W/m2 soil surface for dry solid soil, 20 to 30 W/m^2 in moist soil and up to 40 W/m^2 for a water saturated soil (Figure 18). Thanks to a horizontal ground heat exchanger, it is possible to use very little electricity consumption to run the pump connecting the chiller to the heat rejection loop (only 25 W/kWh for a 4.5 kW chiller). Economically speaking, this solution is more expensive than a traditional wet cooling tower system (more than double cost) due to the significant length of polymer pipes but on a 20 years global cost calculation (avoidance of water treatment and water consumption), this investment is more interesting, especially for new buildings (civil works to burden the pipes more or less free) and for countries where legionella protection legislation consequences make wet cooling tower management expensive.

Boreholes are vertical ground coupled heat exchangers. They are of special interest in cases of little available surface area. The vertical boreholes use the relatively constant low temperature in the soil. Temperature fluctuations can be measured only down to a depth of 15 m. Below 15 m depth the temperature is generally stable over the seasons with less than 10°C declination. This temperature increases every 30m depth by 1 °C. For four kinds of soils the guideline VDI 4650 [VDI 2009] provides the following specific heat transfer values: 30 W/m in dry soil, 55 W/m in schist or similar stone, 80 W/m in solid rock and 100 W/m in a soil with significant ground water flow. Geothermal boreholes are carried out as tube heat exchangers made of a plastic material (high density polyethylene tubes). They are installed in vertical holes drilled into the ground. In order to improve the thermal contact with the ground and seal the borehole, a special sealing material (cement or bentonite) with high thermal conductivity is used. Boreholes are normally drilled down to a depth of about 100 m, but this depends on the geology of the ground and the intended use. An important figure is the specific heat capacity of the borehole. However, this is not the only important characteristic: the number of operation hours and thus the total amount of heat extracted annually is a decisive factor for the long term performance of a borehole system. While the specific heat capacity is a factor that is important during the actual operation of the borehole, the total extracted heat is the factor that determines the long term reliability and thus if the borehole can be considered as a renewable resource. Thus, the real specific power has to be calculated for a long period of time (15 to 30 years) taking into account the hours of full load operation per year (Figure 18).

It is generally recommended that a qualified advice and expertise should be obtained before the drilling of a borehole (or any horizontal geothermal probe). Information about imposed conditions such as the expected kind of soil and the heat transfer should be obtained [7, 20, 21].

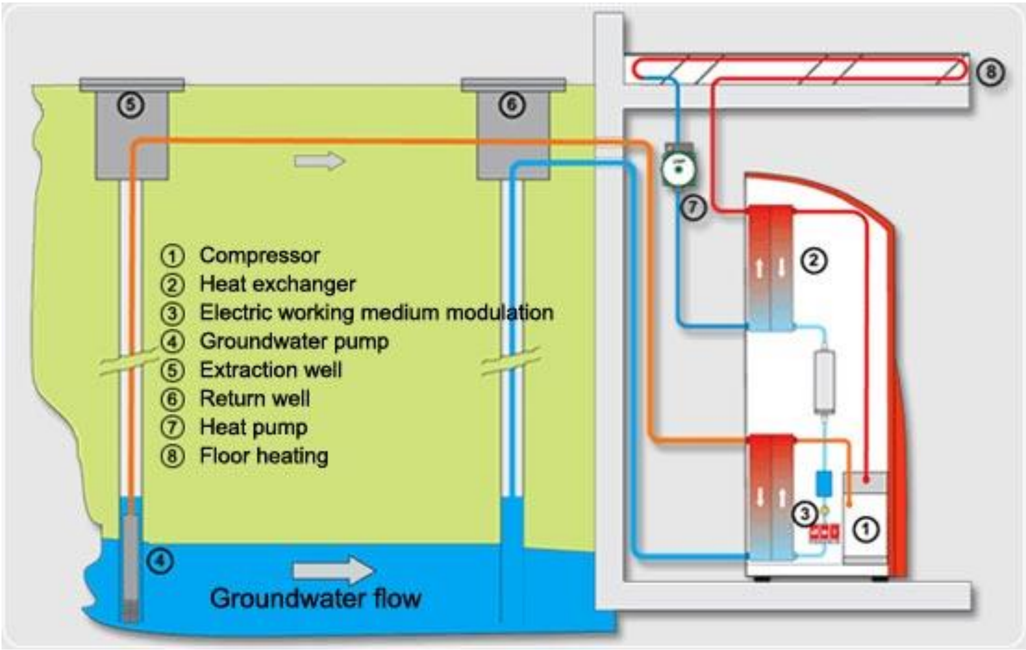


Figure 18: Ground heat exchanger, where ground/soil plays a key role in the heat rejection, both vertical and horizontal ones work similarly [http://www.brunnenbohr.com/geothermal-water.html, assessed on December 2016]

1.9 Role of humidity in solar cooling

Temperature and humidity of ambient air are two critical factors that determine comfort levels of occupants in a given space. In hot climates, it is desirable to reduce the ambient air temperature (cooling) to improve comfort levels, however in hot and humid climates, removal of moisture from the air (dehumidification) is almost as important as cooling. Anyway, dry air is much easier to heat or cool in contrast with humid air.

For instance in locations with very high annual cooling load hours such as the dry hot climate in Riyadh (Saudi Arabia) or the humid and hot climate of Jakarta (Indonesia), the solar fractions drop to a maximum of 75% in Riyadh for a well-insulated building with high loads and to only to 46% in Jakarta. For Mediterranean locations, like Greece, the specific costs decrease with increasing absorption cooling machine fractions, if absorption cooling machines are dimensioned higher. In hot regions there is only a slight difference of the specific costs for higher absorption cooling machine fractions and increasing absorption cooling machine dimensions. A large dimensioning of the absorption cooling machine with a maximum absorption cooling machine fractions is more competitive in desert locations.

Conventional air conditioning systems (for example vapor compression systems) address these issues by cooling air below its dew point, such that water vapor condenses on a cooling coil, thus removing moisture from the air. The dehumidified air is then reheated to the desired temperature. This process of deep cooling to dew point and reheating consequently leads to higher energy requirement. Alternatively, desiccants can be employed to use their hygroscopic properties to dehumidify air. Studies have reported that desiccant systems can reduce energy consumption by as much as 40%. The air temperature is reduced by conventional cooling coils or other components such as evaporative coolers. However, the moisture impregnated desiccants need to be dried in a regenerator, in which the water vapor previously absorbed evaporated out from it by heating. The heat required to regenerate the desiccant can be supplied from low-temperature sources such as waste heat or solar energy. Utilising solar energy for this application is particularly interesting because the greatest demand for cooling occurs during times of highest solar insolation.

Desiccants are natural or synthetic substances, having a high affinity for water, capable of absorbing water vapor from their immediate vicinity. They are available in both liquid and solid states. Solid desiccants are compact and less corrosive. On the other hand, liquid desiccant offer several benefits, including, lower regeneration temperature, lower pressure drop of air across the desiccant material, suitability for dust removal by filtration, and flexibility in utilisation especially when handling large volumes of air. In addition to dehumidification, an added benefit of the desiccants is that they are capable of absorbing inorganic and organic contaminants in the air. The absorption process has the potential to remove biological pollutants such as bacteria, fungi and viruses so improving indoor air quality.

High temperature cooling is gaining more attention in commercial buildings of the tropical climates where temperature and humidity is high all year round. In this air-water system, radiant-convective cooling is provided into conditioned space through using higher chilled water temperature compared to conventional all air system. Radiant cooling panel, radiant slab cooling, passive/active chilled beams are the main design strategies for implementing this concept into buildings. The potential energy saving of this strategy was estimated to be in the range of 6~41% depending on design strategies and operational scenarios of system. Comfortable and healthy indoor environment is achievable for this design when a parallel air system satisfies latent load and ventilation requirement of space [12, 14, 15, 25, 38].

1.10 Energy Savings & Cost

In order to sum some things up, we need to mention the temperature at which each cooling system typically works at and the type of solar collector they utilise. Absorption chillers (single-effect) need water at 80–110 °C and can use vacuum tubes and flat plate solar collectors too, although it's more difficult using the latters. Double effect Absorption chillers need water at 120–150 °C and can use CPC collectors. Adsorption chillers need water at 60–90 °C and can use flat plate solar collectors or vacuum tubes. Desiccant cooling needs water or air at 45-90°C and can use flat plate solar collector or solar air collectors. It is also important to note that when considering the possible use of a heat pump, the sensitivity of the system to low and high temperatures should be taken into account. What's more, it is important to consider the temperature lift that the heat pump can achieve in relation to the cold source temperature.

Careful selection of the heating system in order to lower heat supply temperature is required before looking for higher level heat sources. It is not logical to operate with systems that need the highest temperature attainable by the machine (usually around 60 ◦C), when systems are available which can distribute the heat at temperatures lower than 35ºC (i.e. heating panels or all air systems). It could be shown that a reduction of nominal chiller power by 30% to 40% or more hardly affects the solar cooling fraction for most climates, but significantly increases the machine operating hours and thus improves the economics. The lower the nominal power of the chiller, the higher the recommended ratio of a collector surface area per kW. For a given machine nominal power, solar cooling fractions increase with collector surface area until saturation is reached. Collector surface areas can be as high as 5 m^2 to 10 m^2 per kW with still increasing solar cooling fractions, but acceptable specific collector yield reduction. The economic optimum is reached for less solar cooling fraction and thus lower primary energy savings. Single effect absorption cooling systems easily reach 80% solar cooling fraction for all but very humid climates. Primary energy ratios can be over 3.0, depending on system design and cooling load data. CO_2 and primary energy savings of 30–79% are achievable.

The most common heat pump source is outside air, but this is the least favourable in terms of thermodynamic properties. The main advantage of using air as a heat source is that it is free and immediately available. However, the potential advantages of alternative heat sources can be significant, because air has relatively poor thermodynamic properties compared to water, so it is important that each is fully evaluated at the design stage. Using different combination of solar cooling technologies, components and control strategies, in an experiment, the demonstration plants have achieved high solar fractions values with a sound economy, for some of the plants more than 70% of coverage for the space heating, domestic hot water and cooling loads was reached, so it's clear that the blend of different techniques and installations can take solar cooling to a whole new level of efficiency. In fact, many more solar cooling would be installed worldwide if not for the high initial cost and lack of knowledge and practical experience in design, control, operation, installation and maintenance.

Solar fraction systems by combing the two technologies of "solar combi" and "solar cooling" systems with innovative seasonal storage device systems have many advantages due to the fact that they allow the use of solar energy throughout the year, endeavoring to increase the primary energy savings in buildings and consequently to assist the further deployment of the solar energy market.

According to Aidonis the simulations for Greece showed that the solar combi systems can be combined with the conventional heating systems, giving high energetic results and solar coverage of the total heating load that can reach 40–50%. This applies to pretty much all solar-driven cooling systems in the Mediterranean which if they are designed carefully can achieve energy savings of more than 40%.

A good example of a solar thermal system's efficiency is an ECN (energy research centre of the Netherlands) research house equivalent to a 4-6 people house in the Netherlands. Nearly 2.5kW cooling power can be produced with a very compact chiller (power density of about 7kW/m^3) at a very respectable COP. The chiller in use is an adsorption chiller coupled with a dry cooler as heat rejection system. When applied in combination with measures to reduce overheating in summer (e.g. solar shading, night ventilation – passive cooling), it's expected that 2.5kW of cooling is sufficient to provide a comfortable indoor temperature. The targeted nominal performance of that new prototype is to deliver 2.5 kW chilled water at 15/20°C distribution temperature in one of the research houses at the ECN premises. The hot water temperature is between 80-90°C and the cooling water temperature is 35°C under nominal conditions. What makes this system that has just been described worth noting is the sole fact that only a 2.5kW solar thermal system is enough to cover these needs by making use of cutting edge solar cooling technology. Even with this relatively pricey system payback time is expected to be in less than ten years.

Another good example, although with the use of a more conventional system, is a ten people office in Cyprus, a country with vast amounts of sunshine. An absorption system coupled with a cooling tower is used and the collector type is flat plat collectors– more or less the typical small scale solar cooling system. The total collector area is 15m^2 capable of 6kW of nominal power when the difference with ambient temperature is 50^{o}C. The hot water storage tank is 1m^3 and the heat distribution is made with floor heating. The total initial cost is 14.700€ and the state sponsorship is around half that. The savings in energy both for heating/cooling and hot water production per year can exceed 1.500€ and payback time is just five years. In environmental terms around 60kg of oil per collector are saved each year [12-14, 22, 27, 35, 38].

1.11 Installations

In order to show the advantages of solar cooling systems some installations both in Greece and abroad will be explained in detail, which are only few of the many solar cooling appliances. Not only the type of solar heating/cooling installation will be explained but also the perks of such an appliance and the energy demand it can cover.

L' Amor Rouge Bakery, Nicosia, Cyprus

The bakery is located in the industrial area of Ergates in Nicosia. The building consists of the bakery, the confectionery and the offices with a total surface of 627m². L' Amor Rouge Bakery has been using the first solar cooling and heating system in Cyprus since 2006, with autonomy higher than 59%. The system is composed of 120m² vacuum tube collectors tilted 25° from the horizontal, a 6.8m³ hot water storage tank, a 70.3kW nominal power absorption chiller (LiBr and H_2O solution) and a 212kW nominal power cooling tower (Figure 19). Here are some techno-economic data:

- Annual needs of energy (for hot water, space heating and cooling): 213.65 MWh
- Back up heat source: oil
- Annual consumption of back up heat source: 21.191 L/year
- Back up heat source cost 0,77 €/L
- Number of collectors: 40
- Type of collectors: Vacuum Tubes
- Area of the absorber: 3 m^2
- Total area of the collectors 120 m^2
- Efficiency of the collector: 0.73
- Average daily radiation in plane of solar collector: 5.94 kWh/m^2 /day

Environmental and economic data: The total investment cost was 134.490€ and the percentage of the grant was 40% (53.790€). The payback time was calculated equal to 8.1 years. The solar fraction was estimated at 59.35%. Finally, the overall primary energy savings were estimated at 63.4MWh every year and the total CO_2 savings at 22.44 tons per annum. [41]

Figure 19: The first solar cooling installation in Cyprus, L'amour Rouge Bakery [41]

Center of Renewable Energy Sources, Athens, Greece

The plant is installed in an existing office building, at the site of the Centre for Renewable Energy Sources and Saving (CRES) in Athens. The building covers a total of 427 m^2 with a volume of 1296 m^3, was constructed in 2000. In 2008, the building was renovated and it is currently used as office. The Greek plant operates since December 2011. The plant design includes solar thermal collectors, seasonal underground thermal energy storage, a heat driven cooling machine, heat rejection units and a heat pump. In heating operation, hot water is provided to the building at 7^{o}C. During low demand periods, such as autumn, a large amount of thermal energy is stored with the purpose of recovering it at the following energy demanding heating period. The heat pump, which serves as auxiliary system, is driven by solar energy, resulting in increased COP. In cooling operation, the absorption machine provides chilled water to the building at 7^{o}C. Thermal energy, by the means of hot water of temperature over 65^{o}C, drives the cooling process. The estimated solar fraction is around 85% of the total thermal energy requirements of the building.

Solar thermal & cooling specs:

- Collector type: Selective flat plate (Figure 20)
- Collector area: 149.5 m^2
- Heating and cooling load respectively: 12.3 and 19.4 MWh/a
- Nominal cooling capacity: 35kW
- System's type: Closed cycle Absorption chiller (LiBr)
- Heat Storage: 58 m^3 (water underground thermal energy storage, cold storage N/A)

Auxiliary system: Heat Hump (water to water, driven by solar heat) with a nominal capacity of 18kW and a COP_{heat} of 7 [10].

Figure 20: Selective flat plate collectors in CRES, Athens, Greece [10]

Sarantis Cosmetics Warehouse in Oinofyta, Voiotia, Greece

2.700 m^2 of selective flat plate collectors provide hot/cold air to an area of 22.000 m^2 and the whole installation has been awarded with the Energy Globe Award 2001 as the third best investment for energy sustainable development in the world in 2001 and has been awarded from CRES as the best investment for energy savings in Greece, in 1999. The installation cost 1.305.950€ 50% was a state subsidy. It's an adsorption system that works at around 70-75^oC with a COP of 0.6, using water as a circulator, and is able to provide chilled water of 8^oC and hot water of 55^oC. The two adsorption chillers use a minimum amount of energy to power the heat pumps (only 1.5kW) and the usable cooling output is 350kW for each one of them. There are also three, 350kW each, backup electric-driven chillers for the summer and a conventional petroleum boiler for the winter. The whole solar system was built in Greece.

Environmental and economic data: The solar heat/cooling system is able of producing 1.720MWh per year and covers nearly 66% of the total energy demand. In fact, the heating needs are almost entirely covered by the solar system and only in the hot months of the year the backup chiller is often put to use. 5.125 tons of carbon dioxide is saved every year [8].

Rethimno Village Hotel, Crete, Greece

Built from SOLE, the same manufacturer as in the previous case, Rethimno Village Hotel utilises polypropylene selective flat plate collectors covering a total area of 448m^2 used to heat/cool and area of 3.000m^2. The solar collectors give power to an absorption chiller that uses 70-75^oC hot water and is able to distribute 8-10^oC chilled water. The cooling agent is, again, water. The system only consumes

0.5kWh and has a total power of 105kW. There is also a conventional backup natural gas boiler with a total power of 600kW.

Environmental and economic data: The installation cost 265.000€, 50% of which was a state subsidy and was awarded as the best energy saving installation in 2000 in Greece, from CRES. The solar heat/cooling system can provide 43% of the total demand in energy (1500MWh) and can save 1.1 tons of carbon dioxide each year [8].

Healthcare/Sports Center, Barcelona, Spain

The Spanish Plant is installed at a newly designed building, in the center of Barcelona. The building comprehends a healthcare center in the three lower floors, and 32 social housing flats for the elderly in the upper floors. The building has been designed and built according to the optimization criteria of AIGUASOL, through the detailed simulation and the proposal of different measures (including the optimal size of insulation, the glasses to be used and the size of the balconies).

The installed system consists of: 200 m^2 heat pipe evacuated tube collectors, a stratified storage tank, an absorption chiller, a compression chiller and a condensation boiler. The option to install geothermal heat exchangers was disregarded, due to substantially higher investment costs that could not be justified when energy price is taken in account. Additionally, the heat demand in winter is low and could be easily covered by the solar collectors. The optimization process led to an optimal driving temperature for the absorption chiller (75-80ºC) and for the optimal solar collectors' inclination (25^o). The main components of the Spanish Combi Plus plant are:

- Evacuated heat pipe tubes with water as fluid in the primary circuit (Figure 21)
- Absorption chiller capable of 70 kW with a cooling tower as heat rejection system
- Radiant floor for heating and cooling and dehumidification

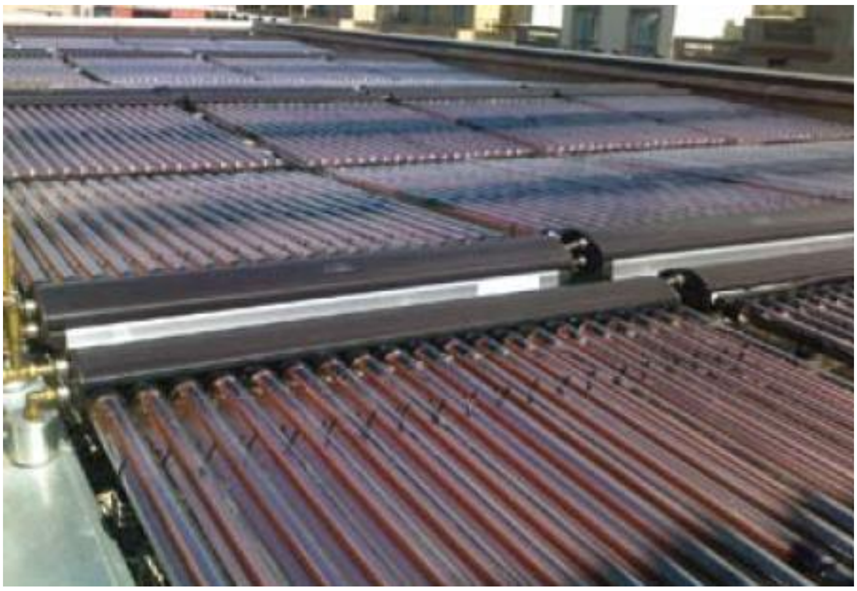


Figure 21: Vacuum tube collectors on the roof of the healthcare centre in Barcelona [10]

Energy production & Savings:

- Cold energy production: 60.418 kWh/year
- Heat energy production: 11.664 kWh/year
- Total energy production: 161.874 kWh/year (together with DHW)

0.12€ / kWc and 0.06€ / kWt_h are saved. The electricity and gas consumption for the healthcare centre every year is around 40.000 kWh so no less than 3.270€ are saved every year from the use of solar cooling and heating [10].

Solar cooling plant in Bolzano, Italy

In Bolzano, in northern Italy, three buildings are equipped with solar collectors assisted by one combined heat and power generator. One of the buildings houses the European Academy's (EURAC) Research Centre. In this same building a sophisticated monitoring system that is capable of collecting a large amount of data has been installed since 2005. Main features of the SHC-CHP installation in EURAC, Bolzano are:

- Solar collectors, gross area: 615 m^2
- 1 Cogeneration Unit: 180 kWe/ 330 kWth
- 2 Condensing boilers: 350 kWth each
- 1 Absorption chiller: 300 kWc
- 2 Compression chillers: 315 kWc each
- 2 Solar tanks: 5m^3 each
- 1 Cold tank 5m^3

The first three compose the heat production facility, the following two the cold production facility and the last two are the storage tanks.

Figure 22: Vacuum tubes collectors on the roof of EURAC, Bolzano [41]

Solar vacuum tube collectors, with a gross absorber surface of 615m^2, provide heat not only for heating purposes and sanitary hot water production, but also for feeding the absorption chiller during the summer (Figure 22). One co-generator and two condensation boilers supply the heating requirement which exceeds the solar fraction. Cooling is provided by the absorption chiller being assisted by two compression chillers, covering the peak demand. The monitoring system includes 13 heat meters and 3 electricity meters. Values are measured every minute and gathered at a central server. One critical aspect within this plant is the presence of a hydraulic junction where all the hot and cold streams are mixed, in particular the ones of the co-generator and the solar loop which often have different temperatures, especially in winter. The monitoring system has demonstrated that the control strategy influences the performance of the single devices, in particular of the solar collectors, the cogeneration unit and the absorption chiller [41].

Chamber of Commerce of Freiburg, Germany

In the chamber of commerce (IHK) is used the first autonomous thermally driven desiccant cooling system, in use from 2001. It's used to heat/cool two big conference rooms 65m^2 and 148m^2 respectively and the building is relatively well insulated. The desiccant system can provide anywhere between 2.500 and 10.200 m^3/h of air. There is no conventional backup system for the summer season, but there is one for the cold months. The flat plate collectors cover an area of 100m^2 and are tilted 15^o from the horizontal and there is no heat storage tank. The collectors can fully provide (100%) the chilled air in the summer and even with a lot of heat hitting the building temperature is kept between a tolerable deviation from the ideal.

Environmental and economic data: The cost of the solar collectors was 210€ / m^2 with installation cost included and the cost of the solar cooling system amounted to 9.50€ per m^3 of air supply, excluding installation cost. The solar cooling/heating systems energy savings are compared with a conventional natural gas boiler and an electricity driven compression chiller. With that in mind, the energy savings are estimated at 30.000 kWh of energy a year and 8.8 tons of CO_2 [8].

Agenzia per lo Sviluppo, Pergine Trento, Italy

The 9.815m^2 two-storey building is located in the industrial area of Pergine and deals with operational innovation. The selective HVAC flat plate collectors cover an area of 265m^2 and are tilted 30^{o}C from the horizontal. The solar cooling system is a single effect absorption system (H_2O/LiBr) and can provide 55^{o}C of hot water in the winter and 90^{o}C in the summer. The heating demand is around 230kW and the cooling demand around 170kW, 108kW of which can be produced from the solar cooling/heating system. There is also a backup electric compression chiller capable of 120kW.

Environmental and economic data: The whole installation is in use since 2004 and cost 540.000€, 32% of which was a state subsidy. The solar cooling system can save 258.000MJ of energy in cold months of the year 176.000MJ in the hot ones. The carbon dioxide emissions are also 28 tons less per year and a whopping 70% of the cooling needs are covered by the absorption cooling system [8].

Research Building Okopark, Hartberg, Austria

The research building Okopark Hartberg is the first Austrian pilot hybrid solar cooling system consisting of a desiccant and an evaporative cooling system. It's a two-storey building used for meetings and each floor is 140m^2 large built with a south orientation (passive cooling). It's been in use since 2001 and the cheap to run desiccant adiabatic cooling can cover 50-70% energy demand of the hot summer days. When it's not enough (usually when the relative humidity is high) the evaporative cooling system comes into action. The open cycle system has a cooling capacity of 30kWc and consists of 12m^2 vacuum tubes collectors. There's also a backup biomass combustion boiler with a hot storage tank volume of 2m^3. Essentially the evaporative sorption chiller is the cold backup system.

Environmental and economic data: The total cost is just over 100.000€ and 60% of it is a state subsidy. The project was founded by the local county. In practice, the general COP is around 0.6 and the adiabatic one is between 3 and 5, the usual cooling load is 20kW and the thermal load is 24kW. The CO_2 is significantly lower compared with conventional heating/cooling methods and the electricity consumption for the wheels and fans to work [8].

University Hospital, Freiburg, Germany

A lab section with an area of 550m^2 of the university hospital in Freiburg is powered by a solar thermal system. Two ventilation systems with variable air flow rate are keeping temperature steady during winter. The system in question is an adsorption chiller with a cooling capacity of 70kWc and a nominal cold air flow temperature of 18^{o}C. 230m^2 of vacuum tube collectors provide the necessary heat for the thermal system to work. The heat rejection system that's used is a cooling tower. There also two backup storage tanks, a hot storage tank with a volume of 6m^3 and a cold one 2m^3 big and the backup heat system is district heating (hot steam). The COP is constant, around 0.6 and the collectors' efficiency is 32%.

Environmental and economic data: The total cost was 352.000 and the solar system was built by Sulzer Infa (private company). Three quarters of the cost was a state subsidy and the annual maintenance cost is 12.000€. The system has been in use since 1999. The CO_2 footprint is greatly reduced and the chiller is built by environmental friendly material [8].

Ineti, Lisbon, Portugal

It's a research building that belongs to the renewable sources department INETI in Portugal. Twelve offices are cooled entirely by a desiccant solar thermal system which has a cooling capacity of 36Wc. 24 compound parabolic collectors area used with a total usable area of 46m^2. 70% of building area is covered with glass windows which are oriented southwest. The relatively weak as far as output is concerned system made the use of heat pumps necessary. The system is capable of 24^{o}C air flow inside the offices and 50% relative humidity when outside temperature is no more than 32^{o}C and relative humidity is around 40%, which is considered very satisfactory.

Environmental and economic data: The system has been in use since 1999 and had very high initial cost because it was designed for demonstration and test purposes. A counterpart solar system today should cost around 75.000€. The system's contribution towards reducing electricity consumption and CO_2 emissions is considered as mediocre. When the desiccant system cannot produce the necessary cool air it's aided by the heat pump [8].

Chapter 2

The second is the practical part of the project. Pre-design solar cooling software called Pistache is used to model a solar cooling and heating system for the students' residence of the Technical University of Crete. The results are analysed and discussed.

2.1 Introduction to Pistache software

The Pistache software is a practical tool for professionals designed to estimate the performance of different solar cooling/heating or domestic hot water (DHW) systems. It was developed by the French MeGaPics and TESCOL and is essentially a program made to simplify the pre-design of a solar installation and to provide energy balance and annual performance indicators as well. What's more it is configured to work with both domestic and large scale installations.

Pistache is composed of a simplified user interface, an option to upload an input file and define its parameters, calculation tables, material databases and a help option with step by step instructions. After naming the project and adding some general info, the location is specified, either manually or with a google maps extension (coordinates, that is longitude and latitude are defined). The tool is based on a one hour time step energy balance approach at system level. It uses an input file composed of meteorological data and building loads.

At the next step, the cooling, heating and DHW demands are analysed and the user specifies the system configuration. The configuration parameters are:

- Thermal efficiency indicators: ηCS, ηHS and COPth
- Global performance indicator: PER
- Solar performance indicators: PSU
- Functions of the solar system: the solar installation is at least used for cooling, but can also be used for heating and/or DHW production
- Priority of the solar system: if heating and DHW preparation functions are selected, the user must indicate the demand that solar energy has to firstly feed
- Backup systems: finally, solar energy can be sustained by a cold and/or a hot backup

The parameters can be used at different stages of the project implementation, from the feasibility study to operation. The cooling/heating period can be fixed by the user or defined automatically according to the cooling/heating demand period. As mentioned before, the Pistache tool proposes two layouts:

- Small scale system for family houses (domestic use in general), small multi-dwellings, using a small size packaged sorption solar system. This configuration is an adaptation of the solar combi system concept including a cooling function, also called Solar Combi +

- Large scale system for multi-dwellings, offices and commercial applications, using customized systems to better suit the demand in every case.

Moving on, in the user interface, the component parameters are defined. The user specifies the main sizing characteristics of each component of the installation: chiller cooling capacity, number and position of the solar collectors and hot and cold storage capacities. In order to help this specification step, several automatic functions to pre-size some components can be used. The automatic pre-sizing concerns: the sorption chiller primary technology (in this tool absorption and adsorption), the solar thermal collector area, the hot/cold/DHW storage volumes, their heat rejection system, the operating temperature (on the building side and the ambient temperature) and the backup systems. Pistache includes the required database for the sorption chillers, for the solar collectors and for the backup system. The user can choose between four heat rejection technologies: wet cooling tower, dry-cooler, adiabatic dry-cooler and geothermal probes.

When all the parameters are specified, the calculation can be processed. The tool uses the so called hourly simplified calculation in order to reduce the calculation time (less than 10 seconds for an annual calculation) while keeping a level of accuracy adapted to a pre-sizing tool. At each time step, the tool runs an energy balance, calculating all the thermal energy flux according to the specific configuration of the installation. The performance of the installation is limited at each time step by the building needs and by the heat, cold and DHW storage capacities. If a part of the available solar energy cannot be used or stored during the time step, it is considered as lost. Significant energy losses prove if the solar system is over-sized. In practice, over-sizing solar installation leads to overinvestment and risks of collector field overheating.

Results and output: At the end of the hourly calculation process, monthly and annual energy balances are exported. The user gets the various energies of the system, according to the installation configuration. The performance indicators are calculated with annual values. In order to help the user to size the system, target values are defined for performance indicators; they consist of minimum and/or maximum limits. Pistache also compares immediately each indicator to its associated target values and specifies the gap in percent. In case of oversizing, automatic warning messages are sent to the user [2, 3, 5].

2.2 Solar Cooling System pre-design in students' residence of TUC

2.2.1 System Design

Now that all the theoretical background has been explained in detail, a thorough study will be made on the use of a solar heating and cooling system in the students' residence of the Technical University of Crete. The purpose of this study is the design of a system capable of providing enough heating in the cold moths and cooling in the warm months of the year, as well as hot water to the 76 students living in the students' residence of TUC. Pistache will be used to indicate the best possible solar heating/cooling system under our circumstances.

The students' residence is a two-storey building located in the campus of TUC, seven km north-east of Chania. The climate in Chania is quite warm (often hot during the summer) from April to October with vast amount of sunshine and little to no rainfalls. Winter months are quite mild (temperature rarely falls below 7-8° C) but also very humid (often above 85%). Moreover it's very rainy from November to March. Since the students' residence is not very big (accommodating only 76 students) there is no need for a large solar cooling system. However, the hot backup system as wells as the hot and cold storage tanks need to be sufficient for those not so sunny days of the year. The warm and sunny, for the most part, climate in Chania makes it ideal for a solar cooling system and the coefficient of performance is expected to be very high.

On the first tab of Pistache presizing tool some primary (Figure 23), yet crucial information is needed such as the time shift from Greenwich Mean Time. The user must fill the geographical coordinates (longitude and latitude) since they determine in large part the weather of a specific region. Possibly the most important thing than must be loaded is the mgp file in which weather data is stored for the area in question. Mgp files are very difficult to get hold of and because of that, weather data from Almeria, Spain is used, a town with quite similar climate to Chania. Except for temperature, mgp files also contain relative humidity and amount of solar irradiation information at any given time of the day. Solar cooling or heating loads are also calculated with the use of this information. This is the most valuable information for Pistache. The average costs of electricity, oil/gas and water must be specified so that a techno economic analysis can be possible; the higher their price the more beneficial a solar cooling/heating system is. Another important factor to be taken into account is the system configuration: a customized system is a big one, designed specifically for large offices, industries etc. where many more things need to be considered whereas a packaged (solar combi plus) is a relatively small one designed for small hotels or houses. The students' residence of TUC is somewhere in between, but a packaged solar cooling system seems more appropriate since the number of students living there is not that high and can be thought as a large house [2, 3, 5].

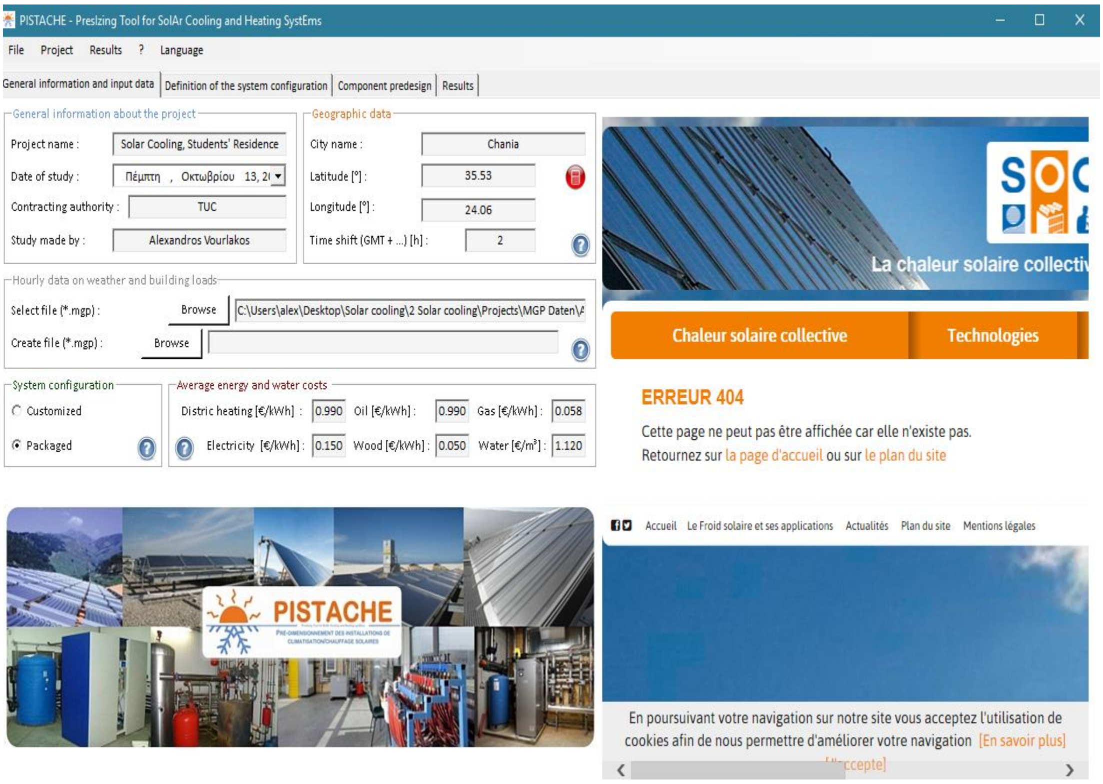


Figure 23: The first tab of Pistache software, where basic information is given such as longitude and latitude or gas/oil prices

On the next tab (Figure 24) the cooling period is determined which can be either user or automatically defined (according to cooling loads). The latter is chosen; a user defined system can be tricky because the user needs to specify the system's starting and ending point every month or season. The installation is used for cooling (obviously) and both heating and hot water production. The solar system will be installed in a students' residence so it must cover as many needs as possible during all seasons. This is why the solar energy will be recovered priority in domestic hot water production rather than heating (because a students' residence is essentially a very big house and should be viewed as such). An ideal solar cooling/heating system is being designed so it will be equipped with both hot and cold backup for the days the given sunshine is not enough. An installation scheme is also portrayed depending on the options that have been chosen. The scheme in display is the most complex because the installation is used for heating as well as hot water production and two backups for the system are used, a hot and a cold one (there could be none of them or one of the two).

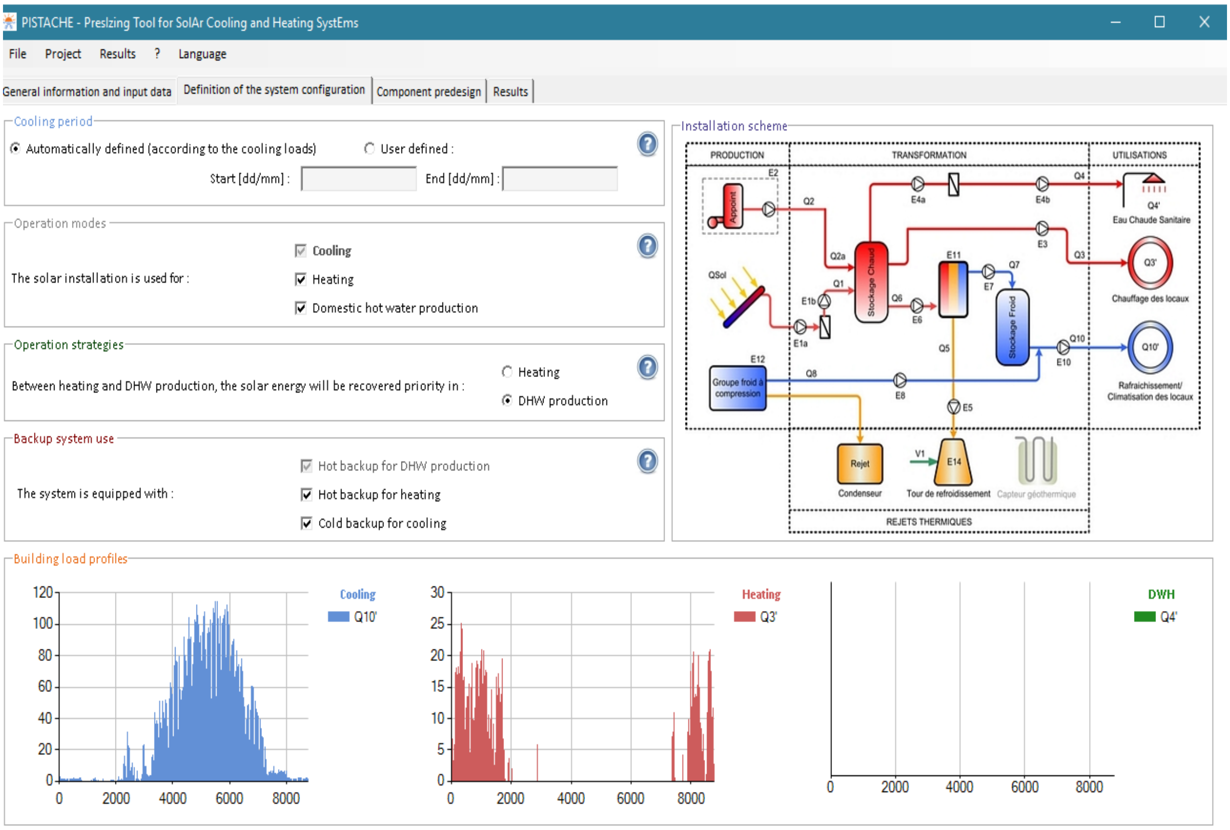


Figure 24: On the next tab of Pistache the purpose of the thermal system is defined, for example if there is going to be hot water production

The next tab is the most crucial (Figure 25), because here the solar cooling system is finally taking shape. The first thing that needs to be defined is whether the system will use absorption or adsorption chillers. Their main difference is that the adsorption process is a volumetric phenomenon, whereas adsorption is a surface phenomenon. Another key difference is the fact that absorption chillers usually utilise a compressor of some sort, while adsorption chillers do not. Obviously, that gives absorption chillers much higher efficiency, especially if they are double effect, in which case the coefficient of performance is double that of an adsorption chiller. Absorption chillers are much more widely used because of that. What's more they have the potential of reaching much higher power outputs. However, absorption chillers have almost one fourth of the adsorption chiller's lifetime (7-8 years in comparison with 30 years), are much more expensive to maintain and require anti-corrosion protection. So despite some very important advantages of the absorption process, the adsorption chiller is selected because their robust construction, little noise, ease of installation and minimal electricity consumption makes it ideal for a students' residence. Adsorption chillers are more eco-friendly, too.

There is an option to select a chiller made from a specific company, but this option is left on "generic". In the nominal characteristics the thermal COP is automatically filled, depending on the choice of chiller (0.45 for adsorption chillers, 0.6 for absorption – no option for double effect absorption chillers). The cooling capacity will be explained later because there is a direct connection with the total collector area. Then the solar collector technology is selected and the best choice is the use of vacuum tube collectors. They are more expensive but take up less space and are more efficient (there is also the choice to choose a collector made from a specific company).

Total collector area and cooling capacity are directly connected: when one of them is defined, the other will be automatically defined too. In this case, the total collector area should be 51.10m^2 (from previous studies of the student's residence) so the cooling capacity varies between 51.60 and 114.60 kWh. If, for any reason, this auto-selection is not ideal, cooling capacity can be changed by the designer and that won't mean the collector area will change number.

Orientation is the desire for the solar collectors to face the true south (not the magnetic one) so that more sunshine throughout the year falls on them. The angle should be either 30^o or -30^o for Europe (it is completely different for the southern hemisphere or for China which is thousands of miles to the east). Tilt is the angle to the horizontal and is directly connected with latitude. A practical equation to calculate that number is (latitude * 0.76) + 3.1 and that equals around 30^o. The chiller – collector distance is the vertical distance between where the collectors are located and the ground where the chillers and/or the backup boilers /chillers are placed. Since this is a two-storey building, but the distance between each floor is larger than typical, 10 meters is approximately right. Further up, the hot and cold storage tank volumes need to be defined. Typically the hot storage tank volume needs to be about twice that of the cold storage tank. 4m^3 of hot and 2m^3 of cold storage tank volumes are enough for a 76-people students' residence. There's the option to automatically define the two numbers here, too and Pistache always doubles the hot storage tank volume compared to the cold one. The heat loss time constant is also automatically determined since it's difficult to set this number on our own.

The other most important part besides the type of chiller is heat rejection system selection. The three main types of heat rejection systems is the cooling tower, the dry cooler and the geothermal probes (both vertical and horizontal). The comparison between cooling towers and dry coolers, as already explained in detail before, is similar to the absorption vs adsorption chiller comparison. Cooling towers are the most common heat rejection system, because their coefficient of performance is very high and require less space compared to dry coolers. They use water as chilling means and their initial cost is lower. Dry coolers on the other hand, which use air as chilling means, need only a small fraction of the vast amount of water the cooling towers need and pose no health problems. Running costs are also 2/3 that of cooling towers, so attenuation also comes fast. Adiabatic dry coolers are relatively new and differ in the process of chilling the water compared to conventional dry coolers. Before the fan draws the ambient air through the finned coil, the air is pre-cooled adiabatically when traversing a humidification pad. This evaporates the water in the air, thus boosting the cooling capacity. They are more expensive but have advantages that offset both conventional dry coolers and cooling towers. They are more efficient than dry coolers and yet consume even less electricity; all that while consuming only one fifth of the water a cooling tower needs. This is why the adiabatic dry cooler is chosen. On the other hand, geothermal probes can be better than both dry coolers and cooling towers (any type of these) because they make use of the always cool ground temperature and are more economical in the long run (that is more than 20-25 years however) but their initial cost is very high, they need large amounts of water similarly to cooling towers, maintenance cost is high and expertise advice is needed for such a system to work properly.

Now that the primary heating/cooling systems have been defined the backup systems must be checked. We need to mention that the choice of cold or hot backup is not very important to the final results, so a wrong choice won't ruin an otherwise good cooling system. A typical domestic gas boiler is chosen for hot backup (efficiency is calculated automatically by the program) and a water condensing compression chiller for cold backup. That of course doesn't mean that opting for an air condensing chiller makes any difference. After all it's just the backup system, which is almost always pretty conventional. A 70kW cold backup system and a 150kW hot backup one are enough for the students' residence (maybe less than that is also enough; the hot backup should be around double the output of the cold backup system – similarly to the storage tanks) but different numbers don't alter the results in any way. Finally domestic hot water temperature, heating water temperature and cooling water temperature must be defined. The temperature is 50°C for the first two and 19°C for the latter, as indicated by past studies.

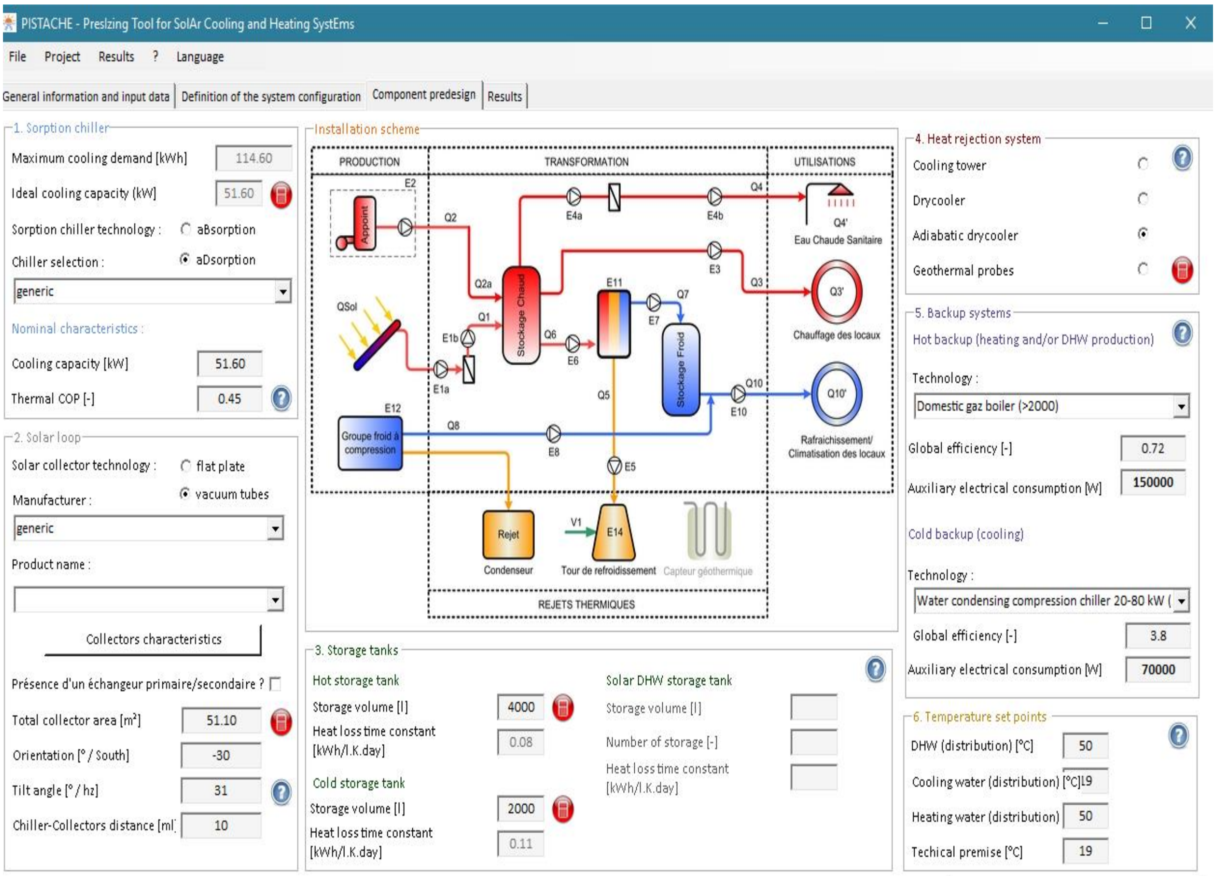


Figure 25: The third tab of Pistache is the most crucial, where info like cooling capacity, type and orientation of chillers and type of heat exchange is given

So, all in all, a packaged solar cooling and heating system has been pre-designed that makes use of adsorption vacuum tube chillers with the help of an adiabatic dry cooler, plus two conventional backup systems: one for heating and one for cooling. Now, it is important to mention that a typical system for the hot climate in Chania would likely be completely different to the one that is depicted here. Absorption chillers aided by a cooling tower are the combination to be expected in a very hot climate because a compressor together with water as chilling means are capable of achieving temperatures well below that of the ambient air. So this should be the “sensible” choice since it also has lower initial cost. However, an adsorption system aided by the all new adiabatic dry cooler can also bring the temperature down to quite pleasant levels while being hugely more economical on the long run and a lot more environmentally friendly since the water consumption is significantly lower. Another decisive factor for this choice is the low amount of noise and vibrations; it’s a students’ residence after all. An adiabatic dry cooler is almost as efficient as a cooling tower with all the typical benefits of a conventional dry cooler and adsorption chillers are gaining popularity because of the natural way they work (while also being very effective).

2.3 Results & Discussion

Pistache software delivers two kinds of results: energy balance and water consumption throughout the year (first two rows) and performance indicators (third row). The first results’ tab, which is displayed below, shows the user a general picture while the other two give the same info basically, but a bit more analytical.

The first list of results is the energy balance and water consumption, as depicted on the first row (Figure 26). Q stands for energy generated by the sun’s heat, either for cooling or heating. The numbers/indicators next to the Q symbol are not to be confused with quarters of the year, they are nothing more than numbering. When the numbers are the same it means that they refer to something of the same category and are further divided with an intonation or letter. It is important to mention that six indicators are zero. That doesn’t mean that the backup heat for heating (Q_{2b}) for instance is zero throughout the year; it’s a software error that will be explained later. Q_{1sol} is the total irradiation on the collector area in the whole year (97.2 MWh) and Q_1 is the amount of it that’s supplied to the hot storage tank (around 48%). Q_2 refers to the backup heat (a for storage purposes, b for heat distribution and c for domestic hot water) while Q_3 is the total heat for heating and Q_3’ is the heating demand – intonation always stands for demand/requirements. Q_4 is all about domestic hot water production (total heat, solar heat and requirements). $Q_6/_7$ is the heat supplied to/cold produced by the adsorption chiller and Q_8 is the backup cold for cooling. $Q_{10}/_{10'}$ are about the cooling demand throughout the year. It’s easy to notice that cold produced by the chiller is only a small fraction of the total cooling needs and that should mean that the system that has been designed is ineffective but that falls into the same Pistache errors that were mentioned earlier and will be explained after all the results have been presented. V_1 is the water consumption in cubic meters by the adiabatic dry cooler (heat rejection system) and $E_{aux}/E_{aux\text{-}sol}$ is the electricity consumption by the auxiliary (backup) systems. Finally, $Q_{1\text{-}lost}$ is the amount of lost solar energy throughout the year and it’s quite important because the rate at which solar energy is lost is calculated; in this case 13.57%, a low and therefore good number. If this rate is high, it means that the collector area is oversized for the given scenario.

On the next tab there are three graphs regarding the energy production and demand or else the comparison between the two. On the first graph, the vertical axis is the energy in kWh and the horizontal the twelve months of the year. The orange color indicates the irradiation on the collector area, whereas the red color shows the usable amount of the irradiation, the rate that is converted into energy. There is also a black line which is the Q_{lost}, the amount of heat that is not used in any way. It's at its highest between February and May. A possible explanation for this is the orientation and tilt angles which should not be the same number throughout the year, but Pistache only accepts one number for each. On the next graph, the cold produced by the chiller is displayed. The vertical and horizontal axes are, again, the energy in kWh and the months of the year. It's obvious that the cold produced in July is a lot higher than May, for example (M7 and M5 respectively) and zero during the winter months. The two colors indicate the difference between the theoretical results and the output of Pistache – the darker blue shows the Pistache output. Generally speaking, theoretical results are better than real ones except for electrical and water consumption results which are over-estimated. The last graph gives the same information, but about the heat produced by the system. The darker red is the Pistache output in comparison with the theoretical result. The load is much higher during M1, M2 and M12 (January, February, and December). Maximum heating load only reaches around 3.300kWh, while maximum cooling load can reach almost ten times that, which is to be expected since winter in Chania is mild, but summer is quite hot. The last graph will be explained below because it's directly connected with the analysis report.

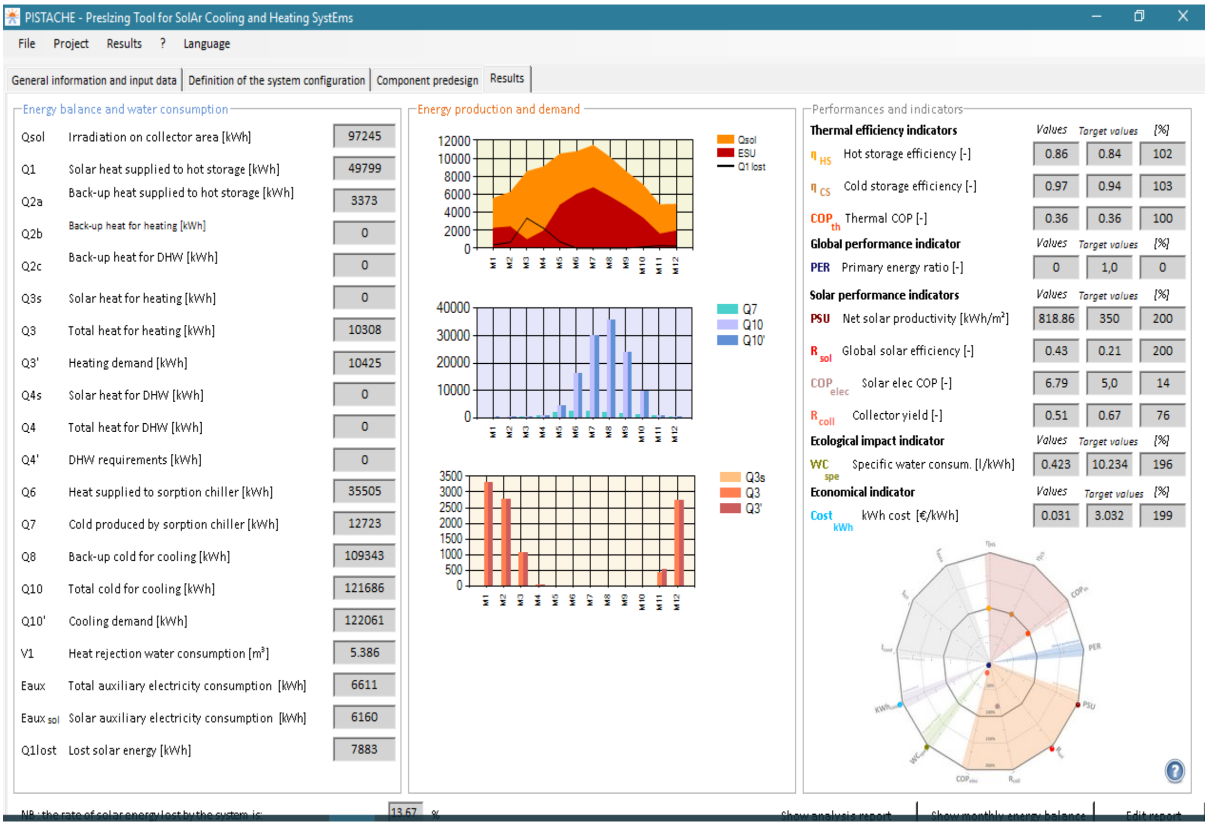
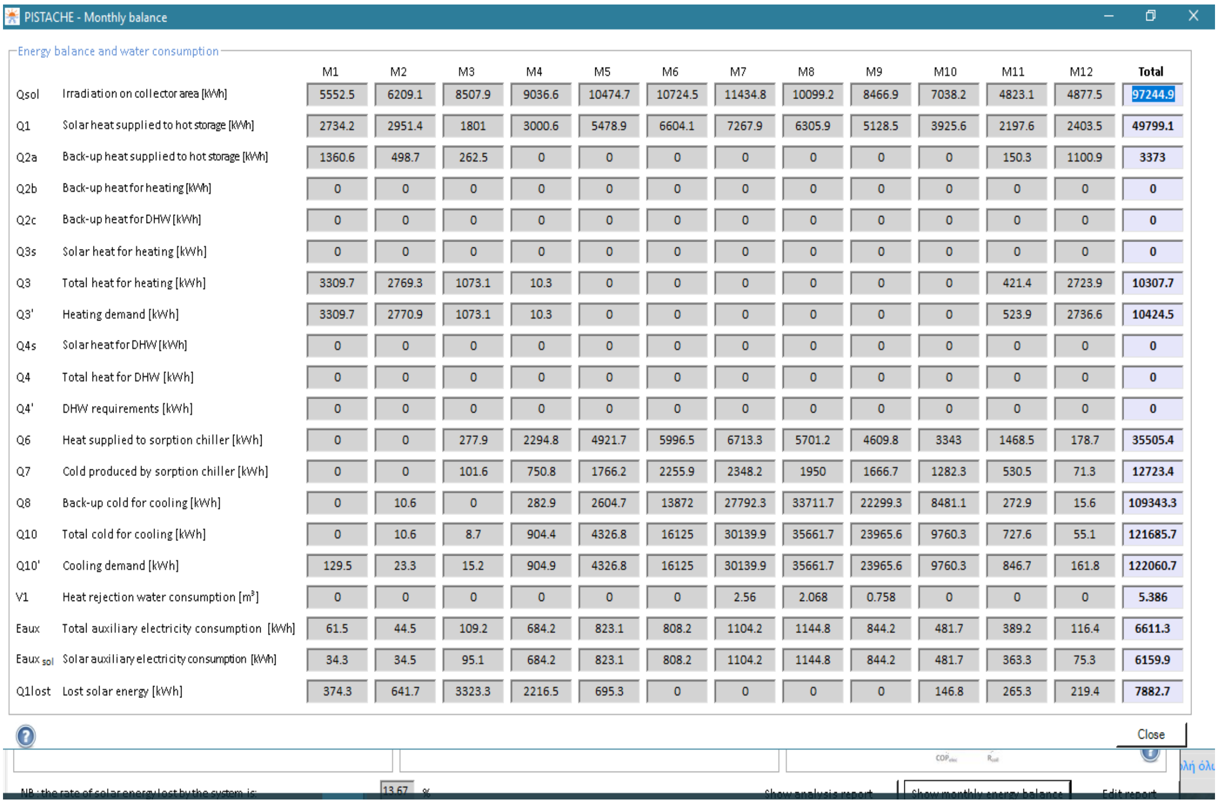


Figure 26: Results summarized, heat/cold demand/production, peak seasons and performance indicators

The next results' tab shows nothing more than the energy balance and water consumption that has already been talked about, but per month separately (Figure 27). The last row displays the total numbers, which are the same as in the tab (first row) before. It's obvious, again, that many numbers are zero, but that's not the case in reality and it's a Pistache error that will be explained in the analysis report.



		M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	Total
Qsol	Irradiation on collector area [kWh]	5552.5	6209.1	8507.9	9036.6	10474.7	10724.5	11434.8	10099.2	8466.9	7038.2	4823.1	4877.5	97244.9
Q1	Solar heat supplied to hot storage [kWh]	2734.2	2951.4	1801	3000.6	5478.9	6604.1	7267.9	6305.9	5128.5	3925.6	2197.6	2403.5	49799.1
Q2a	Back-up heat supplied to hot storage [kWh]	1360.6	498.7	262.5	0	0	0	0	0	0	0	150.3	1100.9	3373
Q2b	Back-up heat for heating [kWh]	0	0	0	0	0	0	0	0	0	0	0	0	0
Q2c	Back-up heat for DHW [kWh]	0	0	0	0	0	0	0	0	0	0	0	0	0
Q3s	Solar heat for heating [kWh]	0	0	0	0	0	0	0	0	0	0	0	0	0
Q3	Total heat for heating [kWh]	3309.7	2769.3	1073.1	10.3	0	0	0	0	0	0	421.4	2723.9	10307.7
Q3'	Heating demand [kWh]	3309.7	2770.9	1073.1	10.3	0	0	0	0	0	0	523.9	2736.6	10424.5
Q4s	Solar heat for DHW [kWh]	0	0	0	0	0	0	0	0	0	0	0	0	0
Q4	Total heat for DHW [kWh]	0	0	0	0	0	0	0	0	0	0	0	0	0
Q4'	DHW requirements [kWh]	0	0	0	0	0	0	0	0	0	0	0	0	0
Q6	Heat supplied to sorption chiller [kWh]	0	0	277.9	2294.8	4921.7	5996.5	6713.3	5701.2	4609.8	3343	1468.5	178.7	35505.4
Q7	Cold produced by sorption chiller [kWh]	0	0	101.6	750.8	1766.2	2255.9	2348.2	1950	1666.7	1282.3	530.5	71.3	12723.4
Q8	Back-up cold for cooling [kWh]	0	10.6	0	282.9	2604.7	13872	27792.3	33711.7	22299.3	8481.1	272.9	15.6	109343.3
Q10	Total cold for cooling [kWh]	0	10.6	8.7	904.4	4326.8	16125	30139.9	35661.7	23965.6	9760.3	727.6	55.1	121685.7
Q10'	Cooling demand [kWh]	129.5	23.3	15.2	904.9	4326.8	16125	30139.9	35661.7	23965.6	9760.3	846.7	161.8	122060.7
V1	Heat rejection water consumption [m^3]	0	0	0	0	0	0	2.56	2.068	0.758	0	0	0	5.386
Eaux	Total auxiliary electricity consumption [kWh]	61.5	44.5	109.2	684.2	823.1	808.2	1104.2	1144.8	844.2	481.7	389.2	116.4	6611.3
$Eaux_{sol}$	Solar auxiliary electricity consumption [kWh]	34.3	34.5	95.1	684.2	823.1	808.2	1104.2	1144.8	844.2	481.7	363.3	75.3	6159.9
Q1lost	Lost solar energy [kWh]	374.3	641.7	3323.3	2216.5	695.3	0	0	0	0	146.8	265.3	219.4	7882.7

Figure 27: Heating and cooling demand/production/requirements analytically

The energy balance and water consumption results may be the most important when about to make the solar cooling/heating system, but the performance indicators show the quality of the system's pre-design. Too many errors mean that the system is not well designed and will probably not work well in real life conditions. However during the program's execution and despite tens of tries and combinations of several systems' characteristics some errors didn't go away; no matter how many attempts were made (Figure 28). There's a complete analogy between performance indicators above and their theoretical explanation below and that's why they are analyzed together. There's also no need to comment on the indicators that behaved normally and resulted in no error, but rather emphasize on the ones that turned out problematic. Numerical results, as depicted above, are indicative of the problems that will be shown on the analysis report. Rates that are below 100% as displayed above mean that an error will come of on the report. Now, it's time to take a closer look at the four errors that couldn't be wiped out, each one separately:

1. "The collector yield is too low. Please check the collector area sizing". This is the same as the R_{coll} solar performance indicator that is shown above. This error means that the collectors are not very effective and are slightly off the target values. Maybe opting for a different solar collector vendor or a continuously variable tilt/orientation angle would solve the problem.

2. “The electrical coefficient of performance is too low. Please check the electrical consumption of the auxiliaries”. It’s the same with COP_{elec} solar performance indicator in the above image. This was actually an error to be expected as there was no sufficient data of the backup systems required for the design of this system. However, the result remained the same in spite of running the program several times with different electrical consumption numbers each time.
3. “The system PER is too low. Please check the auxiliaries’ electrical consumption and the back-up”. It’s the same with PER global performance indicator. This error is partly because of the previous one. However, there is no way for actual value to be zero. It’s thermodynamically impossible to have a system with a primary energy ratio of zero and that would mean a totally ineffective system that’s unable to work. There is little to nothing that could be done with this error.
4. “The solar cooling share is very high; the sorption chiller is maybe oversized”. There is no such indicator in the image above, only in the analysis report. Even though attempts were made to run the program with different numbers under the total cooling capacity, total collector area, chiller-collector distance and cold storage tank volume there was no way to eliminate this error.

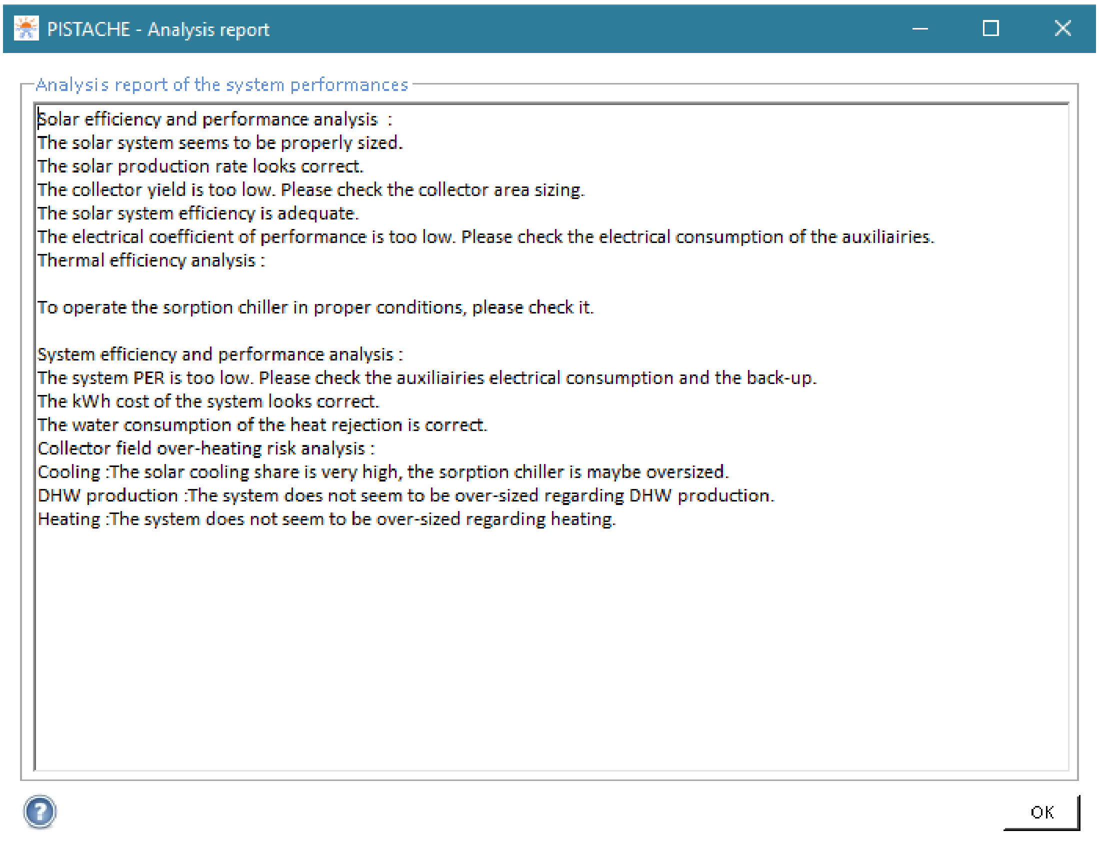


Figure 28: The most important result, the analysis report, actually tells the end user if the results are consistent and reliable and if something has gone wrong

Finally, there is an “edit report” option which can be seen at the first two images of the results (at the bottom right) which opens automatically a blank office word page and fills it with all the necessary information of the system’s design, all in a printable form. The report does not include any new information that has not been already explained but it’s important to cite it because that’s the most probable form an engineer will come in contact with Pistache software for the first time [1-3, 5, 39].

CEA INES - TECSOL Pistache version 2.0.1.600

PISTACHE

PRESIZING TOOL FOR SOLAR COOLING AND HEATING SYSTEMS

General information about the project

Project name :	Solar Cooling
Date of study :	Τετάρτη, Οκτωβρίου 12, 2016
Contracting authority :	TUC
Study made by :	Alexandros Vourlakos
City name :	Chania

System characteristics

System configuration :	**packaged**

Configuration
aDsorption chiller

Sorption chiller technology :	**generic**
Nominal cooling capacity [kW] :	**51.60**
Nominal thermal COP :	**0.45**

Collectors

Collector technology :	**vacuum tubes**
Product name :	**generic**
Apertura area [m^2] :	**1**
η0 (optical effciciency) :	**0.773**
a1 (transmission loss coefficient) [$W/m^2.K$] :	**1.09**
a2 (2^{nd} order loss coefficient) [$W/m^2.K^2$] :	**0.0094**
Total collector area [m^2] :	**51.10**
Orientation to South (°) :	**30**
Tilt angle to horizontal [°] :	**31**
Primary/secondary loop heat exchanger	**no**

Hot storage tank

Storage volume [L]	**4000**
Heat loss time constant [kWh/l.K.day]	**0.08**

Cold storage tank

Storage volume [L]	**2000**
Heat loss time constant [kWh/l.K.day]	**0.11**

Heat rejection system

Heat rejection technology :	**Adiabatic drycooler**
The solar installation is used for :	**Cooling** **Heating** **Domestic hot water production**

Solar energy will be recovered in priority for DHW production

Hot back-up for DHW production and/or heating :	**Domestic gaz boiler (>2000)**
Back-up system efficiency :	**0.72**
Auxiliairies electrical power [kW] :	**200000**

Cold back-up :	**Water condensing compression chiller 20-80 kW (2000>)**
Back-up system efficiency :	**3.8**
Auxiliairies electrical power [kW] :	**70000**

Temperatures

Techical premise [°C] :	**19**
Cooling water (distribution) [°C] :	**19**
Heating water (distribution) [°C] :	**50**
DHW (distribution) [°C] :	**50**

PISTACHE was developed within MéGaPICS project, with the support of the French National Research Agency (ANR), through the Habitat intelligent et solaire photovoltaïque program (ANR-09-HABISOL-007).

2.4 Conclusions

All in all solar cooling/heating for buildings is a very promising alternative to the conventional heating/cooling systems and its adoption is only expected to rise. Primitive solar cooling systems have been used or experimented on for one and a half century but it was not so profitable back then when oil prices were so low. However, they have been used exponentially in recent years and advanced rapidly during the last two decades. Solar cooling is not going to solve our large and ever-growing energy demands but it can a help a great deal in decreasing our dependency on fossil fuels use. After all domestic heating, cooling and hot water production constitutes our biggest daily carbon dioxide footprint and energy consumption. Solar heating/cooling cannot solve alone the vast energy demand but by taking care of a large proportion of the domestic needs it can make way for even more renewable energy sources in our lives.

There are two main types of solar cooling systems: photovoltaic and solar thermal systems. In this project the latter have been more thoroughly examined because of their superior efficiency (around 25% higher) and environmental friendliness. However PV cells are more widely used because of their economic advantages and faster payback times – for some large scale application PV cells can take up to twenty years while a solar thermal system can take up to thirty years. Generally speaking, payback time by using PV cells is around two thirds that of a solar thermal system.

There is no short answer to what's the best solar thermal system. Generally, the best thermally driven solution is the double effect absorption cycle equipped with concentrating parabolic collectors followed by desiccant systems equipped with flat-plate/vacuum tube solar collectors. Adsorption systems options are significantly more expensive. That doesn't mean that they are less effective – quite the opposite, it's just that in many cases a high initial cost doesn't mean quick payback. Size, climate and desired output always need to be taken into account for choosing the best possible solar cooling system. For instance, a pricey and very efficient system may not be worth the investment for a small-scale application but could be very clever on the long run for an industry or a large office.

The results in this project are mainly about the solar thermal systems because the photovoltaic systems have been examined secondarily. As far as collectors are concerned, flat plate are usually the best tradeoff between efficiency and initial cost. Vacuum tube collectors are more expensive but they work better together with advanced solar cooling systems and they take up less space so they should always be taken into account. Solar air collectors are the least effective and are usually used together with desiccant (open cycle) cooling systems for less demanding yet large scale applications (like supermarkets). They are also often used for warming up pools. Compound parabolic collectors are the most expensive and advanced but they are designed for more specialized use, usually with double effect absorption systems.

When solar cooling comes to mind an absorption (closed loop) chiller is more likely to be in use. They are the most widely used, relatively easy to maintain and very effective. They can be used both in countries like northern Europe as well as hot and humid climates in the south because of the compressor that can instantly produce chilled water. The adsorption chillers are gaining popularity more recently and have some important advantages over absorption such as low noise and vibrations, vastly superior reliability and lifetime; although in some cases they can be less effective than absorption chillers especially if combined with an ineffective heat rejection system. Desiccant cooling systems (open cycle) are very effective in certain scenarios: they are low on maintenance cost, very environmentally-friendly and have low initial cost. Double effect absorption chillers are by far the most effective and sometimes the only suitable for large and demanding applications. They are pricey to maintain and not really friendly to the environment compared to other sorption chillers. Then, there are also hybrid systems that are still usually used for research purposes and combine an open cycle with a closed cycle chiller. The first one works the most time while the latter comes into play in more demanding situations.

Evaporative and vapor compression cooling are ways of phase change for the liquid or air that's utilised in a solar cooling system. They refer to both photovoltaic systems and solar thermal systems and do not describe a specific chiller type. Vapor compression is efficient while evaporative cooling is more environmentally friendly and reliable. The dry cooler comparison with the cooling tower is similar to the one between absorption and adsorption chillers. Dry coolers do not pose health issues and are more reliable and environmentally friendly but are less efficient than cooling towers which are effective in every possible scenario. Adiabatic dry coolers try to combine the best of two worlds but are quite expensive. Geothermal probes can either be a worse solution than all the above or a far better one depending on the time spent on research and design. Many things need to be considered when using geothermal probes but they can be the most rewarding on the long run.

High relative humidity does not pose a problem to solar cooling applications but the system may need some adjustment to cope with the more demanding conditions. Usually large-scale absorption systems are used. Alternatively desiccant cooling is also a good solution because of the nature of desiccant cooling itself: the dehumidification that takes place anyway.

There's also the practical part of the project: the pre-design of a solar cooling/heating system in the students' residence of technical university of Crete. It is home to 75 students and a solar cooling system can limit the long term operational cost. The Pistache software was used for the pre-design, a software which extracts data from weather information about the area in question. They are many parameters that need to be defined (such as chiller type, heat rejection system, intended use, collectors' type, angle and orientation, hot/cold storage tanks volumes etc.) and results about the efficiency of the pre-designed system are displayed. After taking into consideration all the possible feasible combinations/ solutions the best solar thermal system for the students' residence is an adsorption chiller with an adiabatic dry cooler heat rejection system and vacuum tube collectors. This system has high initial cost but more than makes up with environmental friendliness, low noise and vibration, no health issues, low maintenance cost and despite all these quite good efficiency.

The total mean irradiation in Greece is around 1.700kWh/m^2/year and around 70% of that is direct sunshine. It essentially means that there's a huge untapped potential for solar thermal systems and the graph above shows that we don't make the most of solar energy (Portugal rates as well as other countries are also low). Many successful appliances have been explained in this project and their energy savings are large; not to mention the vastly reduced CO_2 emissions. Together with passive cooling (proper building orientation, sufficient insulation and right material choice) the solar cooling savings can be multiplied. Even without passive cooling a solar thermal system can easily cover one third of the daily needs of a house or office and save tons of CO_2 emissions every year. In some cases this rate can reach as high as 80% and that practically indicates the possibility of entirely green houses in the future. Of course sizing, climate and desired output, as emphasized before, always need to be taken into consideration. A specific highly effective solar thermal system used in an office in Germany doesn't mean it's going to do well in a house in Egypt. With technology advancement new systems are invented, new combinations of existing systems are possible and many problems are overcome. Solar energy is free and readily available and largely untapped. Its potential is huge, especially in hot climates but as examined before even countries like Germany can benefit a lot from it. There's a solar thermal system for everyone's needs, prices and maintenance cost are only going down and covering the daily needs for cooling/heating/hot water production is the first step in lessening our fossil fuels dependency.

Nomenclature

- COP: coefficient of performance...

$COP = \frac{Q}{W}$ where

- Q is the heat supplied to or removed from the reservoir
- W is the work consumed by the heat pump

...of a heat pump is the ratio of heating or cooling provided for the work required. Higher COPs equate to lower operating costs. The COP may exceed 1, because, instead of just converting work to heat (which could have a maximum COP of 1), it pumps additional heat from a heat source where the heat is required. For complete systems, COP should include energy consumption of all auxiliaries. COP is highly dependent on operating conditions, especially absolute and relative temperature between sink and system, and is often graphed or averaged against expected conditions

- HVAC: (meaning heating ventilating and air conditioning) is a technology of indoor or vehicular environmental comfort by adjusting the space's temperature and humidity.
- HX: heat exchanger, used in solar cooling systems
- IAQ: indoor air quality
- VC: vapor compression
- SDEC: solar heat driven desiccant evaporative cooling
- KWth, KWc, KWe Kilowatt thermal, cold and electric respectively: it's a unit used to measure the potential output from ()a heating/cooling/electric plant and represents an instantaneous flow of energy and should not be confused with units of produced heat/chill/electricity like KWhth
- CRES: the Greek center for renewable energy sources and saving
- PSU: useful solar energy productivity
- PER: primary energy ratio
- $\eta_{CS}/_{HS}$: cold and hot storage efficiency
- Wet bulb temperature: is the temperature a specific quantity of air would have if it were cooled to saturation (100% relative humidity) by the evaporation of water into it. A wet-bulb thermometer will indicate a temperature close to the true (thermodynamic) wet-bulb temperature.
- Dry-bulb temperature: is the temperature of air measured by a thermometer freely exposed to the air but shielded from radiation and moisture. DBT is the temperature that is usually thought of as air temperature, and it is the true thermodynamic temperature.
- E_{aux}: Auxiliary (backup) systems electricity consumption
- Q_{sol}: or Q_{solar} is the amount of heat produced by irradiation
- WC_{spe}: specific water consumption. The specific water consumption is different from the water consumption from the consumer's point of view, which is the consumption per m^3 of field area, not taking into consideration losses within the irrigation network (which is the consumption of water with these losses taken into account).

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