APPLICATION OF SOLAR THERMAL HEATING AND COOLING ENERGY TO DAIRY PROCESSES: A CASE STUDY

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ABSTRACT

The dairy industry is one of the growing sectors in the food industry with significant thermal energy demand for their processes and temperature requirement of maximum 200 °C. The use of solar energy for those process will reduce the fossil fuel dependency, greenhouse gas emission, environmental pollution and help to meet emission targets. Therefore, this study investigates the thermal requirements of a dairy company and provides a schematic of two integration concepts between the solar thermal energy system and their processes which are through the common energy supply line and inlets of individual processes. The study involves a case study that uses natural gas-powered boilers, and electrical powered chiller, ice banks and refrigerators to meet heating and cooling energy demand for the processes such as pasteurisation, fermentation and cold milk tanks. The overall energy consumption of the dairy processes is 1315 kWh at the full capacity operation, of which 1195 kWh can be theoretically replaced by the solar thermal energy. The temperature requirements of the processes are between 0 °C and 4 °C for cooling, and 170 °C for the heating. These thermal requirements can be met by using either parabolic trough or linear Fresnel solar thermal collectors along with thermal energy storage. The solar thermal energy integration concepts developed at supply level and process level use steam drum and absorption chiller to transfer the solar energy to the processes. The supply level integration has more advantages due to its easier control over the conventional and solar energy systems.

Key words: Solar thermal, SHIP, dairy, process demand, solar thermal integration

1. INTRODUCTION

Considering the climate crises associated with the harmful gas emissions, the renewable energy become one of the fastest developing technologies across the world. One of the well-established renewable energy is a solar energy that has been widely used for space heating, domestic hot water and electricity generation [1]. Much attention in the last years has been paid to scale it to the industrial levels. Dairy industry is one of the most promising food industries for the solar energy applications due to their thermal heating and cooling demands [2, 3]. There are thirty - five solar thermal systems used in the dairy industry worldwide, of which nine are located in European countries like France, Greece, Italy and Netherland [2]. Three of them use flat plate collectors to supply hot water for preheating and cleaning processes to meet temperature requirements from 20 °C to 80 °C while the rest use parabolic through collectors and Fresnel reflectors to supply steam at the temperature ranging from 140 °C to 200 °C and pressure from 4 to 12 bar [2]. Solar collectors, heat exchangers and water heating units are important components of the solar energy systems that have been already used in pasteurisation processes to meet operation temperatures ranging from 63 °C to 85 °C [3]. Although the application of various solar thermal systems in the dairy industry have been reported in the literature, there is still lack of consensus weather to be applied to the processes or to the thermal supply lines that feed the processes. The difference between two applications is important as it affects the installation, duration, cost, number of processes provided with solar power, equipment modification, flow control and efficiency of the overall system. Therefore, this study is focused on the integration concepts of an advanced solar thermal system to dairy processes. The objectives of this study are to understand the thermal heating and cooling requirements of the selected case study, and develop integration concepts for solar thermal system application through the existing energy supply line and inlets of individual process levels.

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2. THE CASE STUDY

A dairy company located in Greece is used as a case study. The company has latitude of 37.93 and provided data include weather, annual production rates of the products, and technical details of the production lines, heating and cooling systems. Figure 1 shows the direct normal radiance obtained from the Meteonorm software [4] for the location of the company for 24 hours of 22 December 2005 (winter solstice), 19 March 2005 (spring equinox), 8 July 2005 (summer) and 21 September 2005 (autumn equinox). According to the weather data, the maximum solar direct normal radiance is around 950 Wh/m^2 for 10 hours in summer and changes between 700 Wh/m^2 and 800 Wh/m^2 for 7 hours in spring and autumn. Whereas, it is fluctuating between 400 Wh/m^2 and 600 Wh/m^2 for 6 hours in the winter (Figure 1). Table 1 shows the quantity of the products, skimmed milk, yogurt and yogurt-based dressings, produced during 2019. The corresponding energy consumption in 2019 was reported to be 118,601 m^3 for the natural gas and 1,582,629 kWh for electricity.

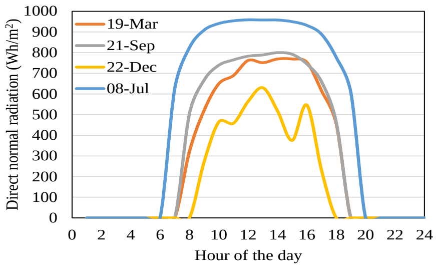


Figure 1: Direct normal radiation for the location of selected case study, Greece 37.93 °N on 19 March, 8 July, 21 September and 22 December [4]

Table 1: The products and annual production rate of the dairy plant produced in 2019.

Product	(kg/year)
Milk	4,062,039
Yogurt	48,734
Dessert	343,737
Milk crème	314
Drinkable yogurt	3,483
Tzatziki	354

Figure 2 shows the production line along with the thermal heating and cooling sections. The heating and cooling systems are also explained in detail in Figure 3 and Figure 4. The raw milk is stored in a raw milk tank (a) which are cooled by the chiller (Figure 4) then processed through the regenerator (b) of the pasteuriser and exposed to non-thermal processes that include centrifugal separation (c) to remove cream, and homogeniser (d) to provide uniform fat distribution. Both, the raw milk and cream pass through the pasteurisation heating (e and j) and cooling (f and k) process in different pasteurisers (l and m). The pasteurisers are using thermal energy in both heating (e and j) and cooling (f and k) units which are powered by boilers and chiller (Figure 3 and Figure 4). The pasteurised milk is stored in the pasteurised milk tank (g) which is cooled by the chiller (Figure 4). The pre-produced pasteurised milk and cream are mixed and added with the necessary culture (h) for the yogurt production in the fermentation tank (i) which is heated by the boilers (Figure 3)

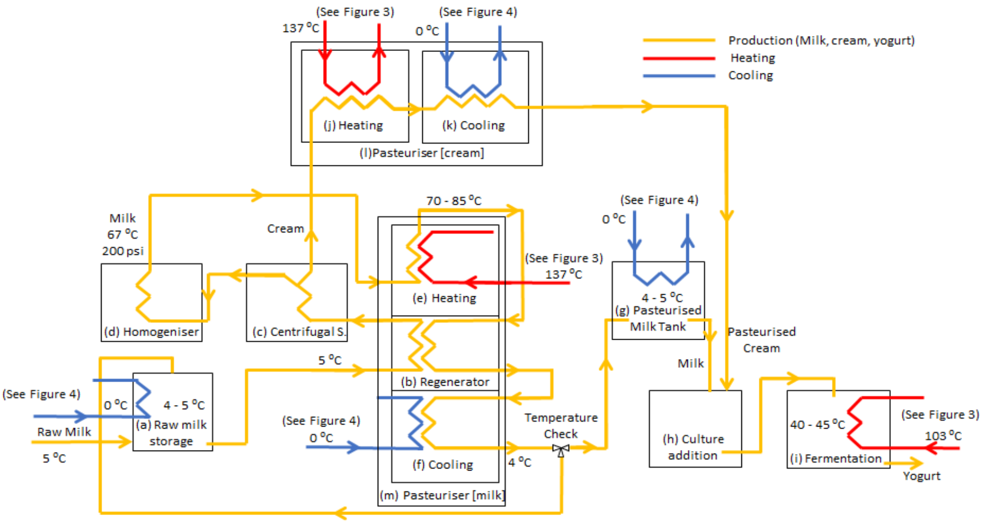


Figure 2: The schematic of production line (yellow) and thermal energy lines for heating (red) and cooling (blue) of the processes.

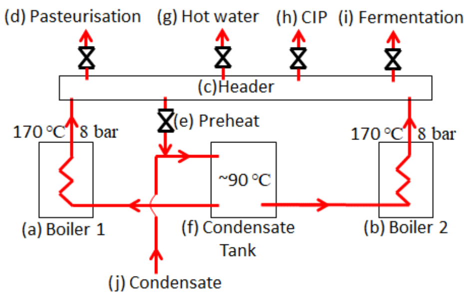


Figure 3: The heating system consist of (a) boiler 1, (b) boiler 2, (c) header, (d) pasteurisation, (e) preheating, (f) condensate tank, (g) hot water, (h) CIP, (i) fermentation and (j) condensate.

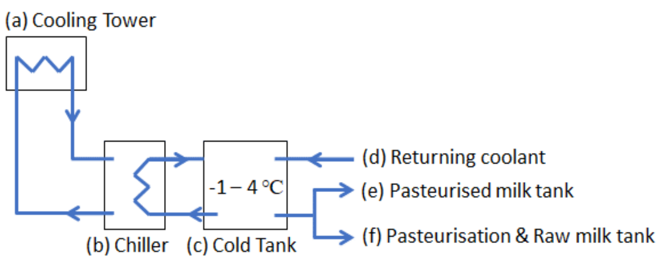


Figure 4: The cooling system consists of a cooling tower (a), central chiller (b) and a cold tank (c) (coolant storage).

Figure 3 demonstrates the heating system which produces steam at 170 °C and 8 bars using two natural gas-powered boilers (a) and (b) with the capacities of 600 kW and 300 kW. The efficiencies of the boilers are 89% with the maximum steam production rates of 960 kg/h and 600 kg/h for the boiler 1 (a) and boiler 2 (b) (Table 2). The produced steam is distributed to the header (c) which has outlets to processes such as pasteurisation (d), preheating (e) of the returning condensate (j), domestic hot water (g), cleaning-in-place (CIP) (h) and fermentation (i). The energy delivered to each process is controlled by pressure reduction valves (PRV) located at the header outlets. For example, the steam is provided at 151 °C to the pasteurisation (d) and at 111 °C to the fermentation (i) processes. The returning condensate (j) from the processes is preheated by a line from the header (e) and stored in the condensate tank (f) at around 90 °C.

Table 2. Technical details of the boilers.

	Power (kW)	Fuel	Efficiency (%)	Outlet steam: Temperature (°C)	Outlet steam: Pressure (bar)	Outlet steam: Max production rate (kg/h)
Boiler 1	600	Natural gas	89	170	8	960
Boiler 2	300	Natural gas	89	170	8	600

Figure 4 presents the cooling system which is powered by an electrically driven chiller (b). The chiller has the capacity of 206.2 kW and uses R404A as the refrigerant. The coolant used in the cooling system is glycol and water mixture (30/70) which is cooled by the chiller (b) and stored in the cold tank (c) at the temperature between -1 °C and 4 °C for 24 hours. The cold tank (c) has 5000 litres of volume and feeds the three processes over two separate lines i.e. the pasteurisation process and raw milk tanks on the same line (f) in series, and pasteurised milk tanks (e) on a separate line (As shown in Figure 4). The returning coolant (d) from the processes directly flow back into the cold tank.

3. SOLAR THERMAL INVESTIGATION

This section investigates the suitability of solar thermal technologies based on the dairy process requirements studied in the section 2. Table 3 presents the summary of the various solar thermal collectors presented in the literature. The temperature range of different types of the collectors varies from 30 ℃ to 500 ℃. The temperature requirement of the case study investigated in section 2 is 170 ℃, and this value is in good agreement with the values given in the literature which vary from 63 ℃ to 200 ℃ [2,3]. According to the Table 3, evacuated tube, compound parabolic, Fresnel reflectors and parabolic trough collectors can meet the temperature demand of the dairy processes. However, considering the relatively high energy demand of the dairy industry, parabolic trough and Fresnel reflectors seem more feasible options as they can operate with thermal oil and have axis tracking, which provides higher solar gain and system efficiency compared to the use of water/air with no tracking options [5].

Table 3: Temperature ranges for various solar collector types and associated heat transfer fluids (HTF).

Temperature (ºC)	Collector type	HTF	Tracking	Absorber	Reference
30-80	Flat plate	Water or air	No	Flat plate	[6]
50-200	Evacuated tube	Water or air	No	Flat plate	[7]
60-300	Compound parabolic	Water or air	1 axis	Line focusing	[8]
60-300	Fresnel reflectors	Water, air, thermal oil	1 axis	Line focusing	[9]
60-400	Parabolic trough	Water, air, thermal oil	1 axis	Line focusing	[10]
100-1500	Parabolic dish	Water, air, thermal oil	2 axes	Point focusing	[11]

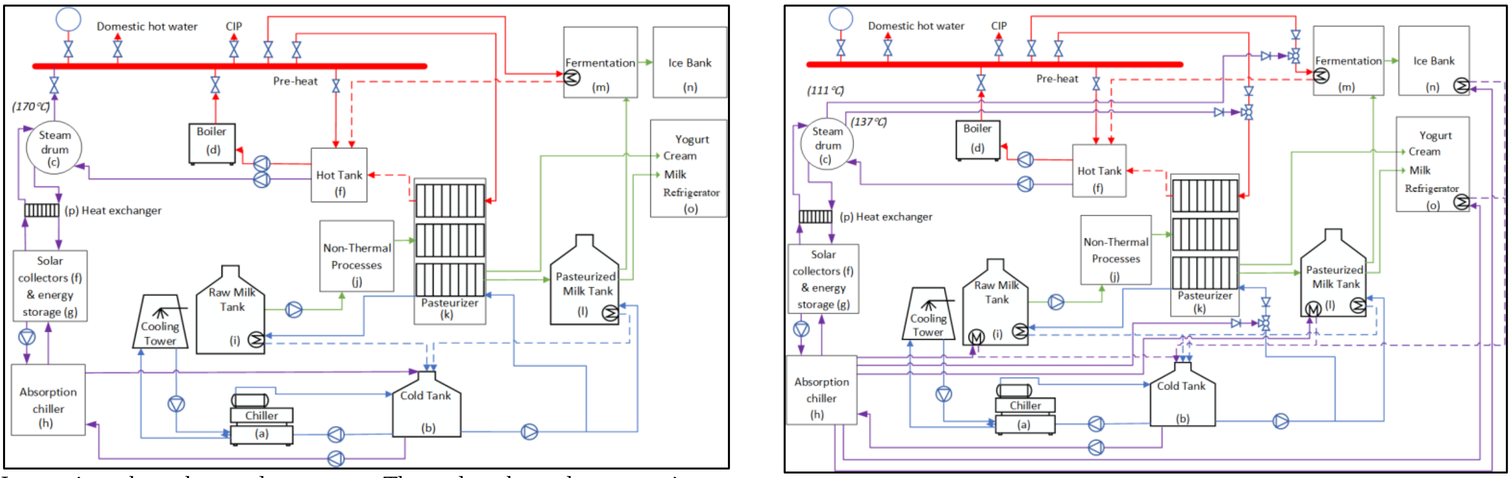
4. RESULTS AND DISCUSSION

Table 4 demonstrates the breakdown of energy consumption of different equipment used in the dairy plant at the maximum equipment capacity. It can be seen that the maximum energy consumption of the dairy plant is 1315 kWh of which 900 kWh is sourced by natural gas and the remaining 415 kWh is sourced by the electricity from the national grid. Considering the equipment given in the Table 5 there are number of units which can be powered by the solar thermal energy such as the boilers, chiller, ice bank, refrigeration and CIP. The total thermal energy demand of the mentioned equipment is 1195 $kWh_{thermal}$ during the maximum capacity operation.

Table 4: Energy consumption of a dairy plant at maximum capacity operation and at average production rate operation (calculated based on annual production in 2019).

Equipment	Energy Source	Energy consumption at the maximum capacity operation (kWh)	Can be powered by solar thermal energy?
Boiler 1	NG	600	Yes
Boiler 2	NG	300	Yes
Chiller	Electric	206	Yes
Ice bank cooler	Electric	4	Yes
Pumps	Electric	33	No
Homogeniser	Electric	37	No
Centrifugal separator	Electric	15	No
Mixer	Electric	18.5	No
Fermentation tank	Electric	16	Yes
Refrigerator	Electric	79	Yes
CIP	Electric	6	Yes
Total		1315	

Based on the existing thermal systems (Figures 2, 3 and 4) and the solar thermal suitability of the units given in Table 4, both the integration through supply line and process level concepts are developed for the selected case study and presented in Figure 5. In the concept of integration at supply level (Figure 5a), it can be seen that a solar thermal powered absorption chiller (h) is used to cool the coolant in parallel to the conventional chiller (a). Similarly, a solar powered steam drum (c) is used to produce steam for the system in parallel to the conventional boiler (d) and heat is transferred from the solar system (f & g) to the steam drum (c) through a heat exchanger (p). Although, the heat exchanger (p) is shown separate from the steam drum (c) in the Figure 5, it can be located either inside or outside of the steam drum (c) depending on the size of the system. The thermal energy storage (g) is connected after the solar collectors (f) in series while heating and cooling demands (h and c) are connected in parallel to each other.



(a) Integration through supply system: The solar thermal energy is transferred to the thermal heating and cooling supply lines of the processes.

(b) Integration through processes: The solar thermal energy is transferred to the inlets of individual processes by separate lines from steam drum for heating and absorption chiller for cooling

Figure 5: Schematics of the supply level (a) and process level (b) integration concepts of solar thermal energy application to a dairy plant

There are few advantages of the supply level integration (Figure 5a) over process level integration (Figure 5b) for the considered company. In both cases, the solar powered cooling and heating equipment (h and c) are connected in parallel to conventional equipment (a and d) through separate feed outlets from the cold tank (b) and hot tank (f), respectively (see Figure 5a). Therefore, any problem or maintenance on the conventional equipment does not affect the operation of solar equipment or vice versa [12]. However, this would require more complex flow control system which would increase the cost for the process level integration due to the individual lines for each process. The easier flow control with the supply level concept also creates a flexibility for plant operator to adjust the load between the conventional and solar energy (within the installed solar capacity) [12]. In addition, the solar system would not require any extra line connection in the case of a new process addition to the dairy factory (i.e. to produce a new dairy product), as the solar system (f and g) feeds the heating loop (red coloured loop). The disadvantage of the supply level integration concept (Figure 5a) is the higher collector outlet temperature requirement [13] and higher losses through the system [14]. Although, the integration at process level (Figure 5b) is considered more efficient method in the literature due to the lack of losses and leakages from the system [15], it is not suggested for the industries like dairy where the solar thermal energy is required for a number of processes [16]. This is because of the complexity of the flow control, cost of additional piping, difficulty of equipment modifications, effort of the installation, incapability of meeting future demand of the company for the production of new products [14-16].

5. CONCLUSION

This study investigated the application of solar thermal energy in a dairy plant. The energy production of the dairy plant is 1315 kWh at the full capacity production while the temperature requirement is ranging from 5 ℃ to 170 ℃ for cooling and heating processes. Parabolic trough and Fresnel reflectors are suggested as the most applicable two solar collector options as they can meet the temperature demand of the dairy processes, and their ability to have axis tracking and operating on thermal oil would maximise the solar gain and efficiency compared to the other reviewed technologies. Two investigated concepts include solar thermal energy integration through the common thermal energy supply line and at the inlets of individual process levels. Both concepts involve thermal energy storage unit(s) which are connected to the steam drum and absorption chiller for the steam production and coolant chilling. The integration of solar thermal energy through thermal energy supply line method is found more advantageous concept compared to the process level integration due to easier control of the conventional and solar energy systems, and ability to handle expansion of the production. The future work includes the numerical simulation of the introduced solar thermal energy integration concepts to dairy processes to evaluate the technoeconomic and environmental impacts.

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