

Design of a low cost data acquisition system to monitor the performance of an on-farm bulk milk cooler

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Abstract: This study focuses on the design, construction, and testing of a data acquisition system (DAS) to monitor the performance of an on-farm DXBMC as a tool to aid decision making for dairy farmers. Various sensors formed the design of the low cost data acquisition system (DAS) and these comprised of relative humidity and ambient temperature sensor, temperature sensors and a power meter. The study was carried out on an existing dairy farm with an average of 800 cows in milking during peak milking period. Temperature sensors monitored the temperature of the milk delivered to the direct expansion bulk milk cooler (DXBMC) as well as the temperature of the room, the power meter was used to measure the electrical energy consumed by the DXBMC during the cooling process. Findings from the study revealed that the peak season recorded the highest average total energy of 6 898.52 kWh as whereas the off-peak season recorded an average total of 3 771.28 kWh. The annual energy consumption due to milk cooling and storage was 64 336.22 kWh. The energy consumption during cooling of milk was 92.57% with the remaining 7.43% consumed during the storage of milk to maintain it at the set point temperature. During that period the average COP was 2.28 and 1.99 for the AM and PM milking times. On average, the DXBMC cooled 57.33 L kWh⁻¹ during the off-peak period and increased by 7.7% to 62.13 L kWh⁻¹ during the peak. The low-cost DAS is simple to use on any dairy farm to provide insight into the operation of the milk cooling system. This allows measures to be taken to enhance performance and save energy where possible.

Key words: Data acquisition System, direct expansion, bulk milk cooler, coefficient of performance (COP)

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1 Introduction

The temperature of milk delivered to the bulk milk cooler (BMC) and the final temperature attained by the milk in the BMC after milking is of critical importance to the performance of the cooling system. Also, the temperature gradient between the initial and the final milk temperature determines the energy consumed by the BMC (Mhundwa et al., 2018). Raw milk must be cooled rapidly to a temperature of 4°C immediately after milking for the safety of the

consumers and also to stop pathogen development (Hasting, 1992), safe storage of milk and prevent the growth of psychotropic bacteria which can grow between 4°C and 7°C (Holm et al., 2004; Upton et al., 2010; Murphy et al., 2013). The BMC is the principal component in dairy farm or facility that is used to cool the milk and also used for storage of milk at the set point temperature of 4°C. There are two types of BMCs used in milk cooling namely the direct expansion and the ice bank (Meul et al., 2007; O’Keeffe, 2007). Both the two systems work with a vapour compression refrigeration cycle (vcrc). The compressor is the most single component that consumes electrical energy during the cooling of milk together with the condenser fan and the agitator. Most

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dairy farms in developing countries have their milk collected for processing every day or every two days by refrigerated trucks that is for the peak and off-peak respectively.

In a typical processing plant, milk undergoes a series of processing activities before it can be rendered safe for human consumption. These entail handling of raw milk (RM), clarification, homogenisation, pasteurisation and chilling (Modi and Prajapat, 2014). At each of these stages, there is a considerable amount of energy that is required. The focus of this study was on RM handling at a dairy farm before the milk can be processed into different dairy products. Specifically on a dairy farm, handling of RM mainly starts as milk leaves the cow udder at 35°C–37°C and must be cooled rapidly to a storage temperature of 4°C in order to stop microbial activity (Lewis and Heppell, 2000; Holm et al., 2004; Upton et al., 2010). The cooling of the RM can be done directly by the BMC from 37°C to the required storage temperature of 4°C or it can be done successively through pre-cooling (Saravacos and Kostaropoulos, 2002). The process of pre-cooling involves the use of a heat exchanger where in most cases, the plate heat exchanger (PHE) is used thereby leading to energy savings in a dairy facility (Morison et al., 2007; Upton et al., 2010; Mhundwa et al., 2016). Subsequently, the milk is stored in the BMC and in most dairy farms storage usually takes one to two days before it can be collected by refrigerated tankers, which serve to maintain the milk at 4°C. BMCs are available in different sizes which can range from 100 L to over 25 000 L (Fabdec Cooling Systems, 2012). Typically, the BMC can be horizontal cylindrical, vertical cylindrical, semi-cylindrical or elliptical. According to South African National Standards (SANS) 708:2008, there are two types of BMCs currently in use that is Type A and Type B. Explicitly, the Type A is a tank that represents refrigerated tank that keeps milk cool through the use of a chilled water system and Type B being the direct expansion system. Furthermore, these types of tanks can either be of the following classes;

Class AD or Class ED. Class AD represents a BMC that is emptied on alternate days or less recurrently and is designed to cool one quarter of its capacity twice in every 24 hours (SANS 708:2007). On the other hand, Class ED describes a BMC that is emptied every day and is designed to cool half of its capacity twice in every 24 hours (SANS 708:2007).

The evaporator on the underside of the BMC is responsible for the rapid cooling of milk from the delivery temperature of 35°C–37°C to a safe storage temperature of 4°C (Ghewade et al., 2007). In order to maintain the temperature, the BMC has two casings which are separated by insulation to prevent its interior from interacting with the surrounding ambient conditions (Pressman, 2010). For an even distribution of the temperature within the milk being cooled and to facilitate thermal exchange between the bulk milk, the BMC makes use of an agitator. The agitator continuously stirs the milk for the whole milking duration and operates at intervals during the storage of milk.

It is worthy to mention that the research on energy auditing of dairy farms has been done and can be found in the literature. Researchers have conducted studies on both direct and indirect energy consumption on a dairy farm as reported by (Meul et al., 2007) Some work has been conducted considering only the direct consumption of electricity and thermal energy for the day to day operations of a dairy farm. Most of the work focused on identifying the energy users and determining their impact regarding overall energy consumption on the farm. Findings revealed that on a dairy farm, the largest energy consumer is milk cooling followed by water heating, vacuum pump operation while other equipment seems to have a secondary impact on energy consumption (O’Keeffe, 2007). The performance of a DXBMC is influenced by ambient the temperature of the incoming milk, ambient temperatures as well as the refrigerant properties.

Energy audit research in the farms is evident in literature. Most of the studies focused on energy consumption and energy efficiency of cattle breeding

systems as direct and indirect energy (Meul et al., 2007; Upton et al., 2014). In addition, some studies have focused on the direct consumption of electricity and thermal energy by identifying the energy users and their impact on the dairy farm's energy consumption. These studies have revealed that the highest consumer of electrical energy is the cooling process (43%) followed by sanitary hot water production (27%) (Rasmussen and Pedersen, 2004). However, similar studies have established the electrical consumption of the milk tank, water heaters and the vacuum pump.

According to Peebles et al. (1994), the electrical consumption of the milk tank accounts for an estimated 18% of the farm's energy consumption which was determined to be 1.76–2.24 kWh/100 kg of milk produced on the farm. Other studies identified that on an annual basis milk cooling is the most energy consuming farm operation with 96.7 kWh/cow/annum which is about 21%–24% of energy consumption of the farm (Murgia et al., 2008). Proposal have been made that energy consumption per head (kWh/head) or per unit volume of milk produced (kWh L⁻¹) should be expressed on daily and yearly basis as the Energy Utilisation Index (EUI) (Edens et al., 2003; Ludington and Johnson, 2003).

Studies conducted in the United States showed that EUI had an average of 0.8 and 1.2kWh/100 L of milk cooled directly from milking to 7°C and with the use of the PC the EUI decreased to 0.6–0.9 kWh/100 L (Southern California Edison, 2004). This suggests that for milk to be cooled to 4°C, the EUI will be higher like in the European and Italian Standards as well as for South Africa. Major electrical energy-consuming processes in dairy farms have been studied, ranging from milking, milk cooling and water heating (Upton et al., 2015; Rajaniemi et al., 2017). These studies have identified milking and milk cooling to be the largest electricity users. It is worthy of mentioning that there is significant studies regarding electricity usage on dairy farms (Upton et al., 2010; Kraatz, 2012; Upton et al., 2014; Upton et al., 2015; Rajaniemi et al., 2017; Shine et al., 2018;

Shine et al., 2019; Shine et al., 2020; Breen et al., 2020).

Most of these studies were hinged upon rigorous data collection mechanisms with expensive metering devices and sensor systems which can be beyond the affordability. Thus simplified low-cost data acquisition equipment will be useful for such farmers to monitor the performance of their dairy equipment in a bid to promote better management of electricity usage in the facility. Also, sub-metering of different dairy farm equipment makes it possible to gather finer data for energy efficiency evaluation of specific equipment regarding the total energy consumption on the farm. This will provide farmers with opportunities to implement strategies for efficient operation of the equipment and energy-saving potential. Furthermore, specific equipment monitoring will also allow for optimisation and scheduling repair and maintenance based on the data gathered and performance metrics deduced. Without loss of generality, there is limited research and published data on the energy utilisation during milk cooling and how they can be predicted at dairy farms in South Africa. Furthermore, there is paucity of information on the performance of the cooling systems at dairy farms in South Africa. Although, the performance of DXBMCs has been extensively studied; however, there is no real defined simplified low cost DAS with minimum sensors and metering that can be used as a decision making tool by dairy farmers on their energy management practices. It is against this background this study seeks to design and construct a low cost data acquisition system (DAS) to monitor the performance of an on-farm direct expansion milk cooler (DXBMC), the data gathered from the DAS will be used to determine the electrical energy consumed and thermal energy extracted from the milk using the experimental data as well as determine the average daily demand and COP of the DXBMC as a tool to predict its performance during the AM and PM milking.

2 Materials and methods

The experiment was conducted on an existing dairy farm in the Eastern Cape Province of South Africa. The farm uses a DXBMC to cool the milk as well as for storage before the milk can be collected. The farm has an average of 800 cows in milking, and they are milked twice a day for every day of the week. The two different milking times are for the morning (AM from 05:00 – 07:00) and the late afternoon (PM from 15:00 – 17:00).

2.1 Description of the milk cooling system

The farm operates a 21 m³ DXBMC as the milk cooling and storage system. The DXBMC uses four air-cooled condensing units and compressors, which all feed into one evaporator that forms the underside of the DXBMC. The DXBMC was housed in a room adjacent to the milking parlour and is equipped with a horizontal agitator for even distribution of milk temperature during the cooling process. The farm operates on a direct milking to the refrigeration

system, where milk is delivered directly to the DXBMC for cooling without passing through any pre-cooling system. The DXBMC is responsible for cooling the milk rapidly to the setpoint temperature and storing the milk at the setpoint temperature until the milk is collected for processing. During the process of rapid cooling and maintaining milk temperature, the DXBMC uses some electrical energy. The energy consumed by the DXBMC depends on the initial milk temperature delivered for cooling, the volume of milk and ambient conditions. These parameters can be used to deduce the performance of the cooling system at any given time. The selection of temperature measuring sensors was made using the Analytic Hierarchy Process as outlined by Al-Hawari et al. (2011). The quantity of the measuring equipment used for this study are listed in Table 1, and Table 2 illustrates the specification for the DAS equipment.

Table 1 Quantity of sensors, loggers and meter





Description	Quantity
HOBO Pro V2 Ambient temperature and relative humidity sensor	1
Landis and Gyr E650 ZMD405CT44.2407 S3 power and energy meter	1
TMC6-HE temperature sensor	2
HOBO UX120-006M 4-channel analog data logger	1

2.2 Data collection

The factors that affect the operation of a DXBMC were used in this study. The study assumes that the system's installation was professionally done; hence only energy consumption, environmental conditions, milk volume and temperature were collected as the data that affect the performance of the DXBMC. The temperature of milk (T_{milk}) delivered to the DXBMC and the DXBMC's room temperature (T_r) was measured using TMC6-HE temperature sensors, these sensors were connected to a Hobo UX120-006M four-channel analog data logger configured to log at 1-minute intervals. Relative humidity (RH) and ambient temperature (T_{amb}) were measured using the Hobo Pro V2 sensor configured to log at 1-minute intervals and was installed at the dairy farm.

Measured data for the temperatures and RH were extracted using the Hobo Pro Software. The power and energy consumption of the DXBMC measured with a Landis and Gyr power meter was extracted using the MAP software. The volume of milk per each milking session was extracted from the on the farm records. This data was extracted from the respective software as excel files imported to MATLAB for further analysis and aggregation to 30-minute intervals. Figure 1 and Figure 2 illustrate the DAS architecture and the schematic layout of the experimental setup, respectively. The system in operation at the farm is a direct milking to refrigeration whereby raw milk is sent directly to the DXBMC without any pre-cooling taking place.

Table 2 Specification for the DAS equipment

Measurement	Description of measuring device
Ambient temperature and relative humidity	<p>The HOBO Pro V2 data logger is a weatherproof logger that provided high accuracy ambient temperature and relative humidity measurements for a broad range of outdoor measurements. Furthermore, for internal temperature, the logger exhibited a measurement range of -40°C to 70°C. For measurements of RH, the logger recorded measurements that ranged from 0% to 100% at -40°C to 70°C with $\pm 2.5\%$ accuracy from 10% to 90% (Onset Computer Corporation, 2016).</p> 
Power and energy	<p>A Landis and Gyr E650 ZMD405CT44.2407 S3 power and energy meter is an advanced digital power and energy meter of Class 0.5S and measures at 99% accuracy. The meter recorded the following parameters; voltage, current, active power, reactive power, apparent power, power factor and energy. Rish Xmer – 50/30(30) Class 1 current transducers (CT) with a CT ratio of 100/5 A, 2.5 VA and I.L of 0.72/3 kV were used with the meter, Also, the meter was equipped with a built-in logging system of standard memory capacity 4 MB (Landis and Gyr, 2012).</p> 
Room and milk temperature	<p>The Onset Computer TMC6-HE temperature sensor had a measurement range of -40°C to 100°C in air and -40°C to 50°C in water (Onset Computer Corporation, 2016). The temperature sensor was housed with a copper-plated sensor tip which had a response time of two-minutes in air provided there was free air circulation. The accuracy of the sensor was dependent on the logger to which it was attached that is with the UX120-006M, the sensor accuracy was $\pm 0.15^\circ\text{C}$.</p> 
Logger	<p>The HOBO UX120-006M 4-channel analog data logger was used to store the recorded temperatures. The logger recorded and stored data of 1.9 million measurements within its 4 032 KB memory for future use. The 16-bit resolution analog logger is a high-performance logger with an LCD, which ensured sensor operation as well as visualisation the data recorded. The HOBO UX120-006M data logger was powered by two 1.5 V AAA batteries and it had the capability to log temperature, current, differential and gauge pressure amongst other parameters. (Onset Computer Corporation, 2016).</p> 

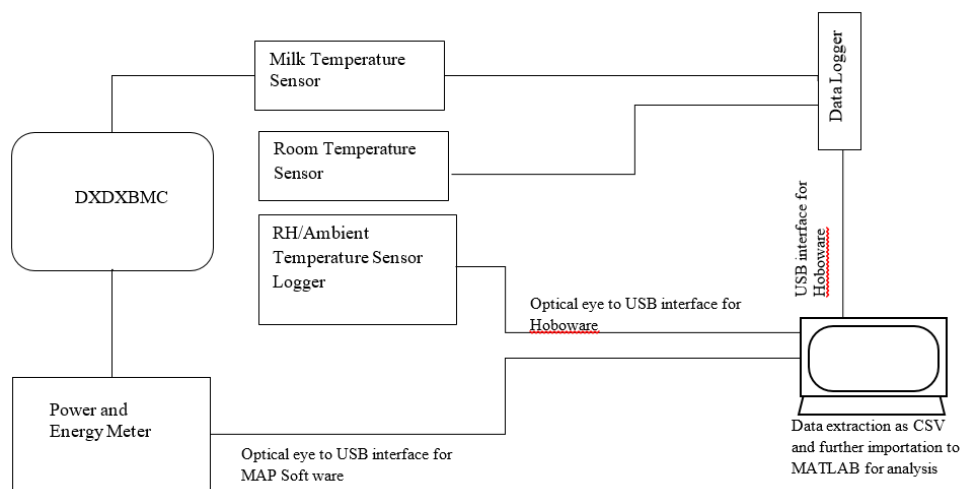
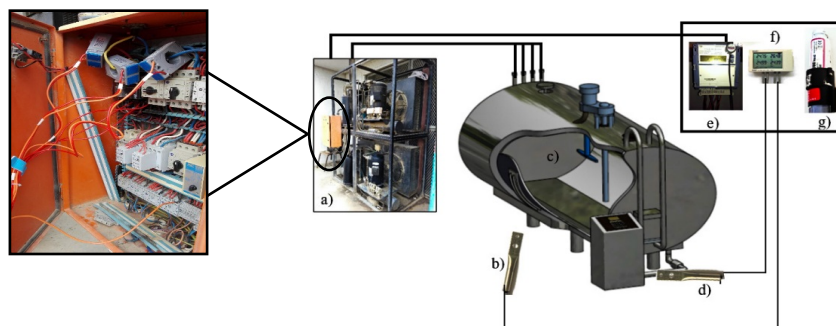


Figure 1 Architecture of the DAS



(a) condensing unit and DB (b) temperature sensors for the DXBMC room (c) DXBMC (d) temperature sensor for milk inlet (e) power meter (f) data logger (g) RH and ambient temperature sensor.

Figure 2 Schematic layout of the experiment illustrating how the sensors and meters were connected

2.3 Calculations and theory

Energy balance was used to calculate the COP of the DXBMC as follows

$$Q_t = Q_m + Q_c \tag{1}$$

Where,

Q_t = the total thermal energy extracted from the DXBMC by the refrigeration unit (kWh);

Q_m = the energy extracted from the milk (kWh);

Q_c = the heat transfer from the ambient air to the walls of the tank (kWh).

The following equation was used to calculate Q_m

$$Q_m = \sum_{t=0}^t \frac{c_p m (\Delta T)}{3600} \tag{2}$$

Where,

C_p = specific heat capacity of raw milk, 3.93 kJ kg⁻¹ K⁻¹ (Modi and Prajapati, 2014);

ΔT =temperature difference of Initial temperature of milk and the final temperature of the milk (°C) [Tin (Inlet temperature of the milk to the DXBMC) - Tset (Set temperature for storage of milk)];

The 3600 on the equation is a constant that is used to convert kJ to kWh;

m = mass of raw(kg) milk in the DXBMC and was calculated as

$$m = V_m \rho m_r \tag{3}$$

The cooling load of the DXBMC was calculated using Equation 1

$$Q = \frac{m C_p (\Delta T)}{3600} \tag{4}$$

Where,

Q = cooling load (kWh);

m = mass of raw milk in the DXBMC (kg);

C_p = Specific heat capacity of raw milk, 3.93 kJ kg⁻¹ K⁻¹ (Modi and Prajapati, 2014);

ΔT =temperature difference of Initial temperature of milk and the final temperature of the milk (°C) [Tin (Inlet temperature of the milk to the DXBMC) - Tset (Set temperature for storage of milk)].

The coefficient of performance was derived from the following equation

$$COP = \frac{Q}{E} \tag{5}$$

Where,

COP = coefficient of performance;

E = energy consumption (kWh).

The electrical energy efficiency evaluation for milk cooling was determined by specific electrical energy consumption and electrical energy productivity. Specific electrical energy consumption is the amount of electricity used by the system to cool a unit of milk to the required set temperature of 4°C, while electrical energy productivity is the amount of milk that can be cooled using a unit of electricity. These were calculated using the following equations

$$SEEC = \frac{E}{L} \tag{6}$$

Where,

$SEEC$ = specific electrical energy consumption (kWh L⁻¹);

L = quantity of milk cooled (L)

$$EEP = \frac{L}{E} \tag{7}$$

Where,

EEP = electric energy productivity (L kWh⁻¹)

2.4 Measurement boundary

The study focuses on the milk cooking and storage only, the boundary of measurement was the BMC and its condensing unit, auxiliary equipment like the milk pump do not form part of the results discussed in this study.

2.5 Data analysis

Average daily profiles for the AM and PM milking were compiled for the period April 2016 – March 2017. Analysis of variance (ANOVA) was used to categorise the variability and consistency of the parameters that affect the performance of the DXBMC. The ANOVA tests were conducted on all the AM and PM milking variables to test for significant differences between data sets on the performance of the DXBMC. Pearson’s correlation analyses were performed to test for significance and the strength of the correlation between the variables, with a p-value of 0.05 or lower signifying significance. The Bonferroni method was used for multiple comparisons tests between the AM and PM milking data.

3 Results and discussion

The study was conducted on an existing dairy farm in the Eastern Cape Province of South Africa. The farm uses a DXBMC to cool the milk as well as for storage before the milk can be collected. The farm has an average of 800 cows in milking, and they are milked twice a day for every day of the week. The two different milking times are for the morning (AM) from 05:00 – 07:00 and the late afternoon PM from 15:00 – 17:00. The monitoring was conducted for a

typical year during the period April 2016 to March 2017. Parameters that affect the performance of the DXBMC were measured. These parameters were limited ambient conditions, energy consumption as well as temperature and volume of milk.

3.1 Temperature profiles

The average monthly temperature profiles for the ambient temperature (Tamb), and milk temperature (Tmilk) during the AM and PM milking session are shown in Figure 3.

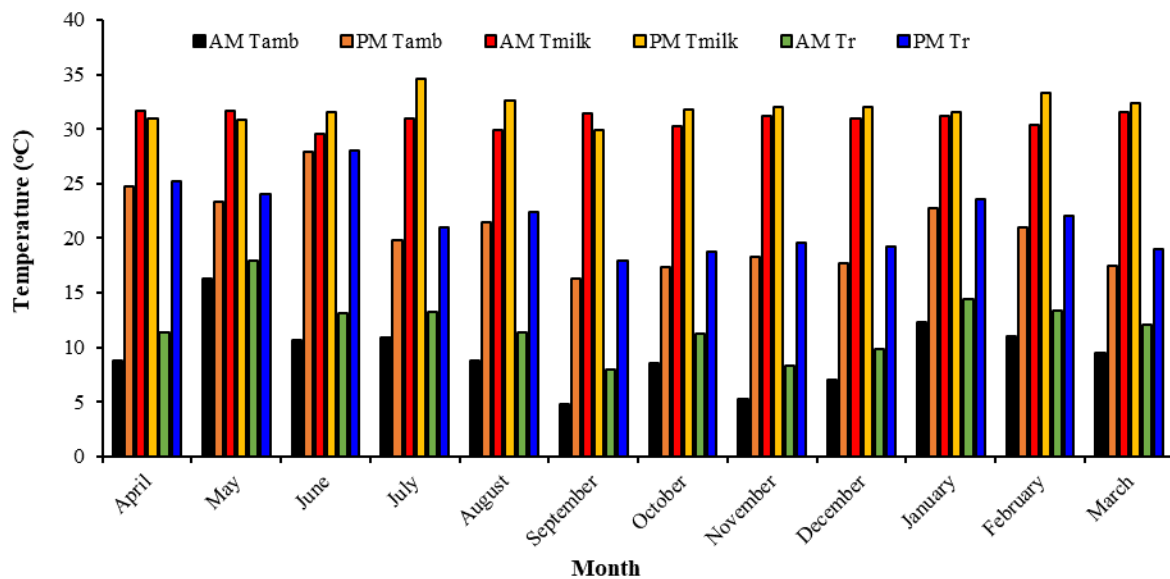


Figure 3 Temperature profiles for April – March

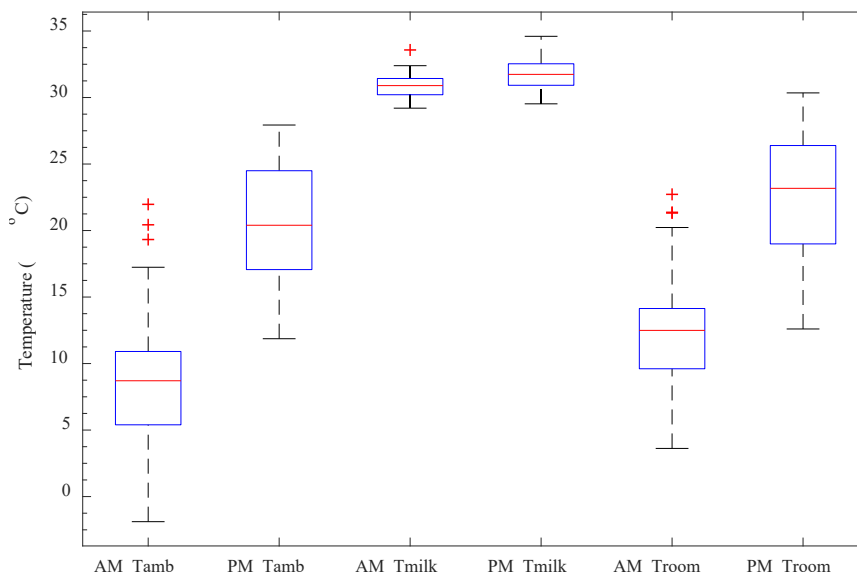


Figure 4 Comparison plot for average AM and PM temperatures

On average Tmilk was 30.89°C and 31.95°C for the AM and PM milking times respectively. Also, the average ambient temperatures for the AM and PM milking sessions were 9.49°C and 20.70°C

respectively. It can be observed that the room temperature for the AM milking was lower than that of the PM milking by an average of 44.7% (9.72°C). As alluded to in Mhundwa et al. (2017) and

Mhundwa et al. (2018), the room temperature is affected by the ambient temperature in that an increase in the ambient temperature it will lead to an increase in room temperature. There was a strong linear relationship as evidenced by the correlation coefficient of +1 between the ambient temperature and the room temperature since the room had one side opened. Notwithstanding it can be deduced that the ambient temperature fluctuations have also led to the fluctuations in the milk temperature since there was no insulation of the milk delivery stainless steel pipes thus heat exchange occurred from the milk during the morning session and to the milk during the afternoon session. One way ANOVA test was conducted on the mean values for the temperature profiles. It was deduced that there was a significant difference between the AM and PM milking Tamb and Tmilk

with p-values of 3.82×10^{-08} and 0.017 respectively. Figure 4 shows compare the measured temperatures for both AM and PM milking.

It can be observed that there was more variability on the Tamb and Troom as was with Tmilk. The difference between the AM and PM milk temperature was minimal at about 1.06°C, while the difference between the AM and PM Tamb and Troom was 11.84°C and 10.46°C, respectively. This signified a strong relationship between the AM and PM milking times.

3.2 Demand profile of the DXBMC

The operation of the DXBMC had two distinct peaks, as shown in Figures 5 in most cases coincided with the milking periods. It can be observed that all the months had a similar trend.

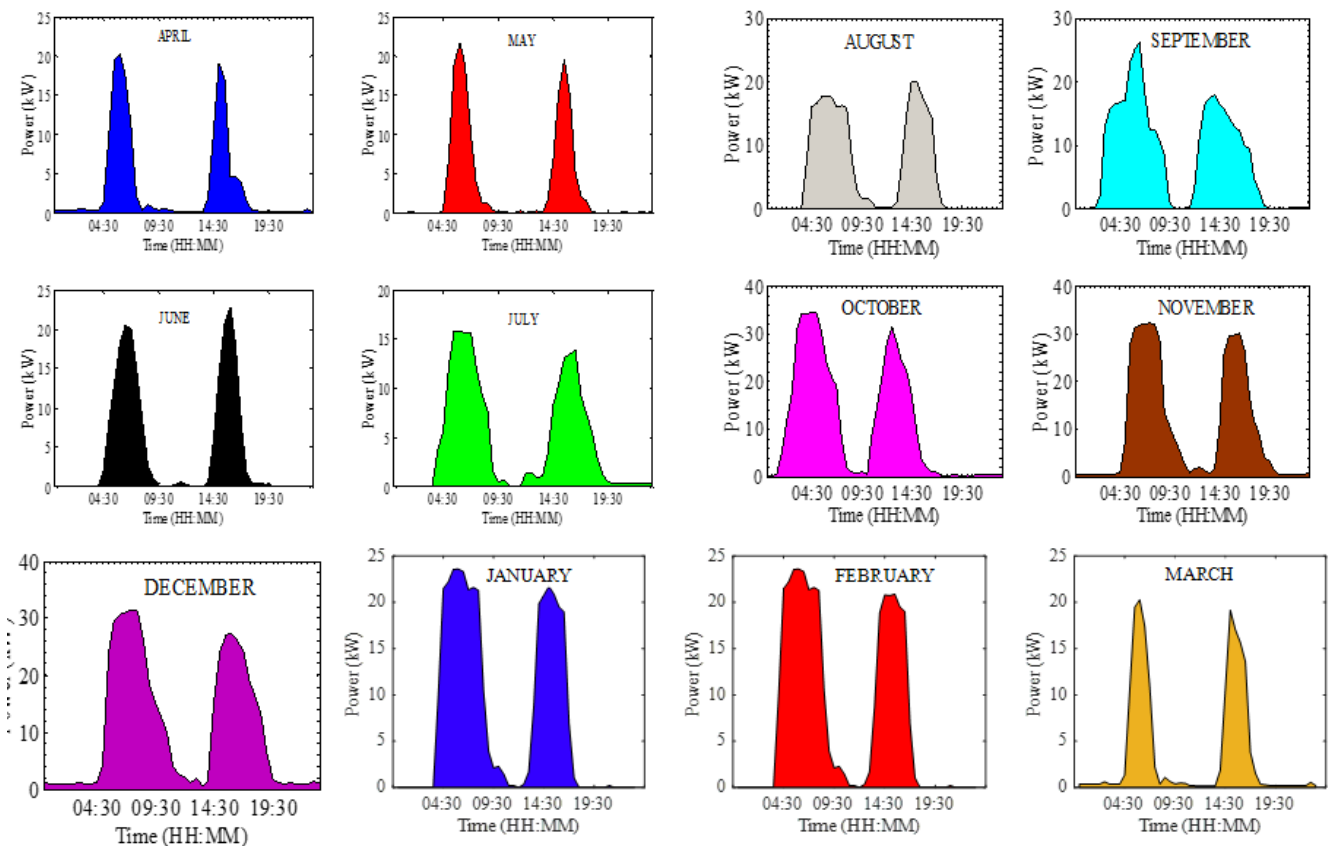


Figure 5 Average daily power profile for the months April–March

Table 3 Monthly average peak power for the DXBMC

Month	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Peak power (kW)	AM 20.27	21.72	20.44	15.84	18.75	26.28	34.6	32.21	31.41	24.86	23.73	22.50
	PM 19.15	19.55	22.95	13.85	20.98	18.02	31.34	30.14	27.4	23.32	22.80	20.55

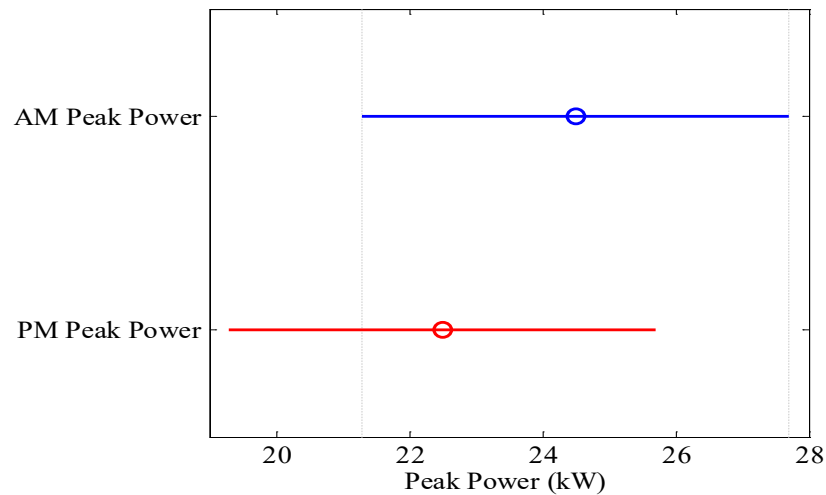


Figure 6 AM and PM peak power consumption of the DXBMC multiple comparison plot

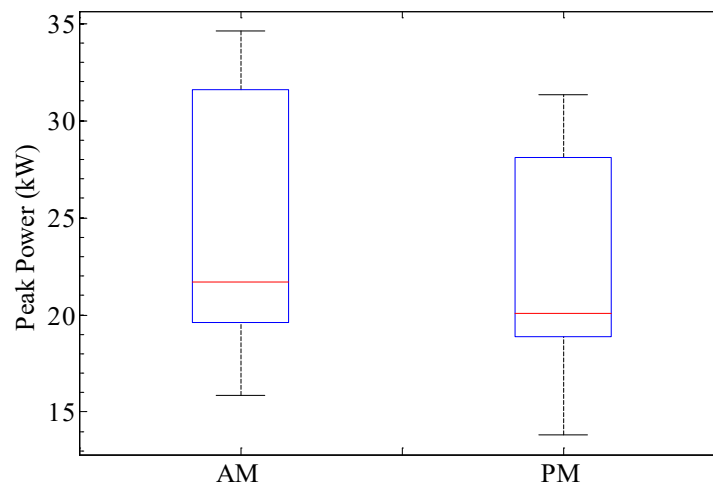


Figure 7 Boxplot for the AM and PM peak power

Generally, from April to July, the AM milking peak power was 9.13% higher than the PM milking power. Table 3 summarises the monthly average peak power for the DXBMC

As shown in Table 3 the peak AM, and PM milking power consumption for September to March was relatively higher than that of April to August by an average of 38%. It was revealed that the months had a similar trend where the AM milking peak power consumption was higher than that of the PM milking. This was due to the difference in the volume of milk delivered to the DXBMC during the two milking times except for June and August. This inconsistency was caused by some unscheduled repair and maintenance work during those months. The slightly lower power consumption during the PM milking period for most of the months was due to the

difference in the milk volume extracted for the different periods. On average, the peak power consumption for the AM and PM milking was 21.72 kW and 20.09 kW, respectively. However, there was no significant difference between the AM and PM peak power consumption of the DXBMC, as shown by the multiple comparison plot in Figure 6.

As indicated in Figure 5, the AM peak power consumption is overlapping the boundary of the PM peak power consumption and also, from the ANOVA test, the p-value was 0.5178. This was because all the compressors for the VCRC were operating irrespective of the volume of milk delivered to the DXBMC. Analysis from the boxplot in Figure 6 illustrates that the peak power consumption during the AM and PM milking periods followed a normal distribution. On average, the peak power

consumption for the AM and PM milking was 21.72 kW and 20.09 kW, respectively. As depicted by the boxplot, it can be concluded that at least 75% of the peak power consumption during the AM milking was between 15.84 kW and 31.61 kW, while for the PM milking, it has values between 13.85 kW and 28.08 kW.

It can further allude that 50% of the time, the peak power consumption for AM milking (19.62 kW to 31.62 kW) was higher than the PM milking (18.87 kW to 28.08 kW). In addition, there was more variability in the AM milking peak power consumption than the PM milking, as evidenced by the wider range. This variability was because most

times, there was some milk in the DXBMC from the previous PM milking at the commencement of the AM milking. The higher peak power during the AM milking can be explained by the amount of milk received by the DXBMC for cooling during that time.

3.3 Typical energy performance of the DXBMC

The typical energy performance of the DXBMC was analysed on an average month for the duration of the experiment. Figure 8 and Figure 9 shows the average daily energy consumption, average total energy consumed during the milk cooling process as well as the total monthly energy consumed by the DXBMC and the percentage of the storage energy of the system.

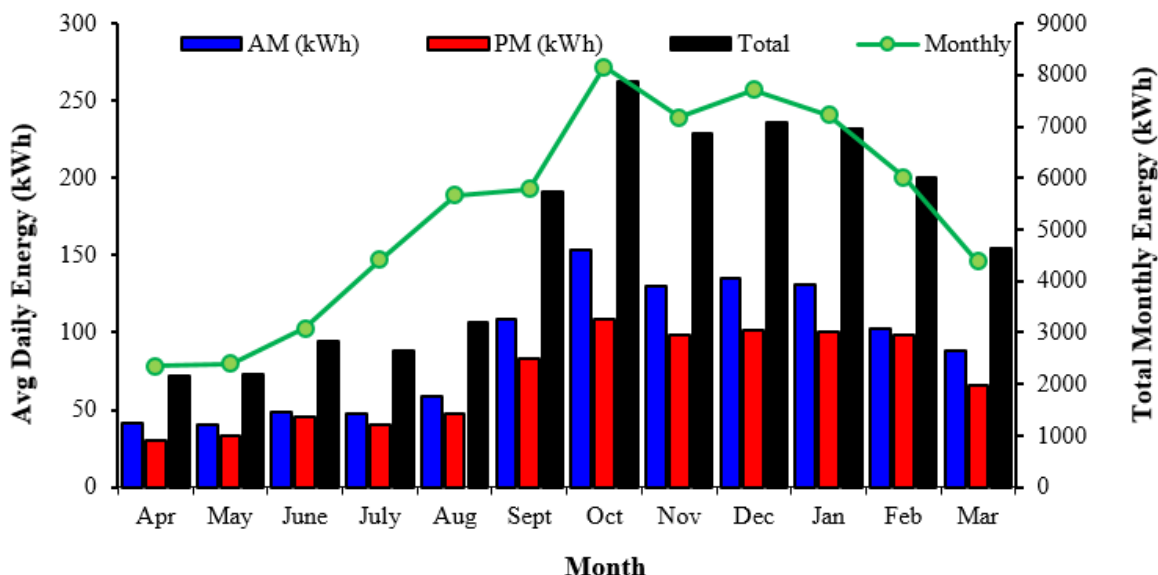


Figure 8 Energy consumption by the DXBMC during the cooling of milk

As shown in Figure 8, energy consumption during the AM and PM milking sessions increased with the months from April to December and started to decrease noticeably from February to March, owing to the onset of the off-peak season. On average, the AM and PM milking energy was 90.45 kWh and 71.07 kWh, respectively. The peak season recorded the highest average total energy of 6 898.52 kWh as whereas the off-peak season recorded an average total of 3 771.28 kWh. The annual energy consumption due to milk cooling and storage was 64 336.22 kWh. As highlighted in Figure 9, with regard to the total energy consumed by the DXBMC, the AM and PM milking sessions, on average, consumed 52.03% and 40.53%, respectively. Explicitly, on average, the

energy consumption during the cooling of milk was 92.57%, with the remaining 7.43% consumed during the storage of milk to maintain it at the set point temperature of 4°C. This is attributed to the fact that during milking time, the VCRC occurred rapidly in order to cool the incoming warm milk to the setpoint temperature. Additionally, during the storage of milk, in most cases, it was only the agitator stirring the milk within the tank to maintain the temperature. In addition, the insulation around the tank shielded the contents from interacting with the fluctuations in the ambient temperature and the room temperature. It can therefore be denoted that cooling the milk is more energy-intense than keeping the milk at the set temperature. Thus, consideration should be given to

the temperature of milk delivered to the DXBMC for rapid cooling. The lower the initial temperature of milk, the less time it takes to reach the setpoint temperature, which in turn imply less energy used.

3.4 Coefficient of performance of the DXBMC

Table 4 shows some typical results achieved during AM and PM milking cooling cycles.

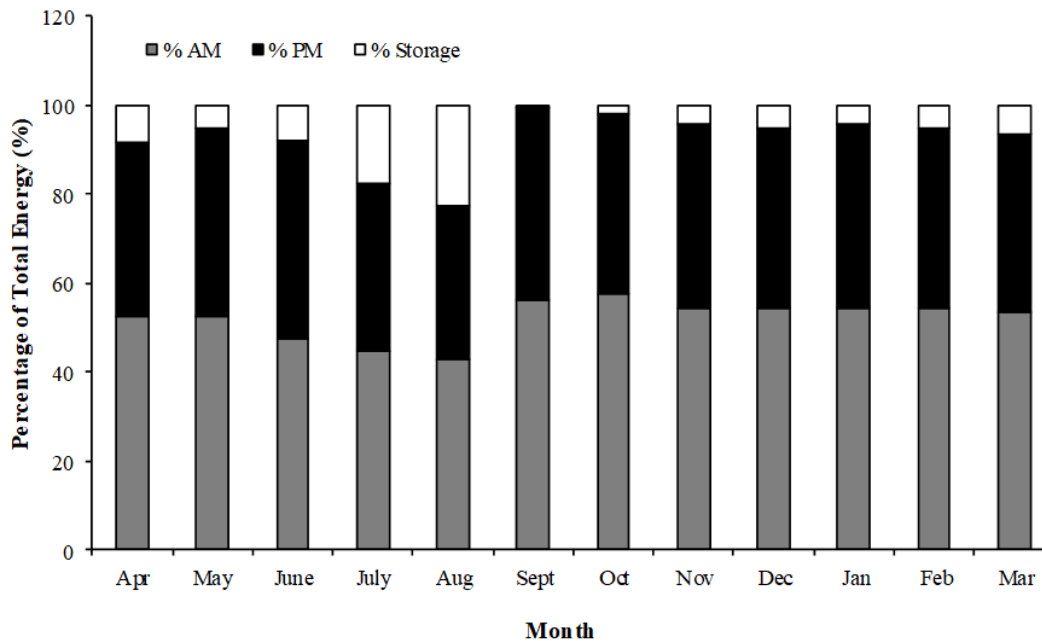


Figure 9 Milk cooling and storage energy consumption

Table 4 Typical randomly sampled results obtained during the AM and PM milking cooling cycles

EC (kWh)	AM Milking					PM Milking					
	Milk Vol (m ³)	Tamb (°C)	RH (%)	Milk Temp (°C)	Avg. Daily COP	EC (kWh)	Milk Vol (m ³)	Tamb (°C)	RH (%)	Milk Temp (°C)	Avg. Daily COP
43.93	2 810	8.73	93.14	31.63	1.99	37.22	1 656	24.76	43.61	30.91	1.35
43.29	2 706	16.35	70.29	31.72	1.95	31.19	2 013	23.38	60.91	30.85	1.95
38.71	2 125	10.72	96.06	29.53	1.58	39.30	1 682	27.93	29.80	31.53	1.33
38.64	2 098	10.87	93.68	30.91	1.65	53.47	3 401	19.87	51.25	34.60	2.19
39.35	2 518	8.75	97.74	29.91	1.87	50.34	3 26	21.50	42.70	32.58	2.39
63.59	4 700	4.81	97.89	31.41	2.28	50.17	3 655	16.31	70.96	29.87	2.13
65.13	4 837	8.57	99.56	30.30	2.20	63.02	3 802	17.30	31.05	31.74	1.89
67.09	4 812	5.28	83.18	31.17	2.20	54.91	3 939	18.25	33.21	32.04	2.27
65.57	4 859	7.00	79.64	31.00	2.26	53.59	4 092	17.75	58.16	32.00	2.41

It can be deduced from Table 4 that the increase in the milk volume led to an increase in the COP of the system. Moreover, the greater the volume of milk delivered to the DXBMC for initial milk cooling resulted in better system performance than the low volume blended milk during the PM milking. Similarly, for an increase in the ambient temperature led to a decrease in the COP of the DXBMC, also a decrease in the relative humidity caused the COP of the system to increase. Although, ambient temperature and relative humidity were inversely

proportional, it can be expatiated that an increase of the individual parameters led to a decrease in the system COP and their decrease led to an increase in the COP of the system.

The highest COP achieved by the DXBMC was concomitant to the energy consumption and an increase in volume of milk as evidenced by the increase from April to November. This suggested that there was a better performance of the system during the AM milking session since for a typical milking day, high energy consumption and volume of milk

were recorded during the said period. The average COP of the DXBMC was 2.20 and 1.93 for AM and

PM milking session. The average COP for the monitoring period is also indicated in Figure 10.

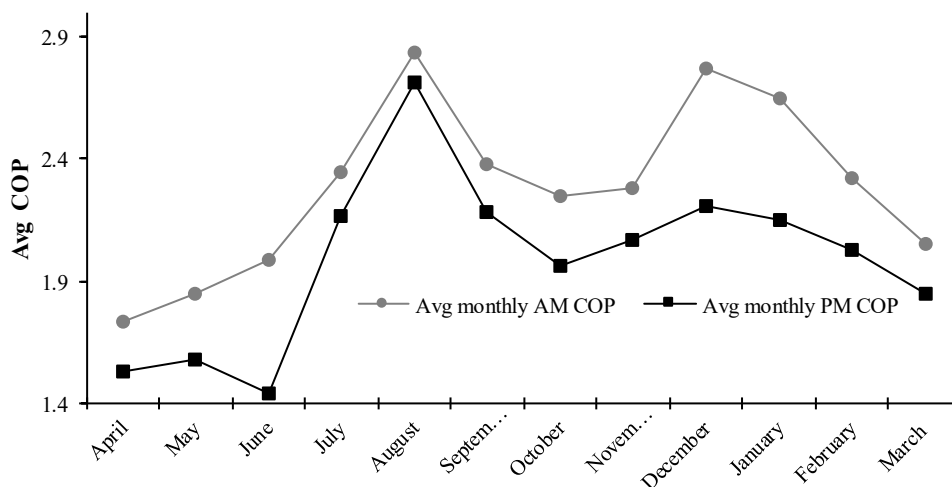


Figure 9 Average AM and PM COP for April – March

Though the milk temperature was almost constant per each milking session, however it was noted that a decrease in the temperature of milk reduced the compressor run time hence enhancing the performance of the DXBMC. However, the COP increased in the month of July since there was an increase in the volume of milk cooled during both AM and PM milking sessions. During that period the average COP was 2.36 and 2.18 for the AM and PM milking times as was also reported in Mhundwa et al. (2017). All the way through the monitoring period, the average daily COP of the DXBMC during the AM milking was higher (1.58–2.75) than that of the PM

milking (1.22–2.47). On average, the AM COP was 13% higher, attributed to the volume of milk as highlighted earlier. More than 50% of the time the AM COP was between 2.02 and 2.84, whereas the PM COP was ranging between 1.715 and 2.175. The average COP was 2.3 and 2.05 for the AM and PM milking, respectively.

3.5 Specific electricity consumption of the dairy farm cooling system

The average daily *SEEC* and *EEP* for the DXBMC during the AM and PM milking periods based on the daily milking cycle is summarised in Table 5.

Table 5 Summary of *SEEC* and *EEP*

	AM		PM	
	<i>SEEC</i> (kWh L ⁻¹)	<i>EEP</i> (L kWh ⁻¹)	<i>SEEC</i> (kWh L ⁻¹)	<i>EEP</i> (L kWh ⁻¹)
Mean	0.01530	66.29	0.01948	53.34
Max	0.01890	85.59	0.02573	76.99
Min	0.01168	52.91	0.01299	38.86

According to Table 4, on average, the *SEEC* and *EEP* were 0.0174 kWh L⁻¹ and 59.82 L kWh⁻¹, respectively. The *SEEC* is slightly higher than 0.01302 kWh L⁻¹ reported by Upton et al. (2014). It can be deduced from Table 5 that the *SEEC* was 21.46% higher in the PM milk cooling period while *EEP* was lower by 19.54%, suggesting that the AM milk cooling period had better utilisation of energy. A comparison of the *SEEC* and *EEP* is shown in Figure

10. Both AM and PM *SEEC* followed a normal distribution with no outliers. For 50% of the time, the *SEEC* was within 0.0172 kWh L⁻¹ and 0.0156 kWh L⁻¹ during the AM milking while the PM milking was between 0.0211 kWh L⁻¹ and 0.0178 kWh L⁻¹. There was more variability in the *SEEC* during the PM milking, as evidenced by the wider range. The variability in the *SEEC* could be attributed to the

onset of the milking cycle when the DXBMC was emptied after the AM milking each day. The AM and PM *SEEC* of the DXBMC were compared using a one-way ANOVA test as shown in Figure 10. The

test depicted that there was a significant difference between the AM and PM milk *SEEC* for the DXBMC with $p < 0.0001$. A comparison of the *EEP* is shown in Figure 11.

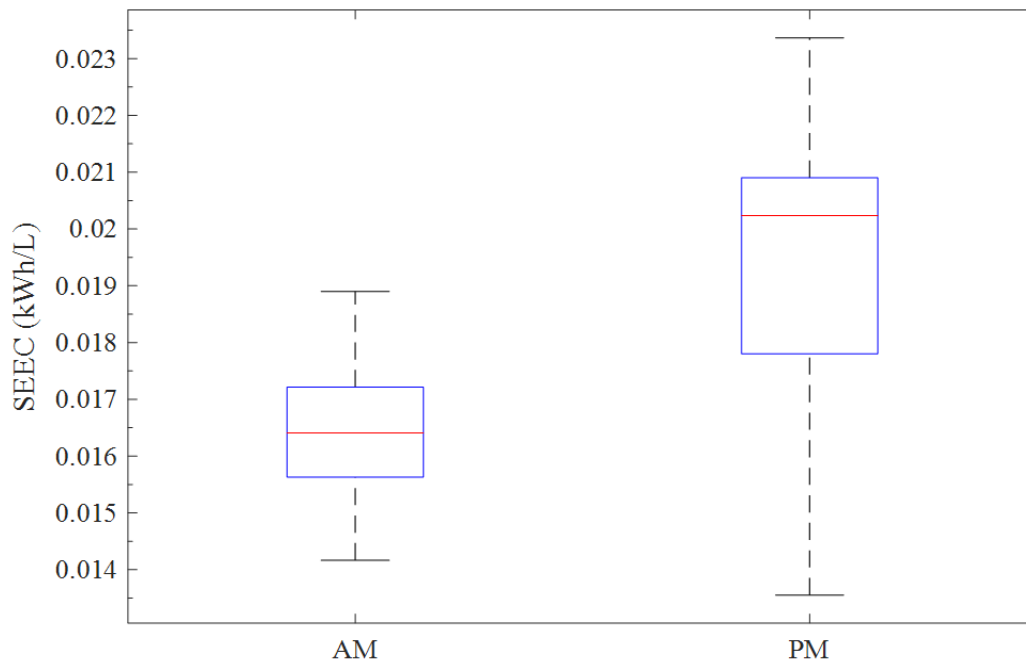


Figure 10 Box plot for the AM milking and PM milk cooling energy

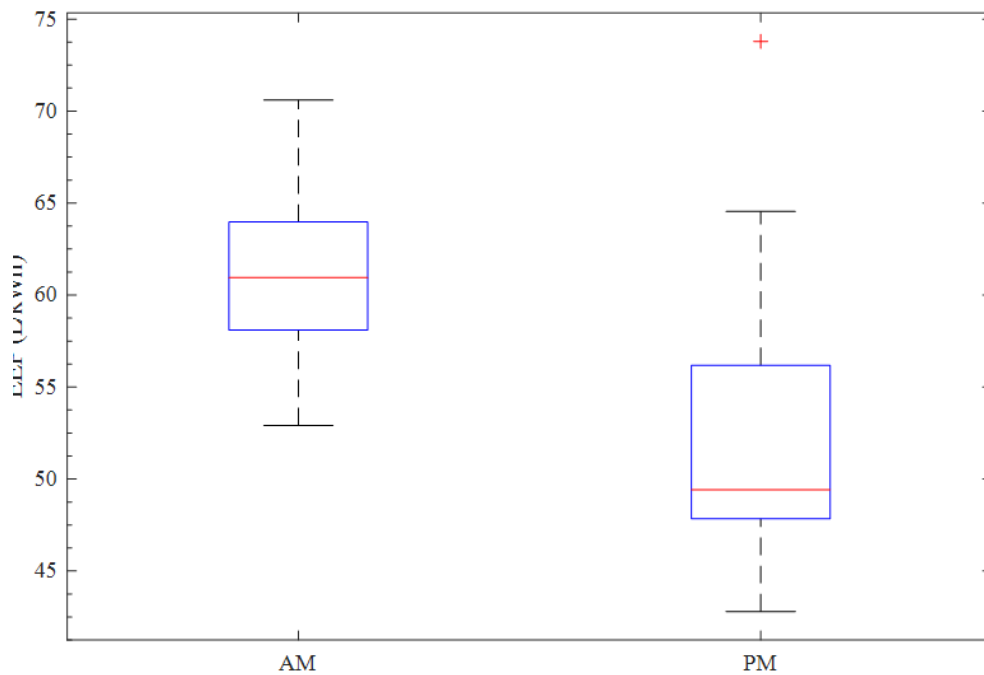


Figure 11 Box plot for the AM and PM EEP

On average, the AM milk cooling cycle had higher *EEP* than the PM milk cooling cycle, as highlighted in Table 5. Most of the days, the *EEP* for the AM and PM milk cooling ranged between 60.39 L kWh⁻¹ – 73.47 L kWh⁻¹ and 45.13 L kWh⁻¹ – 60.33 L kWh⁻¹, respectively. This suggests a 17.88% higher

volume of milk was being cooled per unit of electricity consumed by the DXBMC during the AM milking than during the PM milking, which might be due to the ambient temperature differences. The average monthly *SEEC* and *EEP* for the DXBMC are shown in Table 6 below.

Table 6 Monthly performance of the DXBMC

Month	Mean Number of Cows	Total milk produced (L)	Milk yield per cow (L/cow)	Electrical energy for cooling (kWh)	Specific Electrical Energy		
					kWh m ⁻³	kWh L ⁻¹	kWh/cow
Apr	471	141 566.67	300.57	2 344.55	16.56	0.017	4.98
May	388	136 582.68	352.02	2 399.83	17.57	0.018	6.19
Jun	375	146 962.76	391.90	3 080.06	20.96	0.021	8.21
Jul	487	245 379.47	503.86	4 405.60	17.95	0.018	9.05
Aug	615	373 934.00	608.02	5 669.90	15.16	0.015	9.22
Sep	771	430 865.90	558.84	5 780.79	13.42	0.013	7.50
Oct	853	480 010.40	562.73	8 153.25	16.99	0.017	9.56
Nov	858	444 573.00	518.15	7 170.41	16.13	0.016	8.36
Dec	836	409 954.73	490.38	7 718.27	18.83	0.019	9.23
Jan	800	364 464.00	455.58	7 215.90	19.80	0.020	9.02
Feb	655	261 148.50	398.70	6 013.21	23.03	0.023	9.18
Mar	521	165 808.30	318.25	4 384.45	26.44	0.026	8.42
Total		3 601 250.36		64 336.22			
Avg	628	312 03.29	454.92		18.57	0.0186	8.24

The electrical energy included the energy consumed by the compressors, agitators, and condenser fans as the major components of the DXBMC. On average, the electricity used for cooling of milk on the dairy farm was 18.57 kWh m⁻³ of milk. It was observed that the usage was almost leveled during the monitoring period with an average deviation of 9.19% since there were no major changes on the farm's cooling equipment as well as the milking management system. The electrical energy used for cooling per cow depicted that as production increases so was the electricity used per cow from a minimum of 4.98 kWh/cow to a maximum of 9.56 kWh/cow which was observed for the months of April and October respectively. On average, the monthly electricity used per cow on the farm was 8.24 kWh/cow which translated to an average of 0.26 kWh/cow/day. Also, the average specific energy consumed by the cooling system per litre of milk cooled was 0.0186 kWh L⁻¹ and was almost constant throughout the whole period of monitoring. The *SEEC* ranged between 0.013 kWh L⁻¹ – 0.026 kWh L⁻¹. It could be emphasised that as the season for milk production changed from the off-peak to the peak period, the daily occupancy rate of the DXBMC was increased as evidenced by the increase in the volume of milk produced. The average occupancy of the 21

000 litre capacity DXBMC during the April–August period was 32.38% compared to 68.92% during the September–January period. This, however, suggested that the system tends to perform better during the peak period (September–January). On average, the DXBMC cooled 57.33 L kWh⁻¹ during the off-peak period and increased by 7.7% to 62.13 L kWh⁻¹ during the peak period. These results showed that the farm operated on a slightly more expensive cooling routine during the off-peak season than during the peak period of milk production. Therefore, operating the DXBMC outside the morning and evening peaks would help the farm optimise on the cost of electricity and function economically. It could be noted with 95% confidence that about 96% ± 2% of the electrical energy consumption during the cooling of milk at a dairy farm was during the rapid cooling process to reduce the temperature of milk to the set point temperature of 4°C and the remaining 4% ± 2% was to maintain the milk at the set temperature.

4 Conclusions

The study revealed that the developed low cost DAS was capable to monitor the performance of the on-farm DXBMC efficiently. Practical determination of the electrical energy and COP could be effectively ascertained. This DAS will enable the dairy farmers

to monitor and manage their cooling energy through implementation of energy efficiency measures. Based on the analysis presented in this study the notable key findings are that

The change in milk volume directly affected the energy consumption by the DXBMC and the COP of the DXBMC increased with milk production, thus during the peak season the DXBMC exhibited enhanced performance.

Also, the COP of the system was inversely proportional to the ambient temperature.

The volume of milk cooled per unit of electricity consumed by the DXBMC was 17.88% higher during the AM milking than it was during the PM milking which might be as a result of the ambient temperature differences, thus time of operation of the DXBMC has impact on energy consumed.

The specific electrical energy consumed was 21.46% higher in the PM milk cooling period while electrical energy productivity was lower by 19.54%.

About 96% of the electrical energy consumption during the cooling of milk at a dairy farm is due to the rapid cooling process to reduce the milk temperature to the set point temperature of 4°C and the remaining energy used to maintain the milk at the set temperature.

Sub-metering of different dairy farm equipment makes it possible to gather finer data for energy efficiency evaluation of specific equipment regarding the total energy consumption on the farm. This will allow farmers to implement strategies for efficient operation of the equipment and deduce energy-saving potentials. Furthermore, specific equipment monitoring will also allow for optimisation and scheduling repair and maintenance based on the data gathered and performance metrics deduced.

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