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Solar Energy Use for Energy Savings in Dairy Processing Plants

1. ABSTRACT

New Zealand is one of the world's largest producers of dairy products and has a climate with high levels of solar radiation; however, the use of solar energy in the dairy processing industry has received limited attention. An examination of historical records found that the annual peak in New Zealand milk production and processing occurs at a time when solar radiation levels are increasing markedly.

An F-Chart analysis was used to simulate the performance of large-area arrays of solar collectors and to determine their suitability for heating and cooling in a dairy processing environment. For the study four types of solar collectors were analysed: glazed flat plates, evacuated tubes, evacuated tubes with CPC reflectors and a building-integrated solar collector under development at the University of Waikato (UoW).

It was found that of these technologies, both flat plate and evacuated tubes with CPC reflectors could make useful heating and cooling contributions. Furthermore, the solar fraction was determined mainly by the collector area to storage volume ratio. Finally, it was found that the UoW building-integrated solar collector could make a significant contribution to energy use in dairies and may be an attractive future technology for the industry.

Key words: solar energy, dairy, heating, cooling, processing

2. NOMENCLATURE

ω_s	sunset hour angle
ϕ	latitude
δ	declination
β	collector inclination
ρ_g	ground reflectance
n	day of year
G_{sc}	solar constant
$\overline{H_o}$	monthly average daily extraterrestrial radiation
$\overline{H}$	monthly average daily radiation
$\overline{H_d}$	monthly average daily diffuse radiation
$\overline{H_b}$	monthly average daily beam radiation
$\overline{H_T}$	monthly average daily radiation on a tilted surface
$\overline{K_T}$	mean daily clearness index
$\overline{R_b}$	ratio of horizontal to tilted surface radiation
A_c	collector area
F_R	collector heat removal factor
U_L	collector heat loss coefficient
$\overline{T_a}$	monthly average temperature
Δt	seconds per month
$\overline{\tau\alpha}$	monthly average transmittance-absorptance product
L	heating load
N	number of days in month
T_{ref}	reference temperature
T_i	inlet temperature
T_a	ambient temperature
G	incident radiation
η	collector efficiency
f	solar fraction (% of heating or cooling load provided by solar energy)

3. INTRODUCTION

The New Zealand dairy industry produces over 14 billion litres of milk annually (LIC, 2006). As this is far in excess of local demand, the majority of it is processed for export markets. To process such large amounts of dairy products, it is necessary to supply a large amount of energy.

To illustrate this point, Lovell-Smith and Vickers (1983) found that the production of whole milk powder used in excess of 14 GJ/t. Similarly, Vickers and Shannon (1977) found that significant amounts of energy were used for generating hot water for cheese production and for cleaning in place (CIP) operations.

A number of technologies have been proposed for reducing energy use in the dairy processing industry, both in New Zealand and globally. Lovell-Smith and Vickers (1983) examined the feasibility of “in plant” cogeneration of heat and power (CHP) in spray drying plants. They found that such a system presented an economically viable solution to energy use.

The use of CHP was also investigated by Leal and Silveira (2002). They found that co-generation using molten-carbonate fuel cell technology was both economically and technically feasible for use in medium-size dairy plants.

Ozyurt et al (2004) explored the use of heat pumps in a pasteurisation system. Their system was based on a liquid-liquid vapour compression heat pump. Using a heat pump system they achieved an average coefficient of performance (COP) of 2.44 from their system. They also found that the heat pump could reduce their energy consumption by two-thirds compared to classical pasteurisation systems.

Although researchers have found ways of improving energy efficiency through different technologies, the disadvantage of the CHP, fuel cell and heat pump systems mentioned is that they all require fuel or electricity to operate. To overcome this shortcoming Benz et al (1998) and Benz et al (1999) examined the suitability of solar thermal processing heating systems for some German food processing plants.

The Benz et al studies found that evacuated flat plate and evacuated tube solar collectors were suited to heating applications in a milk spray drying factory. In their 1999 study they found that solar thermal systems could supply heating, over a 20 year period, at a cost of $100 US/MWh. Furthermore, they noted that in a favourable climate, heat costs could be halved and performance doubled.

In a recent study of energy use in the European dairy industry Ramirez et al (2006) noted that CIP accounts for approximately 70% of the energy use in evaporators and up to 26% of the energy used in dryers. They also note that these operations typically use temperatures in the range of 65°C to 75°C.

Similarly, Schnitzer et al (2007) found that in the Austrian dairy industry over 80% of the heating demand was for temperatures in the range from 60°C to 80°C, making solar energy use ideally suited to heating in dairy processing plants. Furthermore, they note that this temperature is suitable for operations such as washing water in cheese production, preheating of cheese milk, outside cleaning, pasteurisation, whey conditioning, and cleaning in place (CIP) operations. All of these operations are commonly used in the New Zealand dairy industry.

Given recent concerns over the environment and the supporting evidence for the use of solar energy, it was decided to perform an analysis of how solar energy could contribute to heating and cooling energy reductions in New Zealand’s dairy industry.

3.1. Solar Radiation in New Zealand

New Zealand presents an ideal environment for the utilisation of solar energy, especially when compared to some northern hemisphere locations. In New Zealand approximately 30% of all dairy farms, and a large number of dairy processing plants, are located in the Waikato and surrounding region, to the south of Auckland (LIC, 2006). As Benz et al (1999) noted that solar thermal energy systems for dairy plants could be improved in more favourable climates, a comparison was made between the solar radiation in the Waikato region (EECA, 2004) and that of Stuttgart, a typical German location (Duffie and Beckman, 2006).

In Figure 1 it can be seen that the daily mean global radiation levels in the Waikato are significantly higher than those in Stuttgart. Examination of the data corresponds well with EECA’s (2001) suggestion that solar radiation in New Zealand is approximately 30% higher than that encountered in Germany. Based on this finding, it is possible that the New Zealand dairy industry could produce thermal energy from solar resources more effectively than Benz et al were able to.

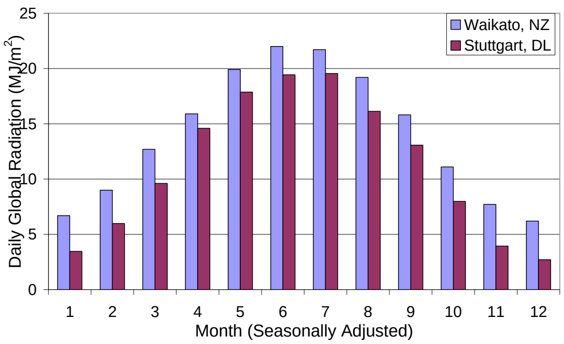

Figure 1: Mean daily global radiation for Waikato and Stuttgart.

In addition to providing heating, solar radiation aids in the production of feed for dairy herds. As such, with the onset of calving in early spring, and increasing levels of solar radiation, there is also an increase in milk production. Vickers and Shannon (1977) and Benseman (1986) showed that in New Zealand, this peak in production occurred in mid to late spring before gradually reducing over summer. In Figure 2 the trend in milk production is compared with the solar radiation levels for a June to May year. From this it can be seen that milk production levels and solar radiation exhibit a degree of correlation.

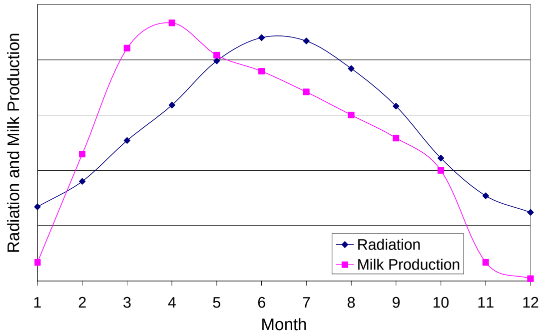

Figure 2: Qualitative relationship between milk production and solar radiation levels for a typical milk production season.

Given the relationship between milk production and solar radiation, combined with the energy used in the New Zealand dairy processing industry, there is obviously significant scope to utilise solar energy in the processing of dairy products.

4. INTEGRATION STRATEGIES

Perhaps the most common difficulty in using solar energy in a continuous operation is determining where and how to integrate it. The pinch method is commonly used to do this. The pinch method uses composite heating and cooling curves as a visual representation of heat and temperature demand in process industries. It shows the point (ie the “pinch”) above which it is necessary for heat to be added and below which cooling is required.

The pinch method was used by Schnitzer et al (2007) to show that in a typical cheese production line the “pinch” point occurred at approximately 20°C. This confirms that the use of solar energy is ideally suited to the dairy environment, as solar heating and cooling systems would be able to deliver energy both above and below this point.

In order to integrate this energy into the system it is possible to use both direct and indirect integration. In Figures 3 and 4 two means for the direct integration of solar heating are shown. The first of these shows the solar array effectively acting as a inline heat exchanger preheating the water, or heating fluid, returning from a process before entering the boiler or heat source. In the second the flow can be diverted so that, instead of using the boiler or heat source, the heat can be supplied by the solar array.

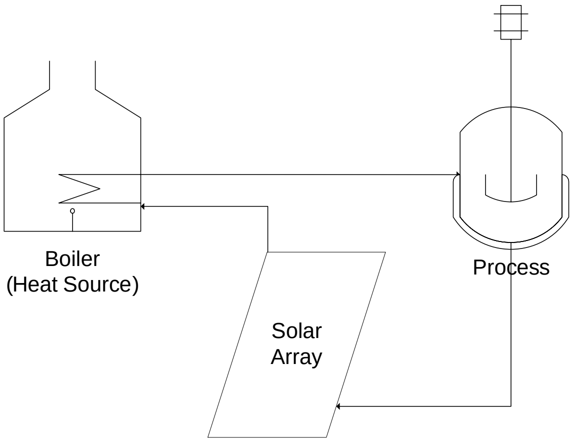

Figure 3: Direct integration of heat from a solar array.

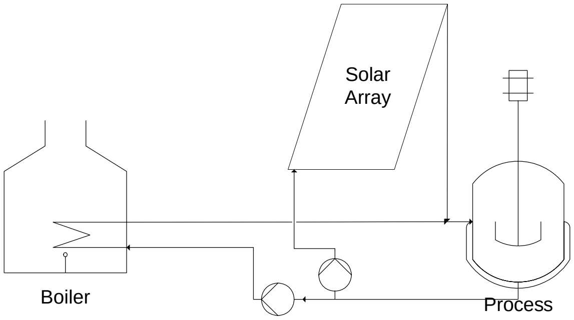

Figure 4: Direct integration of solar heat into a process.

There are a number of arguments for and against using a direct integration as shown in Figures 3 and 4. Typically the setup cost for these systems is relatively low; however, they do require continuous control and by their nature limit the size of the solar array to ensure that they do not provide energy at a higher temperature than is required by the process. Furthermore, these systems will only function during the day.

These shortcomings can be overcome by using an indirect, storage-based system as shown in Figure 5. By installing an intermediate storage tank, heat can be added to the tank by the solar array and used as required. The system does not need to be continuously controlled as with a direct system, and by adding a storage vessel it is possible for heat to be stored and used during periods of low or no solar radiation. The main drawback of an indirect system is that it tends to have a higher initial cost and also a longer payback time.

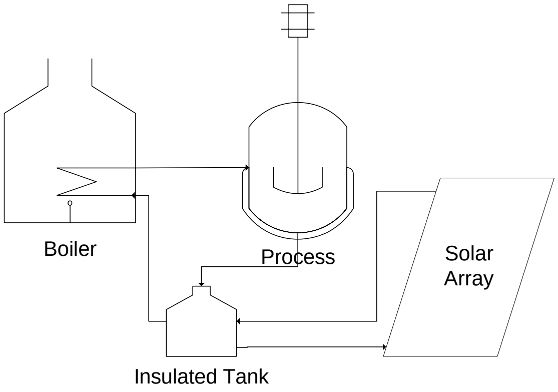

Figure 5: Indirect heat integration from a solar array utilising a storage system.

After examining the options for integrating solar energy into a processing operation, it appeared that using a storage-based solution offered the best solution given the continuous nature of New Zealand's dairy processing industry. This would allow solar energy to be utilised with minimal disturbance to existing systems. It would require little control, and be able to be used irrespective of prevailing solar conditions. A simulation study was conducted to determine the performance of large area arrays of solar collectors coupled with thermal storage tanks for use in the industry, using the Waikato region as a case study.

5. METHODOLOGY

In order to determine the applicability of solar energy for heating and cooling, it was decided that an F-Chart analysis would provide an adequate prediction of the heat that could be supplied by a solar heating system. Before the analysis of the heating system could be undertaken, however, it was necessary to determine some meteorological characteristics. NIWA (2007) provides basic data for the mean monthly air temperature and mean daily global radiation in Hamilton (Waikato) as shown in Table 1. In addition, the mean day for each month and declination on this day are also shown, as given by Duffie and Beckman (2006).

Month	Mean Day	Air Temp (°C)	Declination (degrees)	Global Radiation (MJ/m^2)
JAN	17	18.3	-20.9	21.7
FEB	47	18.7	-13.0	19.2
MAR	75	17.1	-2.4	15.8
APR	105	14.5	9.4	11.1
MAY	135	11.6	18.8	7.7
JUN	162	9.4	23.1	6.2
JUL	198	8.7	21.2	6.7
AUG	228	9.8	13.5	9.0
SEP	258	11.4	2.2	12.7
OCT	288	13.1	-9.6	15.9
NOV	318	15.0	-18.9	19.9
DEC	344	16.8	-23.0	22.0

Table 1: Hamilton meteorological data.

This data, however, cannot be directly applied in the F-chart analysis. Firstly, it is necessary to calculate the sunset hour angle for each day using Equation 1.

$$\cos \omega_s = -\tan \phi \tan \delta \qquad (1)$$

By knowing the sunset hour angle, it is possible to determine the integrated daily extraterrestrial radiation on a horizontal surface using Equation 2. The extraterrestrial radiation is the amount of radiation that would theoretically be received if there was no atmosphere.

$$\overline{H}_0 = \frac{24 \times 3600 G_{SC}}{\pi}\left(1 + 0.033\cos\frac{360n}{365}\right) \times \left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \quad (2)$$

Subsequently, by taking the ratio of the mean daily extraterrestrial radiation to the measured daily mean global radiation, we are able to determine the mean daily clearness index, as shown in Equation 3.

$$\overline{K}_T = \frac{\overline{H}}{\overline{H}_0} \quad (3)$$

The clearness index allows us to determine the fraction of diffuse radiation based on Collares-Perreira and Rabl's correlation, as given by Duffie and Beckman (2006), shown in Equation 4.

$$\frac{\overline{H_d}}{\overline{H}} = 0.775 + 0.00606(\omega_s - 90) - [0.505 + 0.00455(\omega_s - 90)]\cos(115\overline{K}_T - 103) \quad (4)$$

Assuming that the collectors are mounted at an angle to the horizontal it is necessary for us to calculate the average daily beam radiation on the tilted surface using Equation 5, for a site in the southern hemisphere.

$$\bar{R}_b = \frac{\cos(\phi+\beta)\cos\delta\sin\omega'_s + \left(\frac{\pi}{180}\right)\omega'_s\sin(\phi+\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + \left(\frac{\pi}{180}\right)\omega_s\sin\phi\sin\delta} \quad (5)$$

Where: $\omega'_s = \min\begin{bmatrix}\cos^{-1}(-\tan\phi\tan\delta) \\ \cos^{-1}(-\tan(\phi+\beta)\tan\delta)\end{bmatrix}$

Finally, it is possible to determine the monthly mean daily radiation on the tilted surface using the Isotropic Sky model developed by Liu and Jordan and as given by Equation 6.

$$\overline{H}_T = \overline{H}_b\overline{R}_b + \overline{H}_d\left(\frac{1+\cos\beta}{2}\right) + \overline{H}\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (6)$$

Having determined the radiation to which a tilted solar collector is exposed it is possible to determine the solar heating or cooling fraction that can be obtained from a solar energy system using the F-Chart method.

The F-Chart method is commonly used for the design of active solar heating systems and has been developed from a large number of simulations of solar heating systems (Duffie and Beckman, 2006).

For a typical liquid heating system, the solar fraction contributed by a system is given by Equation 7.

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3 \quad (7)$$

Where: $X = \frac{A_C F'_R U_L (T_{ref} - \overline{T}_a)\Delta t}{L}$

$$Y = \frac{A_C F'_R \overline{(\tau\alpha)}\overline{H}_T N}{L}$$

Based on this method it is possible to determine the heating contribution provided by a solar water heating system.

Similarly, solar energy can be utilised as the driving source for an absorption cooling system. However, this requires a number of modifications to the F-Chart model. The solar fraction from a cooling system is given by Equation 8, as derived by Joudi and Abdul-Ghafour (2003).

$$f = (0.0663798 - 0.134709X - 0.00133054X^2) + (0.624435 + 0.0187689X + 0.000195037X^2) + (0.03755762 + 0.00629182X + 0.00041X^2) \quad (8)$$

Where:

$$X = \frac{\overline{COP} A_C F'_R U_L (T_{ref} - \overline{T}_a)\Delta t}{L}$$

$$Y = \frac{\overline{COP} A_C F'_R \overline{(\tau\alpha)}\overline{H}_T N}{L}$$

(COP is the mean coefficient of performance of the absorption cooling system.)

By utilising the F-Chart method it is possible to determine the solar fraction that is provided for useful heating and cooling systems.

6. SOLAR HEATING AND COOLING SYSTEM

For the purposes of this study three solar heating systems were modelled. In the first scenario it was assumed that the solar heating system was coupled to a water tank with a volume of $10m^3$, in the second a tank of 25 m^3 and in the third a tank of 100 m^3. Additionally, it was assumed that the water in each of the tanks would be heated from 40°C to 80°C over the period of a day. This would make it suitable for the applications discussed by Schnitzer et al (2007) and be typical of the daily volumes of hot water used in small, medium and large dairy processing plants (CRES, 2008).

Based on the assumptions for the solar collector system, it would be necessary to produce and store 1668 MJ, 4170 MJ and 16680 MJ respectively. In each case it was assumed that the collectors were in a clear north facing location and mounted at an angle equal to the location's latitude, approximately 38 degrees for Hamilton.

As a general rule, solar water heating systems require between 50 and 100 L of storage volume per m^2 of collector area. For each tank volume, a collector array of approximately 50 L/m^2, 75 L/m^2 and 100 L/m^2 was modelled. Thus for this study, arrays of between 100 m^2 and 2000 m^2 were modelled, although larger arrays are obviously possible. For each scenario, calculations were based on the gross absorber area using efficiency equations from experimental testing by SPF (2007).

Furthermore, for each tank volume and collector area, four solar absorber types were modelled. The first was a glazed flat plate collector with an efficiency given by Equation 9:

$$\eta = 0.682 - 4.3\frac{(t_i - t_a)}{G} \tag{9}$$

The second was an evacuated tube with an efficiency given by Equation 10:

$$\eta = 0.374 - 1.37\frac{(t_i - t_a)}{G} \tag{10}$$

The third was an evacuated tube solar collector with a CPC back reflector with efficiency given by Equation 11:

$$\eta = 0.545 - 1.05\frac{(t_i - t_a)}{G} \tag{11}$$

The final collector analysed was a low cost building-integrated solar collector under development at the UoW. This collector is essentially a glazed flat plate collector; however, unlike the collectors mentioned above it would be able to act as the façade or roof structure of dairy processing plants while having almost no visual impact.

Although not in mass production, the collector has been designed to have an efficiency given by Equation 12.

$$\eta = 0.718 - 5.54\frac{(t_i - t_a)}{G} \tag{12}$$

Using the collector data in the F-Chart allowed the fraction of the heating load provided by the solar collectors for each tank volume and collector type to be determined.

For the solar cooling system, the collector efficiency equations remained unchanged, although it was assumed that the cooling load would be 1668 MJ, equivalent to cooling a 25 m^3 storage tank from 20°C to 4°C. However, because solar cooling systems tend to be less efficient than heating systems, two arrays, equivalent to a 25 L/m^2 and 50 L/m^2 storage system, were modelled. In both cases it was assumed that the COP of the cooling system was 0.4, typical of an absorption cooling system.

7. RESULTS

From the analysis it was found that the solar fraction provided by the solar heating and cooling system was determined solely by the array area to tank volume ratio. As would be expected, the greatest solar fraction is achieved at a ratio of 50 L/m^2 for all tank volumes for the heating systems. For the cooling system, the larger collector system, equivalent to a 25 L/m^2 storage system, offered the best cooling performance.

For the solar heating system, an interesting finding was that at low area to volume ratios, evacuated tubes with a back reflector performed marginally better than the flat plate collectors and the UoW building integrated system. However, at increasing ratios the flat plate collectors and the UoW building-integrated system began to perform better. Additionally, it was found that the evacuated tubes without a back reflector tended to perform approximately 25% less efficiently than both the flat plate and reflector style collectors. This phenomenon is clearly illustrated in Figures 6–8.

The reason for the variation between the four types of collectors can be explained by understanding the properties of the collectors in the study. Firstly, the reason that evacuated tube collectors, without reflectors, perform poorly relative to the other collectors is that their optical efficiency is poor based on their gross area.

Essentially, although the collectors may take up a certain area, the large spacing between the tubes means that a large portion of the radiation incident on that area is not absorbed during the period of the day when solar radiation is at its maximum. This shortcoming is therefore overcome by the addition of the reflector which allows a larger portion of the radiation to be captured.

More interesting, however, is the fact that the UoW building-integrated system and the flat plate collectors perform better at the higher area to volume ratios. This can be explained again by the optical efficiency of flat plate and evacuated tube solar collectors. In Equations 9, 10 and 11 it can be seen that the first term in the efficiency equation, the optical efficiency, is higher for the building integrated and glazed flat plate than the evacuated tubes. However, the second term, the heat loss coefficient, is lower in evacuated tubes than in the other two systems.

As the area to volume ratio increases, the solar fraction decreases, meaning that heating is occurring at lower temperatures. This is favourable for flat plates because at lower heating temperatures their efficiency is higher relative to their heat loss. Conversely, evacuated tubes perform better at the lower area to volume ratios because despite having a lower optical efficiency, they are less sensitive to heat loss.

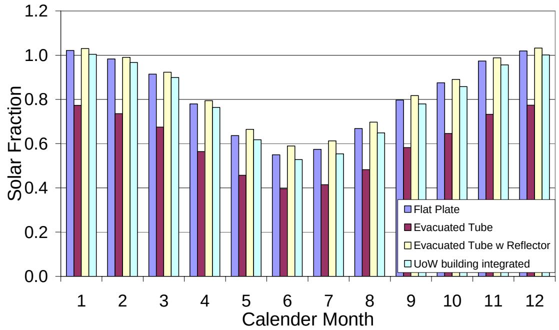

Figure 6: Solar fraction for 50 L/m².

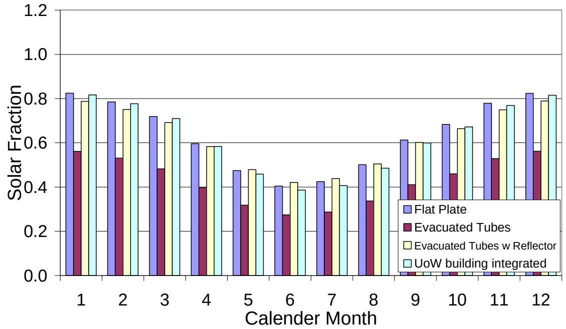

Figure 7: Solar fraction for 75 L/m².

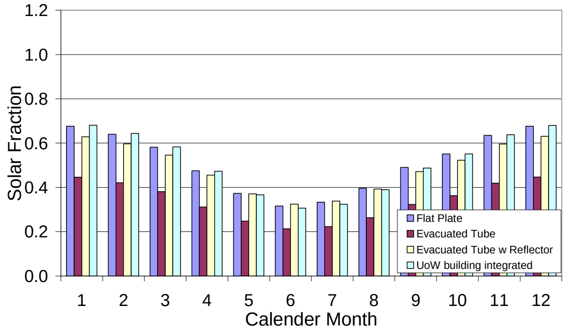

Figure 8: Solar fraction for 100 L/m².

From this it can be seen that both flat plate and evacuated tubes with reflectors offer the best performance of the three solar heating systems.

However, in a typical industrial setting, higher area to volume ratios would typically be used. This would, on a purely performance basis, tend to favour the use of flat plate style collectors as they perform better under these conditions.
As with the solar heating systems, it was found that the evacuated tubes with a back reflector offered a good solar fraction for the two cooling systems. However, the ability to use solar energy for cooling was less effective than for heating. This is because it must be transferred via an absorption cooling system. As was shown, the solar fraction was thus reliant on the COP of this system.

The influence of the COP of the absorption system is clearly illustrated in Figures 9 and 10. In Figure 9 we can see that the system contributes approximately 20% of the cooling load. However, it can be seen that by doubling the collector area that the solar fraction is improved dramatically.

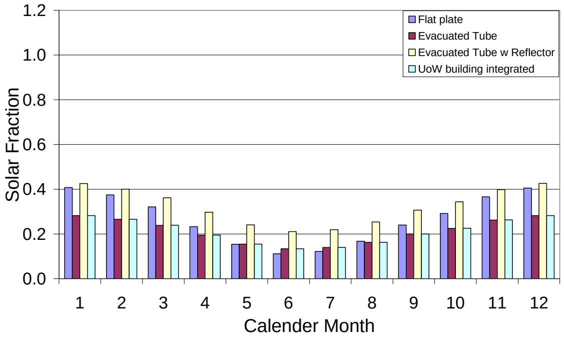

Figure 9: Solar fraction for solar cooling system equivalent to 50 L/m².

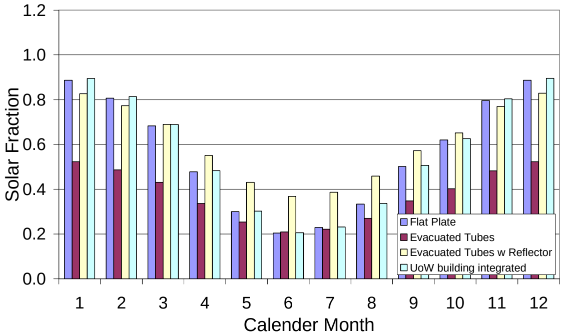

Figure 10: Solar fraction for solar cooling system equivalent to 25 L/m².

From observing the performance of the solar heating and cooling systems it is apparent that both flat plate style collectors and evacuated tubes with back reflectors offer the potential for useful heating and cooling. The use of evacuated tubes without back reflectors, although feasible, would require larger areas for equivalent loads.

8. POSSIBLE ENERGY SAVINGS IN A LARGE DAIRY PROCESSING PLANT

To further highlight the advantages of using a solar heating system, it was decided to examine the magnitude of the energy produced by the four collector arrays in a large processing environment.

In a typical large dairy factory the hot water consumption is approximately 120–150 m³ per day, with cleaning operations occurring at up to 80°C (CRES, 2008. It was decided to model the ability of an array of 2000 m² coupled to a tank with a volume of 100 m³ to provide a load of 16680 MJ, or 100 m³ of 80°C-water per day. This water would be suitable for cleaning operations at the end of a day's production, as suggested by Worley Consultants Ltd (1983).

In Figure 11 it can be seen that during the summer months, most of the solar heating systems are able to meet the heating load. However, for early spring and autumn, it may be necessary to rely on auxiliary heat from a supplementary boiler.

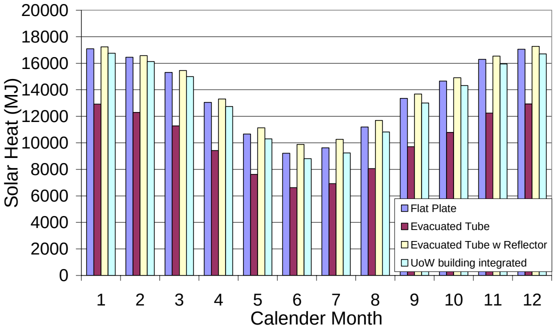

Figure 11: Possible solar heat production for a large dairy processing plant (2000 m² array and 100 m³ store).

As an alternative to a supplementary heat source, it may be possible to increase the size of the solar array. However, it should be considered that for this example the heating load has been assumed to be constant over the year. Given the seasonal nature of the dairy industry, it is likely that this load would vary with production levels and so the array may meet the demand outside the conditions used here.

9. DISCUSSION AND CONCLUSIONS

Examining meteorological data and historical production trends showed that solar energy offered the opportunity to provide a useful amount of heating or cooling in dairy processing plants.

The results presented show that flat plate and evacuated tube with back reflector style collectors offered the best performance in heating and cooling systems. As noted, evacuated tubes without reflectors do not capture enough of the incident radiation falling on their gross area to compete with the alternative technologies.

Furthermore, it was shown that the UoW building-integrated system appears to be able to compete well with the established technologies. Given its ability to integrate directly into the building, it is possible that this may be an attractive future technology for the dairy industry.

Based on these findings it is possible that large scale solar energy plants could make significant contributions to both heating and cooling loads in the New Zealand dairy processing industry.

10. AUTHORS' AFFILIATIONS

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