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SOLAR THERMAL ENERGY FOR INDUSTRIAL TECHNOLOGY

by
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ABSTRACT
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The Lebanese industrial sector is not stacked with large industries; instead, many small and medium sized industries are spread all over the Lebanese geography. As with any sector, the industrial sector faces many challenges, with two prominent problems being the lack of sustainable infrastructure and the inaccessibility to cheap energy. As stated previously, the latest official consensus conducted by the Ministry of Industry, highlights these problems (Industrial Information Authority, 2020). The relatively elevated energy bill that the industries need to pay at the end of each month is enormous, and without a solution to this problem, these industries will not be able to operate continuously and might even have to shut their operations. Being able to reduce energy costs will end up saving on manufacturing costs. This will, in turn, give the manufacturer a competitive advantage in the local market, and the latter will be able to price its products more efficiently.

Renewable energy can be a viable solution to such problems. It is gaining more worldwide acceptance as a reliable and sustainable source of energy, which can be installed at residential/ consumer level or at utility and industry levels. Going one step further, renewable energy can be used to reduce the energy bill for the small and medium Lebanese enterprises. There are two main ways such systems can be used, either to produce electricity or to produce energy (heat) that can be used directly or that can feed into a thermodynamic process indirectly.

Solar energy is the conversion of irradiation into heat. Such systems can be complemented by another process. So, the concept is to collect, gather and store solar radiation from one side, and then use this heat/ energy to run a thermodynamic/ chemical process. This is done by converting the heat into energy (Mekhilef et al., 2011). Other common use of solar energy is to produce electricity. This can be done either directly by the use of photovoltaic panels, or via concentrated solar power technologies. However, this type of solar energy use will not be discussed in this thesis.

This paper sheds light on a specific type of renewable energy technology which can be implemented on the industrial sector of Lebanon, generating solar thermal energy for industrial heat and cooling processes and needs. The processes are numerous, such as energy for heating, cooling, pressing, refining, blending, molding, etc. Almost all types

of industries use such processes in their daily operations. More specifically, the study will focus on the design of a solar thermal energy system, with the aim to produce cooling and heating. The former can be produced by the refrigeration systems and the heating can be produced by heat pump systems.

The study will be complemented by a pilot study on a specific industry and a technical and financial feasibility study will be conducted. The goal is to see and test if such technology can be implemented and how it can serve the purpose for local industries in lowering their energy costs.

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ABBREVIATIONS

WHO	World Health Organization
EDL	Electricity Du Liban
IRENA	The International Renewable Energy Agency
RE	Renewable energy
LPG	Liquefied Petroleum Gas
FPC	Standard flat plate collector
ETC	Standard evacuated tube collector
LFC	Linear Fresnel Collector
PTC	Parabolic Trough Collector
PDC	Parabolic Dish Collector
HCR	Heliostats with central receiver
DNI	Direct Normal Irradiation
F_r	Diffuse Radiation
G_r	Global sun radiation
NC	Non-concentrating collectors
CSP	Concentrated solar power
STPP	solar thermal power plant
HTF	Heat Transfer fluid
COP	Coefficient of performance

CHAPTER I

INTRODUCTION

Energy is considered an essential need for all sectors in any country; such as transport, industry, and a wide range of household services, known as residential sector. The market of energy consumption is expected to increase worldwide by a significant percentage by the year 2030 (Abdelaziz, 2010). The primary source for such energy is fossil fuel, which is finite given that it took millions of years to form. In addition, utilizing fossil fuels has negative impact on the environment and contributes to climate change. According to a statistic released in 2010 by the World Health Organization (WHO), the direct and indirect effects of climate change leads to the death of 160,000 people per year and the rate was estimated to double by 2020 (Mekhilefa, 2011). Therefore, in order to face the challenge of limited natural resources, and to reduce the negative effects on the environment, the search for durable sustainable energy that is environment friendly is increasingly needed by most of the energy stakeholders. Renewable energy (RE) such as wind and solar energy is considered as a strong candidate that is sustainable and environmentally friendly. Renewable energy can be used directly to produce electricity to feed the power transmission lines, and indirectly by industrial sectors as a reliable source of heat and energy.

The industrial sector consumes one third of the total produced energy with the major part being used in industrial heating and cooling. According to a study on industrial heating, thirty percent of industrial applications require heat below $100^{\circ}C$, 27% require heat between 100 and 400°C, and the remaining 43% require heat above 400°C (Claudia Vannoni, 2008). In short, more than half of the industrial heating targets relatively low temperatures, and as such several renewable technology sources can assist in meeting such requirements. Besides, it takes a relatively larger amount of energy to raise the temperature of water compared with heating air, for example. Therefore, even a modest amount of pre-heating can reduce a facility's dependence on fossil fuels and save money in the process.

During the Renewable Energy Conference in Berlin in 2001 (Scheer, 2001), the urgent need arose to accelerate the exploitation of renewable energies, on the one hand because the demand for energy is increasing very quickly, oil prices are rising and oil reserves are decreasing, and on the other hand due to the increasing threats of climate change. The International Renewable Energy Agency (IRENA) was established to assist in accelerating the sustainable energy. The latter represents the global voice of this energy and tries to encourage its implementation and issuance of the necessary documents to inform about it. It also seeks to reach practical solutions and joint agreements on an international scale.

The state of the energy transformation is not homogenous around the world. In developed countries, the renewable energy sector has been evolving steadily with legal frameworks already established, and the necessary investments already taking place. Therefore, renewable energy production plays a major role in the country-specific energy mix. However, this is not the case in less developed countries. There are many reasons for this shortage in those countries, and those reasons are not necessarily related to the technology, but rather to the limited capacity and ability of the local stakeholders to operate in a constrained environment such as inability to secure funds or necessary investments, poor infrastructure, lack of the required legal frameworks, etc.

Lebanon is one of those countries, facing many challenges in the energy sector. There are numerous reasons for this shortfall that range from the lack of necessary power plant capacity to meet the rising demand, the poor transmission grid, the lack of necessary energy related infrastructure, and the burden of the subsidies. According to the Ministry of Energy and Water, \$1.8 billion of fiscal deficits were added to Lebanon's national debt in 2018 alone, while the total deficit due to electricity subsidies, since 1990, have reached a staggering \$30 billion (McDowall, 2019). This means that there is an urgent need for the government to transform the sector in order to increase reliability, affordability, and sustainability. The problem of the power sector and the shortfall in energy supply hinders the development of other sectors, most importantly the industrial sector. The Lebanese industrial sector uses heat for a wide variety of applications, including washing, cooking, sterilizing, drying, preheating of boiler feed water, and much more. Altogether, it is estimated that the 2015 energy demand of the industrial sector in terms of electricity, diesel/gas oil, Liquefied Petroleum Gas (LPG) is $1{,}603\ ktoe$ (LCEC, 2016). This can be considered to be a significant increase from the value of 1994, which stands at $970\ Ktoe$ of end-use industrial energy consumption. Industrial heating applications alone accounts for approximately 36 percent of total delivered energy consumption within the manufacturing sector in the industry. The large size and scale of industrial heating energy use represents a unique opportunity for renewable resources.

A survey conducted by the Industrial Information Authority in April 2020 (Industrial Information Authority, 2020), shows that there are numerous challenges that the industrialists face in Lebanon. These challenges range from power outages, high prices of energy fuels and unavailability of a private / Lebanese workforce. The study concludes with a set of recommendations to solve such problems, among many, the most important one promotes the introduction of renewable energy in the sector. At the moment, only 3.2% of the Lebanese factories that participated in the survey make use of renewable energy in their industries. In fact, Lebanese industries rely on the interrupted Government supplied electricity. Therefore, they have to import their own fuel oil, in order to produce their own electricity on site. This is reflected in the energy bill of such industries, and hinders the development and expansion of this sector.

Moving towards renewable clean energy would be one of the possible solutions which would decrease the dependency on fossil fuels and protect the budget from the impact of changing oil prices in the energy markets. In addition, it would help decreasing air pollution levels, which according to a study carried by WHO in 2014, was three times higher in Beirut than the acceptable levels.

Another important sector that could reap the benefits from the renewable resources is the power sector, which, as described before, is in a demolished state and lacks the capacity in order to meet the increasing demand. In its quest to ramp up its power supply, a law has been passed (Law No. 462) in the parliament in 2002 with the aim to attract investment from the private sector. However, up till now, this law has not been implemented. The government is aiming to find the right balance between public-private partnerships that could bring new blood to a failing sector that has been fully run by a state-controlled company. The law allows private generation of electricity at the consumer level for a capacity up to 1.5 MW. Therefore, consumers could make use of the available renewable energy technologies to generate such power for personal use. In addition, in 2011, Electricity Du Liban (EDL) adopted the single net metering scheme which enables and compensates the export of renewable energy electricity back into the national grid.

In short, the introduction and further development of renewable energy in Lebanon can contribute positively in solving the problems that are witnessed in the industrial and power sector. This thesis aims to shed the light on one particular renewable technology, which is solar energy and more specifically, on one special type and process used in the industrial sector.

CHAPTER II

LEBANON STATUS

Renewable energy is becoming the hope of the future slowly, and for some technologies the future development seems to be more imminent, and thus will have a positive impact on the environment and climate change. According to the world energy forum (Reid, 2020)and by 2030, solar will become the most important source of energy for electricity production in a large part of the world.

Lebanon is able to generate about a third (30 percent) of its energy needs, which is ten times what it currently produces, from renewable sources, according to a study carried by the International Renewable Energy Agency (IRENA) (Agency, 2020). However, Lebanon has failed in the adoption of new policies and the deployment of clean, safe, and reliable energy sources. The strategy introduced to update the main electricity reform paper constituted two different parts. The first update resulted in 2011 in the evolving of the National Energy Efficiency Action plan and the National Renewable Energy Action plan document for the period between 2016 and 2020. While the other one resulted in the introducing of the "National Action Plan for Energy Efficiency" for the same period (LCEC, 2016). These proposals were focused on studies that confirmed the availability of renewable energy sources and their potential for deployment, as well as energy efficiency steps, to reach 12 percent of electricity and heating demand by 2020. All of this, however, has not resulted in significant progress toward renewable energy efficiency.

In 2018 a new goal was identified to meet 30 percent of the total energy consumption from renewable sources (electricity and heating demand) by 2030. The total renewable energy capacity installed so far is 350 megawatts, of them 286 megawatts from hydropower, seven megawatts of biogas from the Naameh landfill site and 56.37 megawatts of solar power. This means that, despite studies showing that Lebanon has substantial renewable energy resources, including solar energy and wind, no significant progress has been made. This failure in achieving much progress is the result of multiple factors among which are financial and political ones.

Lebanon is thus still far from this new global investment in the field of renewable energy, except for some private initiatives. Therefore, the need for this investment is strongly emerging, especially to bridge the deficit in electricity production.

Renewable energy technologies have the advantage of providing stable, clean, and completely localized energy systems. In light of the economic-financial crisis and the outbreak of the Coronavirus, renewable energy sources are a major component of any forthcoming recovery plan. The major challenge would be to change the "the political and sectarian intricacies of the power sector" (Heinrich-Böll-Stiftung, 2019).

The powerful political clout of generator owners jeopardizes the secure supply of electricity. The market size of the generator is approximately $2 billion annually, demonstrating the magnitude of the industry (Dziadosz, 2018). The owners' close relationship with key government officials is a significant impediment to the expansion of traditional energy production. It is important to note that the cost increase in bills and emission rates affects the state treasury, consumers, and EDL, all without achieving a satisfactory level of reliable energy provision.

The adoption of Renewable Energy could have resulted in annual savings of considerable amounts of money spent for energy production for the benefit of the state treasury, not to mention lowering the external costs spent for the treatment of air pollution and carbon dioxide emissions. Furthermore, adopting renewable energy could have offered broader social and economic advantages, and other benefits such as creating new jobs and markets, pumping cash flows, and improving energy security through diversification of its sources. However, success in achieving all of this requires major adjustments to strategies, policies, regulation, technology, infrastructure, and financing mechanisms, and above that all, the Lebanese government's will in imposing the law, fighting corruption, safeguarding public money, and achieving progress through implementing actual solutions in the electricity and power crisis

A. Research objective

The Lebanese industrial sector is not stacked with large industries; instead many small and medium sized industries are spread all over the Lebanese geography. As with any sector, the industrial sector faces many challenges, with two prominent problems being the lack of sustainable infrastructure and the inaccessibility to cheap energy. As stated previously, the latest official consensus conducted by the Ministry of Industry, highlights these problems (Industrial Information Authority, 2020). The energy bill that the industries need to pay at the end of each month is considerable, and without a solution to this problem, these industries will not be able to operate continuously and might even have to shut their operations. Being able to reduce energy costs would cut down manufacturing costs. This will, in turn, give the manufacturer a competitive advantage in the local and international markets.

Renewable energy can be a viable solution to such problems. As detailed earlier, it is gaining more worldwide acceptance as a reliable and sustainable source of energy, which can be installed at residential/ consumer level or at industry and utility levels. Going one step further, renewable energy can be used to reduce the energy bill for the small and medium Lebanese enterprises. There are two main ways such systems can be used, either to produce electricity or to produce energy (heat) that can be used directly or that can feed into a thermodynamic process indirectly.

Solar energy is the conversion of irradiation into heat. So the concept is to collect and store solar radiation and then use this heat/ energy to run a thermodynamic/ chemical process. This is done by converting the heat into energy (Mekhilef et al., 2011). Other common use of solar energy is to produce electricity which can be done either directly using photovoltaic panels, or via concentrated solar power technologies. However, this type of solar energy use will not be discussed in this thesis.

This paper sheds light on a specific type of renewable energy technology which can be implemented on the industrial sector of Lebanon, generating solar thermal energy for industrial heat and cooling processes and needs. The processes are numerous, such as energy for heating, cooling, pressing, refining, blending, molding, etc. Almost all types of industries use such processes in their daily operations. More specifically, the study will focus on the design of a solar thermal energy system, with the aim to produce cooling and heating. The former can be produced by the refrigeration systems and the heating can be produced by heat pump systems.

The study will be complemented by a pilot study on a specific industry and a technical and financial feasibility study will be conducted. The goal is to assess if such technologies can be implemented and how they can serve the purpose for local Lebanese industries in lowering their energy costs and associated carbon emissions.

CHAPTER III

METHODOLOGY

Several tools are developed to model both systems described above (heat production and the thermodynamic processes). These tools are used to size, design, simulate and evaluate the performances of the relevant systems. It is mainly needed as evaluation software that can conduct feasibility studies and sensitivity analysis for its users.

Several local industries were visited, and data related to the cooling and heating process were collected. A full study regarding the implementation of the concentrated solar thermal energy system was performed on a particular industry of the author's choice. The goals were to assess the local Lebanese industrial sector, see where this can be implemented, how it can serve the purpose for local industries in lowering their energy costs, and how it can contribute to environmental sustainability.

The first tool was used to compute the efficiency of the radiation conversion and the collector yield. Different assumptions and configuration were simulated to reach optimal design and therefore maximize the heat production in the most adequate way. This tool is specific to the company that manufactures the solar collector.

The second tool was used to compute the energy performance, energy balance, electrical consumption and overall system performance (cooling and heating). This tool is developed by French organizations Tecsol and INES and funded by the French National Research Agency (Semmari et al., 2014).

The results of the case study are important, as they can give planners, industrialists and investors an idea about the performance of such systems and therefore know if this technology can be applied and benefit them.

As with any case study, additional steps are followed in producing the thesis research and can be summarized by the following: Reviewing academic articles related to Concentrating and Non-Concentrating solar thermal technologies, while focusing on the parabolic trough collector and linear Fresnel Collector which examined the uses and limitations of the two technologies according to the latest in research. Collecting data about the heat and cold demand for some industries including the "Boiler, Heat supply network, and the Fuel Demand". The data was collected through site visits and answering a questionnaire developed by the author and compatible with the software inputs. Conclude with a recommendation for the technology, including its potential across the industrial sector of Lebanon. Furthermore, the limitations and drawbacks of the technology is provided, along with the possible steps for future work.

CHAPTER IV

LITERATURE REVIEW

Solar power has emerged as the most promising alternative to fossil fuels in the last decade. Solar energy conversion systems are devices that absorb solar radiation and convert it to useful energy whether thermal or electrical. Two concepts shall be introduced in our literature review, the first is the concept of conversion of radiation into heat and the second is its conversion into a thermodynamic process.

The heat production (solar) system includes equipment such as: collectors of different types, storage tanks, expansion valves, etc. The configuration of the equipment is case specific and depends on many factors such as the environment where it is intended to be installed, collector tilt angle, collector efficiency, and the working fluid among others. The system gathers the solar radiation through concentrated mirrors and use them for cooling and heating (water or air) in domestic, commercial, and industrial plants.

There are different kinds of solar technologies among which there is the solar thermal collectors which provide heat and can be either used directly or be transformed to other forms of energy (electricity or cold). They are used in a wide range of industrial applications, and they are categorized into three groups, as indicated in Figure 1.

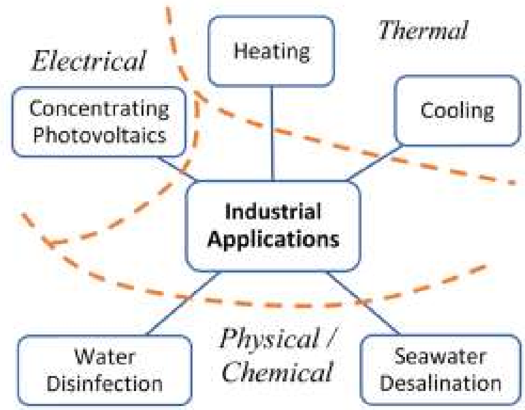

Figure 1 Solar energy in industrial application (Tagle-Salazar, 2020)

Solar collector systems are devices which collect solar radiation from the sun, and converts it to heat which is transferred to the circulating fluid in the device (Kalogirou, 2004). Solar tracking is a method of directing a solar collector or a reflector at the sun. A tracking device ensures that the solar collector tracks and sustains the optimal angle to capture most of the solar energy in order to optimize the productivity of energy much more through following the sun's position throughout the day. Surface adjustment is achieved through tilting it around one axis called single axis tracking. Tilting is performed in a way to minimize the incidence angle. When adjustment is achieved through rotation around two axes simultaneously, it's then called two-axis tracking. Two-axis tracking allows for the most accurate positioning of the solar system, the incidence angle is always zero, i.e., the surface is kept perpendicular to sun light. It provides about 40% increase in energy absorption, but it is more complicated and costly. Table 1 below shows the different types of Tracking devices.

Tracking	*Collector Type*	*Absorber Type*	*Concentration*	*Indicative Working temperature range (°C)*
Stationary (none)	Standard flat plate collector (FPC)	Flat	No	30 - 90
	Standard evacuated tube collector (ETC)	Tubular	No	50 – 130
	Improved Stationary Collector	Tubular Flat	Some yes Some No	80 - 150
Single Axis	Linear Fresnel Collector (LFC)	Tubular	Yes	60 - 400
	Parabolic Trough Collector (PTC)	Tubular	yes	100 – 450
Two Axis	Parabolic Dish Collector (PDC)	Point	yes	100 - 500
	Heliostats with central receiver (HCR)	Point	yes	150 - 2000

Table 1: Common Collector Types with different working temperatures. (Stryi-Hipp, 2016)

Basically there are two types of Solar collectors, the concentrating and non-concentrating which differ in the absorbing area. In the non-concentrating or stationary type, the area intercepting the solar radiation is the same as the absorbing; while in the concentrating collectors, the area of the receiving aperture[1] is much larger than the area of the absorber. According to Fuquanga et al (Fuqianga, 2017) concentrating solar type collectors must be used to have a better efficiency for medium and higher temperatures. Non-concentrating solar thermal collectors can only provide heat at up to 100°C (some

[1] The area via which solar radiation enters the collector is known as the aperture area.

can reach up to 150°C). If temperatures above 100°C are needed, the sunlight should be concentrated, and concentrating collectors can achieve these higher temperatures.

There are four different designs of the concentrating type based on focused geometry: The Parabolic Trough Collector (PTC), Linear Fresnel Collector (LFC), Parabolic Dish Concentrator (PDC) and the Heliostat Field Concentrated (H.L.Zhang, 2013).The total capacity in this fast growing sector reached 500 GW in 2020, compared to 40 GW in 2013 (IRENA, 2020). When temperatures below 130°C are acceptable for room or water heating, flat plate collectors and vacuum tube collectors of the non-concentrating kind are practical and effective (Saha, n.d.). Figure 2 depicts the four categories that we shall discuss in more detail later.

Figure 2: Overview of selected solar thermal Collectors (Haagen, 2013).

A. Solar Irradiation

Direct sunlight, often known as "beam radiation" or "Direct Normal Irradiation" (DNI), is used in Concentrating Solar Power. This is sunlight that hasn't been deflected in the atmosphere and reaches the Earth's surface in parallel beams for concentration. Areas that receive a lot of direct sunshine - at least 1,800 kilowatt hours (kWh) of sunshine radiation per square meter annually - are ideal (Wang, 2016).

Total solar irradiation, also known as global sun irradiation, is separated into diffuse and direct irradiation. Diffuse irradiation is sunlight that has been deflected by airborne particles such as water, dust, and so on. Using concentrating technology, direct sunlight is collected over a vast area and reflected to a smaller absorber.

The relationship between the above three can be expressed as

$$G_r = D_r + F_r \tag{1}$$

Where D_r is the Direct radiation , F_r is the diffuse radiation and G_r is the Global sun irradiation.

However, in locations with moderate overcast or hazy days most PV systems may be used, i.e. where a major proportion of solar irradiance may be dispersed instead of direct. PV systems can also be placed on residential rooftops with minor increments and are in a way compatible with existing land usage. Concentrated solar thermal energy require dedicated land with appropriate resources and facilities.

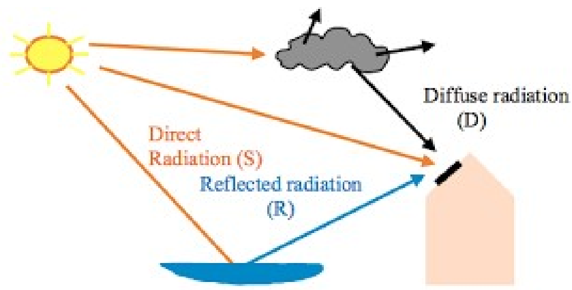

Figure 3 principles of solar radiation (Direct, Diffuse and Reflected radiation) (VASHISHTHA, 2012).

B. Non Concentrating Collectors

Non-concentrating collectors (NC) can use both direct and diffuse solar radiation from different angles. They are installed in a fixed orientation as they don't need to track the sun's position. They may reach temperature of up to 250°C, but since efficiency decreases as operating temperature rises, they normally operate and produce heat at reasonable efficiencies at temperature up to 100°C (Fortuin S., 2012).

The main component of a NC-collector is the absorber, which can be embedded into a collector casing to reduce heat losses. A heat transfer medium allows the useful removal of heat from the absorber. The construction containing the heat transfer medium mostly consists of pipes connected to the back of the absorber sheet or of air channels for air-heating collectors. Since China has by far the largest solar collector market, and almost all collectors made in China are of the vacuum tube type, vacuum tube collectors account for the majority of solar collectors used worldwide except for Europe where 90% of the collectors are Flat plate type collectors. Almost all collectors have used a liquid heat transfer medium in the past, but air-heating collectors are becoming more common (Fortuin S., 2012). Figure 4 demonstrates the structural difference between vacuum tube collectors and flat plate collectors.

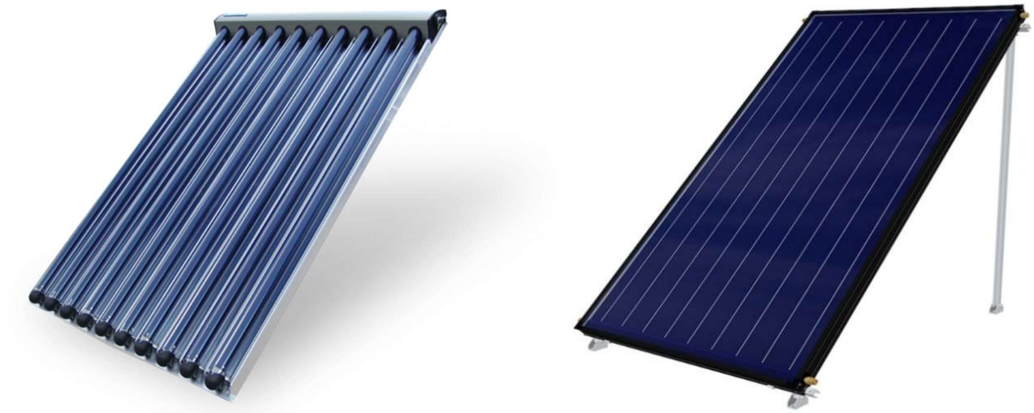

Figure 4 Vacuum tube collectors Vs Flat plate collectors (Anon., 2017)

The main advantage of the vacuum tube over the flat plate collector is the highly reduced convection and conduction thermal losses, due to the absence of air as it's made of vacuum tubes. This high level of vacuum allows its good performance in extremely cold weather, since low temperature and wind have very little effect on the vacuum tubes. Yet, it's more expensive and its initial cost is high compared to the flat plate. Also, if not used frequently, the vacuum tube collector may be over heated exceeding the boiling point causing significant damage to the system. Therefore, the hot water must be used daily to ensure the safety of the system.

C. Concentrating Collectors

There are four different designs of the concentrating type based on focused geometry: Parabolic Trough Collectors (PTCs), Linear Fresnel Collectors (LFCs), Solar Towers (STs), and Parabolic Dishes, with the earliest in use being PTCs.

In fact, the four types utilize two different technologies that concentrate direct solar isolation: Point focus type which concentrates isolation into a single point, and linear focus type, consist of a linear concentrator and a linear absorber. The former includes solar towers (STs) and parabolic dishes while the latter includes the parabolic trough collector (PTC) and linear Fresnel collectors which reaches higher temperatures, because it concentrates isolation into a larger area (Sepúlveda, 2019). Figure 5 below shows the schematic diagrams of the different types of Concentrating solar collectors.

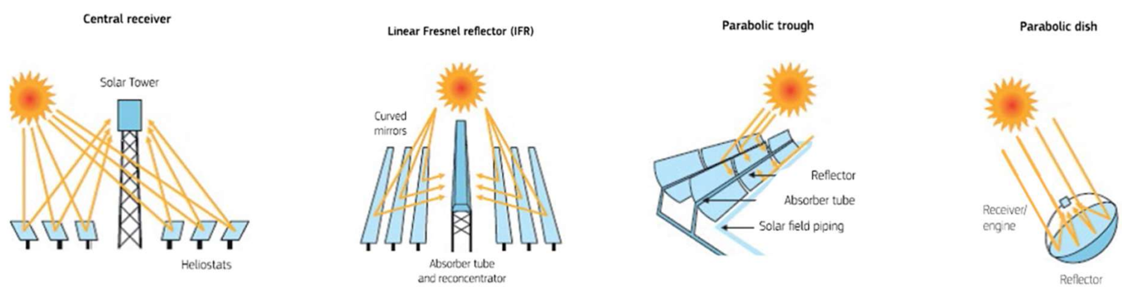

Figure 5 Schematic diagrams of concentrating solar power with different types of collectors (YuanZhao, 2019)

In 2019, the total capacity for concentrated solar power increased by 11% to 6.2 GW. Despite the fact that this was significantly behind the average annual rise of (24 %) of the past decade, Concentrating Solar Power succeeded in expanding into new markets like Kuwait , France and Israel (REVE, 2020).

In terms of regional variety, the solar thermal industry has expanded with both commercial plant sites in addition to the origins of investors, developers and entrepreneurs. Furthermore, the levelised prices of energy from CSP have continued to fall in the past two years.

D. Technology of Parabolic Trough Collector (PTC)

For more than 60 years, there has been little interest in solar focusing technology. However, in reaction to the oil crisis of the 1970s, renewable energy sources drew international attention as a way to replace fossil fuels, prompting the creation of various concentrated solar systems. As of 2018, troughs account about 90% of commercially available concentrated solar power (CSP). (IEA, 2018)

A semi-spherical surface covered with several tiny mirror parts was the original concept for a solar concentrator. A spherical mirror's focal point should be halfway of the spherical segment, directly above the sphere's vertex.

PTCs are one of the most important solar technologies to generate heat at temperatures up to 400 degrees Celsius for electricity generation or heat applications (Kalogirou, 2004). It can only use direct solar radiation, also known as beam radiation or Direct Normal Irradiance (DNI).

It is made up of a linear parabolic mirror which reflects and concentrates the received solar energy onto a tube (receiver) placed along the focal line. The receiver is linear plated with selective coating that has high absorption for solar radiation and low emittance for thermal loss. The concentration ratio, i.e the size of the tube, is determined by the size of reflected sun image and tolerances of the trough (Kalogirou, 2004). Figure 6 below shows the schematic diagram of the parabolic trough solar collector.

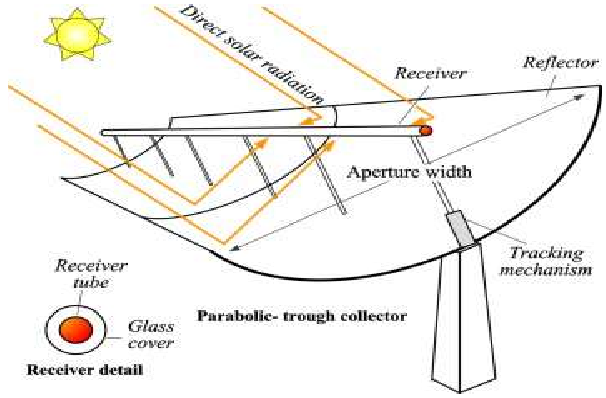

Figure 6: Schematic of a parabolic-trough solar concentrator (Rasul, 2017)

PTC uses direct solar radiation as a heat source, but as the sun's relative position changes every second, a solar tracking system is needed to improve its efficiency. The tracking system is considered one of the most important components in improving thermal efficiency. The tracking system is also important for the protection of collectors, by turning away from hazardous environmental and working conditions like wind, overheating and failure of the thermal fluid flow mechanism (Kalogirou, 2004).

In PTCs, two forms of solar tracking are used as shown in Figure 7: north-south and east-west, each of which can track the Sun around one axis to ensure maximum performance. The advantage of the east-west tracking mode is that little adjustment is required during the day, however, the collector performance at the early and late hours of the day is greater due to large incidence angles -cosine loss-. In case of north-south oriented troughs, the cosine loss is highest at noon and lowest in the early and late hours (Kalogirou, 2004).

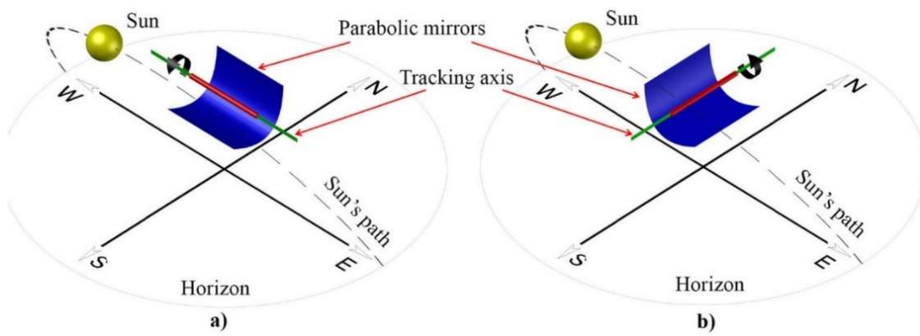

Figure 7 PTC tracking mechanism for the north-west and east-west (Tagle-Salazar, 2020)

Corrosion, abrasion, and dirt all have an impact on the optical performance of the PTC mirrors, resulting in a reduction in collector thermal efficiency (Tagle-Salazar, 2020). Another characteristic that influences the thermal performance of the PTC is optical efficiency (μ_{OP}). It is defined as the fraction of incident radiation that is converted into thermal energy inside the tube. The larger the fraction, the less energy is lost as heat. Optical efficiency is determined by the Solar Collector's absorptivity (α), the cover glass's transmittance (T), the incident angle modifier (κ), and the reflectance of the mirrors (ρ), as well as the interception factor (γ), which is a random error caused by the imperfect practical application of mirror shapes and receiver alignments. It is stated as follows: (Ahmed, 2015)

$$\mu_{OP} = (\alpha * \mathrm{T} * \kappa * \rho * \gamma)\, F_c$$

This efficiency in turn depends on some factors as: Reflectivity of the mirrors, Transparency of the glass case of the receiver tube, Geometrical precision and receiver tube absorption (Fresnel or parabolic presentation). Hence, encasing the receiver tube in glass acts to reduce the radiative and convective heat losses to the atmosphere. Furthermore, coating the absorber tube with a selective coating aids at reduction of radiative heat losses. Constructor can further achieve reduction in heat losses by employing a gap between the receiver and glass envelope under vacuum conditions with very small air pressure (Wang, 2016). Lower levels of solar radiation result in less generated power, hence, additional measures should be implemented to accumulate solar irradiation on sunny days, store it in embedded phase transition and release it in a guided manner in extreme circumstances (Mekhilefa, 2011).

The performance of PTC is strongly influenced by the types of solar irradiation, diffusivity, temperature difference between fluid temperature, and ambient temperature along with their efficiency (Widjajaa, 2018).

The function of the heat transfer fluid (HTF) circulating through the tube is to gather the thermal energy caught by the receiver and to deliver it to the storage system or directly to the power block in the case of solar thermal power plant (STPP) application. Selecting the adequate HTF is application-specific and is dependent on the operating conditions and design peculiarities of each installation. Synthetic oil or molten salt mixture is usually used to run through the heat exchanger tubes and absorb heat concentrated by the mirrors. This fluid can be heated to a temperature of 400 – 600 degrees Celsius.

Ideally, HTFs should have good thermal stability with the ability to work safely around the temperature spectrum of interest, as well as good chemical compatibility with the tubing wall materials. Also, they should be low-cost and environmentally friendly. To prevent decomposition of the oil, troughs using oil are limited to a maximum temperature of around 390 degrees Celsius. The most widely used is molten salts melt at about 220 degrees and stay solid up to 590 degrees. (James. H).

The addition of metallic or nonmetallic nanoparticles to the HTF -which results in the formation of a so-called Nano fluid- is one of the most useful techniques for improving the thermal efficiency of PTCs, as they possess thermal properties different of that of the HTF. Thus, the receiver tube's overall performance is improved due to the increase in thermal conductivity and decrease in the specific heat capacity (Abed, 2020).

The heat transfer process starts as the temperature in the receiver increases. The determination of heat gained and heat losses to and from one component to another is based on energy in transfer under the motive force of a temperature difference between collector components.

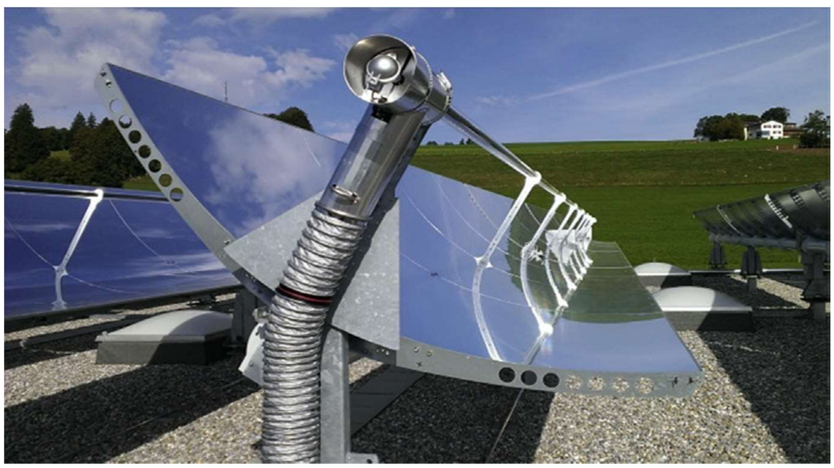

Figure 8 Parabolic through collector with a receiver tube and aperture width of 1.85 m. (Anon., n.d.)

E. Technology of Linear Fresnel Collector (LFC)

Linear Fresnel reflector (LFR) is one of the major systems that concentrate direct solar for producing useful heat in medium and high-temperature levels (< 500 °C) (EvangelosBellos, 2019).

The design of linear Fresnel reflector follows the principle of the Fresnel lens, which was developed by the French physicist Augustin-Jean Fresnel »who invented a multipart lens for use in light houses in the late eighteenth century. The first prototype of a linear Fresnel reflector was built in 1964 in Italy by the mathematician Giovanni Francia.

The major components of the Fresnel are the reflectors (mirrors), receiver tube, and transmission system. The reflectors are segmented long, narrow, shallow, one axis tracking mirror stripes which have a small curvature by mechanical bending and are fixed on a steel structure and placed close to the ground. Its architecture is between that of power tower and parabolic trough concentrator systems. The use of the flat glass reflectors gives it the ability to withstand the harsh desert conditions.

The width of the reflectors, the number of rows, and the gaps between two consecutive reflectors are the most important design parameters. The reflectors must be sufficiently narrow to be able to continuously reflect the direct radiation onto the fixed absorber tube. In case of a very broad mirror, it is impossible to obtain a clear cut Sun image in the focal plane at different Sun positions.

The distance between two adjacent reflectors must be in a way that radiation reflected from any mirror element is not blocked. Researchers have found that increasing the number of reflectors has a direct effect on the time it takes to reach a stable temperature. Yet, they noted that the ideal mirror number is between 10 and 15 and the ideal mirror width is between 10 and 12 cm, after they found that as the reflective surface increases, the total collector performance decreases (Eddhibi, 2017).

Hence, the basic module for the LF consists of a number of primary reflector units (rows) with the number differing from one manufacturing company to another. Those reflectors produce a linear focus on a receiver (absorber) mounted on a series of small towers and fixed on a common focal point of the reflectors, with the Heat

Transfer Fluid (HTF) flowing inside. Due to the construction mode of the receiver, lower HTF leakage risk is obtained (J.Zachary, 2012).

A secondary concentrator is used as shown in Figure 9 in order to reflect the Solar isolates within the accepting angle. Hence, the absorber tube and the secondary mirror are the receiver's main components. A sealed glazed casing encases the whole optical framework.

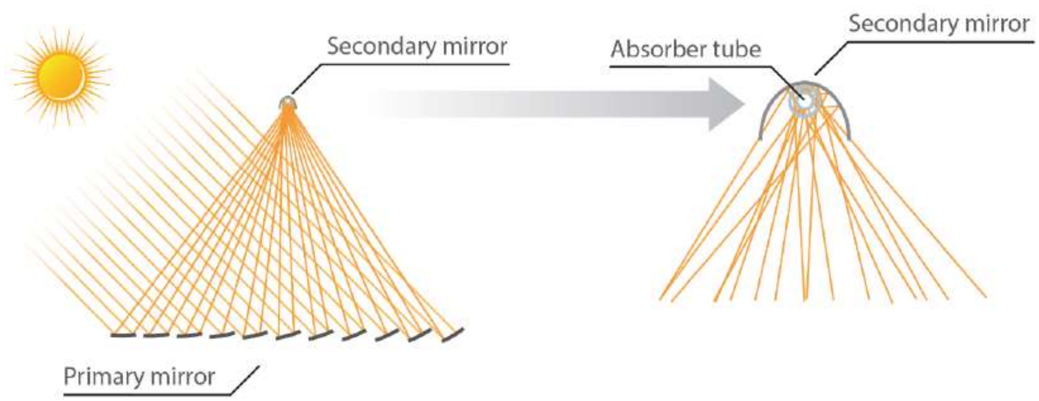

Figure 9 Linear Fresnel LF-11 Solar Collector (Industry, n.d.)

The optimum receiver height is around 15 m, which is the limit value for the least amount of blocking and shadowing impact, as well as spillage losses. The secondary concentrator above the receiver is used to reduce optical inaccuracy and increase the intercept factor. It also increases the target surface's width without impacting the receiver tube (Eddhibi, 2017).

In other words, the target area of the receiver is increased which decreases the requirements on optical accuracy of the primary reflectors.

Moreover, the transmission or the tracking system, is a single-axis tracking for the Fresnel. Since the movement of the parallel reflectors depends only on the sun path, and due to the movement of the sun (daily & seasonal), concentrating solar collectors have to move in order to track the sunlight. Additionally, the system is usually equipped with optical sensors which detect missed irradiation and induce an automatic self-calibration of the system.

Due to the variable inclination angles of the entire solar region, the use of dual-axis tackers seems to be promising for small-scale applications, but larger-scale applications need more structural considerations (Zhu, n.d.).

At the end, Fresnel system can be theoretically oriented east-west or north-south. However, since the high incidence angles in winter bear less weight than in a north-south orientation, an east-west orientation allows for a more equilibrate energy yield during the year. Add to that, the highest power peaks are found in an east-west orientation.

F. Comparison between PTC AND LFC: Advantages and disadvantages

Despite the fact that the parabolic trough concentrator is more widely used and operated than the Linear Fresnel Collector, yet, there are numerous efforts to make the LFC a powerful competitor in the solar concentrator sector. This is because, as opposed to parabolic trough concentrates, linear Fresnel reflectors have important technological and economic advantages:

- As the Fresnel-collector provides high temperatures, not only it can be used for pre- heating but it can also operate parallel to a conventional boiler;
- LFC systems directly heat water flowing through receivers to produce steam at about 270°C, without the need for synthetic heat transfer fluids or heat exchangers (UNDP-CEDRO, 2013);

- Compared to PTC, LFC allows Hybrid operation in conjunction with a traditional coal or gas power plant;
- The majority of Fresnel concentrator-based plants were used to produce heat at low or medium temperatures between 150 and 300 degrees for domestic, chemical, agricultural and food applications (Ahmed, 2016);
- The collector weighs only around 30 kg/m^2. In addition, the wind loads are much lower as the main surface is horizontal. Hence, there is less impact of the wind on the system;
- The Industrial Solar Fresnel collector is equipped with thermometers which automatically defocus the mirrors once a temperature limit is exceeded;
- LFC does not actually require the use of a large land area. simple to incorporate it into a building, and it's also ideal for rooftop installation. As different modules do not shade each other they can be aligned closely, making best use of available space. Hence, less area is required than PTC technology.
- Compared to the parabolic trough collector which requires flexible connections to allow individual tracking of the units, the absorber tube in LFC is fixed above the mirrors. Thus, no flexible, high-pressure, high-temperature joints have to be used;
- As the LFR doesn’t require flexible connections, it can be used for high temperature and high pressure applications. It is used for direct steam generation at the solar platform (RobertPitz-Paal, 2014);
- In comparison to the PTC, linear Fresnel collectors concentrated sunlight hits the absorber tube only from below. This is much better for direct steam

generation due to a better heat transfer. Moreover, thermal stress on the absorber tube are reduced;

- Due to the flat and horizontally aligned mirrors the collector field of LFC can be easily accessed and cleaned. The water demand for cleaning LFC is much lower than that for parabolic trough collectors. In addition, for large collector fields cleaning robots can be used;
- The low cost of operation and maintenance results in a substantial reduction in the levelized energy cost of about 12%, compared to PTC (Ahmed, 2016);
- The whole PTC system including the receiver has to keep tracking the sun, whereas in the Fresnel case, only the tiny mirror facets must be rotated (RobertPitz-Paal, 2014);
- Due to the fixed construction of the receiver, a lower Heat Transfer Fluid (HTF) leakage risk is achieved in LFR in comparison to PTC;
- Regarding the cost, as flat mirrors are cheaper than the parabolic ones, LFC is considered potentially cost saving in comparison with PTC;
- Soiling protection of the absorber tube by a secondary reflector which is not available in the PTC.

However, the LFC has some disadvantages compared to PTC, and they are as follows;

- The key drawback of Linear Fresnel Reflectors is that they are less effective than Parabolic Troughs, with an efficiency of 8-10% for solar-to-electricity conversion;

- The flat arrangement of the reflectors increases the optical cosine losses which in turn reduces the annual optical output by 20-30% compared to PTC (RobertPitz-Paal, 2014).

G. Cooling Demand

The solar energy collected is carried and used by the circulated fluid either directly or through a thermodynamic process. Several types of refrigeration cycles exist nowadays. These are commercialized and used in all the consumptions sectors of the value chain: vapor jet system, vapor-compression cycle, multistage vapor-compression, absorption cycles and others.

The vapor-compression cycle on the other side is the most common system in use today as it yields a high coefficient of performance, which is the ratio of useful heating or cooling provided to the work or heat required. The higher the ratio, the better the performance and efficiency. A combination of heat transfer (latent/ specific heat), and compression performed on the refrigerant is sufficient to remove the heat from a certain medium in an attempt to cool the latter. In such systems, the refrigerant is compressed in the vapor phase and therefore requires a lot of thermodynamic input work, which can be costly at times, as big compressors will need a lot of electric power to create such work.

The absorption and adsorption cycles are the subject of interest in my thesis as this technology can be upgraded and coupled with a renewable energy source (heat from the sun) to enhance the performance of the whole system and make it more cost effective. Such system is considered the most viable for solar application since it allows the use of the heat that can be supplied by the relatively cheap solar collector (Boris

Huirem, 2020). Vapor absorption cycle is a sort of refrigerator cycle in which there is no need to a compressor in the system.

A vapor compressor cycle is usually composed of four major components which are the compressor, condenser, expansion valve and evaporator. Starting with the compressor, the ammonia refrigerant is compressed and sent to the condenser where the process of changing from vapor into liquid state occurs. This is done by extracting heat from the solution (Ibrahim Dincer, Mehmet Kano˘glu, 2010). The liquid refrigerant moves to the expansion valve, in which the pressure is reduced and temperature is decreased (Ibrahim Dincer, Mehmet Kano˘glu, 2010). The process ends at the evaporator, where all the heat is absorbed and where the cooling effect occurs.

On the other hand and as shown in Figure 10, there is no need for a compressor in the vapor absorption cycle. Figure 10 shows the schematic of a basic absorption refrigeration system. Ammonia is known to dissolve in cooled water, so the latter acts as an absorbent for the refrigerant. This mixture, i.e., NH3-H2O, is considered one of the most commonly used because of its thermodynamic properties (Boris Huirem, 2020). Since this mixture is in a liquid state it can be simply pumped and therefore will not require a huge amount of input work in order to move from a low pressure regime to a higher one. With the use of heat coming from an external source, the ammonia is separated from the high pressure solution. Once the ammonia is separated from the ammonia-water mixture, it proceeds to the condenser, and the remaining of the process is similar to the vapor compressor system describe above. In short, the absorption cycle replaces the compressor by a generator-absorber system. This particular process is usually used in industries where an external source of heat is available so we can develop the absorption cycle. The latter can be sourced from solar energy that is collected by the means of concentrated panels.

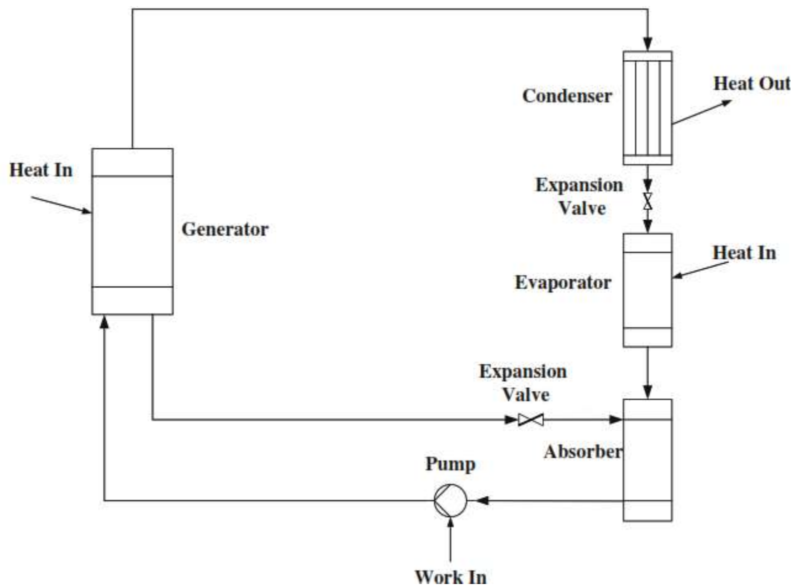

Figure 10 Basic absorption refrigeration system (Dincer, 2016)

The advantage of the absorption system is two-folded. On one hand, it does not require substantial work into the system to compress the vapor refrigerant. Instead, the vapor refrigerant is absorbed by a liquid, forming a liquid solution, which is then pumped to higher pressure. This can be done simply because the average specific volume of a liquid solution is less compared to the situation where the refrigerant is in a vapor state (Moran, 2006). This explains why less work is needed to the whole system. The second main advantage is accredited to the addition of heat to retrieve the refrigerant vapor from the liquid solution before it enters the condenser. This heat must come from a renewable source in order to consider this addition as an advantage. In this case, we can talk of solar thermal energy that complements the refrigeration cycle.

Heat pumps on the other side are quite similar with the refrigeration systems. It uses the same components and principals; however, the system is reversed.

H. Adsorption Cycle

A typical adsorption system includes a condenser, an evaporator, and an adsorbent bed. Thermal technologies based on renewable energy can readily cover the thermal energy requirements of adsorption cooling systems, making them environmentally benign. The adsorption refrigeration is similar to the absorption refrigeration with main difference being that the refrigerant is adsorbed on the surface of a highly porous solid instead of being absorbed by a liquid. In addition, while absorption process is a chemical process, the adsorption can be physical or chemical. In Physical Adsorption the dominant forces are the Van der Waals[2], whereas the chemical adsorption is achieved by the valency forces and the heat of adsorption is usually greater. Adsorbents are porous solids that can mechanically and reversibly adsorb large amounts of a vapor, known as the adsorbate. The micropore and mesopore internal structure is primarily responsible for the adsorption media's large surface area. This porous solid can be one of two types: agglomerates or aggregates (Dincer, 2016).

Though this phenomenon was discovered in the nineteenth century, it was only recently applied to refrigeration. It is one of the solutions for meeting the demands of refrigeration and air conditioning systems that are powered by thermal energy and hence could use waste heat or solar energy. It is also important for cold-storage facilities for food products, vaccines, medicines and artificial insemination services that require cold temperatures for preserving quality and safety. It is also used in meeting

[2] Van der Waals is a general term used to define the attraction of intermolecular forces between molecules (Rasha, 2020)

cooling needs in off-grid locations. Moreover, the benefits of this technology in terms of environmental friendliness and energy usage are also impressive (Dincer, 2016).

There are two key effects of the total energy needed to drive this operation, the first effect induces sensible heating and change in the internal energy of the adsorption bed. The second effect stimulates the desorption of the refrigerant from the adsorbent bed and generates the gas phase.

Hence, the adsorption refrigeration system employs both adsorption and desorption processes that take place on one adsorption bed, the work of which depends majorly on temperature difference. The bed alternates between adsorption and desorption processes. The desorption process requires heating, while the adsorption process requires cooling (Astina, 2017).

The mixture of working fluids used in adsorption systems has a significant impact on the overall system performance. Working fluids commonly used by researchers include activated carbon methanol, silica gel waters, and fiber adsorbent. When zeolite–water working fluid is employed, the COP of the renewable energy adsorption system ranges between 0.1 to 0.12. In another study, Critoph reported that using activated-carbon–ammonia working fluid reduces the COP of the integrated system to 0.05 (Critoph, 1993). While when a renewable energy adsorption cooling system was used, Luo H.L reported a COP of 0.096–0.13 (al, 2007). Table 2 illustrates a variety of working fluids along with their COP. (Dincer, 2016)

Working Fluids	*COP*
Activated Carbon/Methanol	0.10–0.12
Zeolite/water	0.10–0.12

Activated carbon/ammonia	0.05
Activated carbon/water	0.07
Silica gel/water	0.20–0.30

Table 2: The impact of different working fluid on the performance of a solar adsorption cooling system

Both adsorption and absorption chillers are getting greater popularity over the compressor options for being low-energy, silent, and environmentally friendly. They don't produce any gases with greenhouse effects; don't use chlorofluorocarbon or hydro-chloro fluorocarbon refrigerants; don't use a lot of electricity, and don't release a lot of heat into the atmosphere or waterways (Hosansky, 2011).

I. Main advangages of the adsorption over absorption processes are:

- The startup time is very short in adsorption compared to the Absorption that requires about 15 minutes;
- Adsorption systems can withstand high temperatures (520° C) without corroding, whereas absorption systems above 210°C corrode, because there are heat sources that can be used directly with temperatures above 500°C (Singh, 2019);
- Operating temperature is lower in Adsorption than in Absorption as the Adsorption technology can operate at 55°C, but the absorption system requires at least 75°C to operate;
- In case of use in systems where serious vibration occurs, absorption cooling systems are useful for applications with less vibration because of the fear of possible flow of the absorbent, which is a liquid, to the condenser or

evaporator, whereas there is no such fear in adsorption cooling, the process is simple and continuous since the adsorbent is solid (Wang, 2011);

- The absorption systems suffer from the risk of the crystallization of that solution at very low temperatures, whereas in adsorption systems there is no such risk, hence there is no limitations for the cooling temperature;
- In adsorption systems, there is no need for frequent replacement of the adsorbent;
- Continuous monitoring of the absorption system is required, whereas it's minimal in adsorption, as the latter uses silica gel instead of the lithium bromide solution;
- The adsorption Systems do not require a rectifier for the refrigerant or solution pump (Ajib, 2018).

J. Disadvantages of adsorption systems

- Adsorption systems are of higher cost compared to the Absorption technology;
- The coefficient of performance COP, which is the ratio of cooling capacity to thermal energy supplied to the system, is lower in the Adsorption than in the Absorption systems, this is considered as their major disadvantage;
- In the Adsorption system, the concentration of the adsorbent on the surface of the adsorbent differs from the concentration in the bulk because it's a surface phenomenon whereas the absorbent's concentration is same throughout absorption because it's a bulk phenomenon;
- The Adsorption system is intermittent that's why the heat recovery is very complex (Ajib, 2018);

The key points of comparison between absorption and adsorption chillers are shown in Table 3 below.

Comparison	*Adsorption Chiller*	*Absorption Chiller*
Required Hot water temperature	Operate down to 122F 90% at 176F 70% at 160F 45% at 122F	Shut down at 180 F 50% at 176 F 0% at 160 F
24 Hrs continuous operation	Yes	No Li-Br solution concentration increases in the refrigerant during operation. So dilution operation to separate Li-Br from the refrigerant is required each day
More than 8000 Hrs/ year	Yes	No The absorption chiller cannot run 8000 Hrs/year due to requirement of Li-Br and inhibitor PPM level concentration maintenance
Maintenance Cost	Low	High
Minimum load	Standard	Sophisticated control required
Refrigerant	Tap Water	Distilled Water
Adsorbent/Absorbent	Silica gel	Li-Br
Automatic Valves	Butterfly Valves	3 Way Control Valves
Corrosion	No	Strong Heat exchanger bundles need replacement due to corrosion after 2.5 to 3 years when operating at 8000 hours per year
Crystallization	N/A	Yes
Warm up (Start)	0 to 7 min	30 min
Life expectancy	More than 20 years	7 to 9 years
Frequent of replacement of adsorbent	Not necessary	4 to 5 years
Heat exchanger	N/A	To be considered due to corrosion problems
Back up boiler	Not Necessary	Needed at 185 F

Table 3: Comparison between absorption and adsorption chillers

CHAPTER V

CASE STUDIES

In my search for a good candidate industry in Lebanon, I interviewed Mr. Pierre Omran, regional manager at the Ministry of Industry in Lebanon. The purpose of the interview was to learn more about which industries are vulnerable and assist businesses in remaining open during these difficult times that Lebanon is passing through. Acknowledging the fact that the energy bill has a huge burden on the total cost incurred by industries, we decided to start from this dimension. Accordingly, a suitable sector was chosen and it was the dairy industry. In most circumstances, there are two possibilities for lowering energy costs and increasing productivity in the dairy industry:

1- Changing the design of the dairy system to minimize total energy consumption in the processes in order to reduce demand (using energy-efficient machines, insulating buildings, utilizing renewable energy sources, etc.);
2- Maintain the same infrastructure while increasing operational efficiencies (predictive maintenance, energy use control, etc.).

It was decided to concentrate on the first point, which will be reflected in the suggestion of new renewable energy sources to make operations more cost-effective in the long run.

To that goal, visits to a number of dairy-related enterprises were made, with the final decision being to examine the case of the ‘Go Baladi' facility; an organic goat diary since 1985. The factory's main products are the same as those found in every dairy, where most of the Lebanese traditional products are produced: Labneh, Halloum, double cream cheese and so on. From receiving milk from farmers to delivering products to supermarkets and grocery stores, the factory handles the entire process.

Currently the factory is breaking-even in terms of profitability, but with recent electricity cuts, high fuel costs (because to the partial elimination of fuel subsidies in Lebanon), and low purchasing power of Lebanese (due to the present economic crisis), this will not be sustainable in the short future. As a result, new renewable energy sources must be proposed and considered in the long run.

A measurement or calculation of the energy load profile needs to be performed in order to be able to carry out a comprehensive design, and this will be our starting point. The energy load profiles should be identified on a regular, weekly and annual basis for solar thermal heating and cooling system design. Since such information is usually very difficult to obtain, interviews with process planners and plant staff should be done in addition to determining the mass flows and temperatures at the inlet and outlet of each process on a normal working day. After determining which processes should be considered, the energy load for that process, should be calculated in terms of fluid mass flow and temperature at the integration stage during the whole subject period.

Two technologies were identified to provide such systems. In the first case, a concentrated solar technology is suggested in order to produce steam for various processes essential in the dairy product production, while in the second, a non-concentrated solar technology is suggested to produce cooling for refrigerators, ice banks, and in-factory human comfort. In the first case, the new technology is supposed to reduce the amount of diesel used in the boiler to generate steam, while in the second case, the solar technology used will replace the original cooling system, which relies on intensive fuel consumption processes. The formal indirectly translates into a vapor compressions system versus an absorption refrigeration system.

CHAPTER VI

CASE STUDY – CONCENTRATED SOLAR ENERGY

We have contacted the German-based Industrial Solar Firm[3]. They are a leading company in providing solutions for renewable energy and energy efficiency in the medium-range for industrial and commercial customers. While focusing on industrial heating, they are also addressing cooling supply. Their device operates with a variety of heat transfer fluids, including pressurized water and thermal oil to produce steam directly.

Industrial Solar has created solar collectors with uniaxial controlled mirror rows that direct radiation onto a central absorber tube, which circulates the heat carrier. The most widely used industrial application is the Industrial Solar LF-11 Fresnel Collector, in addition, the latter is considered the only product with commercially tested direct steam generation over a long period of time (Anon., n.d.). On the long-term, the collector is being improved, and this will definitely translate into lower manufacturing costs and installation time in the long-term.

To evaluate the most effective engineering system and project execution, a thorough evaluation of the actual energy demand, performance potential and renewable resources should be performed for the target Factory. Several Questions should be answered and the following data should be collected as per Table 4.

[3] https://www.industrial-solar.de/

Subject	*Questions asked*
ENERGY DEMAND	What is thermal energy demand? (kW, MW, t/h) What is the heat medium used: steam, hot thermal oil, air, hot water? What are the temperature and pressure in the main line?
LOAD PROFILE	How many days a year is energy consumed? How is the energy consumption over a day? (indicative) How many days a year is energy consumed? How is the energy consumption over a day? (indicative) Is it a constant or a batch process?
BOILER/ HEATER	Exact boiler specification (producer, serial number, capacity, manufacturing date) Boiler (specification plate) Is it planned to replace the boiler in the near future? How far is the boiler from the place of the solar field If steam is produced, what is the expected steam quality (x)?
SPACE FOR SOLAR COLLECTORS	Is there space for solar collectors, if yes, how much?
ENERGY COSTS	Which fuel do they use? (natural gas, fuel oil, diesel, coal, electricity) How much is the fuel per unit? What is the current fuel fired boiler efficiency?
COMPANY LOCATION	The coordinates, or alternatively link plant on Google Earth

Table 4: Factory Questionnaire

A. Data Collection and assumptions

The first step in reducing energy consumption in a dairy factory is to understand how much energy each piece of equipment uses and which one uses the most. The biggest contributors to energy use are pasteurization and sterilization of milk, which together account for around 70% of energy costs, with the rest coming from waste, feed, lights, and other sources. During and immediately after milking hours, which are often early morning and late afternoon, most dairies face peak demand.

Table 5 below shows the two processes along with their data.

Processes Description	***1***	***2***
Name of the process	Pasteurization	Sterilization
Process type (batch/ continuous)	Continuous	continuous
Number of batches per day	1	1
Time per batch	4 hours	2 hours
Day / night / both	Day	Day
Typical temperature of the process °C	100	90
Hours of operation/ day	5 hours	2 hours
Days of operation/ year	236	236

Table 5 Diary processes Description

B. Boiler Data

Industrial processes rely on a consistent supply of energy. Even brief outages can result in significant losses. As a result, it must be ensured that even when there is little or no irradiation, the highest demand can be met. Storing large amounts of thermal energy for several days is prohibitively expensive. As a result, the most reasonable way is to install a system with the existing fuel-fired backup boiler in order to meet the entire demand. The cost of a fuel-fired boiler over its lifetime is primarily driven by the fuel demand, whereas the cost of a solar system is primarily dictated by the investment.

The diary currently uses the first boiler only, with the second one kept as a backup, as seen in table 6.

Boiler	*1*	*2*
Manufacturer:	ASK	ASK
Type number/Model:	27/388	390
Fuel:	Diesel	Diesel
Year of construction:	1990	1992
Steam generation capacity (CAP)	0.375	1

Table 6: Go Baladi Boilers Data

C. Current Heat Loads

In the line of production, the processes identified as suitable for the use of heat produced through solar thermal technologies are sterilization, pasteurization and sanitization. Currently, heat is produced in form of steam at 4 bars and 100°C which is used directly in the processes. For the production of steam, diesel is used as fuel. Tables 7 to 9 demonstrate the daily, weekly, and monthly distribution of energy demands for the boiler.

DAYTIME	LOAD IN %
0:00	0%
2:00	0%
4:00	0%
6:00	20%
8:00	80%
10:00	80%
12:00	80%
14:00	40%
16:00	0%
18:00	0%
20:00	0%
22:00	0%

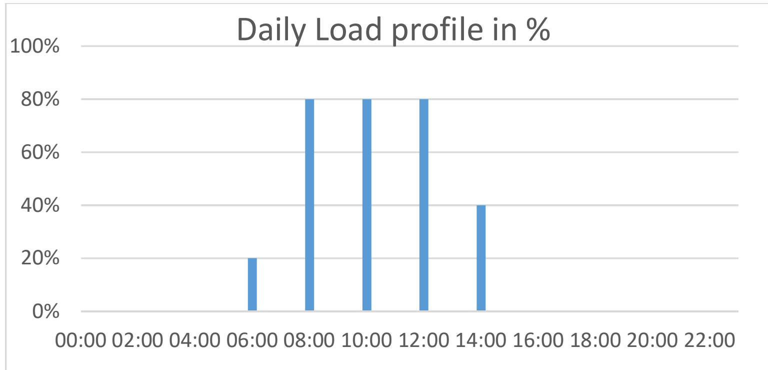

Table 7: Daily Load Profile

Day	Load in %
Monday	100%
Tuesday	100%
Wednesday	100%
Thursday	100%
Friday	100%
Saturday	50%
Sunday	0%

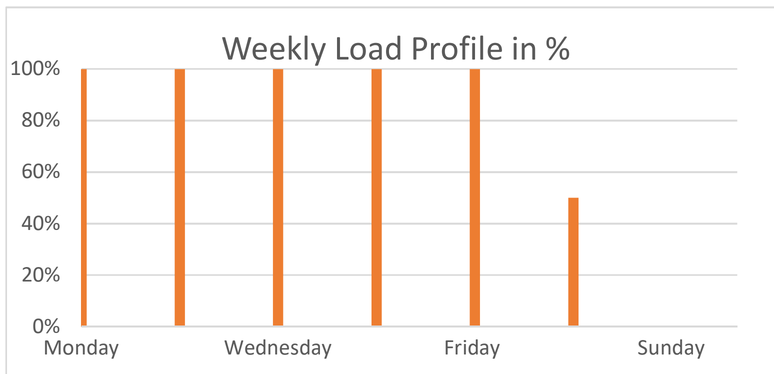

Table 8: Weekly Load Profile

MONTH	LOAD IN %
JAN	50%
FEB	50%
MAR	50%
APR	100%
MAY	100%
JUN	100%
JULY	100%
AUG	100%
SEP	100%
OCT	100%
NOV	100%
DEC	50%

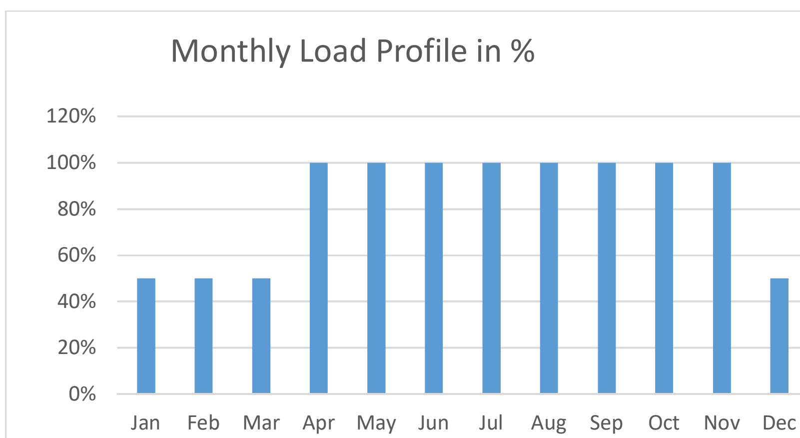

Table 9: Monthly Load Profile

D. Solar Industry

1. Collector Design

Based on the above-mentioned assumptions and industry specific related loads, the Industrial Solar Linear Fresnel Collector (LF) design is calculated, as seen in Table 10. The latter is a concentrating collector type, its uniaxial tracked primary mirrors concentrate the sunlight onto an absorber tube installed above the mirrors. The fact that it is comprised of individual modules eases transportation and installation costs and allow optimal usage of available spaces. Module data is listed in Table 10.

Dimensions	
Width	7.5 m
Length	4.06 m
Height	4.5 m
Aperture area	23 m²
Weight	26,2 kg/m² (per installation area)
Operational Data	
Capacity	601 W/m²
Life expectancy	+25 years
Maximum wind speed operational	100 km/h
Maximum wind speed stowed	180 km/h

Table 10: Collector Design Dimensions and Data

The basic module for the LF consists of 11 primary reflector units with a total mirror surface area of 23 m², in addition to a receiver unit (vacuum absorber tube plus secondary reflector). These models are combined in a longitudinal direction to form collector rows. These rows can be arranged in parallel to form a solar array of any size. Three LF-11 modules are depicted in the Figure 11 below.

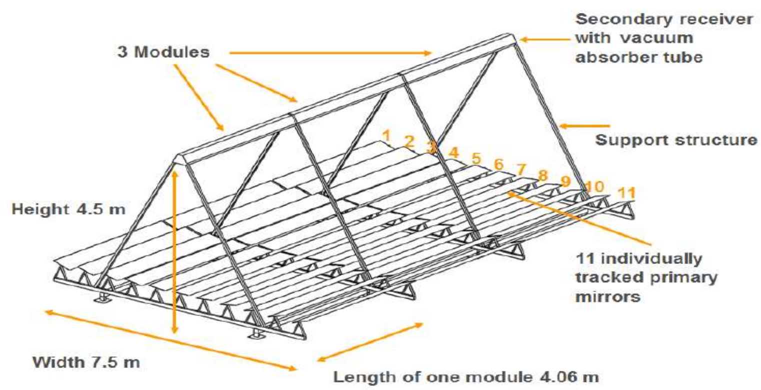

Figure 11 : LF-11 Module

The LF has a temperature operating range of 100-400°C and a pressure operating range of 1 to 120 bar. Temperatures can be controlled with high precision and the control system depends on the customer's demands. Pressurized water systems are typically temperature regulated, with flow rate being adjusted accordingly. Optimal temperature range is from 130°C to 400°C and in the power range from 1 to 30 MW in regions with high direct irradiation.

Based on the information provided above, and considering the steam production at 4 bar and 100 °C, the layout for our Linear Fresnel system will be as mentioned below. The thermal peak power represents the maximum value that can be reached by the system. Table 11 highlights additional information related to the system layout.

A steam/water mixture is produced by the LF collector. Separating the water phase from the steam phase necessitates the use of a steam drum. The integration point receives the saturated steam. The steam drum's water is recirculated and mixed with the boiler room's feed water. The feed water pump and the solar loop pump must be controlled in unison.

System Layout	
Number of modules per string	14
Number of modules	28
Number of strings	2
Thermal peak power	387 KWth
Net aperture area	644 m²
Gross area	902 m²
Heat Carrier	Saturated steam

Table 11: System Layout

Table 11 is populated based on the formulas (1) and (2) found below:

$$\text{Aperture area} \quad = \text{Net Aperture for 1 module } * \text{Number of modules} \qquad (1)$$

$$\text{Net aperture area} \quad = 23 * 28$$

$$\text{Net aperture area} \quad = 644 \text{ m2}$$

$$\text{Thermal peak power} = \text{Capacity for 1 module } * \text{Net aperture area} \qquad (2)$$

$$\text{Thermal peak power} = 601 \ * 644$$

$$\text{Thermal peak power} = 387 \text{ KWth}$$

2. System Location

The LF is known to have a light weight that is uniformly distributed, which consequently allows better and more efficient roof top system installations. Figure 12 shows the proposed rooftop and surrounding area for the solar thermal installation, as per the GPS location coordinates.

Figure 12: Go Baladi Location

3. The tracking mechanism

Due to the movement of the sun (daily & seasonal) concentrating solar collectors have to move in order to track the sunlight. The Industrial Solar Fresnel Reflector is equipped with an automatic tracking mechanism. The control system needs the following data, which can be found in Table 12

- Exact geographic location
- Exact geographic orientation
- Exact date and time

	Name of the Company	Hajjar
	Industrial Sector	Dairy
GEOGRAPHIC DATA	**City**	Chtoura
	Altitude	875 m

	Latitude	N 33° 47 ' 32
	Longitude	E 35° 51 ' 28 "

Table 12: Geographical Data

Based on this information, the system calculates the specific mirror position for each mirror and at different time periods. Additionally, the system is equipped with optical sensors which detect missed irradiation and induce an automatic self-calibration system.

E. Direct normal irradiation in the Chtoura region

The Direct Normal Irradiation (DNI), is normally measured in the following unit: kWh/m²/a. The DNI is influenced by a variety of factors such as evaporation, dust, and altitude.

DNI Data is often presented in form of a typical meteorological year (TMY). The latter is a collation of historical weather data for a specific location, generated from a data bank with a duration that is much longer than a year in duration. It normally computes annual averages that are consistent with the historical averages for the location in question[4], for a visualization of the DNI range for the whole areas, please refer to Figure 13.

DNI varies substantially even over relatively short distances. For determining the expected yield of a concentrating collector the exact project location is used, and we get a value of 2,173 kWh/m²/a.

[4] For more information on the Mediterranean region DNI, please refer to the following link: http://www.solar-med-atlas.org/solarmed-atlas

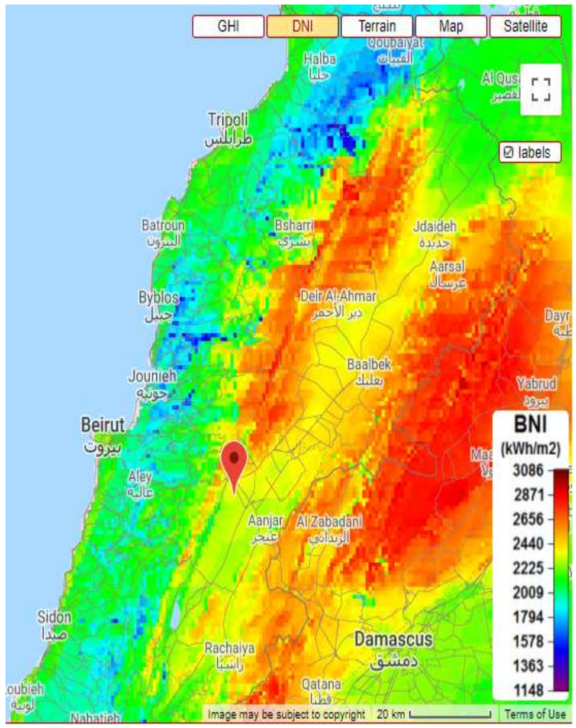

Figure 13: DNI DATA

The absorber tube in our Fresnel System represents the heat source where the heat transfer fluid enters with a temperature of $T_{in} = 80°C$[5] as this is considered a closed loop cuirtuit. As the fluid travels across the absorber, it gets heated to reach an outlet temperature T_{out}, which is set to 180 °C.[6]

The mass flow rate in the absorber tube is manipulated using the circulation pump to maintain a constant outlet temperature. Alternatively, the outlet temperature of

[5] The value for the "Collector inlet temperature" is neither a minimum or maximum nor necessarily correct but the value used for performance simulation.
[6] The value for the "Collector output temperature" is neither a minimum or maximum nor necessarily correct but the value used for performance simulation. Collector output temperature is commonly be above the temperature of the heat supply to customer.

the absorber can also be manipulated by changing the percentage of solar energy delivered to the absorber.

In case the diary factory needs less temperature, it can be reduced either through the control valve by reducing the pressure or by deflecting the mirror in order to decrease the efficiency of concentration or deflection. This can be done by the control algorithm of the system.

To calculate the average system efficiency, the following formulas are applied, and the result is highlighted in Table 13

$$Average\ Efficiency = \frac{Annual\ gross\ heat\ production}{Net\ aperture\ area} * \frac{1}{Direct\ Normal\ Irradiation} \quad (3)$$

$$Average\ efficiency = \left(\frac{691000}{644}\right) * \frac{1}{2173}$$ [7]

$$Average\ efficiency = 49.3$$

Assumptions		
Collector inlet temperature	80	°C
Collector output temperature	180	°C
Direct normal irradiation	2,173	kWh/m²/a
Average efficiency	49.41	%

Table 13 Solar System Efficiency

From a technical standpoint, the Linear Fresnel system can meet a part of the energy requirement from the various processes in the dairy product production chain. It does that without the need to change the type of working fluid (saturated steam). In addition, due to the fact that energy consumption is mainly concentrated during day time, when solar energy is available in larger amount, the performance of the plant is not limited. Considering the installation of the solar technology on the available roof,

[7] Values included in equation (3) have previously been determined in Table 11 in the preceding section.

with a peak power of 387 KWh_{th}, an annual gross heat production 691 MWh_{th} is expected. This production covers around 60% of the current heat needs of the diary factory. Nonetheless, backup systems should always be considered, in order to cover for the remaining energy needs, and these are provided by the boilers.

Figures 14 and 15, show the monthly heat production for the collector on a year basis, and a typical profile of three discrete daily/ hourly heat production, taken from each season respectively.

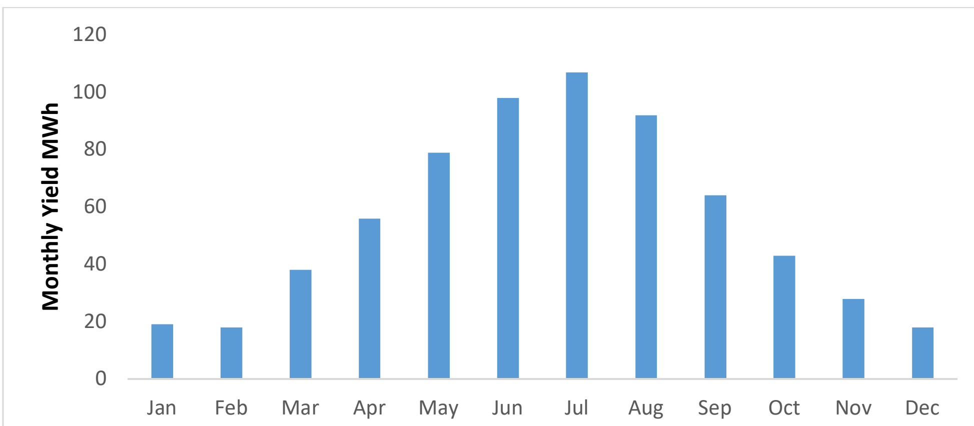

Figure 14. Monthly gross heat production

Characteristics of collector power (in terms of MWhth) on representative days for a collector with 28 modules; i.e. 644 m² primary mirror area Chtoura / LB

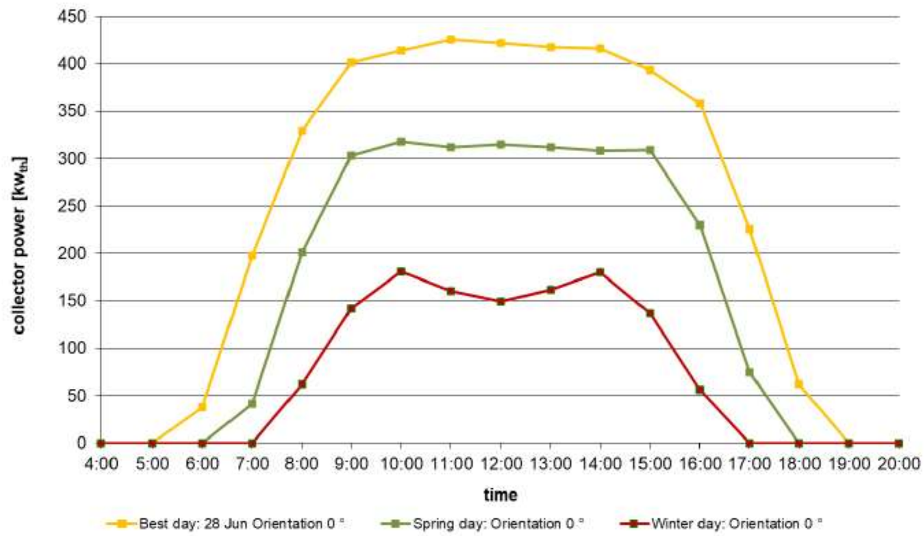

Figure 15. Daily heat profile for three discrete days in separate seasons

Economic Assessment

Industrial Solar LF-11 reported costs, for the 'Go Baladi' proposed installation are shown as follow. These costs are estimates provided to me by Solar Industry company, as part of a student-company collaboration.

CAPEX	334,000 €
Non-fuel OPEX	1.5%

This CAPEX is considered lower than other concentrated technologies like Parabolic collectors (CPC) or the dish reflector (CDR) due to the maturity of the LF technology that has already been tested and deployed in several regions, especially Jordan where several Mega projects have been applied. (Anon., n.d.) The OPEX is a percentage of the whole capital costs estimates and this amount should be paid on a yearly basis. The operation and maintenance costs are considered a little bit higher compared to the non-concentrating technologies since the mirrors need more frequent cleaning cycle in order to avoid any drop in the system efficiency.

Another important note to hint at, is that Fresnel collector can be easily recycled as well: steel, aluminum, glass are the main components of the panel.

Additional details regarding the Budgetary price are shown in Table 14**.**

Budgetary Price	**Cost €**
1 Collector field (without substructure)	
1.1 Collector modules(structure, primary mirrors, secondary reflectors, field cabinets, electric cabling, weather station)	
1.2 Services (engineering & supervision of installation (collector field & periphery), travel & accommodation)	
Subtotal (Collector Field)	**206,000 €**
2 Periphery	
2.1 Hydraulic components (incl. pumps, manual and control valves, drains, vents, mud traps, deaerators)	
2.2 Sensors (incl. volume, mass flow, temperature, pressure, limiter, warning)	
2.3 Storage and other vessels (mixing, drain - if applicable) (incl. insulation, drain, vent, sockets, manhole)	
2.4 Main Cabinet (incl. UPS, Touchscreen, Safety Limiters, Data Logger, PLC etc.)	
2.5 Cables (power & signal)(field cabinets <--> main cabint; periphery <--> main cabinet (up to 50m included)	
2.6 Pressurization / expansion station (if applicable)	
2.7 Heat transfer station (if applicable)	
Subtotal (periphery)	**109,000**
Total costs collector field and periphery	**315,000 €**
Discount (5%)	**16,000 €**
Total costs Industrial Solar	**299,000 €**
3 Various	
3.1 Structural works / substructure (civil grading, foundations, double t-beams)	

3.2 Piping ("Collector field" ↔ "periphery" ↔ "interface"); incl. material purchase, transport, fabrication,welding	
insulation and cladding); (specifications and acceptance test by Industrial Solar)	
3.3 Installation of hydraulic components according to specifications and under supervision of Industrial Solar	
Hydraulic components (item 2.1) provided by Industrial Solar.	
3.4 Cable ways, drawing cables and termination (field cabinets <--> main cabint; periphery <--> main cabinet)	
(cables (item 2.6) provided by Industrial Solar)	
3.5 Local technicians for collector installation	
3.6 Site services (workshop space, material storage space, craning, catering, fresh water, pressurized air)	
3.7 Housing for periphery (if applicable)	
Total Costs	**35,000 €**
Total Investment (turn-key, exworks / customs and local taxes are not included)	**334,000 €**

Table 14. Break down of the capital investment needs

The fuel cost is a major element that should be added to the overall cost-benefit analysis, and as mentioned previously the fuel prices might change a lot in the near future. The variety of possible fuel prices that our candidate factory might face in the near future are shown in Table 15 below. The variability of the prices depends on the national currency rate in relation to the USD on one hand, and on the level of subsidies that the Government can support. At the moment the price of 20 liters of fuel in Lebanon is around 30,000 Lebanese lira (which reflects a subsidy coverage of 85% an exchange rate of 12,000 Lebanese Lira for every dollar.). Regardless of the increase in exchange rates in the future, what I am trying to show here, is simply the fact, that in the near future the fuel subsidies will cease to exist and this will mean 0% support. This scenario is covered in my analysis.

Diesel Prices per 20 Liter / HEPCO ANALYSIS				
Support/Dollar	9,000	10,000	12,000	15,000
90% Support	22,014	22,896	24,659	27,305
80% Support	28,628	30,391	33,919	39,210
70% Support	35,242	37,887	43,178	51,115
60% Support	41,855	45,383	52,438	63,020
50% Support	48,469	52,879	61,697	74,925
0% Support	81,539	90,357	107,994	134,450

Table15. Diesel prices

I have chosen arbitrary thee discrete possible future fuel prices and calculated the equivalent price per unit of energy, instead of the unit of volume, and the results are shown in the table 16

Table16. Energy prices

Energy Price					
Support ($)	20 Liter / $	Ton / $	Ton / Euro	Euro/Kwh	Euro/Kwh + 18% Generator expenses
90% - 10,000	2.289	143.06	170.3	0.014	0.01652
50% - 10,000	5.287	330.4	393	0.033	0.03894
0% - 10,000	9.03	564.3	672	0.057	0.06726

Finally, and in order to study the profitability of the project, include the time value of money and calculate the costs and benefits for each period of an investment during its operation window lifetime, the net present value is calculated. This is done by discounting the future values at a rate of 5%, this is an assumption of the minimum attractive rate of return that is expected in Lebanon, however and in light of the economic crisis, this is subject to increase. The analysis is done on the three different Energy prices and shown in Tables 17,18 and 19

ENERGY PRICE = 0.01652										
Year	Energy price	**Energy production**	**Savings**	**O&M**	**CashFlow**	**Cash Back**	**Discounted savings**	**Discounted O&M**	**NPV**	
0	0.01652				-334,000 €				0	
1	0.0178416	691,000.0	12,328.5	5,010.0	7,318.5	7,318.5	11741.472	4,771.4	6,970.0	
2	0.019268928	687,545.0	13,248.3	5,085.2	8,163.1	15,481.7	12016.55792	4,612.4	7,404.2	
3	0.020810442	684,107.3	14,236.6	5,161.4	9,075.1	24,556.8	12298.0887	4,458.6	7,839.5	
4	0.022475278	680,686.7	15,298.6	5,238.8	10,059.8	34,616.6	12586.21535	4,310.0	8,276.2	
5	0.0242733	677,283.3	16,439.9	5,317.4	11,122.5	45,739.0	12881.0924	4,166.3	8,714.7	
6	0.026215164	673,896.9	17,666.3	5,397.2	12,269.1	58,008.2	13182.87799	4,027.5	9,155.4	
7	0.028312377	670,527.4	18,984.2	5,478.2	13,506.1	71,514.2	13491.73399	3,893.2	9,598.5	
8	0.030577367	667,174.8	20,400.4	5,560.3	14,840.1	86,354.4	13807.82604	3,763.4	10,044.4	
9	0.033023556	663,838.9	21,922.3	5,643.7	16,278.6	102,633.0	14131.32368	3,638.0	10,493.3	
10	0.035665441	660,519.7	23,557.7	5,728.4	17,829.3	120,462.3	14462.40041	3,516.7	10,945.7	
11	0.038518676	657,217.1	25,315.1	5,814.3	19,500.8	139,963.1	14801.23379	3,399.5	11,401.7	
12	0.04160017	653,931.0	27,203.6	5,901.5	21,302.1	161,265.2	15148.00555	3,286.2	11,861.8	1
13	0.044928184	650,661.4	29,233.0	5,990.0	23,243.0	184,508.2	15502.90168	3,176.6	12,326.3	
14	0.048522439	647,408.1	31,413.8	6,079.9	25,333.9	209,842.1	15866.11252	3,070.8	12,795.4	
15	0.052404234	644,171.0	33,757.3	6,171.1	27,586.2	237,428.3	16237.83287	2,968.4	13,269.4	
16	0.056596572	640,950.2	36,275.6	6,263.7	30,011.9	267,440.3	16618.2621	2,869.5	13,748.8	
17	0.061124298	637,745.4	38,981.7	6,357.6	32,624.1	300,064.4	17007.60424	2,773.8	14,233.8	
18	0.066014242	634,556.7	41,889.8	6,453.0	35,436.8	335,501.2	17406.06811	2,681.3	14,724.7	
19	0.071295381	631,383.9	45,014.8	6,549.8	38,465.0	373,966.2	17813.86742	2,592.0	15,221.9	
20	0.076999012	628,227.0	48,372.9	6,648.0	41,724.8	415,691.0	18231.22088	2,505.6	15,725.7	
					120,462.3				**224,751.4**	

Table 17. Net present Value for Low Fuel price

ENERGY PRICE = 0.03894									
Year	Energy price	Energy production	Savings	O&M	CashFlow	Cash Back	Discounted savings	Discounted O&M	NPV
0	0.03894				-334,000 €				
1	0.0420552	691,000.0	29,060.1	5,010.0	24,050.1	24,050.1	29,060.1	5,010.0	24,050.1
2	0.045419616	687,545.0	31,228.0	5,085.2	26,142.9	50,193.0	29,741.0	4,843.0	24,898.0
3	0.049053185	684,107.3	33,557.6	5,161.4	28,396.2	78,589.2	30,437.8	4,681.6	25,756.2
4	0.05297744	680,686.7	36,061.0	5,238.8	30,822.2	109,411.4	31,150.9	4,525.5	26,625.4
5	0.057215635	677,283.3	38,751.2	5,317.4	33,433.8	142,845.2	31,880.7	4,374.7	27,506.0
6	0.061792886	673,896.9	41,642.0	5,397.2	36,244.8	179,090.0	32,627.6	4,228.8	28,398.8
7	0.066736317	670,527.4	44,748.5	5,478.2	39,270.4	218,360.4	33,392.0	4,087.9	29,304.2
8	0.072075222	667,174.8	48,086.8	5,560.3	42,526.4	260,886.9	34,174.4	3,951.6	30,222.8
9	0.07784124	663,838.9	51,674.0	5,643.7	46,030.3	306,917.2	34,975.0	3,819.9	31,155.1
10	0.084068539	660,519.7	55,528.9	5,728.4	49,800.5	356,717.7	35,794.4	3,692.6	32,101.9
11	0.090794023	657,217.1	59,671.4	5,814.3	53,857.1	410,574.8	36,633.1	3,569.5	33,063.6
12	0.098057544	653,931.0	64,122.9	5,901.5	58,221.3	468,796.1	37,491.3	3,450.5	34,040.8
13	0.105902148	650,661.4	68,906.4	5,990.0	62,916.4	531,712.5	38,369.7	3,335.5	35,034.2
14	0.11437432	647,408.1	74,046.9	6,079.9	67,967.0	599,679.5	39,268.6	3,224.3	36,044.3
15	0.123524265	644,171.0	79,570.8	6,171.1	73,399.7	673,079.1	40,188.6	3,116.8	37,071.8
16	0.133406207	640,950.2	85,506.7	6,263.7	79,243.1	752,322.2	41,130.2	3,012.9	38,117.3
17	0.144078703	637,745.4	91,885.5	6,357.6	85,527.9	837,850.1	42,093.8	2,912.5	39,181.3
18	0.155604999	634,556.7	98,740.2	6,453.0	92,287.2	930,137.3	43,080.0	2,815.4	40,264.6
19	0.168053399	631,383.9	106,106.2	6,549.8	99,556.4	1,029,693.8	44,089.3	2,721.6	41,367.8
20	0.181497671	628,227.0	114,021.7	6,648.0	107,373.7	1,137,067.5	45,122.3	2,630.8	42,491.4
					356,717.7				656,695.5

Table 18. Net present value for medium fuel prices

ENERGY PRICE = 0.06726									
Year	**Energy price**	**Energy production**	**Savings**	**O&M**	**CashFlow**	**Cash Back**	**Discounted savings**	**Discounted O&M**	**NPV**
0	0.06726				-334,000 €				
1	0.0726408	691,000.0	50,194.8	5,010.0	45,184.8	45,184.8	50,194.8	5,010.0	45,184.8
2	0.078452064	687,545.0	53,939.3	5,085.2	48,854.2	94,039.0	51,370.8	4,843.0	46,527.8
3	0.084728229	684,107.3	57,963.2	5,161.4	52,801.8	146,840.7	52,574.3	4,681.6	47,892.8
4	0.091506487	680,686.7	62,287.3	5,238.8	57,048.4	203,889.1	53,806.1	4,525.5	49,280.6
5	0.098827006	677,283.3	66,933.9	5,317.4	61,616.5	265,505.6	55,066.7	4,374.7	50,692.0
6	0.106733167	673,896.9	71,927.1	5,397.2	66,530.0	332,035.5	56,356.8	4,228.8	52,128.0
7	0.11527182	670,527.4	77,292.9	5,478.2	71,814.8	403,850.3	57,677.2	4,087.9	53,589.3
8	0.124493566	667,174.8	83,059.0	5,560.3	77,498.6	481,349.0	59,028.5	3,951.6	55,076.8
9	0.134453051	663,838.9	89,255.2	5,643.7	83,611.4	564,960.4	60,411.4	3,819.9	56,591.5
10	0.145209295	660,519.7	95,913.6	5,728.4	90,185.2	655,145.6	61,826.8	3,692.6	58,134.2
11	0.156826039	657,217.1	103,068.8	5,814.3	97,254.4	752,400.1	63,275.3	3,569.5	59,705.8
12	0.169372122	653,931.0	110,757.7	5,901.5	104,856.2	857,256.2	64,757.7	3,450.5	61,307.2
13	0.182921892	650,661.4	119,020.2	5,990.0	113,030.2	970,286.4	66,274.9	3,335.5	62,939.4
14	0.197555643	647,408.1	127,899.1	6,079.9	121,819.2	1,092,105.6	67,827.6	3,224.3	64,603.3
15	0.213360095	644,171.0	137,440.4	6,171.1	131,269.3	1,223,374.9	69,416.7	3,116.8	66,299.9
16	0.230428902	640,950.2	147,693.4	6,263.7	141,429.8	1,364,804.7	71,043.1	3,012.9	68,030.1
17	0.248863214	637,745.4	158,711.4	6,357.6	152,353.8	1,517,158.4	72,707.5	2,912.5	69,795.0
18	0.268772272	634,556.7	170,551.2	6,453.0	164,098.3	1,681,256.7	74,410.9	2,815.4	71,595.5
19	0.290274053	631,383.9	183,274.4	6,549.8	176,724.6	1,857,981.3	76,154.3	2,721.6	73,432.7
20	0.313495977	628,227.0	196,946.6	6,648.0	190,298.6	2,048,279.9	77,938.5	2,630.8	75,307.6
					655,145.6				**1,188,114.4**

Table 19. Net present value for high fuel prices

It can simply be concluded that the higher the future fuel prices become, the less subsidies coverage can be secured from the government, therefore the more profitable it is to replace the existing intense fuel burning boilers by renewable energy technology. Also important to mention that the most likely fuel prices for Lebanon in the near future are the two highest chosen above. In other words fuel prices in Lebanon will most likely double or triple in the short-term, as subsidies are removed and as the exchange currency rates keep on increasing.

F. Cost-Benefit Analysis

The outcomes of the cost-benefit analysis bring us closer to understand the financial consequences of concentrated solar energy for industrial processes. Combined with major environmental benefits we assessed important feasibility concerns from the commercial point of view. In the following, the findings are reported and their respective significance are emphasized;

- Conventional Boilers Vs Solar Thermal Energy investment comparison: The cost incurred by the industry under study to add concentrated solar technology to its existing boilers is around EUR334,000. This can't be compared directly to diesel boilers as the first is an investment paid as lump sum, however the second investment is already installed in the premises but needs continuous running expenses to function.
- Conventional Boilers Vs Solar Thermal Energy operation expenses comparison. Solar energy incurred an annual operational and managerial expenses of EUR5,010 at year one. This is subject to 1.5% increase per annum. This figure is fixed among the three scenarios of CB support we take in this study. Diesel

boilers recorded EUR12,328 in case of 90% support, EUR29,060 in case of 50% support and EUR50,194 in case of no support. The cost ratio of conventional power to solar power in the case of 50% support is 5.8 indicating a significant reduction in expenses using concentrated solar energy.

- Internal Rate of Return (IRR). Based on the expenses savings the IRR of the solar energy adoption is calculated. The result was 2% in case of full support, 11% for medium support and 20% for zero support. The limitation of this calculation is that it can’t be compared to a threshold as this case is taking diesel generators expenses as an opportunity cost. However, this merely explains a huge advantage for solar energy compared with standard IRRs when the support is less than 50%. The higher the IRR the higher the net cash flows of the industry.
- Payback period. This study reveals that in current situation, the investment of solar energy will take 18 years before the cumulative expected cash flow equals the original expenditure. This will become 10 years if half of the diesel price subsidies are removed, and three years less in case of no support program. This clearly shows the advantage of solar technology, as it positions its user in a position that is less vulnerable to external shocks (in this case fuel price variability)
-

In addition, it is worth mentioning that to guarantee financial feasibility for solar thermal energy, the technology needs to be established at stage where it can be aptly used in the industry on a large scale. With reasonable likelihood news on decreasing or eliminating governmental aids on diesel prices, and the absence of appropriate regulations the study reveals a recommendation for shifting (or partial transition) into solar thermal energy for industries in Lebanon.

Of course, the presence of zero interest loan for alternative energy as was done in Lebanon prior to 2020, would ensure a smooth transition, as it lowers the burden that investors might suffer from at the beginning.

It is endorsed for industries embarking on the inventiveness to proceed a cost-benefit analysis to include other relevant costs and check the size of their plants in order to derive a more exhaustive estimates that will end up in a better recommendation and feasibility analysis.

CHAPTER VII

CASE STUDY 2 – PISTACHE PROGRAM

Moving to another solar technology based solution, the second case will be analyzed and the aim is to use the heat available from the irradiation to meet the cooling needs.

To better understand the system at hand and in order to exploit the benefits of the process behind solar technology used in the cooling business, numerical simulations were performed, using the pre-sizing Tool for Solar Cooling and Heating Systems, otherwise known as PISTACHE (Pre-sizing Tool for Solar Cooling and Heating Systems) software. The latter was developed as part of the MEGAPICS project, with the funding from the French National Research Agency (ANR), through the “Habitat Intelligent et Solaire Photovoltaique program” (Semmari, 2013). In order to find the appropriate design and to ensure that the system will perform in the best way possible many simulations and sensitivity analyses will be performed on a specific industry, which will be used as our case model.

The tool is exhaustive and contains options that allow its user, to utilize the solar energy to generate not only cooling, but also heating and domestic hot water. In this analysis, the focus will be on optimizing the use of solar technology and feed the medium scale industry primarily with cooling function, and on a secondary level domestic hot water and heat for offices when and if needed.

Using a simulation and numerical model, the aim is to design and assess the smooth operation of such a solar system, in addition to measuring its thermal performance, most importantly the refrigerating production, the power consumption and the performances of the installation according to external parameters (solar irradiation, outside temperature, etc.). This is done by providing energy balances and performance indicators.

The software is peer reviewed on an Academic level, more specifically in the works of (Le Denn, 2013; Nowag et al., 2012; Semmari et al., 2017) who used the PISTACHE software and tried various components configuration in an attempt to optimize the performance

The results of such studies were compared with real pilot study results. It has observed that there is a difference of around 10% between the real case/ monitoring data results and the simulated results Many other tools are found in the industry, and my choice for PISTACHE is backed by several factors, among which I can enumerate: Available online and for free, suitable for solar cooling, contain all necessary libraries that are friendly users and not case sensitive, compute the energy balance at an hourly step, etc. The complete list of available softwares and modeling tools are found in Table 20.

Table 20. Solar energy related industry software and tools

Software	Available right now	Specific for solar cooling	Free	Suitable for design offices	Predefined configurations	Hourly Time Step	External weather file	External building loads	Component library	Validated with experimental data
TDC Tool		X			X	X	X	X		
EASY Tool		X				X	X	X		
ODIRSOL	X	X	X	X	X	X	X	X	X	
EnergyPlus	X			X		X			X	X
TRNSYS	X			X	X	X	X	X		
INSYL	X		X	X	X	X				
PolySun	X		X			X		X		
TRANSOL	X			X	X	X	X		X	
PISTACHE	X	X	X	X	X	X	X	X	X	X

Moreover, PISTACHE is an easy graphical user interface that facilitates the pre-design of installations to its users. The other programs mentioned above also provide theoretical and realistic data, however what give the edge to PISTACHE is the following: Few parameters are required, well organized and one can easily interpret results as to find the most suitable solution of components design and calculation time is reduced and simplified.

A. Performance of the software (Software design)

The interface is composed of several main parts,

- First, the general information is required

1. General information and input data

We first start by uploading the meteorological data and because the tool is based on a one-hour time step energy balance approach, it uses an input file composed of hourly meteorological data (ambient temperature, relative humidity, global horizontal irradiation). Table 1 lists the input variable, along with the relevant description and the value range of each. The structure of the data is consistent with the output data that will be generated. The values are entered to the system via a file extension (tab text format) which contains 8,760 recorded lines.

Name	Unit	Description	Value
Time	hours	Hour of the year	[1 - 8760]
Month	months	Month number of the year	[1 - 12]
Day	days	Day number of the month	[1 - 31]
Hour	hours	Hour of the day	[1 - 24]
Text	°C	Ambient dry bulb temperature	[-∞ - +∞]
GHZ	W/m²	Global horizontal radiation	[0 - +∞]
HR	%	Ambient relative humidity	[0 - 100]
Temp	°C	Fresh water temperature for DHW	[-∞ - +∞]
HD	kWh	Heating demand	[0-+∞]
CD	kWh	Cooling demand	[0-+∞]
DHWD	kWh	DHW demand	[0-+∞]

Table 21. Input variable definition

After describing the project with the general meteorological information, the location of the system will be defined.

In Figures 16,17 and 18, we show the input data in scatter plots, to better visualize the load profiles of the Temperature, irradiation and humidity exerted by the external environment on the factory.

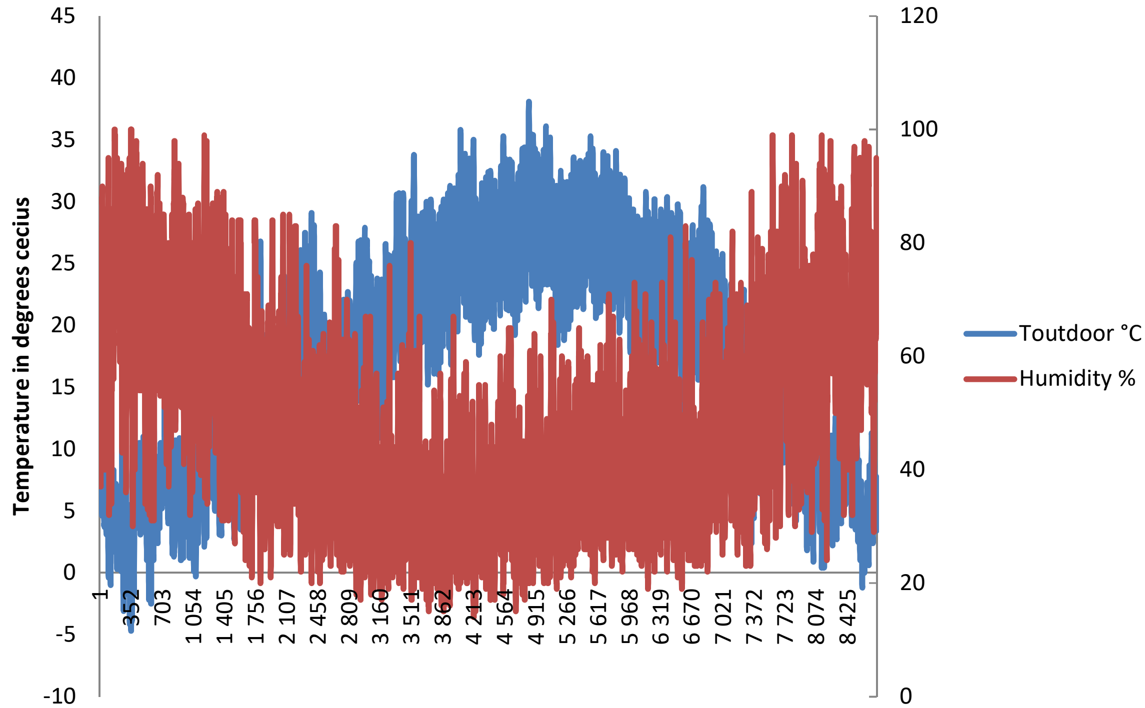

Figure 12. Temperature and humidity profiles of the factory

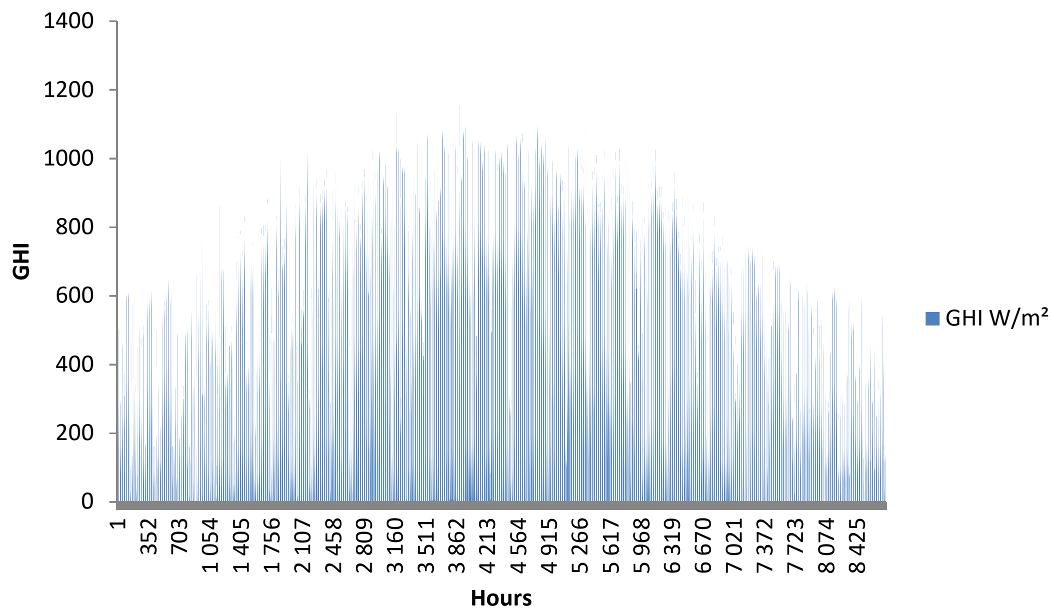

Figure 13. Solar irradiation profile W/m²

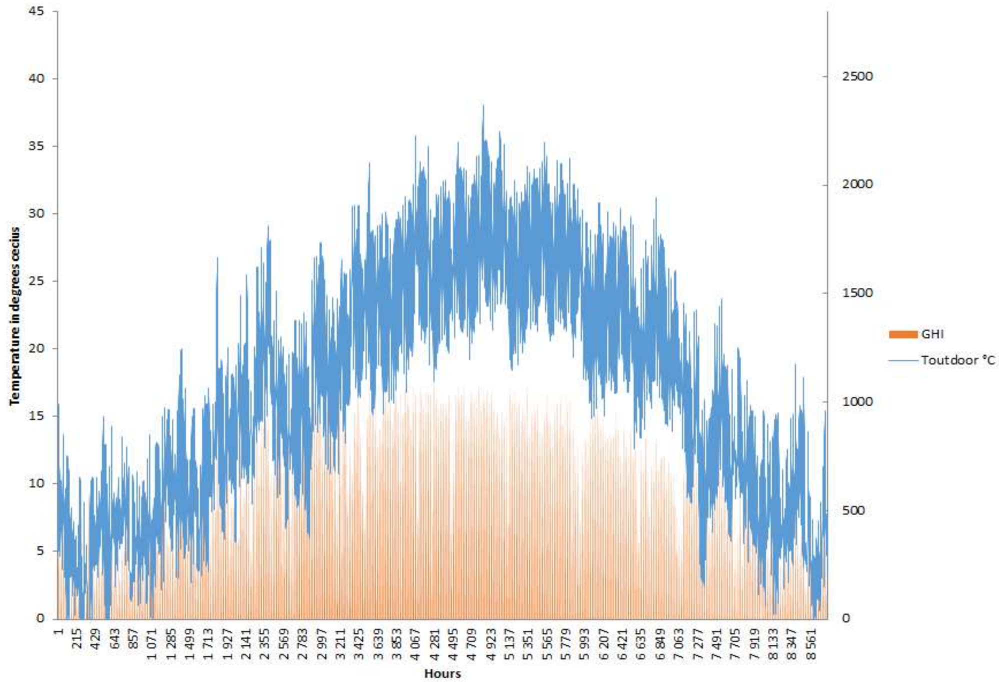

Figure 14. Temperature vs. irradiation profile

B. Cooling Load

Third, the load profile cooling needs, in other words the energy demand for cooling, along with the operating and target temperature set points shall be defined, such as the temperature of the desired heated water. Figure 19 shows the industry cooling loads.

The factory's cooling load is determined by several factors. The first is the requirement to cool: the open space, the ice bank, which contains two 8-kW compressors for cooling water between 0 and 3 degrees Celsius, as well as four 5-kW freezers. The latter is a yearly burden that is constant. The chillers are used to keep the manufactured product fresh and in good condition. The second profile is seasonally driven and consists of the cooling loads to maintain the factory's internal temperature at 23 degrees Celsius

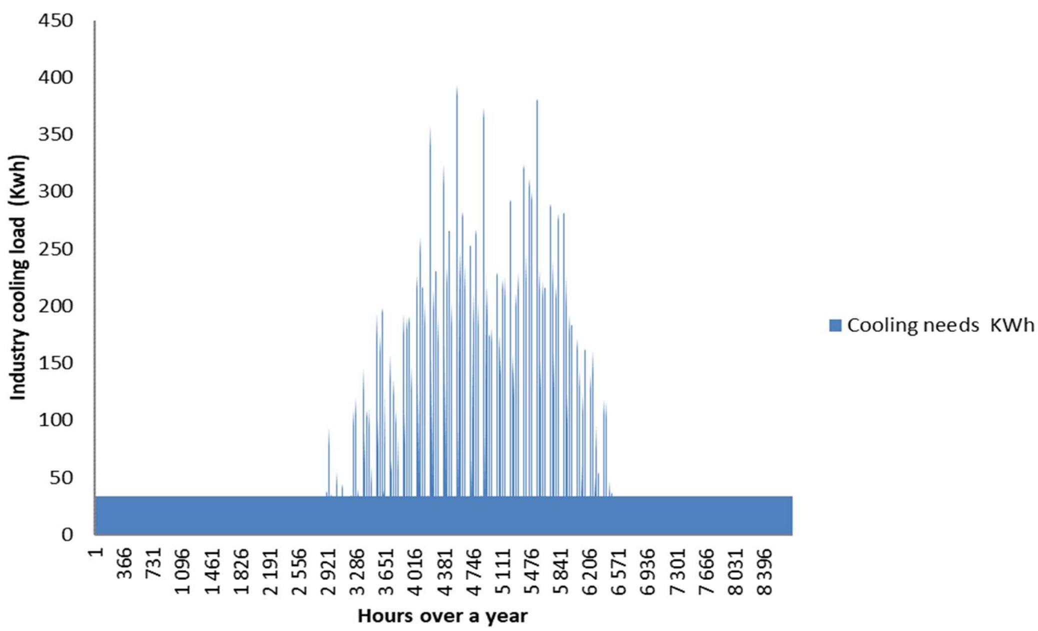

Figure 19. Cooling load for equipment and human need

The second part is to configure the software

1. System configuration

Second, the system has to be configured, designed and the input parameters for the equipment should be filled. First and most importantly, the user shall decide how to use the solar energy, in other words will it only be limited to cooling needs or also for heating and direct water cooling, and if so what is the priority of use. Finally, the user shall decide about the use of back-up system, as renewable energy profiles are subject to environment factors, availability and load profiles. The step that follows is to choose the required main component characteristics at each stage of the system, production, transformation and utilization.

2. Component design

The following are the systems that are included in the software and must be configured:

➢ <u>The cold production sub-system - </u>Chillers (absorption or adsorption)

The modeler should verify and calculate the maximum cooling demand needed (kWh), as well as the ideal cooling capacity (KW) as shown in Figure 20. Two chiller technologies are available, absorption and adsorption. The software library offers a wide commercial list of sorption chillers and different types of solar collectors that are freely available. A generic chiller with a defined nominal cooling capacity and thermal coefficient of performance can be used.

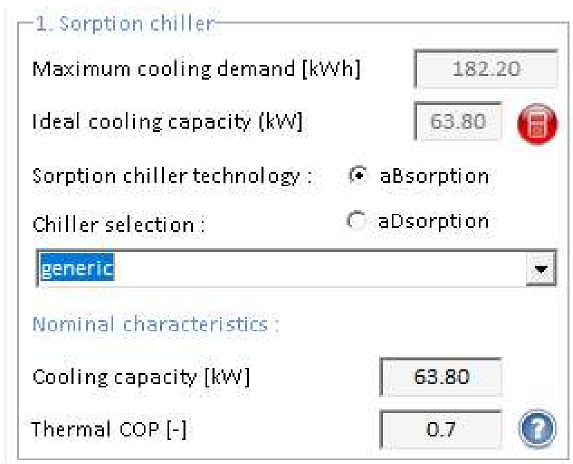

Figure 20. Sorption Chiller requirements (Pistache Program)

The Pistache software makes easy to select between absorption and adsorption chiller with its pre sizing function. The pre sizing function identifies the maximum cooling loads and calculates the sorption chiller ideal cooling capacity for a given solar fraction. The latter is simple the ratio between the chiller cold production and the cooling demand. The default value of 50% set for the cold solar fraction.

The logical question to ask is whether to use the absorption or adsorption chillers. The main difference is that absorption is a volumetric process, while adsorption is a surface process. Another notable difference is that absorption chillers typically use some kind of compressor, while adsorption chillers do not. Obviously, this gives absorption chillers a larger efficiency. As a result, absorption chillers are being used more frequently. Furthermore, they have the ability to produce even higher power outputs. However, absorption chillers have nearly one-fourth the lifespan of adsorption chillers (7-8 years vs. 30 years), are much costlier to maintain, and need anti-corrosion safety. So, even with some significant advantages of the absorption process, the adsorption chiller has a lot of benefits, particularly in the residential areas because of its low energy consumption, ease of installation, and low noise. Adsorption chillers are also considered more environmentally friendly. Here we will set our system for absorption due to its high coefficient of performance.

To define the characteristic of the chiller, the user can:

- Select a chiller among a database
- Choose a generic one, Keep the default values or enter his own nominal thermal COP and cooling capacity.

The decision is also backed with a sensitivity analysis that I have conducted. In Table 21, we use the same manufacturer chiller product, but the difference is that one will be used as an absorption system and the other as an adsorption. As we can see, while setting the cooling demand to be the same for both systems, the total cold that will be available for cooling is approximately the same in both. However, the area of the solar system needed is clearly more in the adsorption system, which means more space and money needed for such system. Besides the energy efficiency is clearly more valorized in the latter system, this can be seen by looking at the thermal coefficient of performance COP_{th} the primary energy ratio (PER), which will be explained later on.

Parameters		Absorption	Adsorption
Collector Area		222	345
Thermal COP	COP	0.7	0.7
Solar heat supplied to Storage	Q1	46291	77052
Heat Supplied to Chiller	Q6	43857	74483
Cold produced by Chiller	Q7	26866	28923
Total Cold for Cooling	Q10	26785	28843
Cooling Demand	Q10'	97023	97023
Heat rejection Water Consumption	V1	195	279
Lost Solar Energy	Q1Lost	158253	247899
Thermal COP th	COP	0.61	0.39
Primary Energy Ratio	PER	0.97	0.67
Global Solar Efficiency	Rsol	0.13	0.14
Net Solar Productivity	PSU	197.5	215.8

Table 21. Sensitivity analysis (Absorption vs. Adsorption)

- The heat production (solar) system (collectors and backup), including state of the art on concentrating and new collectors

Dimensioning a solar cooling system, the modeler shall include the total collector area, orientation and tilt angle.

The user selects the solar collector technology: flat plate collectors or evacuated tubes collectors. To define the characteristics of the collectors, as shown in Figure 21, the user can;

- Select a model of collector among a database;
- Choose a generic one, keep the default values or enter his own.

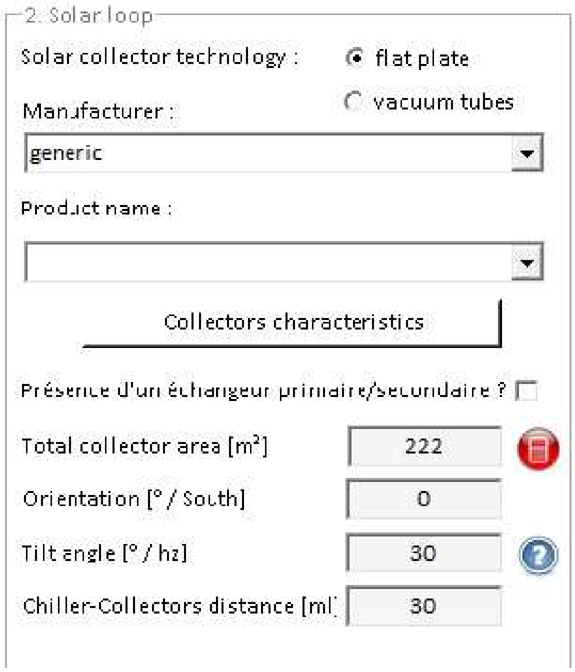

Figure 21. Solar Loop requirements (Pistache Program)

The "collector characteristic" function presents: collector technology, model and manufacturer, reference of the certification and date of validity, aperture and gross area and EN12975 quadratic equation coefficient.

The coefficient default values of the generic collectors have been defined by IEA SHC program Task 26[8]:

- Evacuated tubes : $h_0 = 0.733$, $a_1 = 1.09 \frac{W}{m^2} K$, $a_2 = 0.0094 \frac{W}{m^2} k^2$ [9]
- Flat plate: $h_0 = 0.8$, $a_1 = 3.5 \frac{W}{m^2} K$, $a_2 = 0.015 \frac{W}{m^2} k^2$

The advantage of our program is that the solar collector area and the cooling capacity of the system are inextricably linked: when one is set, the other is

[8] For more info, refer to this website https://task26.iea-shc.org/publications
[9] • a1: Solar collectors 1st order heat loss coefficient W/(K·m²)
• a2: Solar collectors 2nd order heat loss coefficient W/(K²·m²)
• h_0: Zero Loss Efficiency

automatically determined as well. However, the user can make a logical decision of why selecting one manufacturer over another. This can also be seen in the following performed sensitivity analysis that I have conducted. The results are shown in Table 22.

Parameters / Solar collector manufacturer		**Generic**	**SAUNIER DUVAL**
Collector Area		222	178.6
Thermal COP	COP	0.7	0.7
Solar heat supplied to Storage	Q1	45166	31298
Heat Supplied to Chiller	Q6	42679	28791
Cold produced by Chiller	Q7	26135	17746
Total Cold for Cooling	Q10	26060	17692
Cooling Demand	Q10'	97023	97023
Heat rejection Water Consumption	V1	190.4	129
Lost Solar Energy	Q1Lost	153017	123782
Thermal COP th	COP	0.61	0.62
Primary Energy Ratio	PER	0.95	0.94
Global Solar Efficiency	Rsol	0.13	0.11
Net Solar Productivity	PSU	192	157

Table 22. Two different types of solar collector manufactures

It is clear that the generic choice (automatically chosen by the software) is a better design than the randomly chosen manufacturer for the sake of this sensitivity analysis.

- Heat rejection System, where the modeler has four technologies to pick from, these are: Cooling tower, dry-cooler, adiabatic dry-cooler and geothermal probes. As shown below in Figure 22.

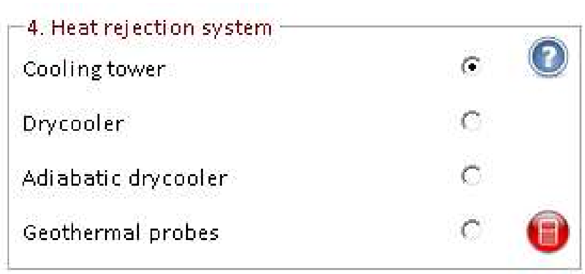

Figure 22. Heat rejection system (Pistache Program)

Apart from the type of chiller, the selection of a heat rejection device is also critical. To begin, let's look at the cooling towers. They are the most common model used among the other heat rejection systems because they have a high coefficient of performance and take up less room than dry coolers, in addition to their low initial cost. They use water as chilling means to reduce the temperature. Dry cooler on the other hand uses air as a chilling means and require a very small amount of water comparing to the cooling tower’s needs. They don’t cause any health problems in addition that their running cost is one third less than the cooling towers.

Hence the main difference between dry coolers and cooling towers 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 (Sparber, 2011).

Adiabatic dry coolers are relatively new and, as compared to traditional dry coolers, vary in the method of chilling the water. Even though adiabatic dry cooler is considered costlier, but they have benefits that outweigh both dry coolers and cooling towers. They are more reliable than dry coolers and use much less energy at the same time, all while using just a fifth of the water needed by a cooling tower. The adiabatic dry cooler was chosen for this purpose.

Geothermal probes can be better than both cooling towers and dry coolers, since they take advantage of the constant cool ground temperature and are more cost effective and efficient on the long run (over 20-25 years), however their initial price is high, they need large quantities of water same as cooling towers, maintenance costs are high, and professional help is required with such a system in order to function properly.

We need to also point out that the option of cold or hot backup isn't critical to the final performance, so any choice won't derail a great cooling system. For hot backup, a standard domestic gas boiler is selected and for cold backup a water condensing compression chiller is selected, for both the efficiency is determined internally by the system.

Additionally, a sensitivity analysis on the choice of the cooling system was performed and the results are shown in Table .

Parameters /Heat rejecting system		Cooling Tower	Adiabatic Dry Cooler
Collector Area		222	222
Thermal COP	COP	0.7	0.7
Solar heat supplied to Storage	Q1	46291	46477
Heat Supplied to Chiller	Q6	43857	44038
Cold produced by Chiller	Q7	26866	24814
Total Cold for Cooling	Q10	26785	24742
Cooling Demand	Q10'	97023	97023
Heat rejection Water Consumption	V1	195	1.64
Lost Solar Energy	Q1Lost	158253	158087
Thermal COP th	COP	0.61	0.56
Primary Energy Ratio	PER	0.97	1.23
Global Solar Efficiency	Rsol	0.13	0.13
Net Solar Productivity	PSU	197.5	198.3

Table 23. Sensitivity analysis (Heat rejection Technology)

The results show debating arguments as to which system performs better. We can conclude that the results are similar as one of the systems perform better when only looking at the COP and the other performs better when looking at the PER. In this case, the system that uses less energy will be selected in a logical sense.

Once all the parameters are defined, the calculation can be processed. This is done with an hourly time step as it allows the hourly load input file to be compared with the potential solar production with the same frequency, and throughout the year. This is critical and shall be made to the highest precision possible, although this can be critical and extensive on the computing side. In addition, and because most of the components have very short term storage capacity (few minutes/ hours), it is better to have an hourly frequency time step. At each time step, the tool calculates energy balance and thermal energy balance according to the user specific design. Finally, the results and output sheets are generated by the software.

C. Description of the whole system and prioritizing our needs

The overall system design can be seen in Figure . The three streams of energy use are highlighted below, as domestic hot water that will be used by the employers of the factory when needed, the space heating that will be used during the winter, and most importantly the cooling needs for both the equipment and the employees. The latter is seasonal (summer), and the former is all over the year.

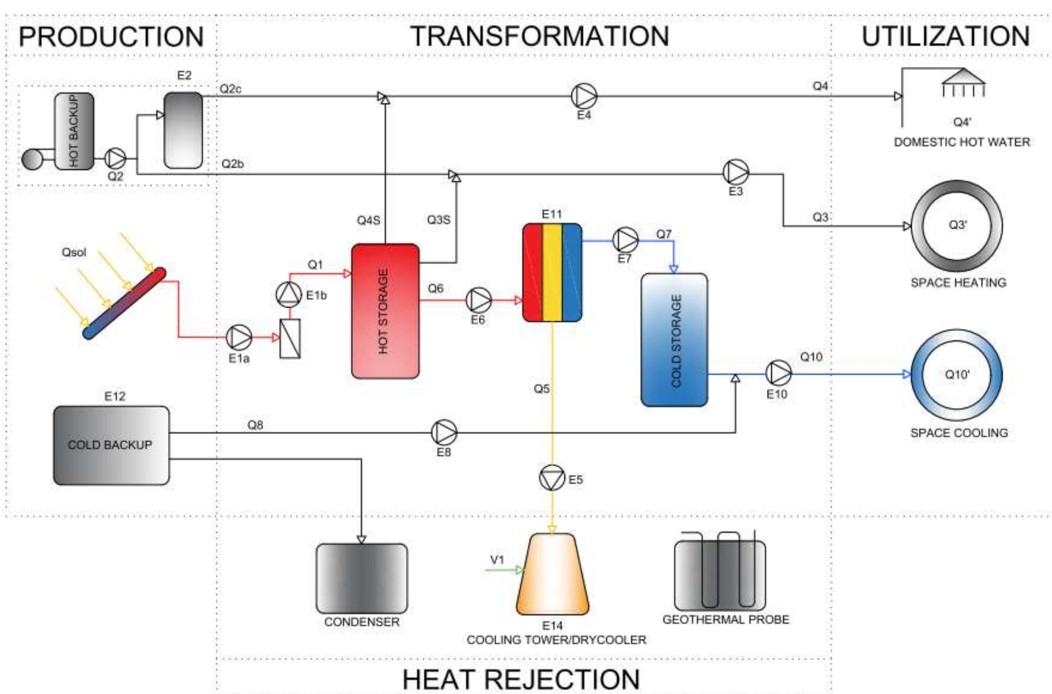

Figure 23. System configuration and equipment

An additional sensitivity analysis is conducted (see Table) below in order to show the better performance of the system when two streams (cooling and heating) are used rather than only one stream.

Parameters /Cooling vs. cooling and heating		Cooling	Cooling + Heating
Collector Area		222	222
Thermal COP	COP	0.7	0.7
Solar heat supplied to Storage	Q1	46291	69013
Heat Supploed to Chiller	Q6	43857	43862
Cold produced by Chiller	Q7	26866	26866
Total Cold for Cooling	Q10	26785	26787
Cooling Demand	Q10'	97023	97023
Heat rejection Water Consumption	V1	195	195
Lost Solar Energy	Q1Lost	158253	62589
Thermal COP th	COP	0.61	0.61
Primary Energy Ratio	PER	0.97	1.49
Global Solar Efficiency	Rsol	0.13	0.19
Net Solar Productivity	PSU	197.5	290

Table 24. Sensitivity analysis (Operation mode, cooling needs vs. cooling + heating)

D. Results section and Performance indicators

Energy performance and primary energy balance, including COP_{el}, electrical consumption of heat rejection and efficiency improvement potential for other components are computed and listed in this section.

For the sake of simplicity, I will present below the results of using only one stream (cooling needs), and in order to have a better visualization of the system at hand, I invite the reader to look at Figure .

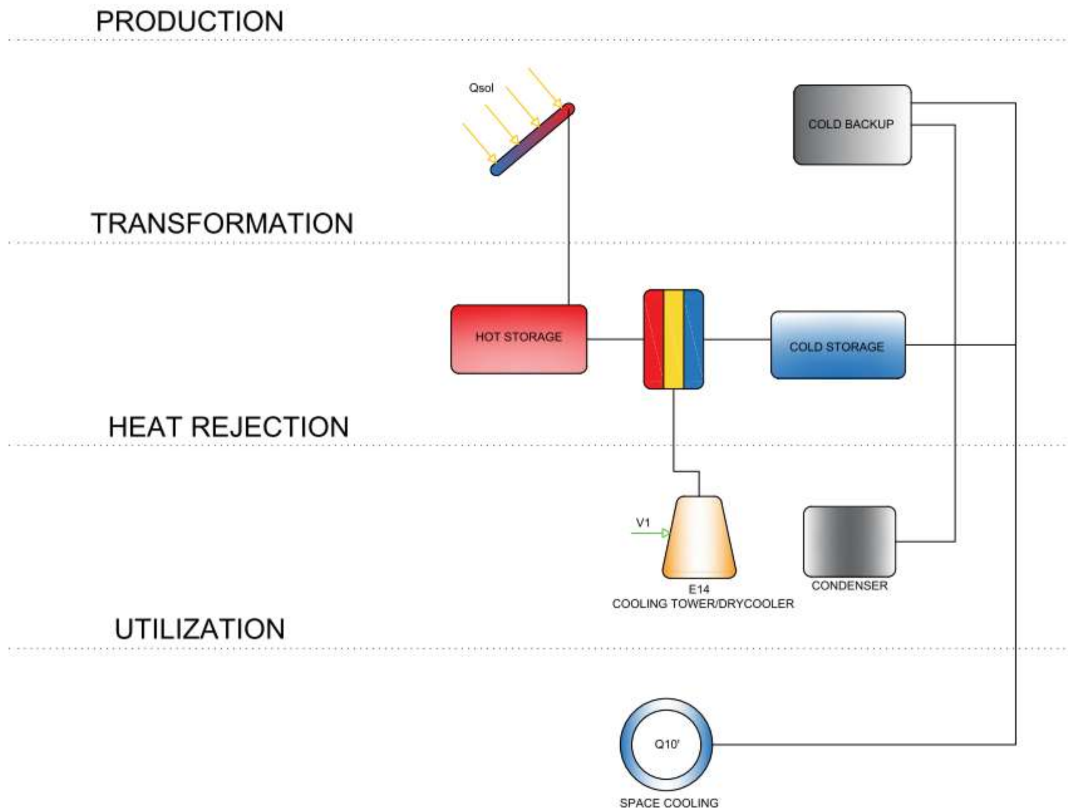

Figure 24. Cooling system of the factory

Nomenclature	Definition
Q_{sol}	Global irradiation on collector area
$Q_1$to Q_{10}	Thermal energy defined according to Figure
$E_1$to E_{14}	Auxiliary electrical consumptions defined according to Figure
ESU	Useful solar energy
COP_{th}	Thermal coefficient of performance of the sorption chiller
PER	Primary Energy Ratio
R_{coll} & R_{sol}	Collector thermal yield and solar thermal efficiency of the system
PSU	Useful solar thermal productivity
η_0, a, b	Collector efficient coefficients
d, f, c_1, c_2	Collector efficient coefficients
$TG, in(t)$	Inlet temperature of the sorption chiller
$TE, in\ (t)$	Inlet temperature of the sorption chiller
$TAC, in\ (t)$	Inlet temperature on the heat rejection side of a sorption side

Table 1. Nomenclature of the overall system

Referring to Figure and Table 1, below is an explanation of the variables and the system performance metrics. Again for this case the solar system is only used to generate cooling in this case, and not to produce domestic hot water and space heating.

The global irradiation on the collector area is a function of the surface area of the latter and the solar intensity:

$$Q_{sol}\ (t) = Collector\ area * Solar\ Irradiation\ (t) \tag{1}$$

The solar energy generated from the collector is calculated as a function of the solar irradiation and the collector efficiency, according the useful heat generated is calculated according to the following equation:

$$Q1(t) = Qsolar\ (t) * \ \mu\ collector\ (t) \tag{2}$$

$$R_{coll} = \frac{Q1}{Q_{sol}} \tag{3}$$

The collector efficiency is also estimated as a function of the collector performance coefficients, average temperature of the collector, solar irradiation and ambient temperature.

$$Collector\ efficiency = \ \eta\ collector\ (t)$$
$$= \ \eta_0 - a * \frac{Tcollector - T\ air\ (t)}{Solar\ Irradiation\ (t)} - b * \frac{\left(T\ collector - T\ air\ (t)\right)^2}{Solar\ Irradiation\ (t)}$$

While the collector area needed to generate the needed energy is calculated using the following formula. It is a function of the chiller design load, the amount of solar irradiation and the efficiency of our collector.

$$Collector\ area = \frac{Chiller\ design\ Load\ (KW)}{Solar\ irradiation\ \left(\frac{Kw}{m^2}\right) * COP_{th} * Collector\ Efficiency} \tag{5}$$

The chiller thermal coefficient of performance is calculated using the above mentioned equation as a function of the Carnot efficiency and in terms of empirical data that are obtained from empirical and experimental trials measured in labs such as CEA-INES (ADD reference Semmari). The COP_0 is the nominal thermal coefficient of performance of the considered chiller.

$$COP_{th} = \frac{Energy\ out\ of\ Sorption\ Chiller}{Energy\ in\ to\ the\ Sorption\ Chiller} = \frac{\text{Q7}}{\text{Q6}} \tag{6}$$

$$COP_{th} = Thermal\ Efficiency = \frac{Cold\ Produced}{Heat\ Supplied} \tag{7}$$

$$COP_{th}\ (t) = d\ * \exp\frac{-\eta\ carnot\ (t)}{c_1} +\ f * \exp\frac{-\eta\ carnot\ (t)}{c_2} +\ COP_0 \tag{8}$$

The chiller thermal coefficient of performance COPth(t) is calculated using equation (8) as a function of the Carnot efficiency (Ncarnot), The Carnot efficiency is the maximal thermal efficiency of the chiller, it can be calculated as a function of the inlet temperatures for an absorption chiller using the following equations.

$$\eta\ carnot\ (t) = \frac{TG, in(t) - TAC, in\ (t)}{TAC, in(t) - TE, in\ (t)} * \frac{TE, in(t)}{TG, in\ (t)} \tag{9}$$

In order to compute the performance indicators, one has to look at the following parameters: Useful solar energy ESU, the collector thermal yield R_{coll} , the solar thermal efficiency R_{sol}, and the electrical coefficient of performance of the solar thermal system COP_{th}, these are well defined as per equations 10 to 13.

Net solar productivity/ useful solar energy, global solar efficiency, solar thermal coefficient of performance and collector yield are all parameters that define the performance of the solar system. These simply evaluate the equipment performance and its ability to use the available solar irradiation. The tool compares immediately each indicator to its associated target values and specifies the gap in percent. In case of oversizing, warning messages are sent to user.

$$ESU\ = Q3 - Q2b + Q4 - Q2c + \frac{(Q10 - Q8)}{COP_{th}} \tag{10}$$

$$R_{sol} = \frac{ESU}{Q_{sol}} \tag{11}$$

$$R_{coll} = \frac{Q_1}{Q_{sol}} \tag{12}$$

Alternatively, the thermal coefficient of performance can also be defined as follow:

$$COP_{th} = \frac{ESU}{E_{aux\,sol}} \tag{13}$$

This simply means the cooling energy divided by the sum of consumed electricity and additional thermal energy multiplied by the efficiency factor of the pump and the fan.

The global performance indicator on the other hand represents the overall system performances and takes into account the solar energy uses as well as the heating and cooling backup energy use. The defined global performance indicator is called primary energy ratio (PER). The primary energy ratio (PER) of the solar cooling systems varies according to the control strategy and type of cooling tower.

$$Primary\ Energy\ Ratio\ (PER)(Solar + Backups) = \frac{All\ useful\ Delivered\ Energy}{All\ supplied\ fossil\ (primary)\ energy} \tag{14}$$

All supplied fossil (primary) energy: Consumed electric electricity in addition to the thermal backup energy.

After defining the equations, variables at hand and the coefficients of system performance, the software runs its optimization algorithm and the results are in Table 26 and Figure 5, Figure and Figure .

System acronyms and abbreviations	Definition	Values (All in energy units, Kwh)
Qsol	Irradiation on collector area	1,377,005
Q1	Solar heat supplied to hot storage	200,671
Q2 (a,b,c)	Back-up heat supplied to hot storage, heating, direct water heating (DWH)	0
Q3s, Q4s	Solar heat for heating, DWH	0
Q3, Q4	Total heat for heating, DWH	0
Q3’, Q4’	Heating demand, DWH requirements	0
Q6	Heat supplied to sorption chiller	195,540
Q7	Cold produced by sorption chiller	124,860
Q8	Back-up cold for cooling	0
Q10	Total cold for cooling	124,695
Q10’	Cooling demand	483,125
Q1 (lost)	Lost solar energy	281,598
Eaux	Auxiliary electricity consumption	91,811
System acronyms and abbreviations	**Definition**	**Value in m3**
V1	Heat rejection water consumption	874

Table 2. Energy balance and water consumption

It is clear from Figure 5 and Table 2 that the total cold that was generated from the solar system is approximately one third of the total cooling demand. The remaining shall be generated from the backup system. Taking into account the industry demand, the environment that surrounds the factory and the system performance at hand, this is what can be produced from the solar system at an efficient pace. Surely and according to equations 5 and 6, additional collector efficiency and solar area size could have played in favor of producing additional cold energy, but this is coming at additional cost.

Another conclusion can be drawn, is that the warmer the month weather profile is, the more solar energy can be produced and therefore the higher the ratio between the chiller cold output over the total cooling demand is generated, which is clearly visible during summer terms.

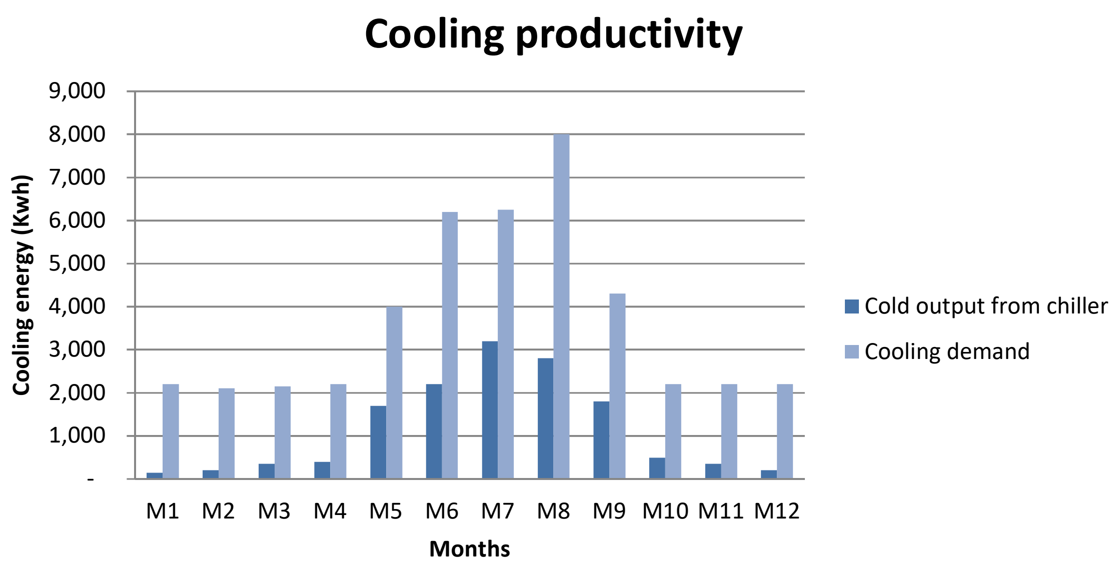

Figure 55. System cooling production vs. demand

When examining the solar collector efficiency in Figure 26, it clearly illustrates that the ratio of useable solar energy produced over the collected irradiation is higher in the summer.

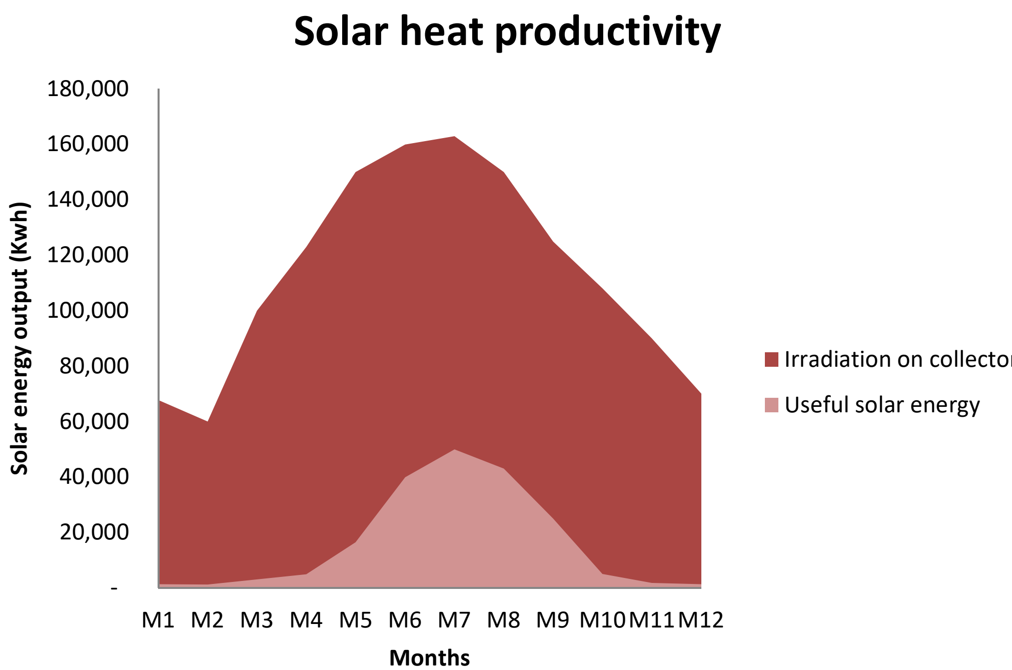

Figure 26. Total solar energy collected vs. useful energy

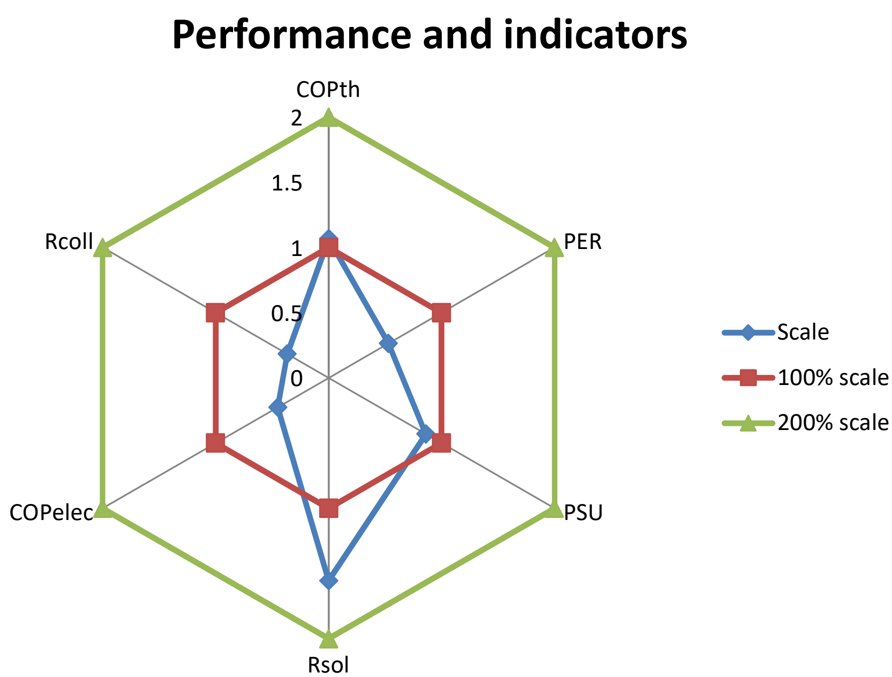

Figure 27. Overall system performance

Energy balance is done at month step and for a year. The indicators summarize the whole installation performances over a year and they are compared to target values. The analysis report helps the user in analyzing the results and proposes solutions to optimize the sizing. The energy balance and water consumption results in addition to the performance indicators are considered very important for the analysis. By looking at Figure , it is clear that the PER value of our system is less than 1 (indicating that the primary energy output equals the energy output), which is understandable given that the backup system is required in this case to meet the factory's overall cold requirement. The collector thermal yield and solar thermal efficiency of the system have fair and expected results, and most importantly, the collector's thermal coefficient of performance (the ratio of cold produced to heat supplied by the solar system) is near to one.

The simulations were done repeatedly, and despite the dozens of trials and combinations of different design parameters, some software related system errors persisted regardless of the number of attempts which have been made. These are of two main categories:

1. “The collector yield is too low”. This error indicates that the collectors are ineffective and somewhat off the goal limits. Changing the solar collector vendors or using a continuously variable orientation angle might solve the problem.
2. “The electrical coefficient of performance is too low”. This was an anticipated error because the backup systems information needed for the design of this system was insufficient.

Overall the system does not seem is to be over-sized taking into-account the cooling objectives set at the start, however the chiller cooling productivity could be re-visited.

CHAPTER VIII

CONCLUSION

Lebanon is currently witnessing a harsh economic crisis, an accumulated debt from the fuel subsidies, and a shortage in electricity. As explained in the thesis, electricity shortage leads to increased fuel bill which hinders the development of industries in this country as the fuel bill is immensely big relative to the profitability of their products. The use of renewable energy technology could be the quickest solution that could aid industries and investors. This study has shown that concentrated solar technology could be feasible as shown in my two Cases Studies discussed previously. International community and the United Nation Development Program could alleviate the current problems witnessed by industries in Lebanon. Such aid could encourage innovation and entrepreneurship in Lebanon to support a clean energy transition. By providing grants, it could alleviate the financial burden of the current energy system on the various sectors and sub-sectors in Lebanon, without the need of the investors to rely on debt or other higher cost alternatives. Additionally, in order to support use of renewable energy on a large scale in the long-term, certain measures should be adopted to enhance the contribution of renewable sources to the energy supply, and perhaps the most important among them would be:

• Inclusion of renewable resources in the national energy plan to replace traditional resources or integrate with them when appropriate. This would provide various economic and environmental benefits.

• Adopting financing arrangements to reduce the cost of manufacturing renewable energy equipment, and providing financial incentives to encourage the use of such equipment and energy-saving mechanisms.

• Elimination of government subsidies for the prices of fossil fuels and electricity to enhance the competitiveness of renewable energy technologies in an equitable manner.

• Supporting universities and technical institutions to introduce vocational training programs and to grant diplomas and advanced degrees in renewable energy to graduate qualified technicians, engineers, craftsmen and experts in this field.

• Strengthen research cooperation and exchange of experience between organizations and research centers interested in renewable energy.

• Sponsoring programs for raising public awareness in the fields of renewable energy, some of which should target policy makers and financial institutions.

• Adopt a technology transfer mechanism to support the local renewable energy equipment industry

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