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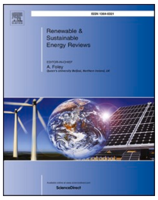

An investigation of the recent advances of the integration of solar thermal energy systems to the dairy processes

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ABSTRACT

The dairy industry uses a number of energy intensive thermal processes like cooling, heating and cleaning that require thermal and electrical energy. Those processes use temperatures between 4 °C and 200 °C that could be potentially powered using solar thermal energy but one of the main challenges is the complexity of selection and integration of the components used for the solar system such as solar collectors, solar heating and cooling equipment. The heating processes with the temperature requirements between 300 °C and 400 °C are mainly powered using solar parabolic trough collectors and linear Fresnel reflectors while cooling processes with solar absorption chillers. The excesses of energy of above 200 °C could be stored in a thermal energy storage system. This study critically evaluates the thermal demands of the dairy processes, reviews their existing solar thermal applications and recommends a concept design for solar thermal energy integration based on the available data. The concept design includes connection of the solar collectors and thermal energy storage to the thermal energy supply line through the absorption chiller and steam drum. The benefits comprise flexibility of the heat transfer fluid selection, independency of solar energy production to conventional production and no further modification of the conventional production system or additional capacity to support the future upgrades are required.

1. The application of solar energy for the industrial purposes

The climate change issues and global temperature rise have led the governments across the world to set up ambitious targets to meet 2050's zero gas emissions [1]. As a result, a number of agreements and directives for the use of the renewable energy sources have been promoted in order to reduce the dependence on the conventional energy sources and harmful gas emissions. One of the renewables that have been widely used for generating domestic hot water and space heating is a solar energy. It has a great potential to be applied to the food industry as one of the top five energy demanding industrial sectors [2–5]. The dairy companies, in particular, require significant thermal energy for their heating and cooling processes like drying, evaporation, fermentation, pasteurization, washing and cleaning [6–8]. The solar thermal energy in dairy industries is mainly used for specific dairy processes that use only solar thermal heating while this study considers integration of the both solar thermal heating and cooling for production of milk, cream, yogurt, cheese, whey, milky drinks and milk powder. Therefore, the main objectives of this study are to review the current thermal requirements of the dairy processes, investigate the potential of using solar thermal systems, recommend an integration strategy for solar thermal application to the dairy processes and calculate the corresponding Levelized Cost of Heat (LCOH).

2. Thermal and electrical requirements in the dairy processes

This section reviews the thermal and electrical energy requirements of the dairy processes for production of various dairy products.

2.1. Mass flows characteristics

The types and quantities of mass flow streams are important characteristics for solar energy applications. Table 1 presents the mass flow streams of two dairy plants. They consist of three main streams for carrying (i) milk to the production, (ii) coolant to the process cooling and (iii) steam to the process heating and cleaning. The temperature of the milk for the major processes like pre-treatment and pasteurization of the raw milk is between 4 °C and 90 °C. If some portion of the milk is used for production of milk powder the temperature increases to up to 200 °C after pasteurization process [11]. The fluid in the cooling stream

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Table 1
Mass flow of typical streams in dairy factories.

Operation	Flow type	Mass flow		
		[9]		[10]
		Δt (h/day)	(kg/batch)	(kg/h)
Pre-treatment	Raw milk	5.0	20,600	1953
Pre-treatment	Losses at pre-treatment	5.0	103	
Pasteurization	Pasteurized milk	5.0	20,497	1953
Yogurt elaboration	Milk to fermentation	3.0	3075	
Yogurt elaboration	Produced yogurt	3.0	2982	24
Yogurt elaboration	Losses at fermentation	3.0	92.2	
Cheese production	Milk to cheese production unit	4.5	16,398	0
Cheese production	Produced cheese	4.5	1804	0
Cheese production	Whey	4.5	14,594	0
Non-fermented drinks	Produced milky drinks	1.0	1751	2
Cleaning of installation	Water for cleaning	2.0	16,000	
Extern utilities	Water from boiler	5.0	45,701	6560
Extern utilities	Coolant	5.0	37,540	5000
Excess of water	Non reutilized water	9.5	22,158	

which is normally kept in a buffer tank and circulated around the processes via piping system is water, brine, ammonia, or glycol/water mixture. The heating stream consists of water, due to the food safety concerns, is converted into steam at the boilers and sent to the processes [12], however a significant amount of water may not be reutilized in the cycle. According to Ref. [9] that is a discharged hot water from the processes that also contributes to additional heat loses.

2.2. Thermal energy requirements

The thermal energy requirements of the dairy processes are associated to the cooling and heating demands, as presented in Fig. 1. The cooling is required for the storage and refrigeration of the dairy products whereas the heating is required for the pasteurization, cleaning in place, fermentation and drying. Table 1 presents a number of studies that investigated the thermal and cooling demand of various processes. The lowest temperature of 4 °C was observed in refrigeration while the highest of 200 °C in spray drying processes. It is a common practice in the industry to produce steam at the higher temperature then reduce to the desired levels to meet process requirements [13–15]. For instance, steam heating could be applied to fermentation processes for yogurt production, cleaning processes, sterilization and pasteurization to reach the required temperatures from 80 °C to 150 °C. According to Table 2, the power requirement of the reviewed dairy plants varies from 76 kW to 6277 kW depending on the production capacity, type of the processes and required temperatures. The heat loads of the processes varies from 0.09 MJ/kg to 0.4 MJ/kg apart of spray drying process which varies from 3 MJ/kg to 20 MJ/kg (Table 2). Table 3 shows the maximum temperatures required for production of different dairy products. The production of milk powder showed the highest temperature of 200 °C while butter the lowest of 11 °C. The other processes require temperatures from 65 to 150 °C. Those data were used as a starting point to estimate the potential contribution of the solar thermal energy to the dairy processes and selection of solar thermal collectors that is discussed in Section 5.

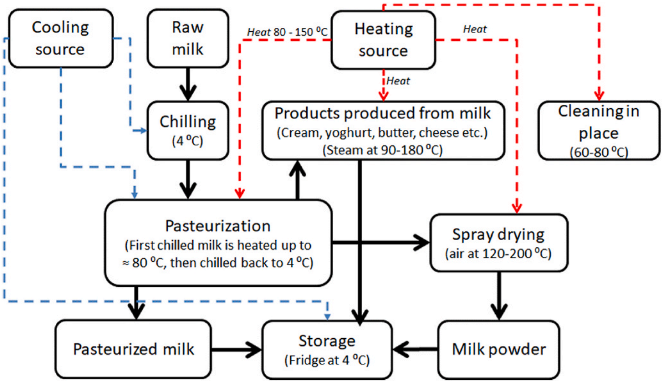

Fig. 1. Schematic of the thermal requirement of a typical milk processing plant. Red and blue lines represent the heating and cooling supplies for the processes, respectively.

Table 2
Temperature requirements in various processes of dairy plants.

Process	Temperature (°C)	Power Consumption (kW)	Heat Load (MJ/kg)	References
Refrigeration	4–10	76–300	0.18–0.2	[9,13,16]
Pasteurization	60–150	181–6277	0.19–0.4	[9,13,16,17]
Concentration	60–120	6130	0.014–0.036	[16–19]
Fermentation[a]	94–140	1026		[13,16,17]
Production	90	817	0.09–0.036	[16,20]
Heating	40–95	167–800		[9,16–18]
Cleaning	60–80	377–628	0.1–0.11	[9,13,16,17]
Sterilization	100–140			[11,17,18]
Spray Drying[b]	120–200		3–20	[11,21]

[a] Fermentation also involves the previous pasteurization process in yogurt production. The fermentation process itself requires temperature around 45 °C [22].
[b] Spray drying presented in the table also covers the evaporation process.

2.3. Electrical energy requirements

The electrical energy is mainly used for powering equipment like refrigerators, pumps, compressors, control units and lighting and processes like sterilization, centrifugal separation and homogenization [3,30]. Table 4 presents several studies with specific energy consumption: electrical ($SEC_{electrical}$) and thermal ($SEC_{thermal}$). The highest $SEC_{electrical}$ of 2.95 MJ/kg was observed for production of whey powder while the lowest at 0.05 MJ/kg for production of milk. The highest $SEC_{thermal}$ of 7.66 MJ/kg was observed for concentration of milk and production of whey powder while the lowest of 0.1 MJ/kg for production of cheese. The main factors affecting the SEC of the products are equipment and their energy efficiencies. The key asset for the solar collector selection is the highest temperature requirement of 200 °C.

3. Solar energy integration to dairy processes

This section reviews various integration concepts of the solar thermal energy systems to industrial processes. The potential applications of solar thermal heating and cooling are reviewed under four subsections

Table 3
Maximum temperature requirements of the popular dairy products.

Max. Temp. (°C)	Products	Reference
11	Butter	[23]
78	Desserts	[24]
95	Fermented products	[25]
65	Whey, casein, lactose	[26]
85	Cream	[27]
90	Coagulated products	[28]
100	Ghee	[29]
110	Concentrated products	[66]
150	Milk	[15]
150	Other products	[13]
200	Dry products: Powder	[11]

Table 4
Electrical and thermal specific energy consumptions of the common dairy products.

		Specific energy consumption (MJ/kg)			
		[31]	[32]	[20]	[33]
Milk	Electrical	0.93	0.05		
Milk	Thermal	1.8	0.1		
Cheese	Electrical	1.1	0.93	0.8	1.21
Cheese	Thermal	3.94	2.38	1	2.11
Butter	Electrical	0.65	0.71	0.5–0.7	0.46
Butter	Thermal	0.85	1.56	0.5–1.2	1.29
Cream	Electrical	1			
Cream	Thermal	0.18			
Milk powder	Electrical	1.23	0.95		
Milk powder	Thermal	15.0	7.4		
Milk protein powder	Electrical		1.74		
Milk protein powder	Thermal		7.66		
Milk concentrated	Electrical	0.6	0.27		
Milk concentrated	Thermal	4	0.79		
Whey powder	Electrical	0.14	1.07	0.4	
Whey powder	Thermal	9.87	7.64	2.7	
Whey protein powder	Electrical		2.95		
Whey protein powder	Thermal		11.2		
Casein and Lactose	Electrical	0.92	1.14	0.6	0.92
Casein and Lactose	Thermal	4.12	5.35	4.1	4.12
Ice cream	Electrical	2.89			
Ice cream	Thermal	1.63			

of direct steam production, indirect steam production, direct heating of milk and solar powered cooling. The outcomes are used in Section 5 to suggest an integration concept for the solar thermal collectors.

There was no standard procedure found in the literature for integrating solar thermal energy to dairy processes. The most common way of solar energy integration is associated directly to the processes or supply lines, as presented in Fig. 2 [17]. The process level integration strategies generally use a heat exchanger to transfer the solar heat to processes with higher temperature requirements but they are not feasible for the processes with lower temperature requirements e.g. cooling [34]. On the other hand, the supply level integration strategy aims to transfer the solar energy to the existing heating and cooling supply lines which enables the use of a solar powered chiller for feeding the cooling required processes. The main advantages of the supply level integration include: (i) avoidance of equipment modification such as pasteurizer, boiler etc. Because any modification on a pressure device like boiler may require recertification of the equipment, (ii) minimised interruption of the production during the installation period, (iii) avoidance of reorganisation of the control systems. The effect of mass flow magnitudes of different streams, the production of specific dairy product and their temperature requirements play significant role on solar energy integration option. To illustrate, for a small-scale plant which only produces primary dairy products such as milk and cream, a supply level integration scenario would be the best choice because of the fewer mass flow branches on the production line, i. e, avoiding processes like fermentation, evaporation and spray drying. Moreover, for such dairy plants the key temperature is set by the pasteurization presses at around 85 °C which can be provided by the non-concentrating solar collectors to keep the solar energy integration cost down. However, the medium and large dairy plants which produces wide range of dairy products such as yogurt, cheese and especially powder products have multiple branches or stages in their production lines for various processes. This diversity on the mass flows along with the higher temperature demand would make supply level integration option more feasible. Considering the European target to decarbonise industrial processes it is vital to investigate advances in solar thermal technologies which could meet the demand of the all dairy products i.e., including high temperature required evaporation and spray drying processes. Therefore, this study covers the supply level integration options under four categories that include: direct steam production by using water as the heat transfer fluid (HTF) and produce steam in the solar thermal collectors (Section 3.1), indirect steam production when solar thermal collectors feed steam in the steam drum and kettle reboiler to produce the steam (Section 3.2), direct heating of milk through the solar collectors (Section 3.3), and solar powered cooling system (Section 3.4).

3.1. *Direct steam production through solar collectors*

The direct steam production uses water as a HTF in the solar collectors to produce steam for the processes, as presented in Fig. 3. Different variations of the direct steam production could be applied to improve the cost effectiveness of the system. For example, in the experimental investigation of [35]; U-type heat pipe was used for the direct steam production that was circulated through the parabolic trough solar collector. The conventional boiler was modified in a way that parabolic trough solar collector receives water from its drum, converts into a steam and sends it back into the boiler at 0.75 MPa pressure with a thermal efficiency of 38.5%. Some disadvantages include variation of the axis tracking requirement and associated cost related to the location and recertification of the modified boilers. Another experimental study used all-glass evacuated tube collectors to produce around 2.3 kg/m^2 steam at 130 °C with an efficiency of more than 40% for the process heating [4]. Although this method can be considered as a simple way of direct steam production without any need of axis tracking and boiler modification, the medium temperature rates are unlikely to be preferred on the large scale dairy plants due to the higher temperature requirements for the dairy processes such as evaporation and spray draying [7]. simulated a fully covered semi-transparent photovoltaic thermal integrated parabolic concentrator for the pasteurization processes. In the simulation, the photovoltaic panels were embedded at the centre of the parabolic collector to produce electrical energy for pumps along with the thermal energy. It was found that the investigated system was capable to pasteurize 216 kg

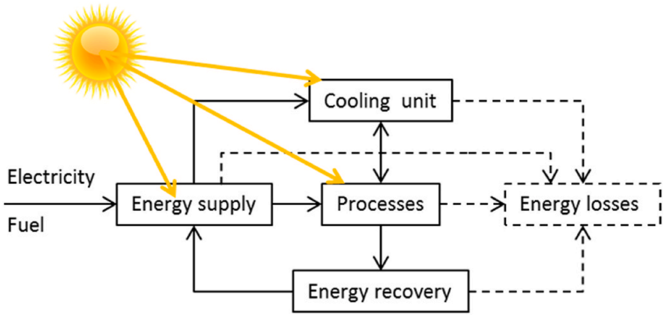

Fig. 2. Solar thermal energy can be integrated directly to processes or at the supply line.

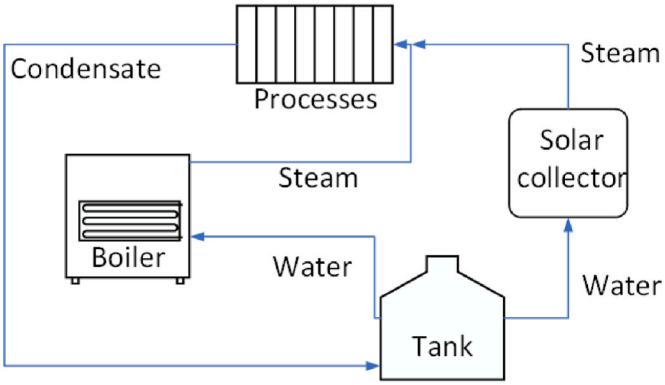

Fig. 3. Basic schematic of the direct steam production using solar thermal collectors.

milk including 5.7 kWh electrical energy produced by the 3 modules of 4.2 m^2 polycrystalline photovoltaic panels used for the pumps [36]. simulated three different strategies for direct solar integration to a dairy company: (i) solar collectors in parallel to conventional heater (ii) solar collectors in series fitted before the hot tank and (iii) solar collectors in series fitted after the hot tank. The most efficient option proved to be the second one with the average solar heating of 2.3 MW compared to option 1 with 1.0 MW.

It can be summarised that the direct steam production is a widely used solar thermal application for the various processes. The only disadvantage is the use of water as the HTF which evaporates at around 100 °C and changes its phase from liquid water to steam. Whereas, advanced HTFs such as thermal oil have higher boiling temperatures which keeps it as a liquid even at the highest temperature required by the dairy industry [37].

3.2. *Indirect steam production*

The indirect steam production method uses a heat transfer fluid (other than water) in the solar thermal collectors which powers a steam production equipment [38]. A closed tank with a heat exchanger, kettle reboiler or steam drum can be powered by the solar energy to produce steam, as presented at Fig. 4 [38]. conducted an experimental study on indirect steam production by using parabolic trough collectors with 10.8 m^2 solar concentrator area and used a thermal oil as HTF. The output of the system was reported to be 8 kg/h steam with the thermal energy efficiency between 24% and 28% [39]. simulated 2000 m^2 flat plate solar collectors with 100 m^3 storage to produce 17,000 MJ solar heat for the dairy processes [3]. theoretically studied photovoltaic-thermal hybrid solar system to maximize the solar thermal energy contribution to pasteurization process and solar electrical energy to pump. Their study reported that the system is highly effective to be used to the medium size dairy plants for milk processing at the production rate of 4000 l/day [40]. addressed the steam drum and kettle reboilers (evaporators) as the most common integration equipment for the indirect steam production in solar thermal applications. A two-state water/steam mixture was used to circulate the water through the external heat exchanger with the natural convection circulation system to convert the water into steam [41]. The kettle reboilers equipped with shell and tube have been used to circulate the solar heated HTF that uses solar heat to convert water into steam. The indirect steam production has been used widely for the process heating, particularly to the dairy industry. The advantage of this work is the use of thermal oil as an advanced HTF due to the thermal efficiency improvements.

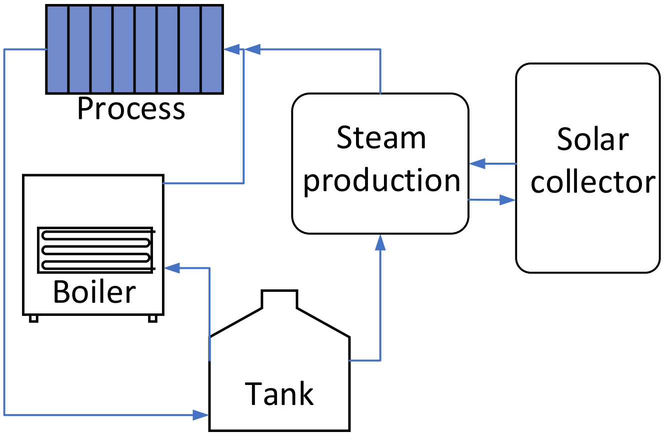

Fig. 4. Basic schematic of the indirect steam production using solar thermal collectors.

3.3. *Direct heating of the milk through a solar collector*

There is limited information available about using the solar collectors for heating milk. One of the rare studies published by Ref. [49] used an experimental setup equipped with a 1.2 m^2 flat plate solar collector to pasteurize 50 l/day milk to the temperature of 72 °C. The milk was circulating through the collector that was designed with 10 matt black painted horizontal tubes placed 10 cm apart from each other. Although, this technique seems technically practical, it may only be applied to the pasteurization processes because processes like separation, mixing and cooling require lower temperatures of 5 °C that may not be possible to achieve.

3.4. *Solar powered cooling*

Fig. 5 shows the most common solar powered cooling technologies used on the market. According to the literature, the absorption chillers are one of the most practical and widely used technologies for the solar thermal applications in the cooling industrial processes. They consist of condenser, generator, absorber, evaporator, pump and expansion valves with a great potential to be used for milk storage and cooling [50–52]. They are powered by a thermal energy sources such as solar heated fluid rather than electrical energy [52]) and use two fluids: the main refrigerant and absorbent. The absorbent absorbs the vapour of the main refrigerant to feed the pump that operate at the liquid phase which in turn minimises the work input [50]. [53,54]; reviewed an experimental study about the single and double effects of solar powered absorption chillers on the water/lithium bromide coolant and found that the both methods are suitable for industrial process cooling [55]. studied solar thermal application to four different case studies that used single-stage and two-stage absorption chillers for space cooling. The first case study used a 100 kW two-stage lithium bromide (LiBR) absorption chiller which was powered by modified flat plate solar collectors with a total area of 500 m^2. The collectors have the outlet temperature of around 75 °C that are used to feed the absorption chiller that refrigerates the water to 9 °C. The other cases used single-stage absorption chillers with the capacities of 100 kW, 200 kW and 360 kW that were powered by evacuated tube solar collectors with the total areas of 540 m^2, 812 m^2 and 655 m^2. This approach provided the collectors with the outlet temperatures of 88 °C, 90 °C and 88 °C that were used to feed the absorption chillers to provide cold water at 8 °C, 15 °C and 11 °C, respectively. Although those technologies have been used for the space cooling with the minimum temperature of 18 °C they may not be suitable for the dairy processes if their temperature requirements are lower. The parabolic trough solar thermal collector that uses ammonia/water

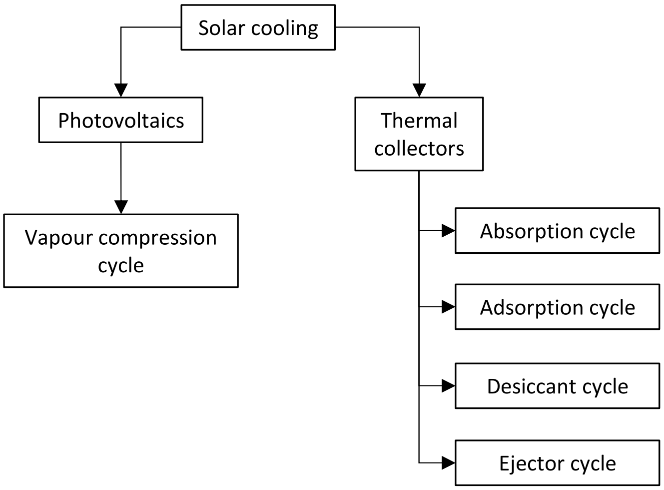

Fig. 5. Solar cooling systems for process cooling, adapted from Ref. [50].

mixture as the HTF to feed the air cooled absorption chiller proved to be more suitable to achieve 5 °C in the dairy processes [56]. The additional benefits include minimising the maintenance, avoiding legionella issues and preventing excessive water consumption. Although ammonia/water fed absorption chillers have been proven to be suitable for the dairy industry process cooling, there are limited information about the application of the solar thermal cooling in the dairy industry. One of the rare studies conducted a pinch analysis of the dairy industry based in Austria to investigate the integration of the solar thermal heat in the processes that require heating and cooling of minimum 624 kW and 95 kW capacity [17]. The investigation showed that a solar field with the area of 1500 m^2 could save 109,000 m^3 of natural gas, which resulted with 218 tons of CO_2 reduction. Other experimental studies used a 1.67 m^2 flat plate collector under the maximum solar irradiance of 1000 W/m^2 to heat water to between 40 °C and 70 °C that was used to circulate around the stainless-steel milk tank for pasteurization of 40 L milk [57] and parabolic trough collector to pasteurize 150 l/day milk at 75 °C while for cooling processes they recommended the use of flat plate solar thermal collector to power adsorption chiller for producing 57 kW/kg specific cooling power [58].

4. Case studies

This section reviews the existing solar thermal systems used in the dairy industry in Europe from 2011. The technical and economical details of the five different solar thermal systems applied in the dairy industry are summarised in Table 5 [60]. The latest solar thermal system (Case 1) was built in Italy in 2015 with the area of 995 m^2 at latitude of 39.68°N and was worth around 141 €/m^2. The Fresnel collectors have been used with steam as a HTF to produce 470 kW thermal power equivalent to 35% of the overall thermal energy demand. The Case study 2 is located in France at the latitude of 46.58°N and used 1500 m^2 flat plate collectors with water/glycol as HTF at 80 °C to produce 1050 kW thermal power. The case studies 3, 4 and 5 are located in Switzerland. The case study 3 has the latitude of 46.80°N and the highest investment cost of 700,000 €. The plant is equipped with 581 m^2 parabolic trough collectors that uses water as HTF to produce 330 kW thermal power that is used to reach 125 °C for milk heating. The case studies 4 and 5 have latitudes of 47.26°N and 46.55°N, respectively and also use the parabolic trough collector areas of 627 m^2 and 115 m^2 with water/glycol mixture and thermo-oil as HTFs to produce 360 kW and 67 kW thermal power, which corresponds to the solar fractions of 15% and 5%. Those studies addressed four technical challenges for the future solar thermal energy application such as large temperature fluctuation at the collector inlet, arrangements of solar thermal collectors, more control over the HTF flow rate and integration of solar thermal storage. The first challenge is associated with the inconsistency between the inlet and return temperature fluctuations of the processes. The large temperatures fluctuations of the returning condensate at the collector inlets affects the solar thermal system to provide constant outlet temperature for the processes [60]. The second technical challenge is reported to have 15 °C differences of the outlet temperature between the different arrays due to the parallel connection of the solar collector arrays. Tichelmann connection for the solar thermal collectors may provide more stable

Table 5
Details of some solar thermal applications for European dairy plants build after 2011(INTEC AEE, 2020).

Case study	1	2	3	4	5
Dairy plant name	Nuova Sarda I. Cas.	Bonilait Dairy	Cremo SA	Emmi Dairy Saignelegier	Lesa Dairy
Reference	Dr Paolo Fazzino	Wolfgang Glatzl	Stefan Minder	Stefan Minder	S. Minder, Mevina Feuerstein
Company of author	CSP-F Solar	AEE INTEC	NEP Solar AG	NEP Solar AG	NEP Solar AG, ewz
Country	Italy	France	Switzerland	Switzerland	Switzerland
Latitude/longitude (N/E)	39.68/8.65	46.58/0.34	46.80/7.12	47.26/7.01	46.55/9.89
Solar thermal system owner		EDF Optima; Solutions ESCO	Cremo SA	Emmi AG, Fromagerie Tete de Moine	Elektrizitatswerk der Stadt Zurich
Integration engineering company			Cremo SA	D. Jaquier Sarl	Weisskopf Partner GmbH
Operation start	2015	2014	2013	2012	2011
Collector technology	Fresnel	Flat plate	Parabolic trough	Parabolic trough	Parabolic trough
Collector name		Vitosol 200	PolyTrough 1800		PolyTrough 1200B
Installed collector area (m^2)	995	1500	581	627	115
Installed thermal power (kWth)	470	1050	330	360	67
Solar collector loop HTF	Steam	Water/glycol	Water	Water/glycol	Thermo-oil
Solar energy storage	No	Water storage	No	Water storage	No
Storage volume (m^3)		30		15	
Conventional heat source	Steam boiler	Hot water boiler	Hot water boiler	Hot water boiler	Steam boiler
Fuel	Fuel oil	Biomass	Fuel oil	Fuel oil	Fuel oil
Solar thermal energy use	Process heating	Cleaning processes	Dairy processes	Dairy processes	Milk Processing
Point of solar heat integration	Supply line	Heat storage	Supply line	Heat storage	Supply line
Temperature range process (°C)		80	a) 150 & b) 110 C		
Temperature range solar loop (°C)	200		a) 170 & b) 125	140–180	
Total investment costs (€)	140,000		700,000	300,000	252,000
Solar energy storage cost (€)				315,000	
Others (€)				156,000	
Process integration (€)				129,000	
Subsidy, € or % of total investment	260,000		25%	300,000	40%
Cost for fuel replaced (€/MWhfuel)	70			80 for fuel, cost of heat 100	
Solar thermal system life time (a)			20	20	15
Annual useful solar heat (MWh/a)	500			255	
Specific solar heat (MWh/am^2)	0.5			0.41	
Specific investment costs (€/m^2)	140.7		1204.82	478.47	2191.3
Solar fraction (%)	35			15	5

All costs given in the table exclude VAT.

outlet temperatures as a result of the steady thermal loss of each solar collector array [61]. The third technical challenge is associated with the lack of flexibility of the flow rate control over the solar collector loop that is needed to achieve desired outlet temperature [60,62]. For example, in the Case 4, the original design of the flow rate was between 6 m^3/h and 15 m^3/h but in order to meet the temperature requirement more efficiently it was amended to 6 m^3/h and 24 m^3/h [60]. An additional benefit was the use of the energy storage that allowed storing of any excessive energy production.

5. Solar thermal energy integration to the dairy processes

This section investigates the suitability of different solar thermal collectors considering the technical specifications, as reported in the literature, to be integrated to the dairy processes.

5.1. Solar thermal collector selection

Table 6 presents different solar thermal collector that have been used in the different industrial processes, as follows: flat plate, evacuated tube, compound parabolic, linear Fresnel, parabolic trough and parabolic dish collectors, suitable heat transfer fluids, axis tracking options and absorber types. They could produce different outlet temperatures that varies from 30 to 1500 °C. The flat plate collectors have the outlet temperature of 80 °C with the possibility to increase to 100 °C with modification of the solar collector [42,55]. Those types of collectors had been used in the dairy industry before 2010 due to their simple design and operation compared to concentrating panels [60,63]. However, their temperature was not sufficient for the processes like evaporation and spray drying that require 200 °C [11]. used evacuated tube collectors to produce steam at 200 °C that was used for milk powder production. The solar contribution for the 400 m^2 area of the solar collectors was 41%, which was estimated to reduce approximately 77 tons of CO_2 emission per year [11]. Although, those collectors have met the temperature requirement of the drying processes, the efficiency of the whole system could be improved with the use of concentrating solar thermal collectors like LFR and PTC that can operate at maximum outlet temperature of 300 °C–400 °C (Table 6). Another consideration is the type and boiling temperature of HTFs. The use of thermal oil, water/glycol mixture and molten salt proved to be more effective and energy efficient due to their ability to generate higher temperature in the solar systems and transfer more energy to the processes.

Table 6
Technical details of solar thermal collectors.

Collector type	Temperature range (°C)	HTF	Tracking	Absorber	Reference
Flat plate	30–80	W and A	No	Flat plate	[42]
Evacuated tube	50–200	W and A	No	Flat plate	[43]
Compound parabolic	60–240	W and A	No	Line focusing	[44]
Compound parabolic	60–300	W and A	1 axis	Line focusing	[44]
Linear Fresnel	60–250	W, A and TO	1 axis	Line focusing	[45]
Linear Fresnel	60–300	W, A and TO	1 axis	Line focusing	[46]
Parabolic trough	60–400	W, A and TO	1 axis	Line focusing	[47]
Parabolic dish	100–1500	W, A and TO	2 axes	Point focusing	[48]

HTF= Heat Transfer Fluid, W=Water, A = Air, TO = Thermal Oil.

According to the [60] the concentrating solar collectors replaced the flat plate collectors used in the dairy industry after 2011 (Table 5). The other solar thermal collector given in Table 6 is the parabolic dish collectors with the maximum collector outlet temperature of 1500 °C, which is beyond the temperature requirements for dairy processes that will increase the costs unreasonably. Therefore, the LFR and PTC are found to be the most suitable solar collectors for the dairy industry application due to their outlet temperatures and energy efficiencies. The materials and fluid that are used in the solar thermal energy system should be safe for the food safety and hygiene as the system is used for food production [12]. In this regard any toxic material or chemicals that can dissolve in the heat transfer fluid should be avoided including the solar system components located outside the plants to prevent any food safety risk.

5.2. An integration concept

The schematic of the recommended integration concept of the solar thermal system in dairy processes is illustrated in Fig. 6. It includes solar thermal collectors (1) and thermal energy storage (2) which are connected in series to produce and store the solar thermal energy that is transferred to the heating and cooling supply lines in parallel. The steam drum (3) and absorption chiller (4), connected in parallel, use the solar energy to feed the heating and cooling energy loops of the processes. The condensate tank (5) contains liquid water that is transported in parallel through the pumps to the steam drum (3) and boiler (6) for the steam production that is used for heating the processes. The boiler feeds the main header (6) which is the primary heating supply line to the processes, whereas solar energy powered steam drum (3) has connection to both low temperature heat exchanger (7) and header (8). The purpose of low temperature heat exchanger (7) is to maintain the stream at a higher temperature when supplied to different processes, which is vital for minimising the thermal capacitance (inertia) challenges. It has an ability to re-heat the water or steam from the pasteurization processes before is used for fermentation and coagulation processes. It also helps to maintain the operational efficiency of the heating system at a higher temperature and overcome the challenges at start up. Similarly, in the cooling side, the coolant is chilled in parallel using absorption (4) and conventional (10) chillers then circulated via pumps to the coolant tank (9). Fig. 7 presents the detailed schematic of the solar thermal integration to dairy processes line for production of the major dairy products including milk, cream, cheese, yogurt, whey, milky drinks and milk powder. The production line starts with the raw milk delivered to the storage tank (a) and transfers to the regeneration section (b) of the pasteurizer (m) where the waste heat of the pasteurized milk (e) is transferred to upstream milk. It is followed by the non-thermal processes of centrifugal separation (c) where the cream is removed and homogeniser (d) before the pasteurization of the milk (e and f) and cream (j and k) in two different pasteurisers (l and m). The pasteurized milk, if the temperature check is satisfactory, is stored in the pasteurized milk tank (g) then used for the production of dairy products such as yogurt (h and i), cheese (n), milk drinks (o), and milk powder (p). The final products are stored in the cold storage (s). The steam which is produced by the solar thermal powered steam drum is integrated to the production line from the units of pasteurization heating (e and j), fermentation (i), coagulation (n) and heat exchanger (r) for spray dryer. It should be noted that the solar produced steam can also be transpired for low temperature applications such as wash water and space heating in parallel to the process given in Fig. 6. The coolant which is cooled by the solar powered absorption chiller is integrated to the production line from raw milk storage tank (a), pasteurization cooling (f and k), pasteurized milk tank (g) and storage room (s). Similarly to the solar powered heating, it can also be utilised for the space cooling by circulating the coolant through heat exchangers. The recommended integration concept offers a number of advantages in terms of design and operation, as follows: (i) HTF selection, (ii) independent operation of

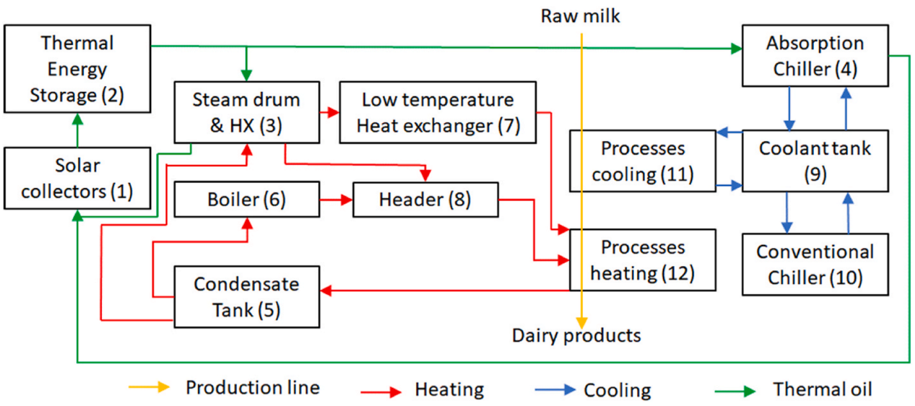

Fig. 6. Basic schematic designed for the integration of solar thermal technology to dairy processes. Red, blue, yellow and green lines represent heating, cooling, milk (production) and solar thermal loops, respectively.

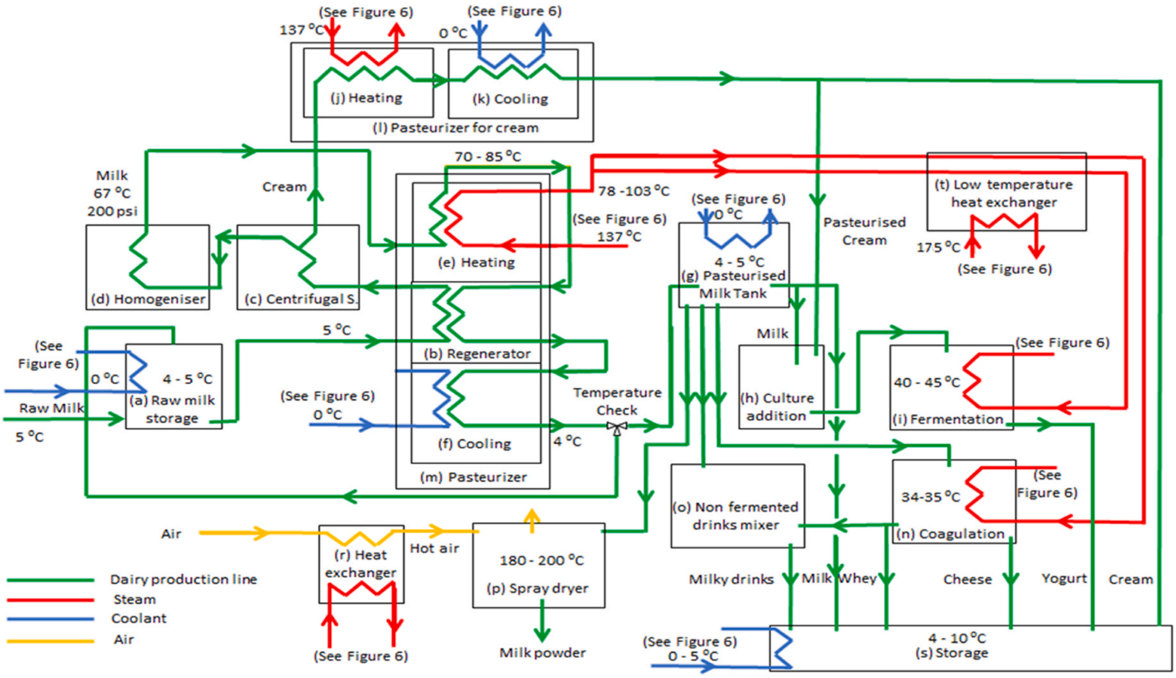

Fig. 7. Detailed schematic of the solar thermal energy integration to the dairy processes for the production of milk, cream, cheese, yogurt, whey, milk drinks and milk powder.

solar energy system, (iii) minimum interruption of the production process during the installation period, (iv) no modification or recertification requirement of any conventional boilers or chillers, and (v) minimum changes on piping network and flow control mechanism in a case of capacity upgrade of the solar or production systems. This approach gives flexibility in HTF selection of the solar loop because does not interfere with the heating and cooling loops. In addition, the steam drum (3) and absorption chiller (4) have separate outlets to the condensate tank (5) and coolant tank (7) which provide independent operation of the solar and conventional energy systems. Those energy systems could work independently in a case of any maintenance issue within the system or interruption of the production lines. Moreover, no modification to the conventional boiler is required which prevents the recertification or redesign of the pipe network and flow control units in a case of system capacity upgrades of the solar or process side. In other words, the potential upgrades on the solar energy system like addition of new solar collectors and/or process demand like increasing the production rate or adding a new product to the company inventory can be supported by the suggested integration concept which will save some labour effort, time and material purchase. Operation and maintenance (O & M) of the solar thermal energy systems are important to have maximum efficiency from the designed and built system. According to the [64] dust and soiling is an ongoing problem about the maintenance of the solar thermal systems especially for the regions where the natural cleaning by rain is not frequent. According to review conducted by Kassem et al. (2017), O&M cost of the LFR technology is lower than PTC technology due to the simpler design and reflector geometry. Moreover, the receivers that normally operate under high pressure are rotating together with the parabolic reflectors in the PTC systems as they are mounted together, whereas the linear reflectors are rotating independently from receivers as they are detached. Moreover, the flat geometry of the mirrors makes cleaning process easier with minimum water consumption with the robotic technology (Kassem et al., 2017).

5.3. Economic analysis

The economic aspect of a solar thermal integration system is quantified by Levelized Cost of Heat (LCOH) (Equation (1)) [65]. has defined the LCOH as the cost for a particular system which operates at a specific temperature to generate heat. Therefore, the size, design and operating conditions of a system is vital to calculate the LCOH.

$$LCOH = \frac{TIC\ x\ FCR + OC}{ATP} \tag{1}$$

where *TIC* is the Total Installed cost in $, *FCR* is the Fixed Charge Rate, *OC* is the annual operating cost in $, and *ATP* is the net thermal power generated in a year in MW_{th}.

The FCR given in Equation (2) is in the function of Project Financing Factor (PFF) and Capital Recovery Factor (CRF) [59].

$$FCR = PFF\ x\ CRF \tag{2}$$

The CRF can be calculated as given in Equation (3) [65].

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3}$$

where *i*, is the discount rate and *n*. Is the annuities received by the company. These important economic factors are likely to be different for each company, city, country and region.

This LCOH is typically calculated for theoretical case scenarios or experimental applications of solar thermal technology to industrial processes with the help of software applications such as System Advisory Model (SAM). As this review study covers the solar thermal energy integration as a concept for the dairy industry but not for a specific plant, the regional economic factors like *i*, *n* and *PFF* are taken as unity. This means, any economic help from the governmental authorities, charities, funders or any financial bodies is not considered in the analysis. The parameters provided by the [59] is used to conduct the LCOH analysis for a solar thermal application to industrial processes (Table 7).

Fig. 8 presents the LCOH for the PTC solar thermal integration for a 1 m^2, 1 kW_{th} energy storage system for the annual net solar thermal power range between 0 and 1000 MW_{th}. According to the analysis, the LCOH is around 60 $ per MW_{th} solar power for the dairy integration for the net annual solar thermal power of 400 MW_{th} and above. This value is higher than the LCOH range provided for concentrated solar thermal system by the [65] which was between 30 and 50 € per MW_{th}. The difference is attributed to the economic benefits like the discount rate and annuities which are ignored in this analysis.

6. Conclusion

In this study a number of peer-review papers have been critically evaluated considering the thermal requirements of dairy processes and different integration scenarios. Five case studies of commercial dairy plants dealing with the solar thermal energy integration were also considered. It was found that the pasteurization heating is the major process for producing dairy products with the maximum temperature requirement of 150 °C. The other processes like pasteurization cooling and fermentation require lower temperatures as 5–40 °C while spray drying higher temperatures above 180 °C. In terms of the solar thermal collectors, Parabolic trough and Fresnel reflector were found to be the most suitable for integration due to their higher temperature attainments of 200 °C and heat transfer as a result of using thermal oil as HTF. It is important that they are integrated through the energy supply lines of the processes that also include steam drums and absorption chillers to meet heating and cooling demands.

The reviewed studies highlighted four technical challenges of the solar thermal energy integration to the dairy processes, as follows: (i) difficulty to obtain constant collector outlet temperature due to the large temperature fluctuations of the returning condensate in a array (ii) the thermal loss in the solar collector arrays as a results of different pipe lengths, (iii) limited control over the solar loop flow rate and (iv) lack of solar thermal energy storage. These challenges could be addressed using a storage tank for the returning condensate, Tichelmann connection between the solar collector arrays, solar loop pump complying to the safety factor in the provided flow rate range and solar thermal energy storage. The key areas for further investigation include the use of phase change materials for building more energy efficient solar thermal storage, better solar thermal collectors like evacuated tube, LFR and PTC to provide high technoeconomic and environmental benefits and design a new solar system based on the thermal energy requirement of the particular case.

Table 7
The parameters and method used to conduct LCOH analysis, adapted from Ref. [59].

Parameter	Method
Direct cost	
Solar system	$150/m2
Site improvements	$25/m2
HTF system	$25/m2
Storage	$62/kWh-t
Contingency	0.07 x (solar system + site improvements + HTF system + storage)
Indirect cost	
Engineering, construction and ownership costs	0.1 x (Direct cost)
Total installed cost	Direct cost + Indirect cost
Lifetime	20 years
Annual maintenance cost	1% of total installed cost
Annual insurance cost	0.5% of total installed cost
Specific electricity cost	$0.06/kWh
Annual operating cost	Maintenance cost + Insurance cost + Electricity cost

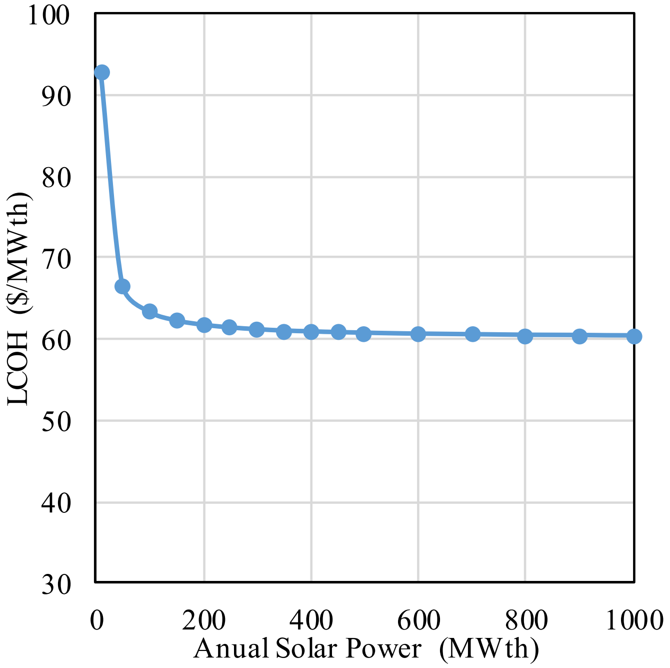

Fig. 8. Levelized cost of heat (LCOH) for a solar thermal energy integration to dairy processes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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