THESIS WORK

Master of Science in Energy and Environment

Instituto Tecnológico de Buenos Aires - Karlsruhe Institute of Technology

FEASIBILITY STUDY OF ADSORPTION SOLAR COOLING SYSTEMS IN ARGENTINA

Diego Nadur
Mechanical Engineer (ITBA)

Tutor
Dr. Andrés Sartarelli (UBA)

Examiners
Dra. Ing. Cecilia Smoglie (ITBA)
Prof. Dr. Ing. Martin Gabi (KIT)

Buenos Aires
31/10/2017

Summary

This work is a feasibility study of introducing adsorption solar cooling systems in Argentina. After comparison of various solar cooling technologies, adsorption was chosen because of operation simplicity, use of environmentally friendly working fluids, not use of electrical or mechanical energy and possible use of sun or any other thermal source of energy. - The parameters for the dimensioning and calculus of performance of the refrigerator were defined considering one application of main interest for small milk producers in Argentina: the refrigeration of 30 liters of milk during 3 days. The comparison of the proposed prototype with the current systems in the local market showed its potential to compete.

Resumen

Este trabajo es un estudio de factibilidad de la introducción de sistemas de enfriamiento solar de adsorción en Argentina. Después de comparar varias tecnologías de enfriamiento solar, se eligió la adsorción debido a la simplicidad de operación, el uso de fluidos de trabajo respetuosos con el medio ambiente, el no uso de energía eléctrica o mecánica y el posible uso de cualquier otra fuente de energía térmica. - Los parámetros para el dimensionamiento y cálculo del rendimiento del refrigerador se definieron considerando una aplicación de interés principal para pequeños productores de leche en Argentina: la refrigeración de 30 litros de leche durante 3 días. La comparación del prototipo propuesto con los sistemas actuales en el mercado local mostro su potencialidad de competir.

Zusammenfassung

Diese Arbeit ist eine Machbarkeitsstudie zur Einführung von Adsorptions-Solar-Kühlsystemen in Argentinien. Nach dem Vergleich verschiedener Solarkühlungstechnologien wurde die Adsorption aufgrund der Einfachheit des Betriebs, der Verwendung von umweltfreundlichen Arbeitsfluiden, der Funktion ohne elektrischer oder mechanischer Energie und möglicher Verwendung von Sonne oder einer anderen thermischen Energiequellegenauer analysiert. Die Parameter für die Bemessung und Berechnung der Leistung des Kühlschranks wurden in Anbetracht eines Hauptanwendungszwecks für kleine Milcherzeuger in Argentinien festgelegt: die Kühlung von 30 Litern Milch über 3 Tage. Der Vergleich des vorgeschlagenen Prototyps mit den derzeitigen üblichen Systemen auf dem lokalen Markt zeigt seine Konkurrenzfähigkeit.

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1 Introduction

1.1 Environmental impact of electricity generation

(Fatih Birol, 2016) Electricity generation is one of the main air pollutants in the world. Most of our electricity comes from coal, nuclear, methane gas and other non-renewable sources. Producing energy from these resources takes a severe toll on our environment, polluting our air, land, and water. Renewable energy sources can be used to produce electricity with fewer environmental impacts. It is possible to make electricity from renewable energy sources without producing CO_2 and other greenhouse gases, the leading cause of global climate change.

1.2 Air pollution

(Fatih Birol, 2016) Energy production and use, mostly from unregulated, poorly regulated or inefficient fuel combustion, are the single most important man-made sources of air pollutant emissions: 85% of particulate matter and almost all of the sulfur oxides and nitrogen oxides. These three pollutants are responsible for the most widespread impacts of air pollution, either directly or once transformed into other pollutants via chemical reactions in the atmosphere. They are emitted mainly as a result of:

- Poverty: the wood and other solid fuels that more than 2.7 billion people use for cooking, and kerosene used for lighting (and in some countries also for cooking), create smoky environments that are associated with around 3.5 million premature deaths each year. These effects are felt mostly in developing Asia and sub-Saharan Africa, where incomplete burning of biomass accounts for more than half of emissions of particulate matter. Finer particles, whether inhaled indoors or outdoors, are particularly harmful to health as they can penetrate deep into the lungs.
- Fossil fuel-intensive development and urbanization: coal and oil have powered economic growth in many countries, but their unabated combustion in power plants, industrial facilities and vehicles is the main cause of the outdoor pollution linked to around 3 million premature deaths each year. Coal is responsible for around 60% of global combustion-related sulfur dioxide emissions – a cause of respiratory illnesses and a precursor of acid rain. Fuels used for transport, first and foremost diesel, generate more than half the nitrogen oxides emitted globally, which can trigger respiratory problems and the formation of other hazardous particles and pollutants, including ozone. Cities can easily become pollution hotspots, as they concentrate people, energy use, construction activity and traffic. The impact of urban vehicle emissions is heightened by the fact that they are discharged not from the top of tall chimneys but directly into the street-level air that pedestrians breathe.

1.3 Climate change and global warming

According to the Framework Convention of the United Nations, it is defined by "Climate change" a change of climate directly or indirectly attributed to human activity that alters the composition of the global atmosphere and which to natural variability adds the observed climate over comparable periods of time.
(United Nations, 1992) Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere

and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.

The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification.

| –0,6 | –0,4 | –0,2 | 0 | 0,2 | 0,4 | 0,6 | 0,8 | 1,0 | 1,25 | 1,5 | 1,75 | 2,5 |
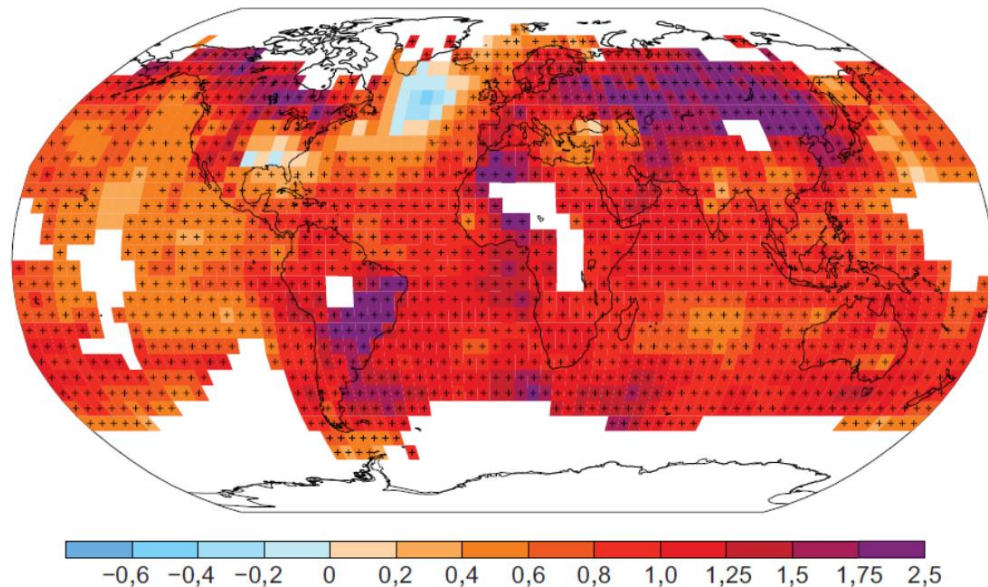
Figure 1 – Temperature variation. Source: Convention of the united nation

1.4   The relationship between greenhouse gases and temperature

(A report by the U.S. Climate Change Science, 2008) There is no doubt that the climate has been warming since the 19th century. The main cause is the increase in concentrations of greenhouse gases (and especially carbon dioxide), which have been growing since industrialization, primarily as a result of human activities.

The connection between greenhouse gas concentrations in the atmosphere and the warming of the climate was made more than a century ago. Greenhouse gases trap and re-emit radiant heat in the atmosphere, which warms the Earth's surface and climate through what is commonly called the greenhouse effect. The primary greenhouse gases are carbon dioxide, methane, nitrous oxide, water vapor and ozone; additional greenhouse gases are covered under the Kyoto Protocol2. Carbon dioxide is the most important – it is produced in large quantities by human activities, is in the highest concentration of all the greenhouse gases and is very long-lived: about one-third of the carbon dioxide increase due to emissions this year will remain in the atmosphere in 100 years, and about 20 per cent will still be present in 1000 years. This means that carbon dioxide emissions continue to affect the climate long after they are released.

The record of the distant past confirms current observations that increasing greenhouse gas concentrations have a warming effect on the climate. The historical record has been established by samples of ice cores, which provide 800,000 years of information regarding the composition of the gases in the atmosphere (trapped in bubbles within the ice) and temperatures over time. Additional information on the climate of the past has been obtained from deep sea sediments and geological formations and fossils, which extend our understanding of the Earth's climate to millions of years ago.

Since 1750 and the beginning of the Industrial Revolution, human activities, primarily the burning of fossil fuels and deforestation, have dramatically increased the amount of carbon dioxide in the atmosphere (by 40%), as well as methane (by 150%) and nitrous oxide (by 20%). Based on ice core records, current concentrations of these three greenhouse gases substantially exceed the concentrations which existed over the last 800,000 years.

It is extremely likely that most of the warming observed since the 1950s has been caused by increases in greenhouse gas concentrations that have been produced from human activities. This assessment is supported by very strong scientific consensus that climate change has been caused by human activities – from a study of almost 12,000 peer–reviewed journal article abstracts published between 1991 and 2011 which mention anthropogenic global warming, more than 97% endorsed this conclusion (Cook, 2013).

Figure 2 – Carbon dioxide, methane and nitrous oxide concentration shows the level of carbon dioxide, methane and nitrous oxide over the past 1 000 years, showing rapid increases in concentrations in all three major greenhouse gases, particularly since the 1950s.
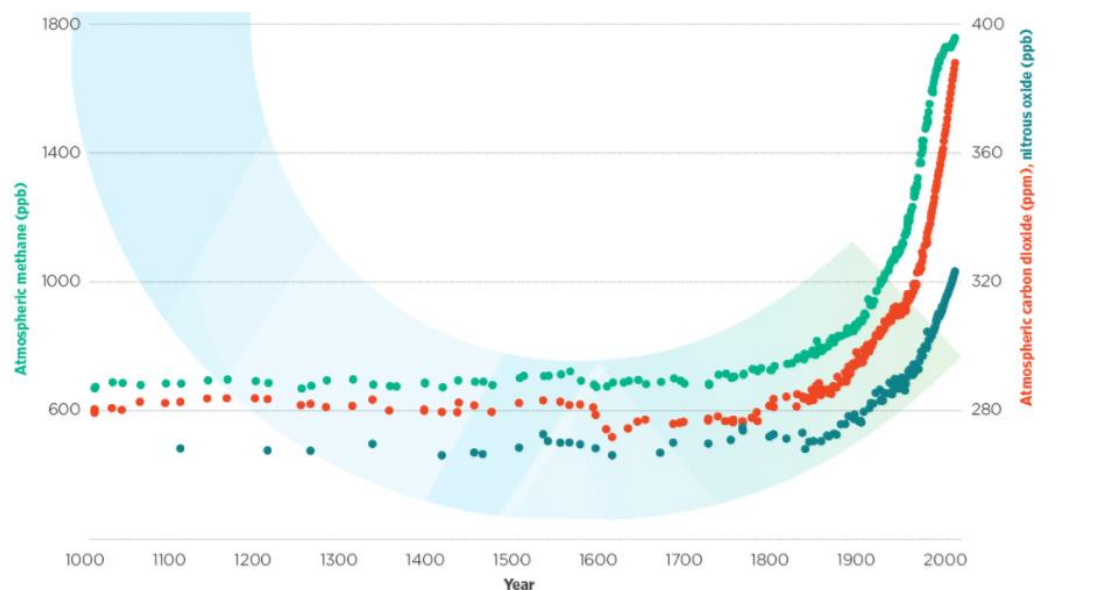
Figure 2 – Carbon dioxide, methane and nitrous oxide concentration. Source: Abrupt Climate Change

1.5   Why solar cooling?

(Deng, 2011) The increasing scarcity of energy resources, global warming and blackouts resulting from weather conditions have stimulated the search for more efficient methods of energy conservation, reducing greenhouse gas emissions and ensuring power supplies. Meanwhile, increasing demand for cooling and heating power in buildings calls for resurveying traditional energy production.

(FUNDELEC, 2011) The company of the Wholesale Electric Market (CAMMESA), in its reports divides consumers into four categories: residential, intermediates and the elderly. In other words, the Argentine households are identified as residential users. According to the statistics of CAMMESA, during 2010, the electricity consumption of the sector residential sector accounted for between 34.5% and 46.3% of the total demand the users. In the last two decades, the demand for residential cooling has increased exponentially creating a significant demand on the electrical grid during the summer months. Figure 3 presents the residential consumption impact of the main artifacts:
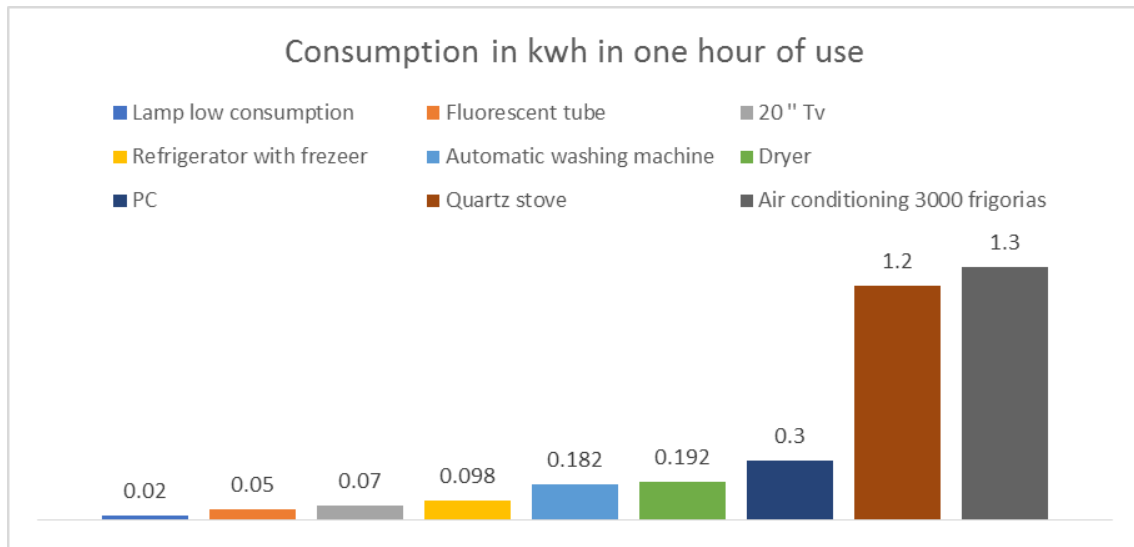
Figure 3 - Consumption in kwh in 1 hour of use. Source: ENRE.

It can be concluded that in homes that have air conditioning, in months of extreme heat or cold, consumption will rise according to your level of use. The implementation of solar cooling systems could assist in reducing this energy consumption, and consequently, reduce greenhouse gas emissions released into the atmosphere as a result of the generation of the required electricity to power typical air conditioners.

In many countries, especially in developing countries in the South, with increasing economic development and population growth, demand for cooling is increasing rapidly due to

- Increasing standard of living.
- Demand for indoor comfort Urbanization.
- Urban heat islands: climate change.
- Affordability of the technology.

(Schmidt, 2015) Often, this increase in electricity consumption caused by air-conditioning generates:

- Growing primary energy consumption.
- High peak loads.
- High demand on electric grids.
- In many countries, power grids are meeting their limits (high demand for peak power plants).
- Increasing greenhouse gas emissions (from power generation and from leakage of refrigerants).

(Energypedia, n.d.) The main arguments for solar assisted cooling (SAC) originate from an energy saving perspective:

- Application of SAC saves electricity and thus conventional primary energy sources.
- SAC leads to a reduction of peak electricity demand this can benefit the electricity network and lead to additional cost savings of the most expensive peak electricity.
- Environmentally sound materials without ozone depletion and no global warming potential are used with SAC
- Coincide of solar energy supply and demand in many cases.

1.6 History of solar cooling

(Bolocan, 2010) The first known artificial refrigeration was demonstrated by William Cullen at the University of Glasgow in 1748. Between 1805, when Oliver Evans designed the first refrigeration machine that used vapor instead of liquid, and 1902 when Willis Haviland Carrier demonstrated the first air conditioner, many teams of inventors contributed with many small advances in cooling machinery. In home applications, refrigeration became a reality in 1834 with the invention of the cooling compression system by the American inventor Jacob Perkins. In 1878, A. Mouchot and his assistant Abel Pifre displayed Mouchot's engine at the Universal Exhibition in Paris, and won a Gold Medal for his works, most notably the production of ice using concentrated solar heat.

1.7   Background of solar cooling

Solar cooling consists of using thermal energy collected from the sun as the principal energy input for the cooling system to cool and dehumidify the space. This replaces the existing electrical power input typically required in a vapor compression refrigeration cycle. The benefit of this system is that it has the potential to reduce the amount of electricity used. These systems can be effective as the availability of solar radiation coincides with the energy demands imposed on buildings by cooling loads, allowing for the greatest amount of cooling to be generated when it is needed most. Figure 4 presents an overview of these mentioned technologies:
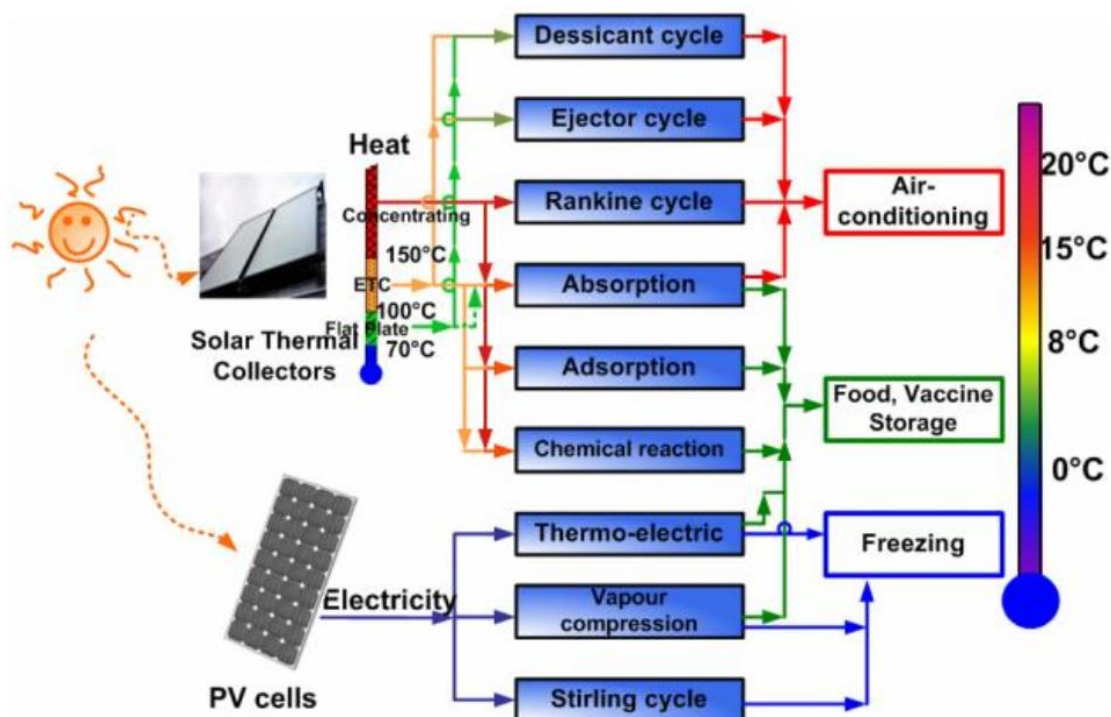
Figure 4 – Solar-cooling Technologies. Source: Pridasawas (2016).

(Cruickshank, 2012) Typical solar cooling systems are comprised of solar collectors, a heat rejection loop, and a thermal energy storage. Solar collectors are used to capture solar energy, and the type of collector selected for a solar cooling system is based on the type of process and the temperature of the required heat input. Lower temperature applications often use flat plate collectors, while evacuated tube collectors and parabolic troughs are typically selected for applications requiring higher temperatures. Most solar cooling applications also require a

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heat rejection loop or external heat dump, typically in the form of a cooling tower. This is critical for removing excess heat created from the thermodynamic processes used in solar heating.

1.8   Overview of Solar Cooling Technologies

First of all, there are two bigs groups of methods that have been commonly implemented, "Solar Electrical Cooling'' and ''Solar Thermal Cooling''. The first group use conventional compression chiller with photovoltaic pannels. The second group can be dividied into ''Open and Closed cycles''. The first method involves the use of a desiccant material in a cycle that directly conditions the air. Closed cycles method produce chilled water that can be used in combination with any airconditioning equipment such as an air-handling unit, fan-coil systems, etc. This method like ''Solar Thermal Cooling'' uses either an absorption or adsoption process. Figure 5 presents a summary:
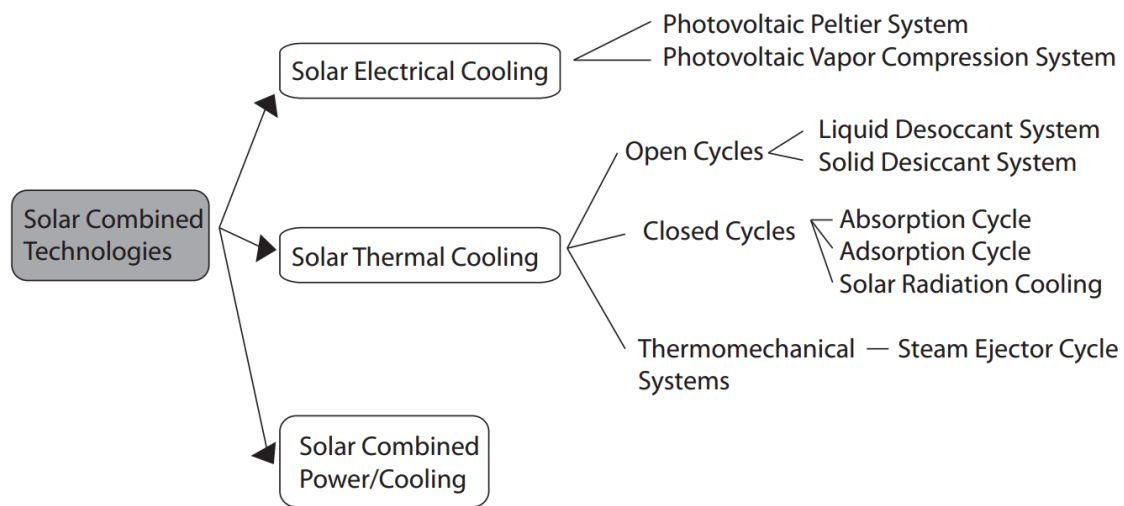
Figure 5 – Summary of Solar cooling technologies.

1.9   Comparison of sources for solar cooling

Figure 6 summarizes two bigs groups of methods that have been commonly implemented, "Solar Electrical Cooling'' and ''Solar Thermal Cooling''.
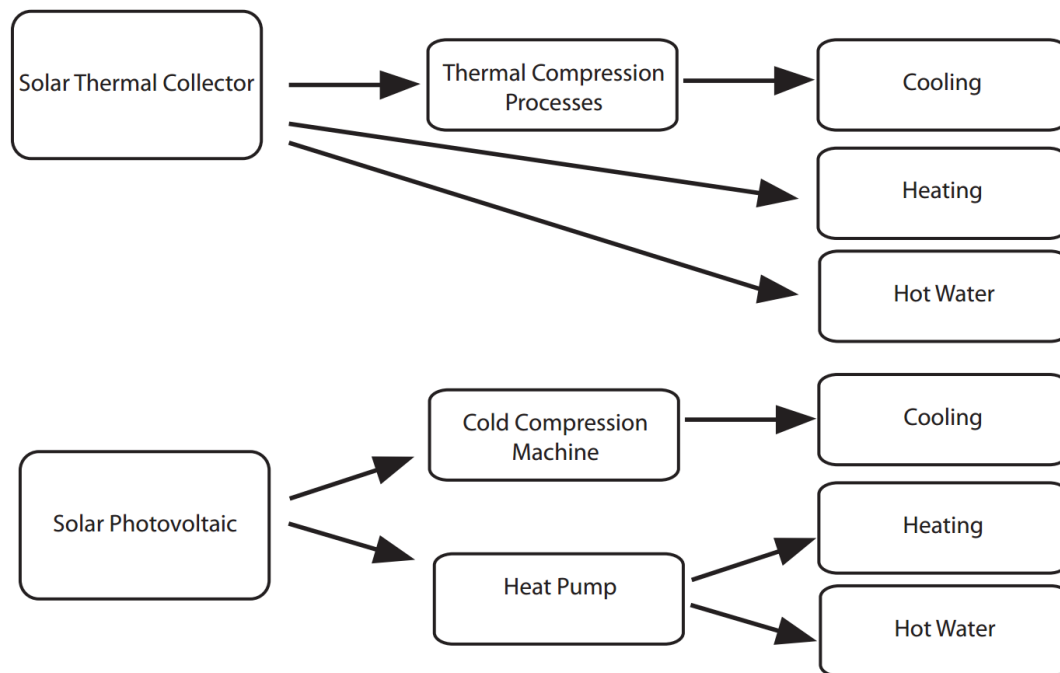
Figure 6 – Solar-cooling technologies.

1.9.1   Solar electrical cooling

According to Robins, the main feature of solar electrical cooling are:

Principle.

Photovoltaic power is used to drive conventional compression chiller.

Strengths

- Established.
- Proven technology.
- Very large market for conventional chillers.
- Advantageous cost degradation for PV.
- Cooling demand correlates well with solar supply.

Weaknesses

- In the long term, conventional chillers and PV lead to load mismatch in power grids.
- Today, still harmful refrigerants (high GWP potential).

1.9.2   Solar thermally driven cooling

According to Robins, the main feature of solar electrical cooling are:

Principle:

Thermal compressor (using absorber or adsorber), regeneration with solar thermal heat.

Strengths

- Efficient utilization of solar heat over the year.
- No additional stress on power grid.
- Low-noise operation (few moving parts).
- Use of waste heat (e.g. industrial process heat) possible.

Weaknesses

- Economic feasibility currently only achieved in exceptional cases.
- Backup system necessary.
- In most cases, no feed-in of surplus solar heat into grid is possible.

2   Literature review

2.1   Collectors

Solar collectors transform solar radiation into heat and transfer that heat to a medium (water, solar fluid or air). The solar heat can then be used for hot water, heating or cooling systems. The quantity of solar energy striking the Earth's surface averages about 1,000 watts per square meter under clear skies, depending upon weather conditions, location and orientation (Goodstal).

Per definition, any collector efficiency is calculated as the ratio between the useful heat obtained and the solar gains, represented by the solar irradiation and the total collector surface.

$$\eta_{col} \equiv \frac{Q_{useful}}{I x A_c}$$

Where,

Q_{useful} is the useful heat obtained.

I is the solar irradiation.

A_c is the collection area.

(Kalogirou, 2004) There are basically two types of solar collectors: no concentrating or stationary and concentrating. A no concentrating collector has the same area for intercepting and for absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux.

2.1.1   Stationary collectors

These collectors are permanently fixed in position and do not track the sun. Three types of collectors fall in this category:

- Flat plate collectors (FPC).
- Stationary compound parabolic collectors (CPC).
- Evacuated tube collectors (ETC).

2.1.1.1   *Flat-plate collectors*

A typical flat-plate solar collector is shown in the following figure:

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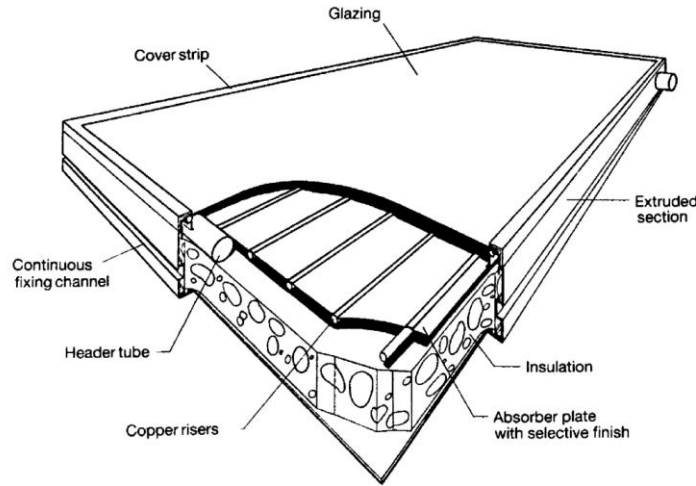
Figure 7 – Flat plate solar collector. Source: F. Schmidt.

When solar radiation passes through a transparent cover and impinges on the blackened absorber surface of high absorptivity, a large portion of this energy is absorbed by the plate and then transferred to the transport medium in the fluid tubes to be carried away for storage or use. The transparent cover is used to reduce convection losses from the absorber plate through the restraint of the stagnant air layer between the absorber plate and the glass. FPC are usually permanently fixed in position and require no tracking of the sun. The collectors should be oriented directly towards the equator, facing south in the northern hemisphere and north in the southern. The optimum tilt angle of the collector is equal to the latitude of the location with angle variations of 10–158 more or less depending on the application FPC are by far the most used type of collector. FPC are usually employed for low temperature applications up to 100 ^{0}C.

2.1.1.1.1 Flat plate collectors performance

(Cooper & Dunkle) If I_n is the intensity of solar radiation, in W/m², incident on the aperture plane of the solar collector having a collector surface area of A_c, m², then the amount of solar radiation received by the collector is:

$$Q_i = I_n . A_c$$

However, a part of this radiation is reflected back to the sky, another component is absorbed by the glazing and the rest is transmitted through the glazing and reaches the absorber plate as short wave radiation. Basically, it is the product of the rate of transmission of the cover and the absorption rate of the absorber.

$$Q_i = I_n(\tau\alpha) . A_c$$

Where,
τ is the rate of transmission of the cover.
α is the absorption rate of the absorber.
As the collector absorbs heat its temperature is getting higher than that of the surrounding and heat is lost to the atmosphere by convection and radiation. The rate of heat loss (Q_o) depends on the collector overall heat transfer coefficient (U_l) and the collector temperature.

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$$Q_o = U_l . A_c (T_c - T_a)$$

Where,

T_c is the collector average temperature

T_a is ambient temperature.

In conclusion:

$$Q_u = Q_i - Q_o = I_n \tau \alpha . A_c - U_l A_c (T_c - T_a)$$

Where,

Q_u is the energy extracted by the collector.

It is also known that the rate of extraction of heat from the collector may be measured by means of the amount of heat carried away in the fluid passed through it.

$$Q_u = m C_p (T_0 - T_i)$$

Where,

m is the mass.

C_p is the specific heat capacity.

T_0 is the out temperature.

T_i is the in temperature.

It is convenient to define a quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature. This quantity is known as "the collector heat removal factor (F_R)" and is expressed as:

$$F_R = \frac{m C_p (T_o - T_i)}{A_c [I_n \tau \alpha - U_l (T_i - T_a)]}$$

The maximum possible useful energy gain in a solar collector occurs when the whole collector is at the inlet fluid temperature. The actual useful energy gain (Q_u), is found by multiplying the collector heat removal factor (F_R) by the maximum possible useful energy gain.

$$Q_u = F_R A_c [I_n \tau \alpha - U_l (T_i - T_a)]$$

A measure of a flat plate collector performance is the collector efficiency (η) defined as the ratio of the useful energy gain (Q_u) to the incident solar energy.

$$\eta = \frac{Q_u}{A_c I_n}$$

2.1.1.2 *Compound parabolic collectors*

CPC are non-imaging concentrators. These have the capability of reflecting to the absorber all of the incident radiation within wide limits. Compound parabolic concentrators can accept incoming radiation over a relatively wide range of angles. By using multiple internal reflections, any radiation that is entering the aperture, within the collector acceptance angle, finds its way to the absorber surface located at the bottom of the collector.

2.1.1.3 *Evacuated tube collectors*

Conventional simple flat-plate solar collectors were developed for use in sunny and warm climates. Their benefits however are greatly reduced when conditions become unfavorable during cold, cloudy and windy days. These solar collectors consist of a heat pipe inside a vacuum-sealed tube, as shown in the following figure:
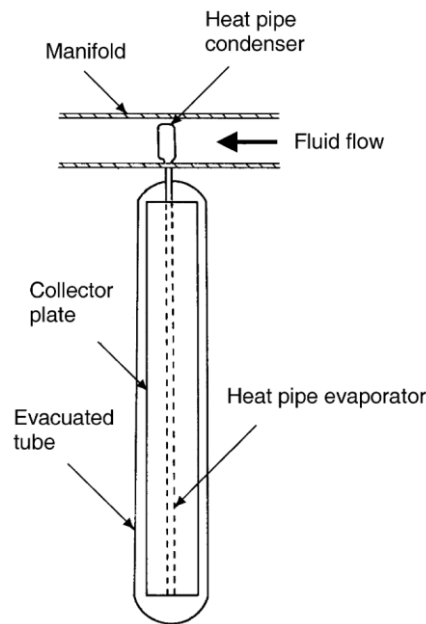
Figure 8 – Evacuated tube collectors. Source F. Schmidt.

ETC have demonstrated that the combination of a selective surface and an effective convection suppressor can result in good performance at high temperatures. The vacuum envelope reduces convection and conduction losses, so the collectors can operate at higher temperatures than FPC. Like FPC, they collect both direct and diffuse radiation. However, their efficiency is higher at low incidence angles. This effect tends to give ETC an advantage over FPC in day-long performance.

The heat pipe contains a small amount of fluid (e.g. methanol) that undergoes an evaporating-condensing cycle. In this cycle, solar heat evaporates the liquid, and the vapor travels to the heat sink region where it condenses and releases its latent heat. The condensed fluid return back to the solar collector and the process is repeated.

2.1.2 Sun tracking concentrating collectors

Energy delivery temperatures can be increased by decreasing the area from which the heat losses occur. Temperatures far above FPC can be reached if a large amount of solar radiation is concentrated on a relatively small collection area. This is done by interposing an optical device between the source of radiation and the energy absorbing surface. Concentrating collectors exhibit certain advantages as compared with the conventional flat-plate:

- The working fluid can achieve higher temperatures.
- The thermal efficiency is greater.
- Reflecting surfaces require less material and are structurally simpler than FPC.

Their disadvantages are:

- Concentrator systems collect little diffuse radiation.
- Some form of tracking system is required.
- Solar reflecting surfaces may lose their reflectance with time.

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2.2   Thermodynamic fundamental of cooling processes

Firstly, any cooling system has the Carnot Refrigeration Cycle as the ideal thermodynamic reference cycle for its development. This cycle is an ideal refrigeration or heat pump machine model for constant temperature external heat source and heat sink. The heat pump or refrigeration are machine or device that moves heat from one location (the "source") at a lower temperature to another location (the "sink" or "heat sink") at a higher temperature using mechanical work or a high-temperature heat source. Thus a heat pump may be thought of as a "heater" if the objective is to warm the heat sink (as when warming the inside of a home on a cold day), or a "refrigerator" if the objective is to cool the heat source (as in the normal operation of a freezer). In either case, the operating principles are identical. In conventional chillers, this power is supplied by the mechanical compression; the thermodynamics of this cycle can be analyzed on the next diagram:
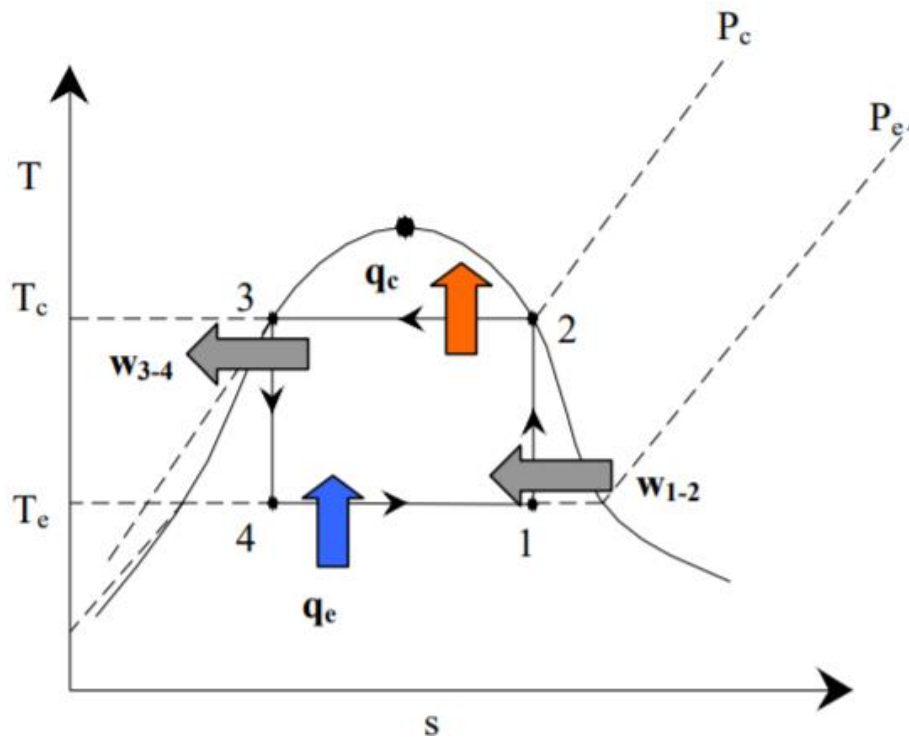
Figure 9 – Carnot refrigeration cycle on T-S diagram.

(Kharagpur) The cycle involves two isothermal heat transfer processes (processes 4-1 and 2-3) and two isentropic work transfer processes (processes 1-2 and 3-4). Heat is extracted isothermally at evaporator temperature Te during process 4-1, heat is rejected isothermally at condenser temperature T_c during process 2-3. Work is supplied to the compressor during the isentropic compression (1-2) of refrigerant vapor from evaporator pressure P_e to condenser pressure P_c, and work is produced by the system as refrigerant liquid expands isentropically in the turbine from condenser pressure P_c to evaporator pressure P_e.

As shown in Figure 10 the basic Carnot refrigeration system for pure vapor consists of four components: compressor, condenser, turbine and evaporator. Refrigeration effect ($q_{4-1} = q_e$) is obtained at the evaporator as the refrigerant undergoes the process of vaporization (process 4-1) and extracts the latent heat from the low temperature heat source. The low temperature, low pressure vapor is then compressed isentropically in the compressor to the heat sink

temperature Tc. The refrigerant pressure increases from P_e to P_c during the compression process (process 1-2) and the exit vapor is saturated. Next the high pressure, high temperature saturated refrigerant undergoes the process of condensation in the condenser (process 2-3) as it rejects the heat of condensation ($q_{2-3} = q_c$) to an external heat sink at T_c. The high pressure saturated liquid then flows through the turbine and undergoes isentropic expansion (process 3-4). During this process, the pressure and temperature fall from P_c, T_c to P_e, T_e. Since a saturated liquid is expanded in the turbine, some amount of liquid flashes into vapor and the exit condition lies in the two-phase region. This low temperature and low pressure liquid-vapor mixture then enters the evaporator completing the cycle.
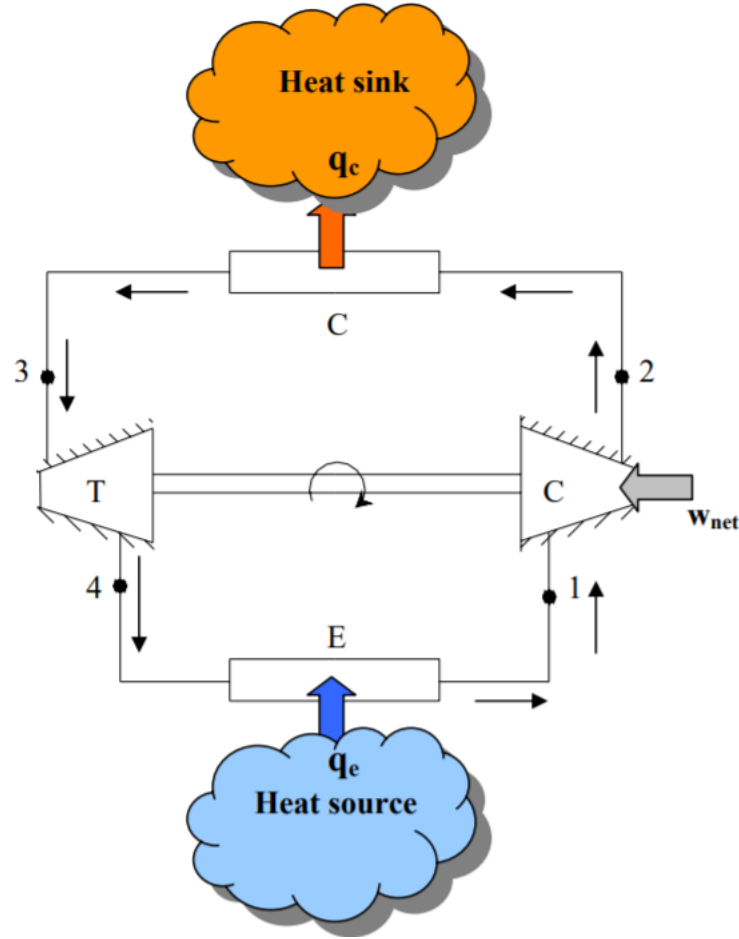
Figure 10 – Schematic of a Carnot refrigeration system.

For the reversible, isothermal heat transfer processes 2-3 and 4-1, it can be written:

$$q_c = -q_{2-3} = -\int_2^3 Tds = T_c(s_2 - s_3)$$

$$q_e = -q_{4-1} = -\int_4^1 Tds = T_e(s_1 - s_4)$$

$$s_1 = s_2$$

$$s_3 = s_4$$

Where,
T_e is the evaporator temperature.
T_c is the condenser temperature.

The coefficient of performance or COP of a heat pump, refrigerator or air conditioning system is a ratio of useful heating or cooling provided to work required. In this case:

$$COP_{Carnot} = \frac{Refrigeration\ effect}{Net\ wotk\ input} = \frac{q_e}{w_{net}} = \frac{T_e(s_1 - s_4)}{T_c(s_2 - s_3) - T_e(s_1 - s_4)} = \frac{T_e}{T_c - T_e}$$

2.3 Open systems

(Schmidt, 2015) Open systems are being used for direct conditioning of supply air to buildings with regard to humidity and temperature (without providing cold water). The key elements in these systems are sorptive dehumidification of air and adiabatic evaporative cooling. In this system, the water is sprayed over the top of a fill package inside the tower and trickles to the bottom. Air is drawn through the fill package from the bottom to the top via a fan. Some water evaporates, thus cooling the remaining water. The cooled water is collected at the bottom of the tower and returned to the solar cooling system. There are three different systems:

- Direct evaporative.
- Indirect evaporative.
- Open sorption systems.

2.3.1 Direct evaporative

The principal concept in this system is that the humidified air is supplied to room and it is important to mention that this system is applicable only if outdoor air is relatively dry.
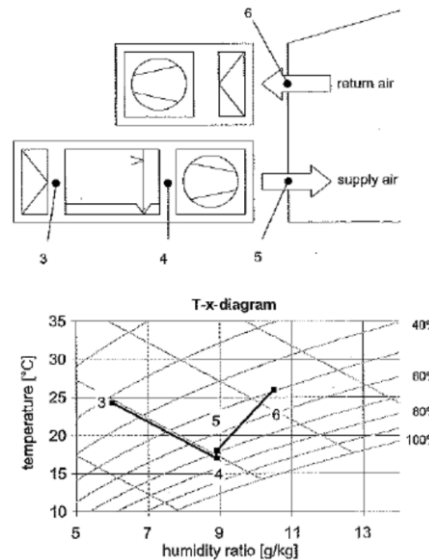
Figure 11 – Direct evaporative. Source F. Schmidt.

2.3.2 Indirect evaporative

In this system, humidified air steam is used to cool supply air without transfer of moisture to supply air stream. In many cases, it makes sense to use the return air from building as the air stream that is humidified (return air enthalpy below outside air enthalpy).

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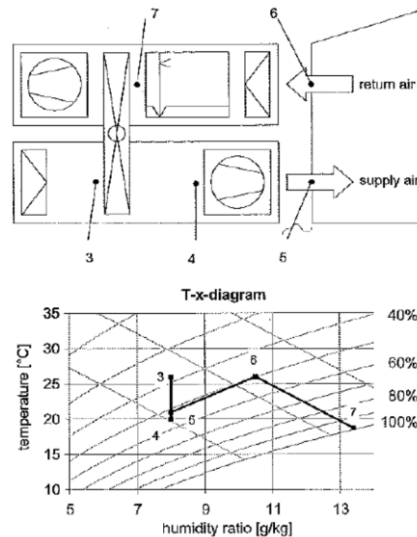
Figure 12 – Indirect evaporative. Source F. Schmidt.

2.3.3 Open sorption systems.

Sorption process is being used when direct and indirect evaporative cooling are not sufficient to reach desired supply air conditions. Comparison with closed systems, heat rejection is integrated into process, therefore no cooling tower required. Open systems can be used a standalone-solution for air-conditioning especially if high air volume flows are required. Most common system type uses sorption rotor as key component. In general, this type of system is used in Europe for moderate climate.

The operating principle of a solid desiccant cooling system and the corresponding psychrometric chart are described in the following figure, where a rotary desiccant wheel is employed. First, ambient fresh air flows through the desiccant wheel, where the latent load is removed by the adsorption of desiccant material. Then a sensible heat exchanger is employed to eliminate the released adsorption heat and preheat regeneration air. After that, an evaporative cooler is usually installed before process air is supplied to the air-conditioning room to adjust the temperature and humidity ratio of the supply air. Now the refrigeration process is completed. Simultaneously, in the regeneration air process, return air from the air-conditioning space is cooled in an evaporative cooler and then flows through the sensible heat exchanger to cool process air. Afterwards, regeneration air is heated in the air heater to the required temperature and used to regenerate the desiccant material.

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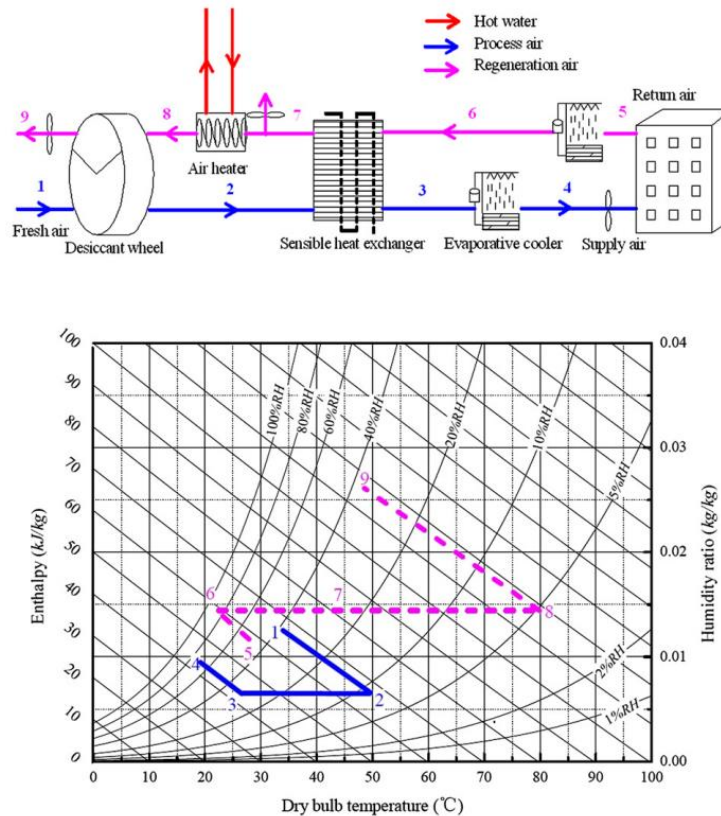
Figure 13 – Open sorption systems. Source F. Schmidt.

The main components are:
- Desiccant wheel with silica gel or lithium chloride
- Heat recovery wheel.
- Humidifier.
- Solar thermal collector field to provide the driving heat.

2.4   Closed systems

(TECSOL)The main component of closed cycle systems is the thermally driven chiller, which provides chilled water. The cold water can be used either in air handling units for cooling and de- humidification processes or is distributed with a chilled water network within the building to the rooms to operate decentralized room installations, like fan coils and chilled ceilings. Chillers with absorption as well as adsorption technology are available on the market. The most part of them (about 88 %) use absorption technology, but only about 12 % use adsorption technology.

The main components are:
- Solar thermal collector field (types: flate plate, evacuated tubes, etc).
- Hot water storage tank (types: stratified storage, buffer storage, etc).
- Heat backup (fossil fuel).
- Thermally driven chiller (absorption or adsorption).
- Hot water distribution network.
- Heat rejection unit (cooling tower dry/wet, ground tube).
- Cold water distribution network.

2.5 Absorption systems

(Deng, A review of thermally activated cooling technologies for combined cooling, 2011) The most common working pairs in absorption refrigeration are lithium bromide-water and water-ammonia. The lithium bromide-water pair is widely used for air cooling applications, with evaporation temperatures about 5-10 ^{0}C; while the water-ammonia pair is mostly used when evaporation temperatures are below 0 ^{0}C for some small size air conditioning and large industrial applications.

The basic principle of a lithium bromide-water absorption chiller is describe in the next picture, which is the simplest and most commonly used design. In the absorption cycle, compressing refrigerant vapor is achieved by the absorber, the solution pump and the generator, in combination. Water evaporated from evaporator (which outputs a cooling effect) is absorbed into a strong lithium bromide solution in the absorber, and the absorption process need to release heat of absorption to the ambient. After absorbing the water vapor, the lithium bromide solution becomes a weak solution, which is then pumped to the generator to be heated. As heat is added to the generator, water will be desorbed from the solution in a vapor form. The vapor then flows to the condenser, where it is condensed and condensing heat is rejected to the ambient. The condensed water flows through an expansion device, where the pressure is reduced. The strong solution from the generator flows back to the absorber to absorb water vapor again, a heat recovery heat exchanger could be used between the strong solution and weak solution lines. The entire cycle operates below atmospheric pressure, since water is used as the refrigerant. The advantages of absorption chillers over conventional electric chillers are that they consume little electricity, they can be used for waste heat recovery applications, they have very few moving parts-leading to low noise and vibration levels, and they do not emit ozone depleting substances.
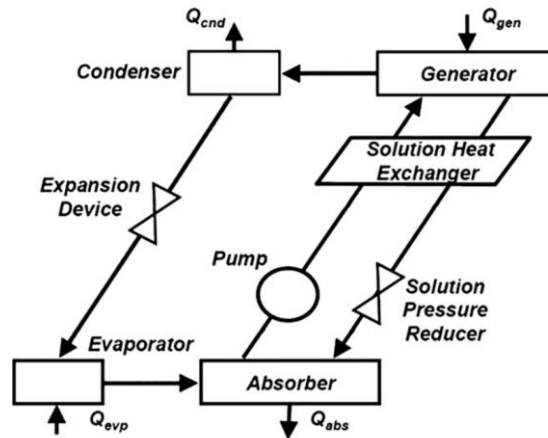
Figure 14 – Absorption chiller. Source: Deng (et. Al. 2011)

The next figure shows a pump cycle plotted in a p-T diagram.
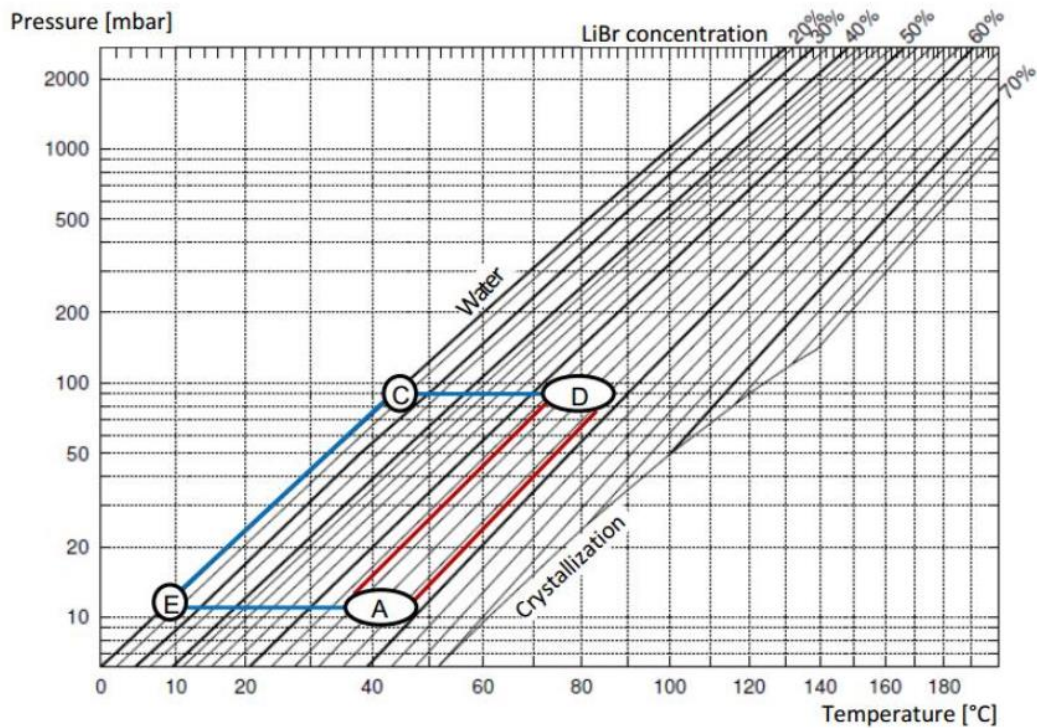
Figure 15 – Absorption chiller p-T diagram. Source: Kühn (2013)

2.5.1 Problem for water-ammonia absorption chillers

For some small and industrial applications, water-ammonia machines are widely used. However, the toxicity/inflammability issues of ammonia, unusable copper and brass materials resulting from ammonia corrosion, and relatively high investment costs, restricts further application of water-ammonia chillers.

2.6 Adsorption systems

There are two types of adsorption refrigeration working pairs:
- Physical adsorption working pairs, such as zeolite-water, activated carbon-methanol, activated carbon-ammonia and silica gel-water.
- Chemical adsorption working pairs, which are mainly, metal hydride-hydrogen and metal chloride (e.g. $CaCl_2$, LiCl, etc.)-ammonia.
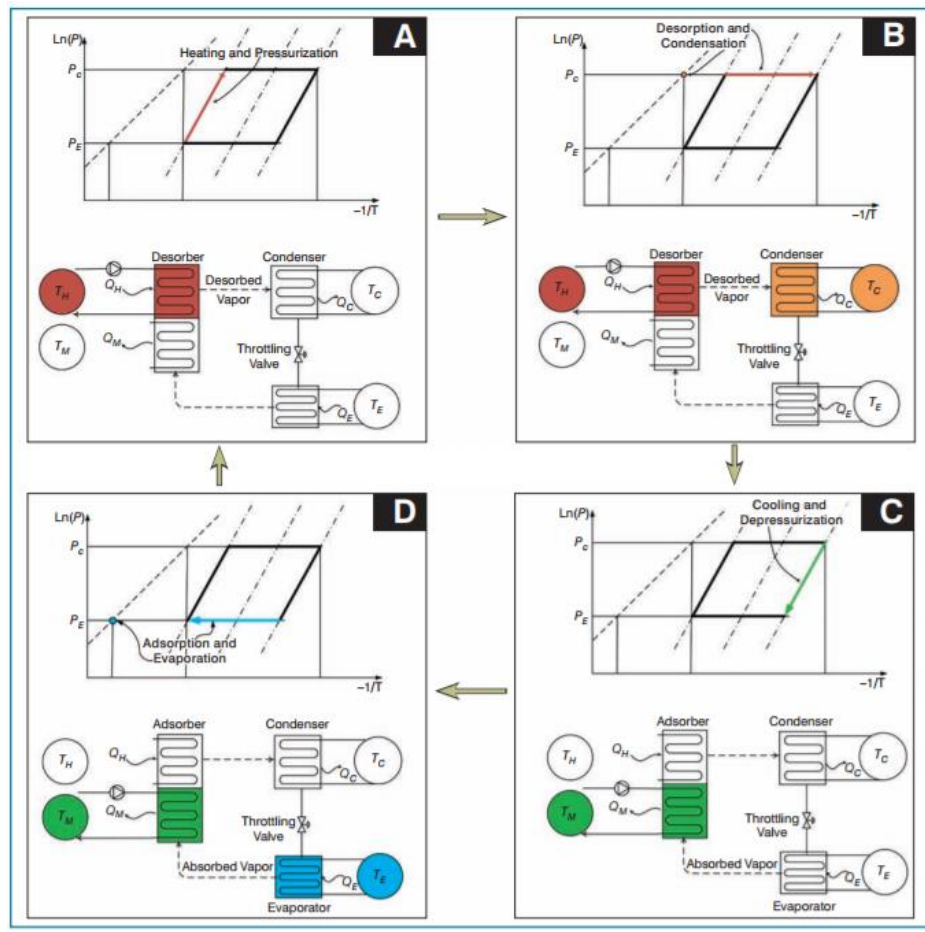
Figure 16 – Adsorption system. Source:

A basic adsorption cycle consists of four steps (Figure 16): heating and pressurization desorption and condensation, cooling and depressurization, and adsorption and evaporation. In the first step, the adsorber is heated by a heat source at a temperature of T_H. The pressure of the adsorber increases from the evaporating pressure up to the condensing pressure while the adsorber temperature increases. This step is equivalent to the "compression" in the vapor-compression cycle. In the second step, the adsorber continues receiving heat and its temperature keeps increasing, which results in the desorption (or generation) of refrigerant vapor from adsorbent in the adsorber. This desorbed vapor is liquefied in the condenser and the condensing heat is released to the first heat sink at a temperature of T_c. This step is equivalent to "condensation" in the vapor-compression cycle. The pressure is set at the vapor saturation pressure set by the temperature of the condenser (in the ideal case where the liquefaction is produced entirely in the condenser). At the beginning of the third step, the adsorber is disconnected from the condenser. Then, it is cooled by heat transfer fluid at the second heat sink temperature of T_M. The pressure of the adsorber decreases from the condensing pressure down to the evaporating pressure due to the decrease in the adsorber temperature. This step is equivalent to the "expansion" in the vapor-compression cycle. In the last step, the adsorber keeps releasing heat while being connected to the evaporator. The adsorber temperature continues decreasing, which results in the adsorption of refrigerant vapor from the evaporator by adsorbent, producing the desired refrigeration effect (the system pressure is set by the evaporator temperature). This step is equivalent to the "evaporation" in the vapor-compression cycle. The basic adsorption refrigeration cycle is an intermittent system and the cooling output is not continuous. A minimum of two adsorbers

are required to obtain a continuous cooling effect (when the first adsorber is in the adsorption phase, the second adsorber is in desorption phase). These adsorbers will sequentially execute the adsorption-desorption process.
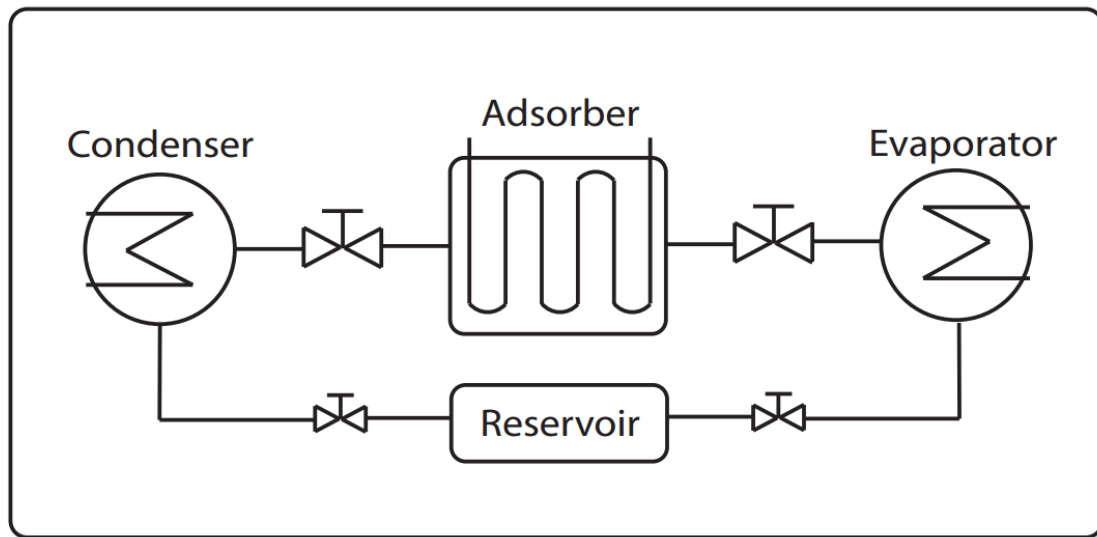
Figure 17 – Schematic Adsorption system.

2.7   Solar PV + Compression chiller

(Kim & Infante Ferreira, 2007) A solar electric refrigeration system consist mainly of photovoltaic panels and an electrical refrigeration device. The biggest advantage of using solar panels for refrigeration is the simple construction and high overall efficiency when combined with a conventional vapor compression system. The next figure describes the system.
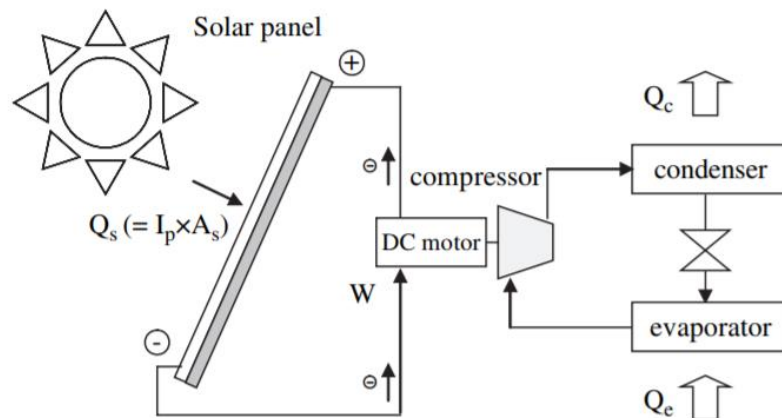
Figure 18 – Schematic diagram of a solar electric compression air-conditioner. Source: Kim, Infante Ferreira (et. Al. 2007).

There are several challenges in the broader commercialization of this type of systems. Firstly, the systems should be equipped with some means to cope with the varying electricity production rate with time, e.g. electric battery, mixed use of solar and grid electricity or variable capacity compressor. Secondly, the price of a solar photovoltaic panel should be further decreased to compete with other solar cooling technologies. In addition to this, there is a high Global Warming Potential (GWP) due to the use of harmful refrigerants.

2.8   Problems for adsorption chillers

There are three main problems in adsorption refrigeration technology:
- The low thermal conductivity of the adsorbent.
- The relatively low cycle mass of the working pair, which means that the adsorption capacity difference between adsorption phase and desorption phase is low.
- The internal solution heat exchanger cannot be applied to the adsorption cycle due to the non-fluidity of solid adsorbent, which limits the effective utilization of heat.

These problems lead to low COP_{th} (0.4-0.5) and large volume in the chiller. In addition, a cooling tower and a hot water tank should also be adopted in this system. As a result, the initial cost of the adsorption refrigeration system is high. The operation at vacuum conditions may pose another maintenance problem if water or methanol is used as the refrigerant.

2.9   Absorption vs adsorption

The main difference between this two system is that adsorption have two or more adsorbent beds in order to provide continuous operation, and each of the adsorbent beds alternates generator and absorber function due to the difficulty of transporting solid sorbent from one to another. The second is that adsorption systems generally have a distinct advantage in their ability to be driven by a relatively lower temperature heat source, but have a somewhat lower COP_{th} compared to absorption systems under the same conditions. The third is that adsorption systems do not need a liquid pump, or rectifier, for the refrigerant, and there is no corrosion problem due to the working pairs, which are normally used, so adsorption chiller is considerably simpler, quiet operation, requiring no lubrication and thus, little maintenance. Based on these characteristics, adsorption refrigeration technology has been considerably developing.

Adsorption chiller need water at 60 –90 ^{0}C and can use flat plate solar collector or vacuum tubes Absorption chiller (single-effect) need water at 80 –110 ^{0}C and can use vacuum tubes and it is more difficult with flat plate solar collector. Absorption chiller (double-effect) need water at 120 –150 ^{0}C and can use CPC collectors. Desiccant cooling need water or air at 45-90 ^{0}C and can use flat plate solar collector or solar air collectors.
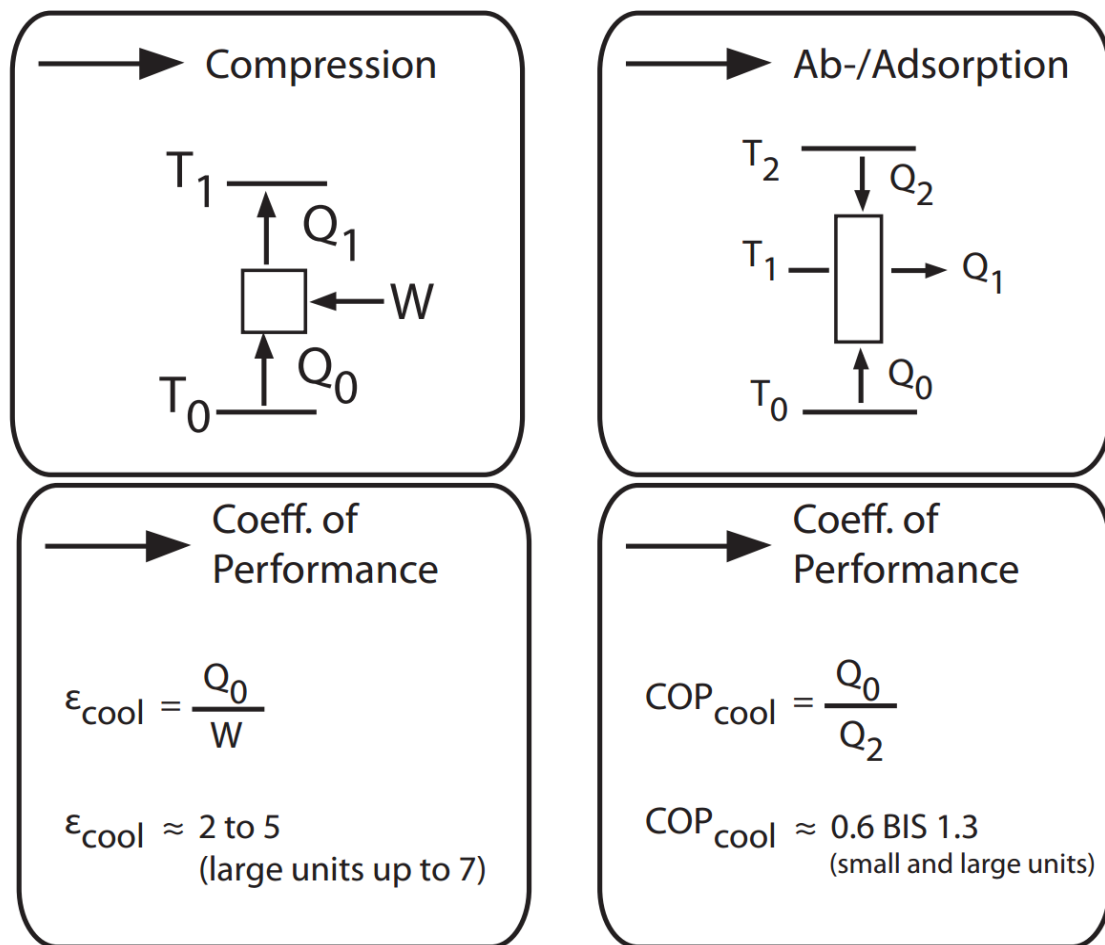
Figure 19 – Different COP.

2.10 Conclusion

After describing the different technologies existing in the solar refrigeration literature, it is proposed as a conclusion the design of a solar cooling machine by adsorption to solve a problem that will be described in the following chapter. To finish, is presented the following figure where Kim and Infante Ferrerira develop in their paper the different technologies with their associated costs.
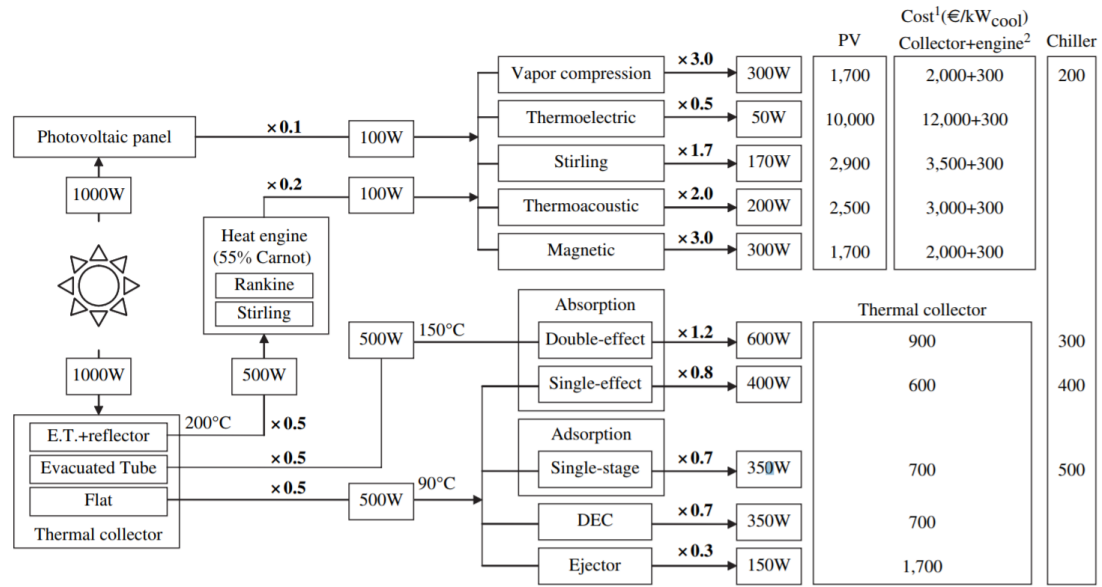
Figure 20 – Performance and cost of various solar refrigerator systems. Source: Kim, Infante Ferreira (et. Al. 2007).

3 Definition of the problem

3.1 The need to cool

(Ferrer, Silvetti, Caceres, & Soto, 2002) In the northwest region of the province of Cordoba, there are about 950 goat producers who are mainly engaged in the production of milk and the sale of goats. Many of these producers are organized cooperatives and peasant groups, including the most important is the "Small Producers' Association Northwest Cordobes" (APENOC). The region, located a few kilometers from the large salt flats (La Rioja), is characterized by climatic conditions extreme: fresh water shortages, maximum temperatures near 42 ° C, very little humidity (with an average of annual rainfall of about 100 mm.) and salty soil. To this must be added the lack of infrastructure necessary for the development of the agricultural activity, for example the electric power line or access to other traditional sources of energy.

In this context and from the productive point of view, one of the main problems that small producer to ensure the quality of their products is refrigeration. In addition, this aspect is a limiting factor in economic development: the inability to conserve milk under optimal one of the factors that causes the sales value of its production to be very low. This can be explained by the logic current production and sales chain. In general terms, the use that producers make of milk can characterized by three circuits:

- feed the small goats, use the surplus to feed other animals, discard
- feed the small goats, transform over, sell "dulce de leche" and / or cheese.
- feed the small goats and sell the surplus.

In the latter case, fluid milk can take two circuits:

- Local industrialization and sale of cheeses to the regional tourist industry.
- Regional industrialization and export of milk powder.

Undoubtedly, one of the main problems of producers is the great gap between the value produced and the appropriate value of their production. This can be explained as follows: the producer is paid at his residence 70 cents per liter of milk, at 50 Kilometers is sold at 6 pesos a liter and more than 200 kilometers at 16 pesos ("Agencia Córdoba Science, 2007") . Then, if its production could be conserved until reaching a sufficient volume, its value of sale could be appreciably greater since it would be possible to generate small scales that allow its manufacture (cheeses, sweets).

3.2 Milk basics

(Cousin, 1991) Milk is a nutritious food of inestimable value that has a short shelf life that requires careful handling. It is a highly perishable food because it is an excellent medium for the growth of microorganisms, especially bacterial pathogens, which can lead to deterioration of the product and diseases in consumers. Milk processing allows it to be preserved for days, weeks or months and contributes to reducing foodborne illness. The shelf life of the milk can be extended by several techniques such as cooling (which is the factor most likely to influence the quality of raw milk) or fermentation.

The effectiveness of cooling to maintain milk quality depends on several factors that we study below:

- Storage temperature

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- Storage period
- Initial contamination
- Cooling speed

3.2.1 Storage temperature

(Luquet, Leche y productos lacteos, 1985) Cooling the milk to a temperature between 3 and 4 ° C slows the growth of the germs as it can be seen in the following table.

Milk stored for 24 h. to one temperature of: (in ° C)	Bacteria / ml
0	2,400
4	2,500
5	2,600
6	3,100
10	11,600
13	18,800
16	180,000
20	450,000
30	1,400,000,000
35	25,000,000,000

Table 1 - Luquet et. Al. (1985).

Currently recommended in most of the countries a temperature of conservation of the milk of 4º C like the more effective to control bacterial growth. A temperature below 3 ° C can lead to freezing phenomena that should be avoided, as they may alter composition and quality of milk.

3.2.2 Storage period

(Luquet, Leche y productos lacteos, 1985) Regardless of the temperature at which the milk is stored, the longer the storage period, the greater the bacterial growth. This fact you can check practically in the figure below.
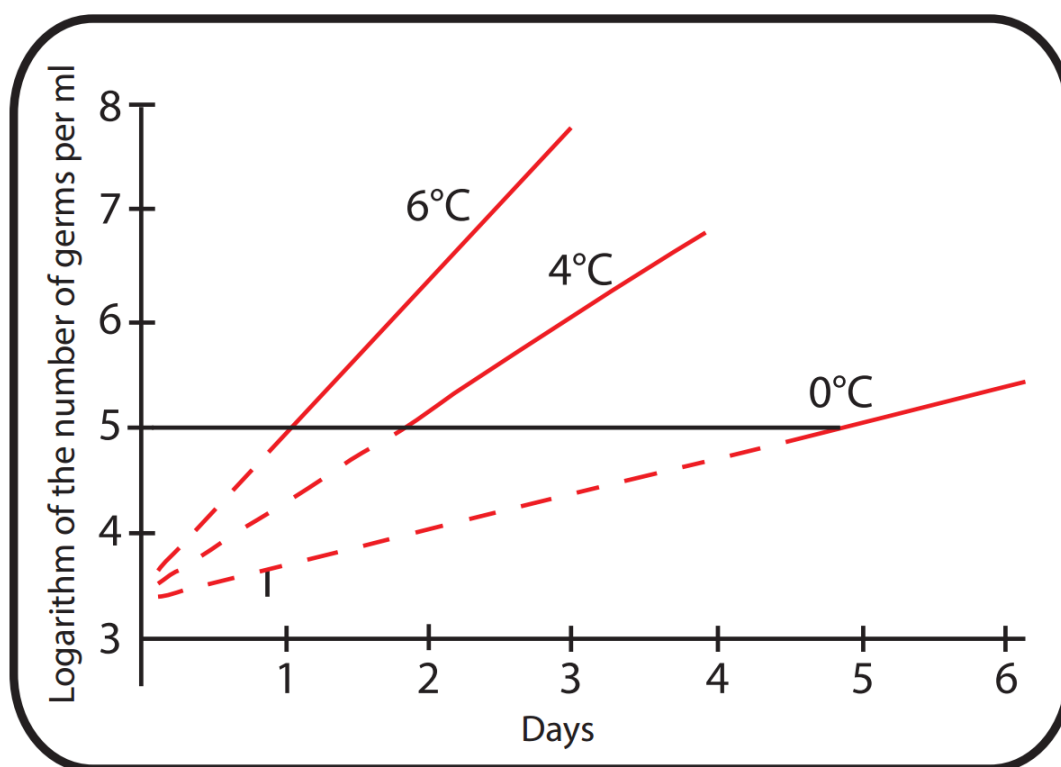
Figure 21 - Evolution of germ content in milk as a function of storage temperature. Source: Luquet et. Al (1985).

Breeders with collection every two days should keep in mind that any storage temperature above 5 ° C may be the reason for not obtaining a good bacteriological quality of milk at the time of collection.

3.2.3   Initial contamination

(Luquet, Leche y productos lacteos, 1985) The number of germs that are already present in the milk when the cooling begins is a factor that has great importance to obtain good results.

Production conditions	Temperature of storage (°C)	Freshly milked	Standard count per ml after:		
			24 h	48 h	72 h
Cows and clean milking equipment	4.4	4,295	4,138	4,566	8,427
	10	4,295	13,961	127,727	5,725,277
	15.5	4,295	1,587,333	33,011,111	326,500,000
Cows and unclean milking equipment	4.4	136,533	281,646	538,775	749,030
	10	136,533	1,170,546	13,662,115	25,687,541
	15.5	136,533	24,673,571	639,884,615	2,407,033,333

Table 2 – Initial contamination. Source: Luquet et. Al (1985).

The above shows that to obtain milk of good bacteriological quality it is not enough to cool it and keep it cold, but also the whole process of milking and storage must be carried out with a

rigorous hygiene, so that the bad ones results are not necessarily due to a malfunction of the cooling tank.

3.2.4   Cooling speed

(Luquet, Leche y productos lacteos, 1985) The speed of the initial cooling of the milk is another factor that influence the total number of germs, since it is not the same a cooling practically instantaneous than one of longer duration.

Initial contamination (germens/ml)	25,000		75,000		125,000	
	24 h	48 h	24 h	48 h	24 h	48 h
Instant cooling	22,000	23,500	79,500	87,750	132,500	188,250
Cooling in 3 hours	23,000	25,500	87,000	101,250	212,500	496,250
Cooling in 5 hours	25,250	30,200	115,500	237,750	273,400	613,800

Table 3 – Evolution of germ content in milk. Source: Luquet et. Al (1985).

For about three hours after milking the growth of bacteria is very slow (bacteriostatic phase), to subsequently increase rapidly. By Therefore, it is necessary to take advantage of this period to cool the milk to the conservation.

3.3   Value added in the Goat Milk Chain for Producers of northwestern goats from Córdoba.

Given the impossibility of accessing traditional cold equipment due to the lack of electrical power in most of the region (structural problem), it is observed that the possible ways to solve the problem of the generation of cold are, at least two.
(Cyrulies, et al.)It is defined that the door-to-door collection system (van with cold room) used so far works with serious difficulties in coordination, because of the number of goiters, the distances of the collection circuit, the condition of the roads, among others, which causes a high degradation in milk quality. On the other hand, this alternative does not solve the problem of the producer who wants to conserve milk (to accumulate liters) to produce his own derivatives: cheeses, "dulce de leche", nor does he solve the problem of generating cold for housing: water-cooling, meat, remedies.
Due to the above, there is evidence of the lack of milk refrigeration equipment raw materials available in each of the region's dairy farmers, adapted to conditions (low economic income, poor status, considerable distances between dairy farms and process plants agro industrial, lack of electrical fluid and environmental conditions adverse weather conditions, with temperatures of 27 ° C in annual average).

3.4   Objectives of design

It defined a cooling a volume of 30 liters per day of goat's milk with below characteristic:
- Cool from 35 to 3 ^{0}C.
- Cool In a time preferably not more than 3 hours.

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- Keep the milk at that temperature steadily for 3 days.

4   Sizing of a adsorption system

4.1   Theoretical cycle of adsorption refrigeration

The behavior described by each of the stages in the refrigeration systems is described below:
- Stage 1, isobaric behavior, the amount adsorbed increases while the temperature of the system decrease; the step represents the adsorption of the adsorbate in adsorbent. It is at this stage that the desired pictorial effect is achieved.
- Stage 2, there is heating and compression at constant volume, this is the transient phenomenon to reach the point of desorption of the adsorbate.
- Stage 3, the desorption of adsorbate occurs. In this step the isobaric heating of the system is observed, favoring a decrease of the amount adsorbed by the effect of the desorption. The desorbed material is condensed.
- Stage 4, there is an isosteric cooling of the system with decrease in pressure, due to the dissipation of heat from the system to the environment.

This theoretical cycle can be represented schematically in a diagram P vs T or in a diagram Clapeyron (ln P vs 1 / T). The figure below presents an ideal cycle of adsorption refrigeration. In a diagram of this type, the steps of constant adsorbant amount are conventionally called isothermal stages, which are usually straight lines in a Clapeyron diagram.
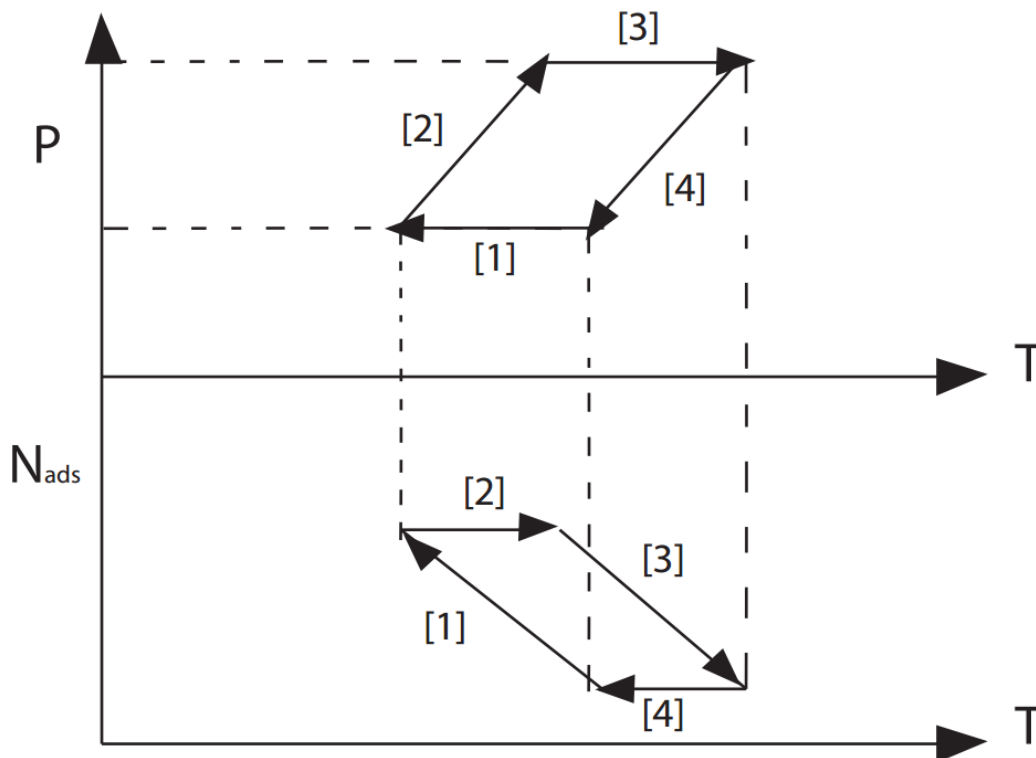

Figure 22 - Ideal thermodynamic refrigeration cycle by adsorption.

The stages of a single cycle operated with solar energy are described below:
- At the beginning of the morning, the generator is at low temperature and pressure, and its adsorbate content is elevated (point 1-2). The concentration at this point is

N_{adsmax}. As solar radiation is absorbed, the temperature and pressure increase to a constant adsorbed amount (step 2).

- When the pressure equals the saturation pressure of methanol at the condenser temperature (point 2-3), condensation begins. The condensation phase (step 3) takes place at constant and hard pressure while the heating on the generator is sufficient.
- At the end of the day (point 3-4), the generator starts to cool down and the pressure in the circuit is reduced. In principle the cooling is at constant concentration (step 4), but when the pressure drops to the saturation pressure value at the evaporator temperature, evaporation (step 1) commences in which the heat necessary for its evaporation is obtained of the enclosure that seeks to be cooled and during which the refrigerant is again adsorbed and takes place the production of cold. The process lasts until the concentration is maximum in the generator.

4.2 Initial parameters

Average Ambient Temperature: 30 ^{0}C.
Average solar radiation: 13 MJ/m2.
Temperature in the condenser: 30 ^{0}C (desorption phase).
Temperature in the evaporator: –5 ^{0}C (adsorption phase).
Condensation pressure: 22 kPa.
Maximum generation temperature: 120 ^{0}C.

4.3 Chiller design

The Dubinin - Radushkevich (D-R) and Dubinin - Astakhov (D-A) equations are widely used to fit the equilibrium uptake data of vapors onto carbon based adsorbents. (Ruzhu Wang) According to the Dubinnin-Radushkevich theory, the adsorption potential of activated carbon that is made up of the micro pores with the efficient radius in the range of 18-20 x 10^{-10} m obeys the Gauss Distribution.
The D-A expression:

$$x(p, T) = W_0 e^{-\frac{1}{E}\left(T ln \frac{P_{sat}}{P}\right)^n}$$

The expressions of D-R and D-A differ only by the value of exponent "n". In the case of the D-R model, this exponent is worth two.

Where,

$x(p, T)$ stands for the equilibrium uptake (kg/kg) for the adsorbent/refrigerant pair.
W_0 defines the maximum adsorption capacity (kg/kg).
E is the adsorption characteristic parameter (kJ/kg).
T is the temperature at which the carbon is found either when it adsorbs the methanol (adsorption phase) or when it desorbs (desorption phase) in K.
P defines equilibrium pressure (kPa) of refrigerant at adsorption temperature.
P_{sat} is saturation pressure (corresponding to a temperature T) (kPa).

For this project is used an especial type of carbon that was design to increase adsorption efficient:
- Product code: CNR115

- Product name: NORITÒ CNR115
- Product define: a chemically granulated activated carbon of 2 millimeters in diameter of a renewable raw material, designed for the control of evaporative emissions of gasoline driven vehicles.
- Product parameters:

W_0	1/E	n
0.316	1.12E-06	2

Table 4 – Carbon parameters.

Assuming a collector temperature of 100 ^{0}C during the day and one of 25 ^{0}C during the night, with a Condenser temperature of 30 ^{0}C during the desorption step and an evaporator temperature of -5 ^{0}C during the adsorption a fraction of methanol contained in the carbon is obtained:

$$xd = 0.094$$
$$xa = 0.249$$

Where,

xa is the fraction of methanol.
xd is the fraction of activated carbon.

The methanol to be circulated through the system is determined once the heat to be absorbed by the evaporator is known. The latter is obtained by determining the energy required to cool 30 liters of milk 0.3 ^{0}C.

$$Q_m = M_m . Cp . (Tf - Ti)$$

Where Q_m is the heat necessary to cold the milk, M_m is the mass of the milk to be cold per day, Cp is the specific heat capacity of the milk and Tf / Ti are initial and final temperatures.

M_m	Cp	Tf	Ti
30Lx1.032 kg/L	0.92 kcal/kg. ^{0}C	0.3 ^{0}C	34.3 ^{0}C

Table 5 – Equation parameters.

$$Q_m = 968 \, Kcal$$
$$Q_m = 4050 \, kj$$

Taking into account that in the ideal situation the milk need 4050 kj per day to cold down, it is necessary take a safety coefficient for the chiller.

$$Sc = 2$$
$$Q_m = q_m . Sc = 8100 \, kj$$

The heat in the evaporator is expressed by:

$$Q_{evap} = M_{me}.hfg$$

Where,

Q_{evap}: heat that absorbs the evaporator, kj.

M_{me}: mass of refrigerant (methanol), kg.

hfg: latent heat of vaporization, kj/kg.

The latent heat of vaporization of methanol at -5 ^{0}C is 1216 kJ/kg (Perry, 2001), and in Q_{evap}= 8100 kJ, from the last equation, the mass of refrigerant required is 6.7 kg of methanol for the process. Therefore, the mass of activated carbon is:

$$M_{me} = M_{ads}.(xa - xd)$$
$$M_{ads} = 43\ kg$$

With these mass of activated carbon the refrigerator can cool the milk in ideal conditions (assuming that it has perfect thermal insulation). To measure the prototype a necessary mass of activated carbon of 50 kg is assumed.

4.4   Collector design

4.4.1   Basic concepts

First, we must know the following basic concepts for the execution of these calculations:

- Angle of inclination β: Angle that forms the surface of the modules with the horizontal plane (Figure 23). Its value is 0 ° for horizontal modules and 90 ° for vertical modules.
- Azimuth angle α: Angle between the projection on the horizontal plane of the normal to the surface of the module and the meridian of the place (Figure 23). Typical values are 0 ° for modules oriented to the south, -90 ° for modules orientated to the east and + 90 ° for modules orientated to the west.
- Declination (δ): It is the angle that forms the plane of the equator of the Earth with the line located in the plane of the ecliptic, which joins the centers of the Sun and Earth (Figure 24). This angle varies along the Earth's orbit around the Sun, reaching maximum values in the summer solstices (maximum positive decline, δ = 23.45 °) and winter (maximum negative declination, δ = -23.45 °) and Null values at the equinoxes (null declination, δ = 0 °). Although the decline varies, it can be assumed to remain constant throughout a day.
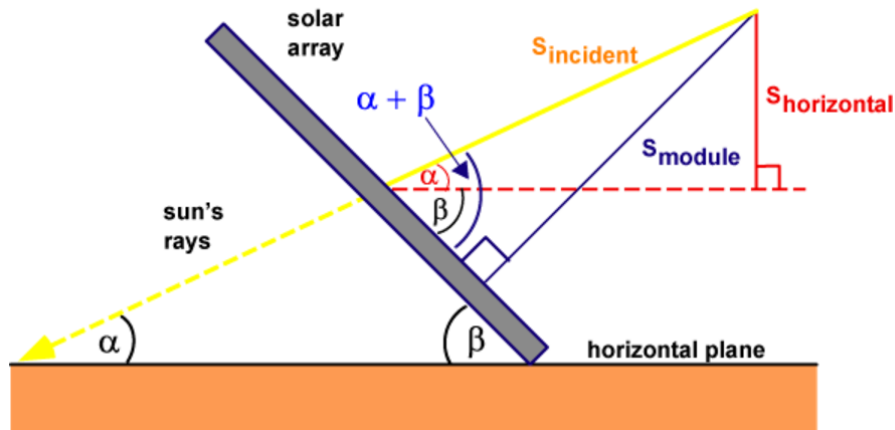
Figure 23 – Angle.

A surface receives the highest possible amount of energy if it is perpendicular to the direction of the Sun. As the position of the Sun varies throughout the day, the optimum position of the surface will also have to be variable.
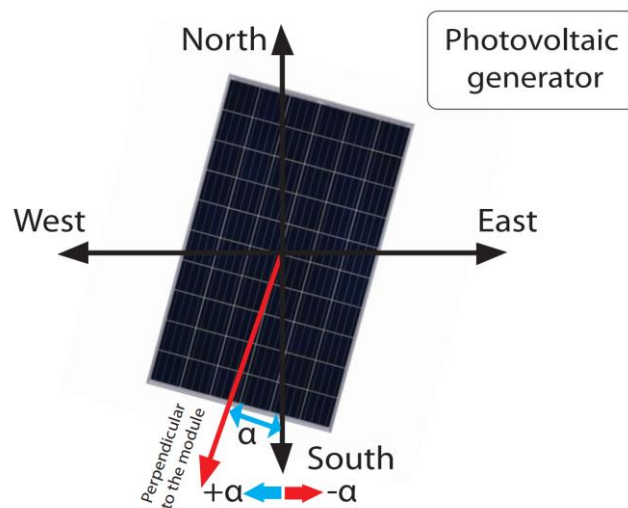
Figure 24 – Solar radiation

Once the coordinates that allow us to place the Sun in the sky have been described, the surface of the panel thermo-solar must be placed in such a way as to receive as much solar energy as possible. This depends on several factors:

- The orientation of the surface of the panel thermos-solar.
- The inclination of said surface.
- Consumption throughout the year: annual, weekend, holidays, etc.

So that a surface receives the solar radiation perpendicularly, (Figure 25) we will have to incline the surface an angle β with the horizontal equal to that which forms the vertical of the place with the solar radiation. We will have to vary the angle of inclination from β = φ - δ in the summer solstice (Figure 25.c) to β = φ + δ in the winter solstice (Figure 25.a), passing through the value β = φ in the equinoxes (Figure 25.b).
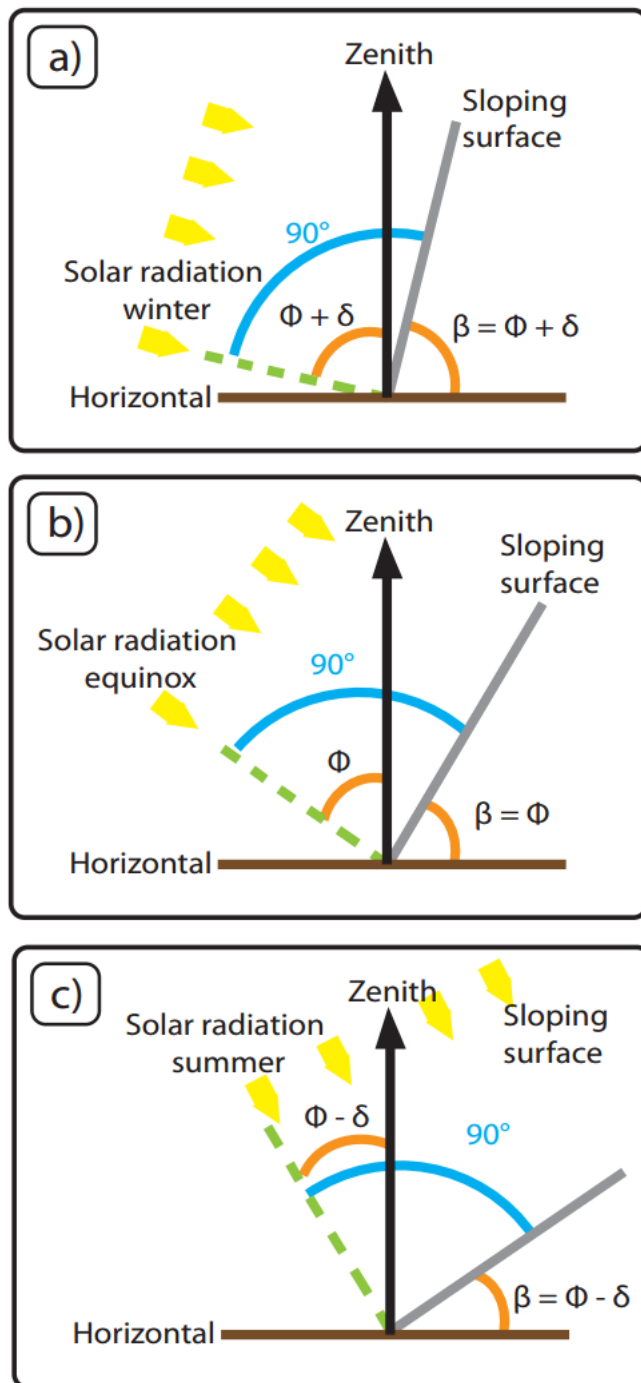
Figure 25 – Solar radiation change

4.4.2   Optimum Angle

In order to determine the optimal slope of a fixed surface, a formula based on statistical analysis of annual solar radiation on surfaces with different inclinations located at different latitudes is used, which provides the optimum slope according to the latitude of the place:

$$\beta_{op} = 3{,}7 + 0{,}69.\parallel \varphi \parallel$$

Where
β_{op}: optimal tilt angle (degrees).
φ: latitude of place, unsigned (degrees).

$$\beta_{op} = 28^0$$

The formula is valid for applications of annual use that seek the maximum uptake of solar energy throughout the year.

4.4.3   Collector Area

The collector used by these refrigerators is generally of parabolic cylinder-diffuser type (CCP) type, such as the double tube shown in the lower figure.
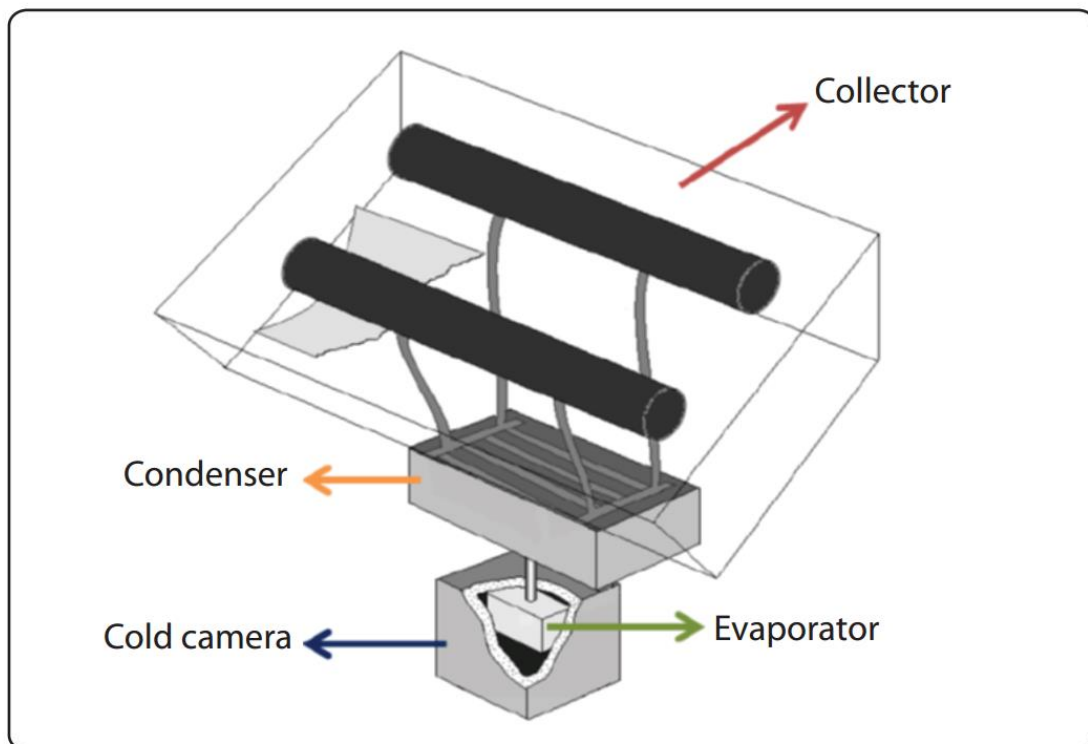
Figure 26 – Schematic collector diagram. Source: Sartarelli.

4.4.3.1   Balance equilibrium

In general, a detailed analysis of the collector must take into account both the energy received during the desorption phase of methanol and the mechanisms of loss in order to evaluate how much of that energy is used to desorb the methanol, as this depends the cooling capacity of

the device. The graph below shows the various flows of energy entering and exiting the collector. In the balances, it only considered one tube (the other was drawn in dotted line).
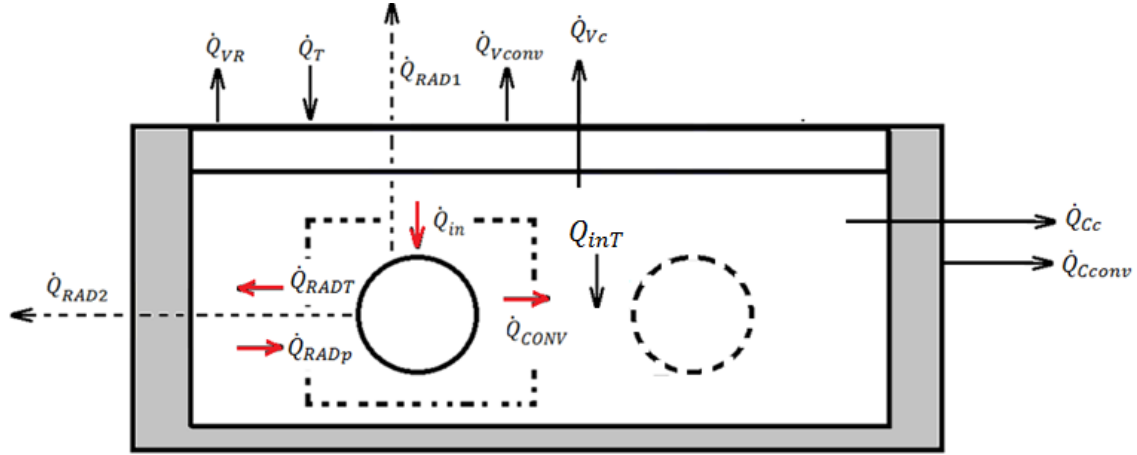
Figure 27 – Collector Balances.

Energy balances, when the thermal equilibrium is reached, can be expressed by the following equation (all energies "$\dot{Q}$" are per unit of time).

$$\dot{Q}_T - \dot{Q}_{Cc} - \dot{Q}_{Cconv} - \dot{Q}_{Vconv} - \dot{Q}_{Vc} - \dot{Q}_{Vr} - \dot{Q}_{CM} = 0$$

Where,

$\dot{Q}_T$ is the total energy (radiant more diffuse: $\dot{Q}_{dif}$) which affects the collector.

$\dot{Q}_{Cc}$ and $\dot{Q}_{Cconv}$ are the energy lost by conduction and convection, respectively, from the interior of the collector to the environment, not counting which is lost through the glass of the cover.

$\dot{Q}_{Vc}$ and $\dot{Q}_{Vconv}$ represent the energy lost by conduction and convection, respectively, through the glass of the cover.

$\dot{Q}_{Vr}$ is the energy that is lost by radiation due to the temperature at which the cover is found.

On the other hand, $\dot{Q}_{in}$ is the energy that radiates to the collector tube, part of this energy "$\dot{Q}_{CM}$" will be assigned to the refrigerant pair, and is the one that will define the cooling capacity of the system. It can be expressed as:

$$\dot{Q}_{CM} = \dot{Q}_{in} - \dot{Q}_{CONV} - \dot{Q}_{RADT} + \dot{Q}_{RADp}$$

Where,

$\dot{Q}_{CONV}$ is the energy lost by the convective tube into the collector.

$\dot{Q}_{RADT}$ is the energy that the collector loses by radiation to the internal surfaces of the collector (including the inner side of the glass whose temperature is not ambient).

$\dot{Q}_{RADp}$ is the energy that the tube receives by radiation from the internal surfaces of the collector.

The radiation loss to the outside (i.e. towards the clear sky) indicated by $\dot{Q}_{RAD1}$ is negligible since the glass is practically opaque to the infrared radiation, corresponding to a temperature of about 120 ^{0}C, which is the one reaching the collector tube . The same is true for the radiation loss through the collector cover indicated by $\dot{Q}_{RAD2}$, since the cover is completely opaque to all radiation. Obviously, $\dot{Q}_{CM}$ (which is used to desorb the methanol) enters as a loss when calculating the temperatures of the internal parts of the collector.

The knowledge of these flows fixes the temperatures of all the internal surfaces of the collector.

4.4.3.2   Energy transferred to the refrigerant pair

The collector tubes receive direct solar radiation at the top and at the bottom receive the same type of radiation reflected by the stainless steel cylinder-parabolic mirrors, whose reflexivity is around 50%. Here it must take into account that the tubes intercept not all the reflected radiation because there are geometric factors that put a limit to the percentage of radiation captured. It concludes that because of these, only 45% of the reflected radiation affects the bottom of the tubes, besides all of them only the direct type radiation arrives. The top of the tubes also receive some diffuse radiation of much smaller amount. Direct radiation is attenuated by approximately 5-7% after passing through the glass cover. The tubes absorb approximately 90% of the radiation that they receive and part of that energy is basically by two types of mechanisms: radiation and convention (and much less by conduction through the pipes that connect it to the condenser). The radiant energy lost, as well as the convectively transported heat, are basically redirected into the collector and from there they pass into the atmosphere mainly by convective mechanisms, and to a lesser degree by radioactive (the glass cover of the collector reaches a temperature of 40-50 ^{0}C). The next figure shows how useful thermal energy (which is transferred to the cooling torque) depends on the temperature difference between the collecting pipes and the environment.
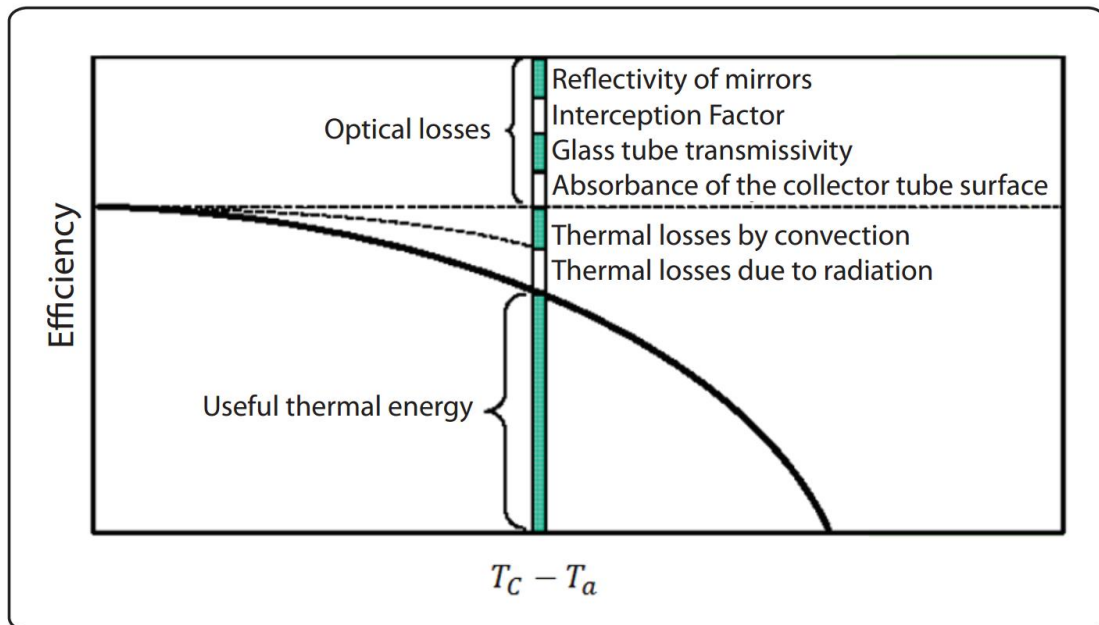
Figure 28 – Collector thermal losses.

If the energy (per unit time and area) that reaches the collector cover is $\dot{q}_T$, the energy transferred to the refrigerant pair can be approximated by the expression:

$$\dot{Q}_{CM} = \left[\dot{q}_T \frac{A_t}{2} \tau_V (1 - R_V) \varepsilon_T + \dot{q}_{dif} \beta \frac{A_t}{2} + \dot{q}_T \frac{A_t}{2} \tau_V (1 - R_V) \varepsilon_T \frac{A_c}{A_t} F_g R_E \right] - \dot{Q}_{CONV} - \dot{Q}_{RADT} + \dot{Q}_{RADp}$$

Where,

τ_V is an attenuation factor that depends on the thickness of the glass. In this case the factor is worth approximately 0.98.

R_V is the reflectivity of the glass. (≈ 0.04).

A_t is the effective area of the tube.

$\dot{q}_{dif}$ represents the diffuse radiation (which only reaches the top of the tube).

β is a attenuation factor of this radiation which takes into account both the transmissivity through the glass thickness of the cover as its attenuation by reflection. This term involving diffuse radiation is generally neglected in the calculations.

The third term inside the bracket represents the reflection of the direct radiation and there ε_T is the absorption factor of the radiation by the tube ($\varepsilon_T \approx 0.9$).

A_c is the area of capture of the parabolic mirror.

R_E is the reflexivity.

F_g is a geometric factor that realizes that not all reflected radiation is concentrated in the lower part of the tube.
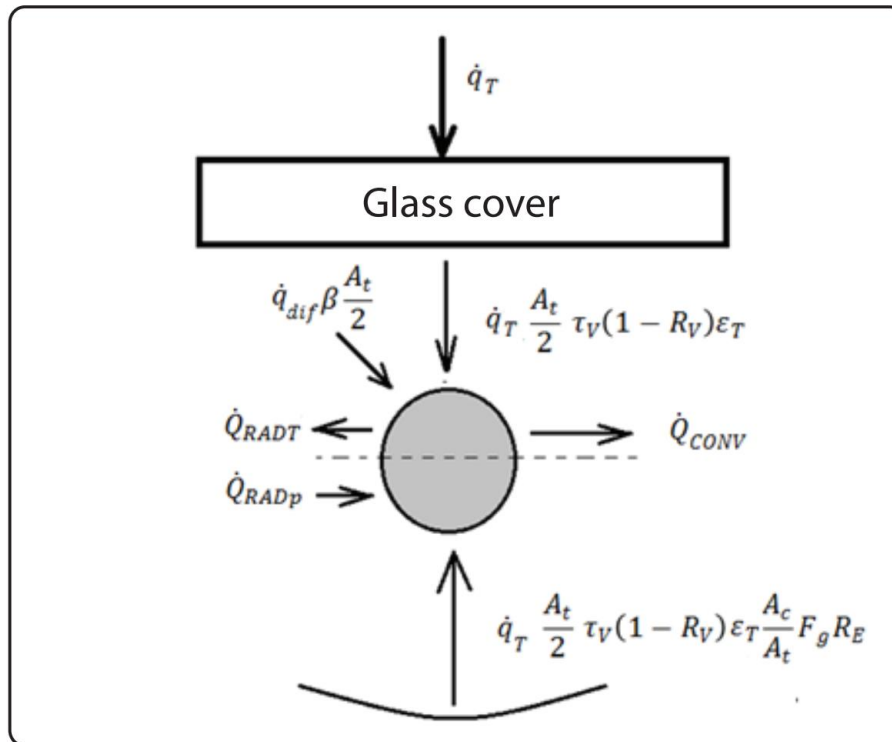
Figure 29 – Energy transferred to the refrigerant pair.

4.4.3.3 Calculation of $\dot{Q}_{RADT}$ and $\dot{Q}_{RADp}$

(Cengel, 2004) The radiation fraction emitted F_{ij}, by one surface i and which is intercepted by another surface j is known as shape factor, vision factor or configuration. In order to determine this, there are integral methods, and a very simple method developed by H.C. Hottel in the 50's (the method of cross-strings). This method can be used for uneven surfaces as well as for surfaces that are partially blocked by others; surrounding them. So that in order to determine the radiation emitted by a surface i to another surface j (per unit of time), it can be written:

$$\dot{Q} = \varepsilon F_{ij} A \sigma T^4$$

Where,
ε is the emissivity of the material.
A is the area.
$\sigma = 5.67 \; 10^{-8} \; \frac{W}{m^2 K^4} \, T$ (Constant of Boltzmann).
T is the absolute temperature.
When there are two facing surfaces with different emissivity ε_1 and ε_2, it becomes necessary to determine the total radiation as a function of the infinite reflections that occur between both surfaces, then the equivalent emissivity is:

$$\varepsilon = \varepsilon_{ij} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

Taking into account all of the above, it is possible to calculate how much net energy ($\dot{Q}_{RADT}$ - $\dot{Q}_{RADp}$) is transferred, by radiation, from the absorber tube to the internal enclosure of the collector, calculating what is transferred to the inner surface of the enclosure glass cover). For it is necessary to know:
- Geometry (to be able to determine shape factors).
- Emissivity of the materials that make up the surfaces.
- The temperature of internal surfaces

4.4.3.4 Convection losses

(Kreith & Bohn, 2001) The energy (per unit area and time) lost by a surface due to convection can be written:
- in terms of the temperature difference ΔT (between the surface and surrounding environment).
- The heat exchange area " A ".
- A convection coefficient " h_{CONV} " which depends on the difference in temperature, the diameter of the tube and the thermal conductivity of the air (k_a).

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$$h_{CONV} = \frac{N_u k_a}{D}$$

Where,

N_u is the Nusselt number which represents the ratio of convection heat transfer to heat transfer by conduction and it is expressed in terms of Rayleigh (Ra) and Prandtl (Pr).

$$N_u = \left[0.6 + \frac{0.387 \, Ra \, D^{1/6}}{\left(1 + \left[\frac{0.559}{Pr} \right]^{9/16} \right)^{8/27}} \right]^{1/2}$$

The Rayleigh number is written as:

$$Ra = \frac{gCev \, \Delta T \, D^3}{v^2} Pr$$

Where,

g is the acceleration of gravity.

Cev is the coefficient of thermal expansion (considering air as ideal gas, this coefficient is written as $1/(\frac{\Delta T}{2})$).

v is the average kinematic viscosity of air for a temperature range of 20-100 ^{0}C. In this case $v = 1.96 \, 10^{-5} \, m^2/s$.

Pr is the average Prandtl number for a temperature range of 20-100 ^{0}C. $Pr = 0.71$.

Taking all of these considerations into account, we obtain the following curve, which shows how the efficiency of a typical CCP collector is modified as a function of the temperature difference between the collector tube T_C and the environment T_a.

45
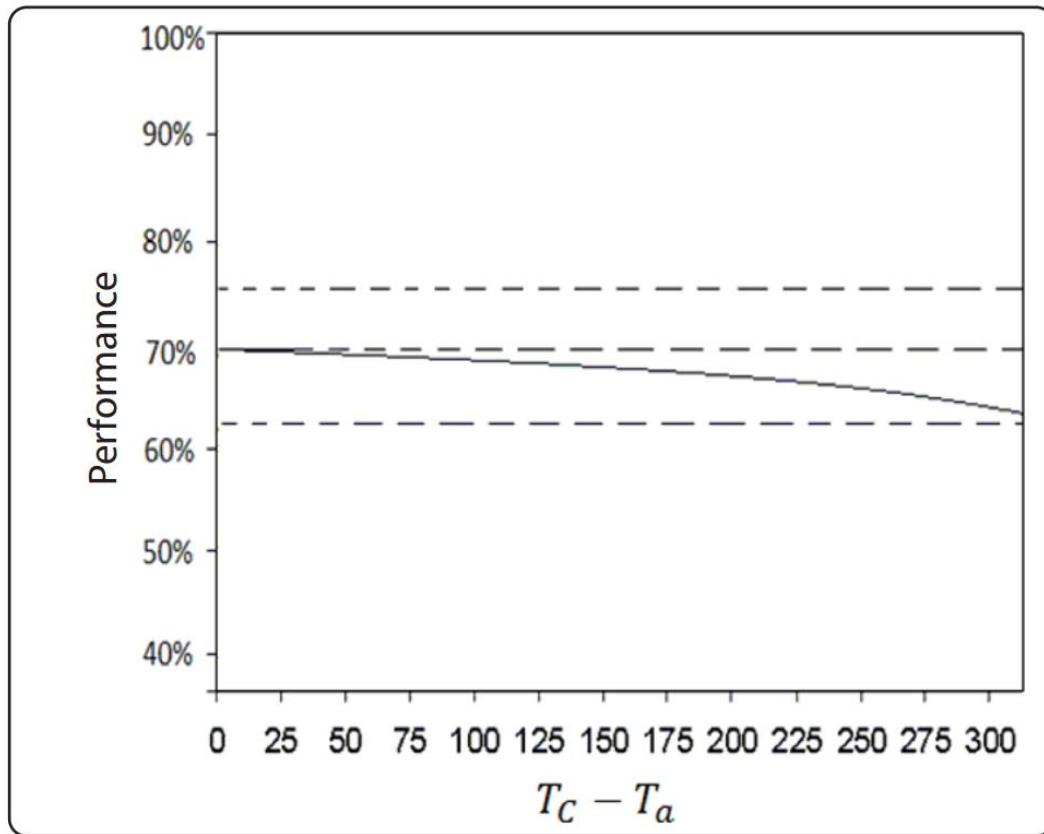
Figure 30 – Collector efficiency. Source: Kreith (2001).

It is concluded from the graph that the performance for working temperatures greatly exceeds 60%.

4.4.4 Incident energy in the collector

The direct radiation that reaches the earth's surface depends on how "clear" the atmosphere is. One of the approximations that can be used to calculate this is the Hottel model.

$$I = I_{ext}(a_0 + a_1 e^{-K/cos\theta_z})$$

$$a_0 = 0.4237 - 0.0082(6 - h)^2$$

$$a_1 = 0.5055 - 0.00595(6.5 - h)^2$$

$$k = 0.2711 + 0.01858(2.5 - h)^2$$

To take into account the type of climate, correction factors are introduced, obtaining the new corrected coefficients:

$$a_0^* = a_0 r_0, \qquad a_1^* = a_1 r_1, \qquad k^* = k r_k$$

Type of weather	r_0	r_1	r_k
Tropical	0.95	0.98	1.02
Summer (middle latitudes)	0.97	0.99	1.02
Winter (middle latitudes)	1.03	1.01	1
Subarctic summer	0.99	0.99	1.01

Figure 31 – correction factors depending on weather. Source: Sartarelli.

These parameter values are valid for a sky with 23km of visibility and for a height h not greater than 2.5km. . I_{ext} is the maximum radiance of atmosphere (approximately 1300w / m²). To calculate the energy received by the collector for 5 hours, Sartarelli created a program that takes into account the radiation received according to the Hottel model and the angles of inclination of the collector, which are more optimal. With this program, it was obtained that the lowest energy value corresponds to the month of June and is about 15MJ. Although supposing that this would be the most unfavorable condition is an error, if we take this energy value for our calculation of the collector area the area gives us:

$$A_C = \frac{15000}{8100} \, m^2 = 1.8 \, m^2$$

We will take as area 2m².

4.5   Condenser area

To calculate the energy needed to condense methanol, we must take into account the enthalpy difference between vapor and liquid (1160 kJ/kg), which for 6.7 kg equals 7.78 MJ. The heat in the condenser can be expressed (considering a condensation time of 3 hours):

$$Q_{cond} = h_{cond} m_{me} \frac{1}{t}$$

$$Q_{cond} = \frac{1160 \frac{kJ}{kg} \text{ x } 6.7 \text{ kg}}{3 \text{ x } 3600 \text{ s}} = 719.63 \text{ w}$$

$$Q_{cond} = H A_{cond} \Delta T$$

$$A_{cond} = \frac{719.63 \text{ w}}{\left[\left(350 \frac{w}{m2} * K\right)\right]} (1^{\circ}K)$$

$$A_{cond} = 2.06 \, m^2$$

It would take a transfer area of 2.1 m². It implies 20 tubes of 100 cm and a diameter of 1 ½ inches.

5 Prototype

5.1 Collector

(Cyrulies, Sartarelli, Vera, Echarri, & Samson, 2010) In this case, a closed, insulated drawer has been constructed been constructed with a glass cover inside which is the collector system itself, a mirror system with a collection area with a collection area of approximately 2 m². The drawer has lids that, when open, allow accelerating the cooling of accelerating the cooling of the collector by the circulation of air, which favors the adsorption of methanol. methanol.
In order to capture the solar energy required for desorption, a parabolic cylindrical concentrator system was used for concentrator system was used for each collecting pipe shown in

Figure 32. The design requires that the orientation of these concentrators be in the approximate east-west direction.

Figure 32 – Collecting pipe. Source: Sartarelli.

On the other hand, the adsorbent is placed inside tubes in an annular space; said tubes are placed inside the manifold, which in turn must be insulated. Figure 33 is a representation of the tubes is made, as well as their dimensions.
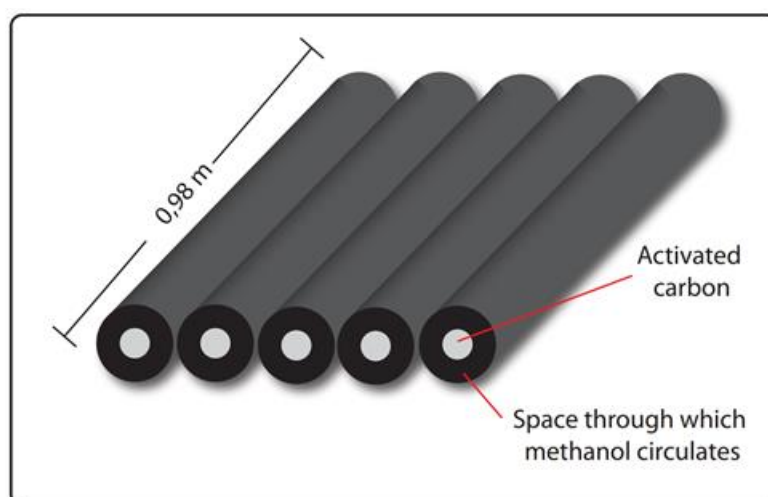
Figure 33 – Collector. Source: Sartarelli

The material of the tubes is of stainless steel, of 76 mm of external diameter; the annular section is formed with a metal mesh, occupying a diameter of 30 mm. The activated carbon will go in the annular section, placing 1.5 kg per tube, to cover the total amount of activated

carbon. The tubes shown in Figure 33 are inside a rectangular box, the top cover being a 3 mm thick glass; the sides and bottom of the box shall be of galvanized sheets and shall be provided with an insulation system to minimize energy losses in the system.

5.2 Condenser

(Vera, Echarri, Sartarelli, Cyrulies, & Samson, 2008) It consists of two grids formed by about 20 meters of 1 ½ inches copper pipes welded with silver that total a transfer surface of 2.1 m². These pipes are immersed in the water contained in a galvanized sheet of corrosion-protected galvanized sheet with a capacity of 150 liters. The walls have a lateral coating on paper that is moistened with the contained water, in order to improve the efficiency of the condenser through the evaporative effect. This method has given satisfactory results in the previous prototype built by the research group.

5.3 Evaporator

It is a container of expanded polystyrene-coated outer and inner PVC. Inside is the evaporator, which is connected to the condenser system by a single channel through the top wall. The chamber has a net volume (discounting the ice container with the evaporator) of 40 dm³. It is accessed through a front top cover.

5.4 Final prototype

It is presented below an outline of the final prototype to be constructed for the problematic raised.
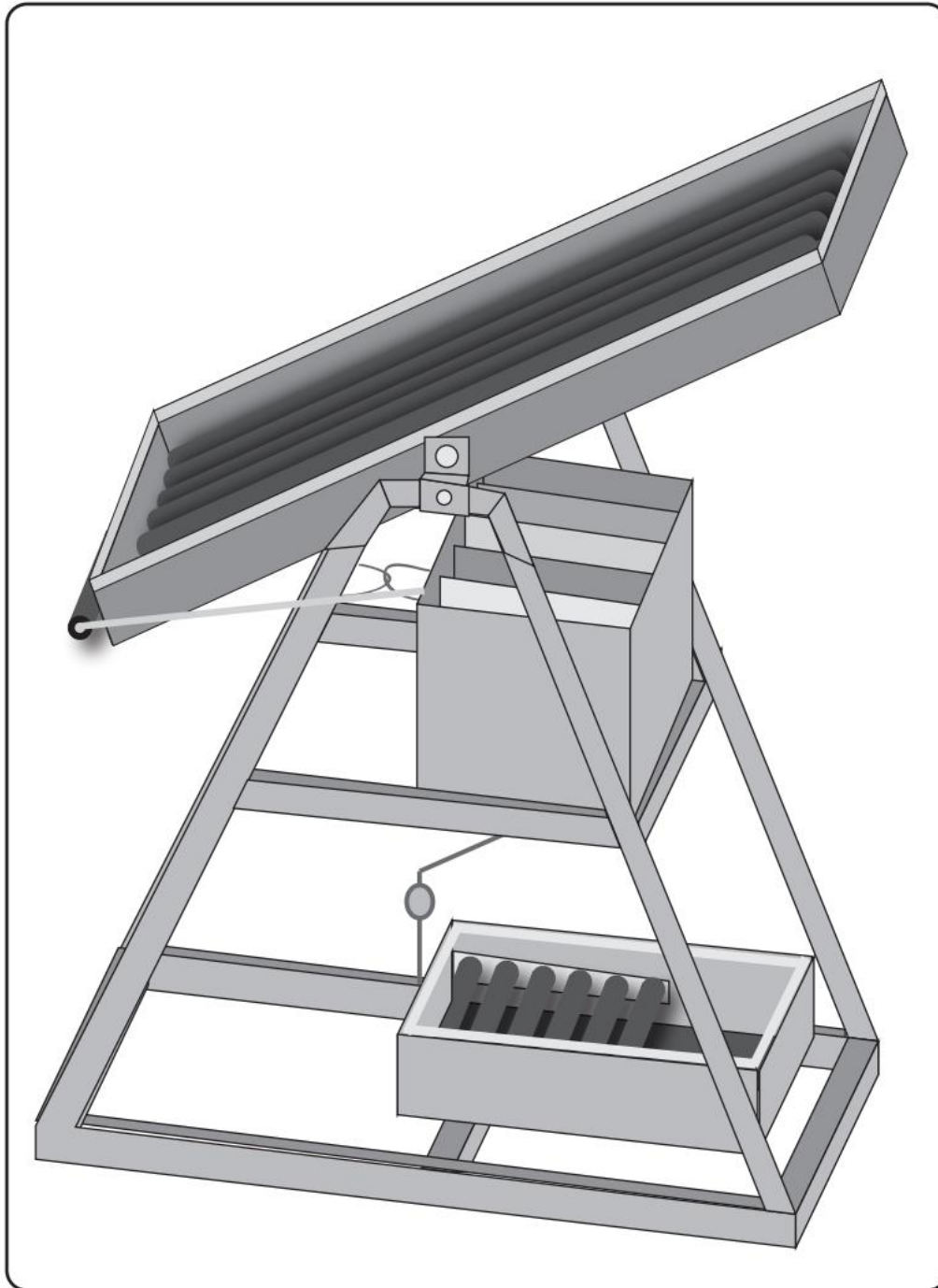
Figure 34 – Final Prototype.

The activated carbon is first charged into the collector, and then vacuumed for several hours for a couple of days. While the vacuum is made, the pipes of the collector are heated with electric stoves in order to take them to more than 150 ^{0}C. This process of cleaning the coal is essential to remove all the water (moisture) and other things it contains adsorbed. After this process, a valve that is attached to the condenser pipe charges the methanol. As the whole system is left empty when the valve is opened, methanol enters the evaporator only.

An important data to describe the effectiveness of a thermally activated cooler is the operating thermal coefficient called COP. This is defined as the ratio between the heat extracted in the refrigeration process and the heat of activation of the system.

$$COP = \frac{q_{CM}}{q_t}$$

5.4.1 Material cost

The list of raw materials for the construction of prototype is detailed below.

Item	Total price
Square pipe (5X5)	733
One-inch and 1/2 copper spout	1,333
Barrel	90
Square pipe (2X2)	600
Cylindrical stainless steel	1,740
Mirror	1,020
Stainless steel iron	850
Galvanized sheet	500
PVC Sheet	889
Glass wool	444
Carbon activated CNR115 or AC35	2,500
98% Methyl Alcohol	150
Total	**10,850**

Table 6

It is concluded that the most critical raw material is the activated carbon. This is due not only its cost, but also it is difficult to accesses to it in Argentina. This adds to the fact that the specification of the carbon is critical for the efficiency of the absorber. Therefore, it is a critical input where it should be ensure its supplies to be able to produce in series.

6 Analysis of manufacturing and selling in Argentina

This chapter develops, based on assumptions, a possible investment project for the production and sale of solar adsorption chiller.

6.1 General costs

There is a distinction between Fixed Costs and Variable Costs for both the pre-operational stage (before beginning to sell the product) and for the operational stage as follows:

	Pre-operational stage	Operative
	Administrative expense	Maintenance
	Human resources	Human resources
	Depreciation	Depreciation
Fixed costs	Marketing expense	Marketing expense
		Selling expenses
		Supplies
Variable costs		Tax

Table 7 – General cost

6.1.1 Preoperative costs

As an initial assumption the first 2 years of the project does not produce sales so there is only fixed expenses (it is assumed a high investment in marketing and human resources costs to find and capture market niches that have the need for the proposed product). These are the administrative expenses, the initial staffing structure (HR) and the depreciation of the fixed assets purchased.

6.1.2 Operative costs

When sales begin to occur variable costs are incorporated. These are:

- Selling expenses, which refer to commissions paid for product sold.
- The expenses in the materials that make up product for its manufacture.

Also added are marketing expenses, which although fixed for the first two years, are assumed to grow as the project grows (5% of planned sales are considered). The cost of labor is assumed at 200 pesos per hour and pays 21% of V.A.T.

6.2 Break even

The break-even point is approximately 29 units per year. This volume is assumed to be reached in the fourth year of the project. In addition, this analysis represents an annual sales growth of

30% on average.

Ideally, two analyzes of sensitivities should be made:

- The risks associated with the production and availability of raw materials (in particular the availability of activated carbon).
- The risk associated with the commercial area, where it is assumed an expansion in areas of Argentina where the network does not reach and there is a need to cool fresh products, particularly milk.

6.3 Tax structure of the project

The company presents negative results in the first 3 years of the project, which has a balance in favor of IG that is reintegrated in the following years, without exceeding the 5-year maturity. No fees were considered for real estate or rolled as considered negligible with respect to the project amounts. Neither, the presumed minimum income tax that should be paid in the first years of the project (when going to loss) and then deducted from the IG. Social contributions were 23% and were included in the results table for labor.

6.4 Cash flow

From the cash flow of the project, the financial needs to be covered were determined. These needs come from the bump that the initial investments generate and the successive investments. The next figure below represents the summary of the cash flow.

			0	1	2	3	4	5	6	7	8	9	10
INCOME STATEMENT													
Units				0	20	24	29	38	49	69	97	146	219
Revenue	$	-	-	190,800	228,960	276,660	362,520	467,460	658,260	925,380	1,392,840	2,089,260
O&M	$	-	(11,000)	(31,000)	(36,000)	(41,000)	(51,000)	(62,000)	(83,000)	(111,000)	(161,000)	(234,000)
G&A	$	-	-	(9,540)	(11,448)	(13,833)	(18,126)	(23,373)	(32,913)	(46,269)	(69,642)	(104,463)
Marketing	$	-	(280,000)	(280,000)	(211,448)	(213,833)	(218,126)	(223,373)	(232,913)	(246,269)	(269,642)	(304,463)
Sales commissions	$	-	-	15,264	18,317	22,133	29,002	37,397	52,661	74,030	111,427	167,141
EBITDA	$	-	(291,000.0)	(129,740.0)	(29,936.0)	7,994.0	75,268.0	158,714.0	309,434.0	521,842.0	892,556.0	1,446,334.0
Depreciation	$	-	(66,667)	(66,667)	(66,667)	-	-	-	-	-	(25,000)	(25,000)
Earnings Before Tax	$	-	(357,667)	(196,407)	(96,603)	7,994	75,268	158,714	309,434	521,842	867,556	1,421,334
Income Tax	35%	-	125,183	68,742	33,811	(2,798)	(26,344)	(55,550)	(108,302)	(182,645)	(303,645)	(497,467)
Net Income		-	(232,483)	(127,664)	(62,792)	5,196	48,924	103,164	201,132	339,197	563,911	923,867
CASH FLOW													
EBITDA		-	(291,000.0)	(129,740.0)	(29,936.0)	7,994.0	75,268.0	158,714.0	309,434.0	521,842.0	892,556.0	1,446,334.0
Income Tax		-	-	-	-	-	-	-	-	-	(451,546)	(497,467)
Capex		(200,000.0)	-	-	-	-	-	-	-	-	(50,000.0)	-
WK Var.		(42,000.0)	61,110.0	27,245.4	6,286.6	(1,678.7)	(15,806.3)	(33,329.9)	(64,981.1)	(20,845.9)	-	-
FLOW		(242,000.0)	(229,890.0)	(102,494.6)	(23,649.4)	6,315.3	59,461.7	125,384.1	244,452.9	500,996.1	391,009.8	948,867.1
VAT Payments													
Investment VAT	21.0%	(42,000.0)	-	-	-	-	-	-	-	-	(10,500.0)	-
Sales VAT	21.0%	-	-	40,068	48,082	58,099	76,129	98,167	138,235	194,330	292,496	438,745
Costs VAT	21.0%	-	(61,110)	(67,313)	(54,368)	(56,420)	(60,323)	(64,837)	(73,253)	(84,743)	(105,060)	(135,014)
VAT Position		(42,000)	(61,110)	(27,245)	(6,287)	1,679	15,806	33,330	64,981	109,587	176,937	303,730
VAT Credit (bop)		0	42,000.0	103,110.0	130,355.4	136,642.0	134,963.2	119,156.9	85,827.0	20,845.9	-	-
VAT Credits		42,000.0	61,110.0	27,245.4	6,286.6	-	-	-	-	-	-	-
VAT Debits		-	-	-	-	(1,678.7)	(15,806.3)	(33,329.9)	(64,981.1)	(20,845.9)	-	-
VAT Credit (eop)		42,000.0	103,110.0	130,355.4	136,642.0	134,963.2	119,156.9	85,827.0	20,845.9	-	-	-

Figure 35 – Income Statement, Cash Flow

To sum up, the TIR of the project is 22% in 10 years.

7 Proposed vs actual technology

In order to compare costs and performance it is decided to do a market analysis of the products available that producers can use without electricity. The most commercialized product is the bottled gas refrigerator in Argentinean market.

7.1 Bottled gas refrigerator

The following product is proposed:
- Brand: SIANAGAS
- Model: RG-310
- Type of cooling: Absorption
- Approximate Gas Consumption: 180Grs / 24hs
- Measurements: High: 0.60 m - Width: 0.39 m - Depth: 0.46 m
- Capacity: 40 L
- Initial cost: $ 15,650
- Gas cost per year: $ 9,855

Figure 36 – Gas refrigerator

7.2 Cost comparison

The following figure analyzes the opportunity cost between the two proposed technologies:

Year		0	1	2	3	4	5	6	7	8	9	10
New Technology												
CAPEX	$	-$33,390										
OPEX	$			-$2,500		-$2,500		-$2,500		-$2,500		-$2,500
Actual Technology												
CAPEX	$	$15,650										
Natural gas	$		$9,855	$9,855	$9,855	$9,855	$9,855	$9,855	$9,855	$9,855	$9,855	$9,855
Flow		-$17,740	$9,855	$7,355	$9,855	$7,355	$9,855	$7,355	$9,855	$7,355	$9,855	$7,355

Figure 37 - Flow comparison

From the previous flow, it is conclude that although the value of the proposed solar refrigerator is approximately double the refrigerator that producers can get in the market, the TIR in favor of our technology is 49% (maintenance of activated carbon change every two years). This is mainly due to the continuous expenditure generated by the current technology in the consumption of bottled gas. The current net value of the proposed technology is $8,200

with a rate of 20%. This means that producers have a saving of $8,200 pesos in 10 years using the new proposed technology.

8 Conclusion

A feasibility study of introducing adsorption solar cooling systems in Argentina was made. A prototype of interest for small milk producers is proposed as a competitive solar refrigerator, with the characteristics indicated below.

Advantages
- Not use of electrical or mechanical energy (compressor)
- Possible use of various sources of thermal energy (sun, natural gas, waste…)
- Operational simplicity with regard to absorption systems.
- Use of environmentally friendly working fluids.

Disadvantages
- Intermittent operating cycle.
- Low COP compared to other technologies
- Use of activated carbon with specific properties, which are critical to ensure a reasonable COP and is not produced in Argentina.

Technical performance
- Lower thermal COP than other technologies, but using an unlimited and free energy source like the sun.
- None consume of electrical energy, which is not available at isolated areas.

Main components defining the overall costs
- Solar collectors
- Activated carbon

9 Suggestions

It is recommended to analyze different absorber materials (like zeolite) in order to compare availability and costs. In addition, other thermal sources should be used to compare costs. To sum up, the proposed prototype could be an interesting opportunity for development of regional economics at isolated places, where refrigeration can be a difference in daily life.

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11 New lines of research

- Maintenance and chemical effects on coal and methanol.
- Possible backup equipment for large industrial projects.
- Analysis of cold storage systems.