Simulation of a Solar Fired Absorption System for a Case Study in the Dairy Industry

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Abstract

The aim of this study is to evaluate the performance of a single effect hot water-fired Water/LiBr absorption chiller that supplies the cooling demands in the dairy industry sector in Chile. The high levels of radiation of the Chilean center regions enhance solar absorption as a viable alternative to electrically driven mechanical vapor compression systems. Different plant configurations were simulated with TRNSYS 18 for a designed cooling fraction covered by the absorption chiller in a range of 14 % to 20 %. Areas of a solar field between 80-230 m^2 of evacuated tube collectors coupled with an auxiliary gas system provided heat for the absorption system. The results showed a solar fraction for the studied cooling system of values between 30 % to 66 % and COPs between 0.40 to 0.51. A LCOC varying from 0.164 to 0.22 USD/kWh was obtained. The configurations of solar absorption system for the different studied collector´s area obtain a negative NPV. However, a reduction in the collector´s prices, different storage capacities or different system configurations may improve the results of the economic study.

Keywords: Solar absorption refrigeration system, solar integration to dairy industry, economic evaluation

1. Introduction

Traditional power generation methods based on fossil fuels and hydroelectric dams still dominate the Chilean power grid. At the end of 2017, only 18 % of the energy sources in the country were renewable, where solar photovoltaic and wind technologies designed for electricity generation have had the greatest growths in the last years. Reducing the dependency on fossil fuel-obtained electricity and on conventional refrigeration fluids are both serious concerns regarding global warming and the need to pursue more sustainable energy sources.

In the Chilean manufacturing industry, food and beverages production represents nearly a third of the annual electricity consumption (1,220 GWh), from which between 30 % and 50 % of the electricity demand is used for refrigeration purposes (Instituto Nacional de Estadisticas (INE), 2014). Most of the time, refrigeration demands are supplied by vapor compressor systems or conventional chillers, which require a large amount of electricity to operate, therefore explaining the high electricity consumption values for refrigeration purposes.

Thermally driven chillers or absorption chillers are an alternative to traditional vapor compressor systems, supplying chilled water for air conditioning and dehumidification processes or for water cooling applications in industry. Closed absorption cycles operate with a pair of fluids which work as a heat removal solution, in an evaporation-condensation process which can be divided into three stages: Evaporation, Absorption and Regeneration. To extract heat, the liquid refrigerant is evaporated in a low partial pressure environment, and then is absorbed in gaseous form by the other liquid, transferring the heat from its surroundings to it. Finally, the solution is heated by an external source and thus, the refrigerant is evaporated and then condensed to reutilize it in the cycle. Special care must be taken to maintain the absorption chiller within nominal conditions, to avoid crystallization or corrosion issues caused by the selected working pairs (Akhtar et al., 2015). Water and lithium-bromide is a frequently used working pair, in particular for applications where sanitary conditions must be guaranteed, as in the food industry. Other materials can be used for similar purposes, such as a refrigerant and a highly porous solid in an adsorption cycle, however these are much bulkier and expensive than absorption systems, which are also more efficient and have greater cooling capacities (Zhai and Wang, 2009).

Thermally driven chillers need an external source to heat the solution in the absorption cycle. This source can be of different nature, such as, a fossil fuel boiler or solar thermal collectors. The temperature range required from the

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heat source, around 70 to 100 °C, matches perfectly the temperatures reached by solar thermal collectors, such as flat plate collectors or evacuated tube collectors. Therefore, there is a great opportunity for integrating solar thermal heat together with absorption chillers (solar absorption systems) in order to supply refrigeration demand in industrial processes without a high electricity consume.

Solar absorption systems have been previously studied, however in most of the cases for air-conditioning systems for residential and commercial buildings and in a few cases for industrial applications. A number of simulations have been carried out for LiBr-water absorption cycles, such as systems coupled with evacuated tube collectors in Malaysia (Assilzadeh et al., 2005) and parabolic trough collectors in Iran (Mazloumi et al., 2008). Experimental studies in Madrid with flat-plate collectors for 35 kW (Syed et al., 2005) and 4.5 kW (Lizarte et al., 2012) cooling capacities were carried out, obtaining mean COP values of 0.42 and 0.53, respectively. In Thailand, a solar fraction of 81 % was reached by evacuated tube collectors for a 10 ton absorption system (Pongtornkulpanich et al., 2008).

In Sun et al. (2015) a solar and gas fired absorption system for joint cooling and heating in a commercial building is presented. The need to combine a sustainable source such as solar thermal energy with a stable traditional gas to operate the absorption cycle was highlighted. As a result, gas consumption was reduced in 49,7 % for the chiller. In Akhtar et al., (2015) a feasibility study of solar-driven absorption cooling cycle for air-handling applications was presented for Tetrapak Lahore, Pakistan. The studied variables for the economic analysis were the solar collector area and type, cooling capacity and cooling area. The estimated payback period was of 4.1 years for a solar fraction of 69 %. In Mexico, solar cooling potential was studied in the food industry (Best B. et al., 2013) for an air cooled ammonia-water absorption chillers driven by a Fresnel solar field. Here, a 19 % reduction of electricity consumption was obtained in simulations for a subsystem in a large-scale pork processing plant with operating temperatures between -2-2 °C.

Food and beverage production industries in Chile represent a high refrigeration demand. Furthermore, most of the industries are located in the center of the country where high radiations levels are available (GHI yearly average of 2015 kWh/h). Hence, the industry selected for this work is the food and beverage industry. This study focused on the economic and thermal performance assessment of a solar assisted absorption systems in a sub-sector from the food and beverage industry in Chile.

The following sections will contain: In Section 2 the context of the Chilean diary industry is presented, along with a description of the proposed system. In Section 3, configurations and design parameters of the simulations will be summarized. Section 4 contains the results of these simulations, the thermal and economic evaluation. As a conclusion, an assessment of the different configurations is made.

2. Dairy industry and production process

Food industry was selected as the focus for potential solar cooling integration due to an analysis of the most commonly utilized thermal processes and their required operation temperatures. In Tab. 1, Chilean electricity consumption has been extracted from the Annual National Industrial Survey of 2014 (Instituto Nacional de Estadisticas (INE), 2014) and expressed in its relative weight for the main industrial sectors. This survey does not include information of the mining sector, where thermal demands are also important. Furthermore, cooling demands are negligible in this industry. The food and beverage industry are the second most energy-consuming manufacturing sector in the country, preceded by wood and paper industry, which is exclusive to the southern regions and whose refrigeration needs are also small in comparison to the food sector. Hence, the focus of this work is on the food industry.

Tab. 1: Electric consumption of selected industrial sectors in Chile.

Sector	Electric yearly consumption (MWh)	Relative weight (%)
Food and beverages	1.220.000	27,3 %
Textiles	65.400	1,46 %
Wood and paper	1.475.000	33,0 %
Chemicals and pharmaceutics	914.000	20,5 %

Plastics	325.400	7,28 %
Non-metallic minerals	409.000	9,15 %

Dairy and meat companies represented the biggest energy consumption for refrigeration areas in the industry. Tab. 2 shows the estimated refrigeration demands for the biggest sub-sectors in the food industry, where dairy and met represent 24 % and 21 %, respectively. Although dairy industry is mainly located in the south region of Chile, the largest processing plants are close to Santiago, which is in the center of the country. Additionally, the industrial processes are highly standardized and require refrigeration temperatures over 0 °C, allowing the use of commercially available, non-toxic Water/LiBr absorption chillers to supply the cooling demand. Both reasons make the dairy industry a better alternative to integrate solar refrigeration, which also is reflected in the number of case studies of solar driven plants in other countries (Farjana et al., 2018).

Tab. 2: Estimated refrigeration demands for sub-sectors in the food and beverage industry.

Sub-sector	Electric yearly consumption [MWh]	Electricity destined for refrigeration purposes [%]	Electricity destined for refrigeration purposes [MWh]	Main refrigeration process	Relative refrigeration demand [%]
Meat	242.039	54 %	130.701	Freezing	21%
Fish	167.936	17 %	28.549	Freezing	8%
Fruit & vegetables	124.418	16 %	19.907	Storage	3%
Dairy	128.882	41 %	52.842	Process cooling	24%
Wine	47.462	58 %	27.528	Process cooling	12%
Non-alcoholic beverages	80.727	45 %	36.327	Process cooling	11%
Bakery	118.362	60 %	71.017	Storage	21%

In the typical Chilean dairy plant in the central region, the main products are milk (53 %) and yoghurt (37 %). The thermal demand for their production derives from several processes: cooling for storage (4° C), preheating for secondary processes (e.g.: cream extraction by standardization at 40-60 °C), pasteurization (LTLT, HTST, UHT at 60-72-130 °C, respectively) and process cooling (4-30 °C) (Bylund, 2015). These processes are summarized in Tab. 3. Assuming typical and standardized plant processes, it has been identified most energy-consuming refrigeration process is the post-pasteurization cooling process, followed by cooled storage (Masanet et al., 2014).

Tab. 3: General heating and cooling processes in dairy production.

General Process	Operational Temperature [°C]	Function
Cooling for storage	4 °C	Cool milk entering the storage and maintain constant temperature.
Preheating	40-60 °C	E.g.: Standardization
Pasteurization*	60-72-130 °C	Heat treatment to reduce unwanted bacterial concentration in dairy products.
Process cooling	4-30 °C	E.g.: As part of the pasteurization process or intermediate states between other dairy products.

*Operational temperatures and times depend on the heat treatment applied (LTLT, HTST, UHT, etc.)

From the Office for Agricultural Studies and Policies (Oficina de Estudios y Políticas Agrarias (ODEPA), 2014) information of dairy sub-products production of every industrial plant is recollected, as well as their reception of fresh milk from regional farms. This was crucial to determine average production levels. For the simulations, the average regional production of 15200 ton/year was taken as the base case. Also, with the purpose of evaluating the integration of solar refrigeration for big companies (representing more than 50 % of the regional production) a high-level production of 47.200 ton/year was assessed. For both cases, a constant monthly demand was considered, as the year-round variation is less than 10 %.

Production of dairy sub-products varies from type, country and processes applied. This study focused on the performance of an absorption solar refrigeration system that supplies part of the thermal need to the post-pasteurization process and part of the cooling demand required for milk storage (at 4 °C) due to the match between required process temperatures and chiller working temperatures. In Fig. 1 a scheme of the solar integration to the process is presented, where the solar field and auxiliary heating source is connected to an absorption chiller coupled to the post-pasteurization cooling for storage. Other integration points have been identified, such as reception storage cooling, additional pre-heating and/or pre-cooling of pasteurization and even pasteurization al low temperatures. However, a bigger investment and alteration to standardized processes must be made and escapes the proposed scope.

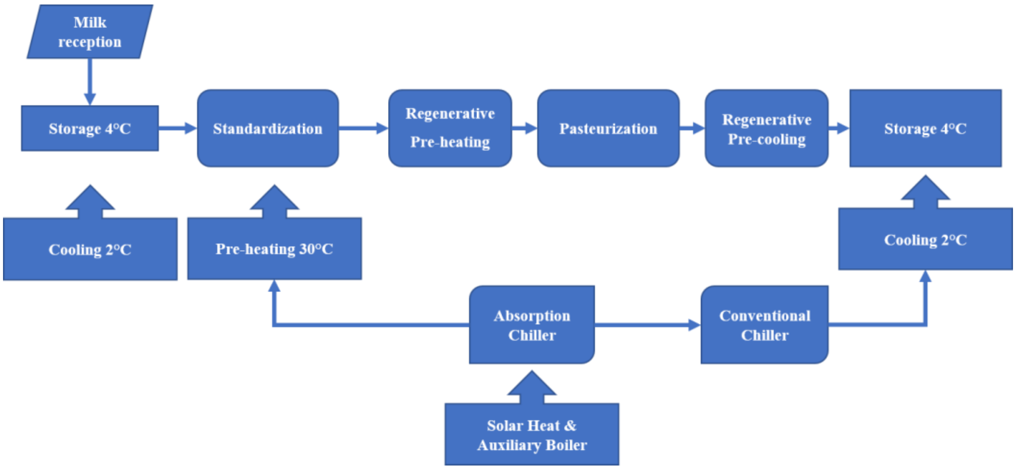

Fig. 1: Scheme of solar integration to dairy process

3. Simulation design

The simulated system was designed to satisfy between 14 % to 20 % of total cooling demand by the absorption chiller assisted by a conventional chiller. The analyzed demands for the cooling were based on two levels of dairy production, constant throughout the year:

- Model 1: Average regional production amounts to 15.200 ton/year. Operation time of 10 hours daily. The absorption system was designed to satisfy around 20 % of the cooling demand.
- Model 2: High level production plant is 47.200 ton/year. Operation time of 8 hours daily. The absorption system was designed to satisfy around 14 % of the cooling demand.

Moreover, two plant configurations were analyzed: configuration A (see Fig. 2), focused on the chilled water production and using a preheating section to reduce the cooling water outlet temperature. The cooling water outlet temperature will preheat the milk from 4 °C to maximum values of 28 °C (Model 1) to 34 °C (Model 2). In configuration B (see Fig.3), the solar field, in addition to heat the water to feed the absorption chiller, uses the excess hot water in the collector circuit for a second preheat of the milk up to 60 °C before returning to the solar field. In the absorption chiller, the milk is cooled down from 24 to 13 °C in configuration A and from 19 to 12 °C in configuration B.

The hot thermal energy required for the absorption chiller is supplied by solar energy with assistance of a gas boiler. The absorption chiller considered in the simulations is a single effect water/LiBr absorption system with working temperatures of hot water 88/83 °C, cooling water 31/35 °C and chilled water 12/7 °C. The chiller provides the pasteurization cooling with the chilled water produced. A small conventional chiller has been integrated in the system to support the absorption chiller and maintain the operational temperatures within 12-7 °C, however it is used in less than 0.5 % of the energy. For the cooling water circuit, a cooling tower is considered to support the absorption chiller when the water is not cold enough to enter the absorption chiller.

Different areas of solar collector field (80-230 m^2) coupled to the refrigeration system were considered in the TRNSYS 18 simulation. Evacuated tube collectors have been chosen for this configuration to reduce ambient heat and efficiency loss due to the great daily thermal oscillation present in the center regions of the country. Type 71 of the TESS Library of TRNSYS was selected. The Incidence Angle Modifier (IAM) data of the collector was obtained from commercially available evacuated solar collectors (Apricus).

The absorption chiller was simulated based on a Maya-Yazaki model using the type 107 of TRNSYS. The main data parameters of this absorption chiller are shown in Tab. 4.

Tab. 4: Inlet and outlet temperatures simulated in hot water-fired absorption chiller (Maya-Yazaki).

Model	SC10	SC20	Inlet Temperature °C		Outlet Temperature °C
Power (kJ/hr)	126.720	253.080	Min.	Max.	
Hot water (kg/hr)	8.640	17.280	70	95	83
Cooling water (kg/hr)	18.360	36.720	29,5	31	35
Chilled water (kg/hr)	5.472	10.980	12	15,5	7

Moreover, an automatic control is incorporated to the system. First, pumps, auxiliary heater and both chillers' operation hours are limited to a six day-week and 8 to 10 hours a day for the different configurations. The pasteurized milk will first be cooled with the conventional chiller from 60 °C (estimated outlet temperature from regenerative cooling section) to 24 °C (Model 1) or 19 °C (Model 2), then it will be cooled down by the chilled water of the absorption chiller with help of the conventional chiller.

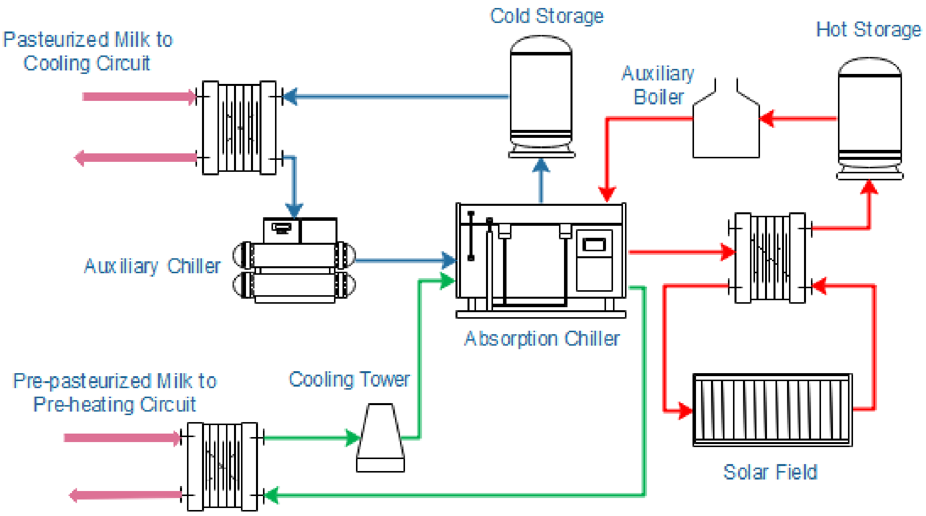

Fig. 2: Scheme of solar refrigeration integration for configuration A

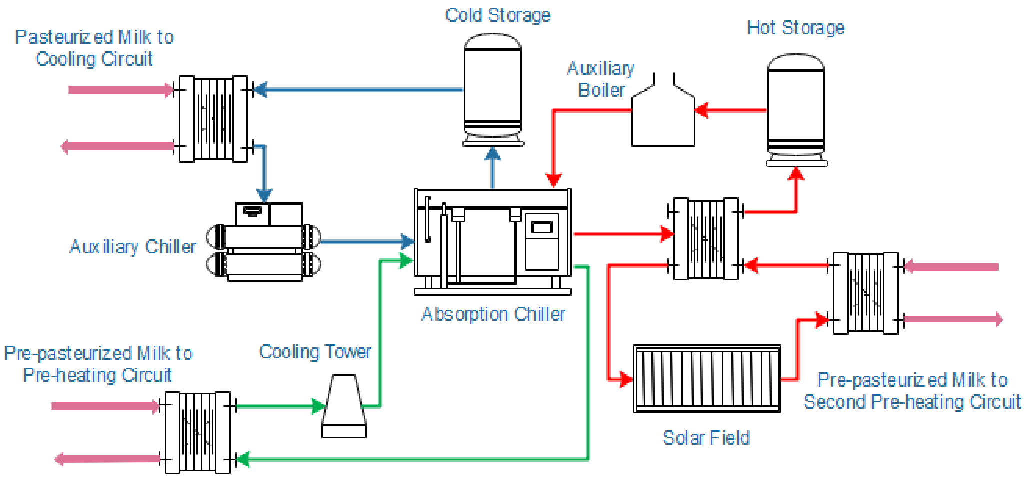

Fig. 3: Scheme of solar refrigeration integration for configuration B

4. Results conclusions

In Tab. 5 the results of the simulations are presented: the chilled water energy produced by the solar absorption chiller and the conventional chiller, the heat produced by the solar field and the gas boiler and the energy supplied by refrigeration towers to cool down the water for the medium temperature circuit of the absorption chiller.

The results show that for the considered solar collector´s area a considerable amount of energy from the boiler was necessary to supply the thermal energy to the absorption chiller. However, the larger the area of the collector's field was, the lower was the amount of energy required by the boiler. The medium temperature circuit of the absorption chiller must be also supported by a cooling tower to reach the 31 °C necessary to enter the chiller. Nevertheless, the chilled circuit worked almost completely without support from the conventional chiller.

Tab. 5: Results of the simulations for the different configurations.

Simulation	Collector's area (m^2)	Absorption chiller power (kW)	Cooling supplied by conventional chiller (kWh/year)	Cooling supplied by absorption chiller (kWh/year)	Cooling energy supplied by refrigeration towers (kWh/year)	Solar thermal energy (kWh/year)	Thermal energy supplied by boiler (kWh/year)
1A	80	35.2	171	88,946	45,555	58,760	122,280
1A	105	35.2	171	88,946	45,555	76,425	104,250
1A	130	35.2	171	88,947	45,555	93,100	82,012
1A	155	35.2	171	88,947	45,575	106,176	66,463
1B	80	35.2	210	88,915	45,237	66,749	157,781
1B	105	35.2	210	88,915	45,237	86,153	134,625
1B	130	35.2	210	88,915	45,237	104,874	113,078
1B	155	35.2	210	88,915	45,237	122,293	93,304
2A	150	70.3	1,897	148,312	11,252	80,947	228,537
2A	180	70.3	1,896	148,312	11,252	93,802	211,759
2A	200	70.3	1,896	148,312	11,248	106,637	195,390
2A	230	70.3	1,896	148,312	11,254	120,347	177,445
2B	150	70.3	2,409	141,313	34,061	133,898	159,323
2B	180	70.3	2,409	141,311	34,058	151,391	132,415
2B	200	70.3	2,409	141,310	34,058	170,252	113,376
2B	230	70.3	2,409	141,309	34,059	188,509	97,640

The solar fraction of the system was calculated as the solar energy used for the chiller versus the total thermal energy required for the chiller. The results showed that the larger the solar collector's area was, the higher the solar fraction was. The same happened for the COP of the absorption chiller of the different cases. However, the collector´s area had less impact in the COP of the absorption chiller than in the solar fraction. The COP and the solar fraction for studied configurations (1A, 1B, 2A or 2B) and collector's areas (80,105,130 and 155 m^2) are shown in Fig. 4.

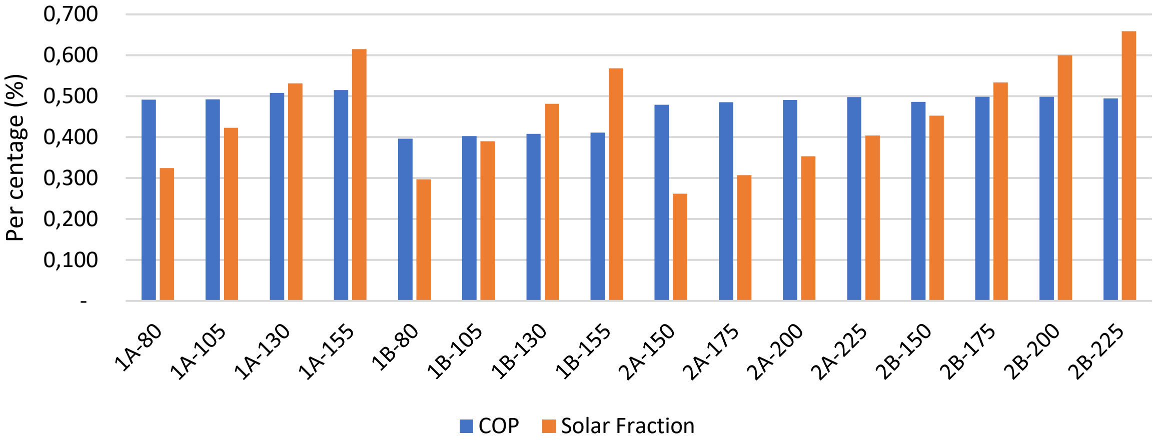

Fig. 4: COP and Solar Fraction.

In the plant configuration B, the solar field, in addition to provide heat for the absorption chiller, preheats the milk. In order to compare which configuration was more efficient regarding the milk pre-heating for the same collector´s area, the total fossil fuel energy required (see Fig. 5) to heat up the milk from 4 to 60 °C has been obtained. The results showed that the configuration B required less fossil-fuel energy to heat up the same amount of milk.

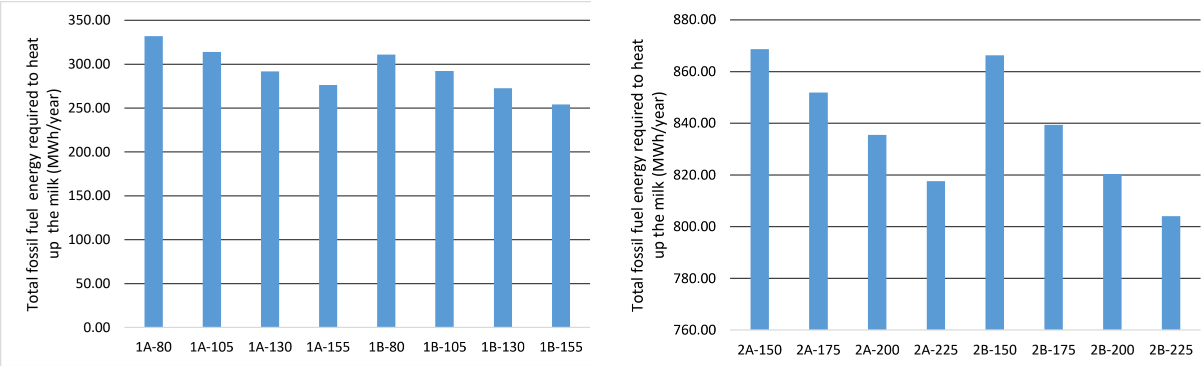

Fig. 5: Total fossil fuel energy required to heat up the milk from 4 to 60 °C for the studied cases (1A, 1B, 2A or 2B) and collector's areas (80,105,130 and 155 m2).

Furthermore, an economic-analysis of the configurations presented has been also performed. The investment and operational cost and other economic parameters considered in the study are shown in Tab. 6.

Tab. 6: Parameters for the economic analysis.

Name	Cost
Absorption chiller	800 USD/kW cooling
Solar field	250 USD/m²
O&M Chiller	2% investment cost
O&M Solar	2% investment cost
Electricity	0.13 USD/kWh
Natural Gas	0.03 USD/kWh

Additional components	10% of total inversion cost
Discount rate	10%
Lifetime of the systems	20 years

The results of the LCOC for the different cases are shown in Fig. 6. The LCOC for configuration A is lower than for configuration B, reaching the lowest value at 0.164 \$/kWh for the configuration 2A with a collector area of 150 m^2. Moreover, in this case, the larger the collector´s area is, the lowest the LCOC is. The cases with higher milk process demand (case 2) obtained also lower LCOC.

$$LCOC = \frac{I_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E}{(1+r)^t}} \qquad \text{(eq. 1)}$$

Where I_0 are the investment costs, C_t the operation and maintenance costs, r the escalation rate, T is the lifetime of the system in years, t is every year considered and E is the cooling energy produced by the absorption chiller.

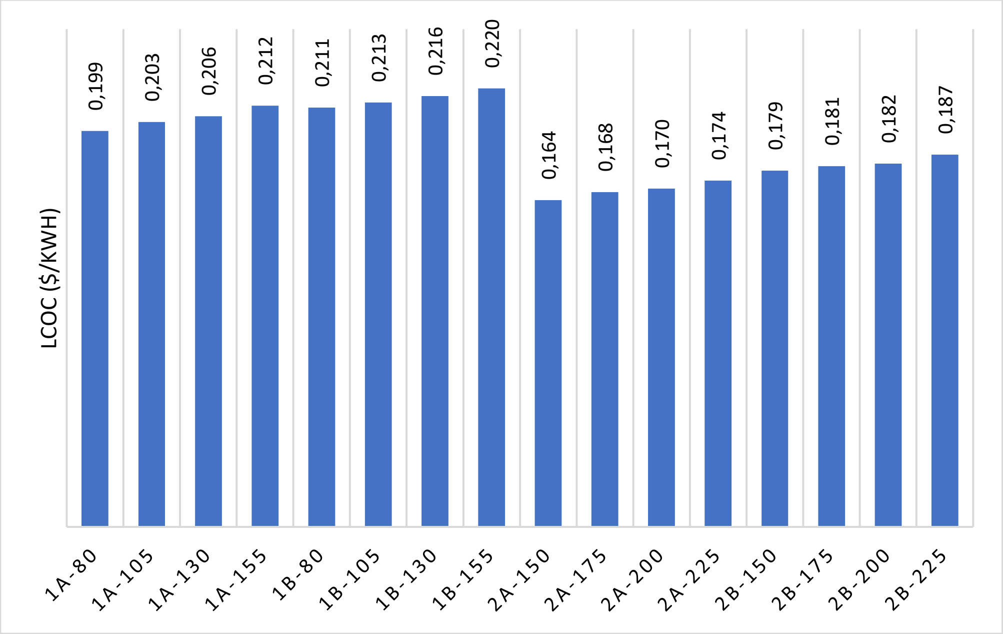

Fig. 6: Levelized Cost of Cooling of the different configurations in USD/kWh.

A negative NPV was obtained for all configurations presented. This is mainly due to the high investment costs of the collector and absorption chiller and the operational costs of the boiler and refrigeration towers in comparison with the savings in cooling energy produced by the absorption chiller. Nevertheless, a decrease in the collector´s prices, different storage capacities or system configurations and the possibility to cool down completely the cooling water circuit with a process stream may improve the results of the economic study.

5. Conclusions

A set of 16 simulations with different collector´s area, process demand and system configurations for a designed cooling fraction covered by an absorption chiller in a range of 14 % to 20 % has been performed. The analysis showed that the higher the collector's area is, the higher is the solar fraction of the cooling system and the COP of the absorption chiller. However, the solar fraction is more sensible to variations in the collectors' area than the COP. The results showed a solar fraction for the studied cooling system of values between 30 % to 66 % and COPs between 0.40 to 0.51. A LCOC varying from 0.164 to 0.22 USD/kWh was obtained. Configuration A provides better LCOC values in comparison to configuration B in a range between 4 to 9 % lower. Nevertheless, configuration A requires more external fossil fuel consume to heat up the milk from 4 to 60 °C in a range from 0.3 to 8 % more energy is required by configuration A in comparison to configuration B. Although a combined economic analysis of the whole system considering all heating and cooling demands of the milk process has not been performed, configuration A seems to be more cost-effective, since electricity to supply cooling demand is more expensive than the fossil fuels such as natural gas, required to supply the thermal demand. Moreover, configuration B, requires of an extra heat exchanger and a complex control system.

The studied configuration of absorption chiller power by solar thermal energy with the considered collector´s area obtains a negative NPV. However, a reduction in the collector´s prices, different storage capacities, different system configuration and the possibility to cool down completely the cooling water circuit with a process stream may improve the results of the economic study.

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