RACE for 2030
RELIABLE AFFORDABLE CLEAN ENERGY

B4: Fast track

Using phase change materials for flexible demand in industrial refrigeration

Final report

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Using phase change materials for flexible demand in industrial refrigeration

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What is RACE for 2030?

The Reliable Affordable Clean Energy for 2030 Cooperative Research Centre (RACE for 2030) is a 10-year, $350 million Australian research collaboration involving industry, research, government and other stakeholders. Its mission is to drive innovation for a secure, affordable, clean energy future.

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Executive summary

Almost one quarter of electricity consumption across Australia is used for Heating, Ventilation, Air Conditioning and Refrigeration (HVAC-R). Implementing viable energy saving and power management strategies across this sector is therefore important for improving energy productivity. While sourcing cheap renewable energy would help HVAC-R users to decarbonise their operations, renewable energy generation is most abundant in the middle of the day and often not aligned with the peak needs of heating and cooling output. Therefore, technologies are required to decouple energy use from peak periods and address the disparity between power generation capacity and energy demand across electricity networks.

While Battery Energy Storage Systems (BESS) can be used to address these issues, their costs are often prohibitive for large scale applications. Use of a Phase Change Material (PCM) Energy Storage System (ESS) in conjunction with solar photovoltaics (PV) for industries where cooling constitutes the major portion of electricity usage has proven to be more cost-effective than BESS (Belusko *et al.*, 2017). However, there are efficiency penalties as a result of introducing a secondary Heat Transfer Fluid (HTF) to interface the PCM ESS with the existing refrigeration system, which affects the economic return on investment for the system owner. Moreover, integration is not feasible in some applications, depending on the preferred type of HTF.

In this study, a new method for interfacing PCM ESS with a cooling system was assessed. The system was analysed in the context of Misty Downs Dairy in South Australia, where a significant HVAC-R load is required for milk cooling. The main research activities of the study were as follows:

1. A computing modelling simulation (using MATLAB) was run to compare the performance of two alternative PCM ESS: the existing system operating with Dynalene as a single-phase HTF, and the proposed system using carbon dioxide (CO_2) as a two-phase HTF.
2. Data on the existing dairy refrigeration system were collected and used to validate the results provided by the corresponding MATLAB model.
3. Concept design of a PCM ESS with CO_2 as the HTF was developed for the Misty Downs Dairy. This design indicates the necessary upgrades for existing PCM ESS.
4. An economic analysis was conducted comparing the current and proposed systems in terms of costs, expected savings and payback period.

The pumping energy required to charge and discharge a PCM ESS is significantly lower when CO_2 is used as the HTF. Furthermore, the proposed system achieves a higher heat transfer rate, resulting in a higher coefficient of performance (COP) for the cooling process. The study identified both a considerable energy saving and reduced peak demand. A 26% reduction in grid power consumption can be realised, resulting in 41% lower overall cost of energy for the proposed system compared to the conventional PCM ESS. The extra cost of implementing the new system was estimated to be higher than the installed cost of the original system by only 4.6% , delivering an economic payback in just over one year. These results suggest that using CO_2 as the HTF in PCM ESS can be a viable investment option for power consumers across the HVAC-R industry. This research indicates a strong case to test this proposed new technology in practice.

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1 Introduction

The disparity between power generation capacity and demand has always been a challenge for the electricity supply system. The rapid deployment of both network-level and consumer-level renewable energy generation over the past 20 years has exacerbated the issue by exerting further stress on power networks, particularly at times of peak generation. Frequency instability and even blackouts during periods of peak demand as well as periods of high renewable generation feed-in, are symptoms of this issue.

There are multiple strategies in place to overcome these challenges. For instance, Battery Energy Storage Systems (BESS) can be used to reduce the stress on the network during peak hours but also improve the system frequency response and avoid potential stability risks. However, this type of energy storage is limited in size and capacity and comes at a high cost for large scale applications. The focus of this research is on the development of a new low-cost Phase Change Material (PCM) Energy Storage System (ESS)that can interact with the power system as a cost-effective replacement for BESS, specifically for Heating, Ventilation, Air Conditioning and Refrigeration (HVAC-R) applications, which are a major consumer of electricity.

This introductory section covers a brief explanation of PCM thermal storage technology and how it compares with BESS in the way it interacts with power networks. The remainder of the section covers the integration of PCM ESS with CO_2 refrigeration systems. Section 2 reviews the drawbacks of the existing arrangement and elaborates the advantages of using CO_2 as the Heat Transfer Fluid (HTF) for integration of PCM ESS with the refrigeration plants. This will be followed by a case study in Sections 3 and 4 to demonstrate the benefits of the proposed solution in a real-life scenario. The concept design of the system including the associated costs is assessed to establish the economic returns of the implementation.

1.1 What is a Phase Change Material energy storage system?

Just about any material can be used to store thermal energy. For example, we can store energy in a body of water by increasing its temperature to a higher degree than is needed, and this energy can be released over a period of time at the desired temperature. This is an example of **sensible** thermal energy storage.

A phase change material is a substance that releases or absorbs thermal energy during a phase transition, such as freezing of water to form ice. Materials such as water generally have a larger capacity to absorb or release energy when they go through a phase change, referred to as **latent heat of fusion**.

The use of PCMs for thermal energy storage is not a new concept. Storing food with ice inside engineered pits in the middle of the desert is a strategy adopted by Persians dating back to the fifth century. Even today, despite the advancements of mechanical refrigeration, we still benefit from thermal energy stored in phase change materials. A typical example is storing food or beverages in an insulated box with a pack of ice.

The concept of PCM ESS in cooling applications can be described as follows:

1. **Charge cycle**—The PCM is frozen by cooling it. This cooling is generated by converting electrical energy to mechanical energy and then to thermal energy by the same refrigeration plant that keeps a product or process at a desired temperature (e.g. food products at 2°C in a cold store or wine casks at 18°C in a wine cellar). This is comparable to storing electrical energy in a BESS.
2. **Discharge cycle**—The cooled PCM is used to keep the same product or process at the desired temperature while it is melting. Transferring thermal energy from the product to the ice storage during

discharge requires electrical energy; however, this energy is around 20 times less than that required to run the main refrigeration plant. In the case of using a BESS, during discharge the stored electrical energy is released to run the refrigeration plant.

The focus of this study is on PCM ESS with ice-on-coil technology. The storage consists of a tank containing the PCM, as shown in Figure 2. A coil is submerged in the PCM with a Heat Transfer Fluid (HTF) pumped through it during both charge and discharge. During the charge process, the HTF is cooled by the refrigeration plant to a temperature lower than the freezing temperature of the PCM. Ice forms on the coil gradually to a point where a full block of ice is generated. During the discharge process the block of ice that was formed on the coil will melt from inside out while being exposed to the thermal energy that the HTF is picking up from the process or product to keep it at the desired temperature.

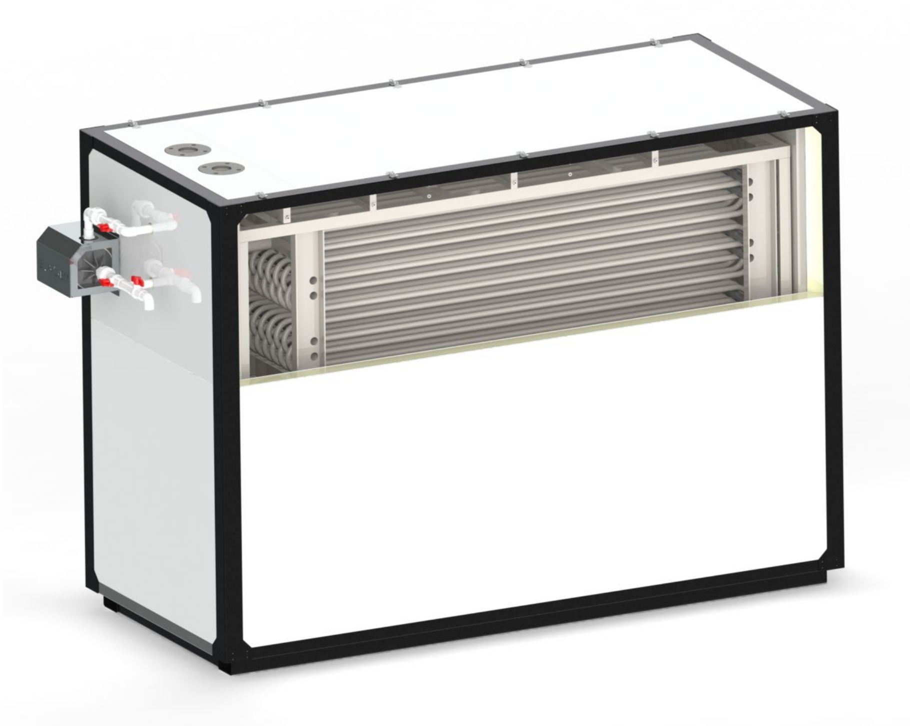

Figure 1. PCM ESS tank with stainless steel coil.

Integration of PCM ESS with refrigeration requires a secondary loop containing the HTF. This loop will have a pump and heat exchangers to absorb cooling from the refrigeration plant during charge and deliver the cooling to the process during discharge. In systems with a secondary refrigeration loop it is possible to connect the PCM ESS tank to the existing loop and redesign the existing pumping mechanism and pipework to fit the purpose. An example of such systems will be demonstrated in Section 4 of this report.

1.2 A high-level comparison: PCM ESS and BESS

The total energy consumption of the HVAC-R sector accounts for 23.6% of total electricity consumption in Australia (Department of the Environment and Energy, 2018). This signifies the importance of incorporating viable energy saving- and power management strategies across this sector.

PCM energy storage technology enables demand flexibility for cooling processes. For cooling processes, PCM ESS compares favourably to BESS:

- PCM ESS is a more cost-effective means of energy storage solution for the HVAC-R sector. An internal comparison between the products of Glaciem Cooling Technologies and available batteries on the market shows that electric batteries are two to three times more expensive than PCM ESS.
- The useful life of lithium batteries is limited to between five and seven years before their capacity drops significantly. PCM ESS has an expected life of 25 years, which is the design life of the tank and the coil inside it. This type of storage does not experience deterioration of capacity.
- The size of the target PCM ESS technology is about half that of the equivalent electrical battery. For instance, a 2.4 MWh DYN900 PCM0 is slightly larger than a 20-foot container. An equivalent electrical battery made by QH in China is the size of two 20-foot containers.
- PCM ESS requires electrical energy to operate even during discharge. However, this power is about 20 times smaller than the power required to run the main refrigeration plant. The difference between the power consumption of the main plant and a charged PCM ESS is large enough to enable it to serve as a means of energy storage.

1.3 Interaction of PCM ESS with the power network

There are several strategies to alleviate problems on the power network during periods of high demand or high non-synchronous generation and low minimum net demand. These strategies include but are not limited to the introduction of synchronous condensers or large lithium-ion batteries, such as Hornsdale Power Reserve in South Australia. Alternatively, power management activities, also known as load flexing, such as load shedding, load shaping and load shifting, can be incentivised by the power network and adopted by energy consumers. Introduction of peak demand tariffs, and Power Purchasing Agreements (PPAs) or the provision of the spot price forecast (AEMO) for the benefit of the larger-scale consumers are a few examples of such incentives.

The HVAC-R sector could use PCM ESS to adapt to power network requirements as well as addressing minimum net demand and maximising utilisation of onsite solar photovoltaic (PV) with a better economic outcome.

Below is an explanation of different types of load flexibility and the way PCM ESS could enable them.

Peak demand reduction (load shaving)

At times of high stress on the power network, strategies can be incorporated to reduce demand. Current demand tariffs incentivise consumers to monitor and control their peak power consumption. Use of energy storage could be a means of reducing the peak load during these times. For instance, in a supermarket, refrigeration and air conditioning constitute 50% of total power consumption. If we assume that a supermarket can consume up to 300 kVA during peak load, 150 kVA of this is allocated to refrigeration. Assuming the power required for operating the refrigeration plant integrated with PCM ESS can be reduced to 50 kVA when the system is discharging, the peak demand will be reduced by 30%.

Load shedding

Load shedding involves partial removal of power consumption in order to reduce load on the power network. Both automatic and manual load shedding are possible when PCM energy storage is used in conjunction with a cooling system. PCM ESS can take over the cooling demand instantaneously when the cooling plant, which is the major power consumer, shuts down.

Load shifting

Load shifting involves changing the timing of energy usage based on availability of energy or the economics of energy usage. For example, energy can be stored in the middle of the day when there is an abundance of solar PV or when the cost of electricity is at its lowest, and then released when renewable sources are not available, or the power price is higher. In networks where renewable resources constitute a considerable proportion of generation, low renewable energy and high pricing events will tend to occur simultaneously.

As an example, Figure 1 shows the timing of dominant cooling loads in a typical dairy over a 24-hour period. Assuming that the dairy has a peak/off-peak tariff structure and has onsite solar PV, utilisation of solar energy and off-peak grid power is limited because of the offset on the timing of the main loads. Having PCM ESS integrated with such systems allows the operator to store the available solar energy when the process load is minimal and release it to meet the cooling load to avoid peak or off-peak grid power. On winter days when solar energy is limited, the storage can be charged using off-peak power and discharged during peak hours.

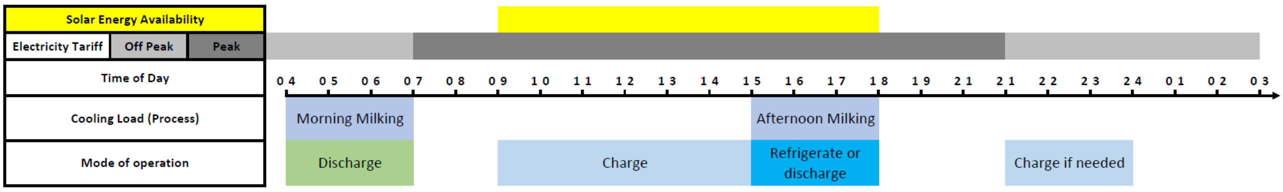

Figure 2. Daily milking schedule at Misty Downs Dairy.

Load shaping

Load shaping involves matching the load to the generation profile. PCM energy storage can operate as a buffer of energy that can be managed to increase the load on the grid by storing energy and reduce the load by releasing the stored energy to meet the load instead of operating the main plant.

Frequency management

While strategies are adopted to mitigate the impact of renewable energy generation on frequency management at the power generation level, reducing the amount of power fed back into the grid from rooftop solar PV is one to avoid underfrequency load shedding (UFLS). For a power consumer with onsite solar PV, this means that a part of their generation plant should be shut down, which hinders utilisation of their asset. Using PCM ESS in conjunction with large refrigeration plants collocated with solar PV, such as at wineries, abattoirs or supermarkets, can assist self-consumption of PV output and help eliminate or reduce export of excess power from solar PV plants and assist power networks in reducing the risk of frequency deviation.

1.4 CO_2 refrigeration system

Carbon dioxide (CO_2) is a naturally occurring substance with attractive properties as a refrigerant.

CO_2 has a low global warming potential index of 1. It is non-flammable and nontoxic with a high heat transfer coefficient and a low compression ratio. These qualities have made CO_2 a growing refrigerant in HVAC-R sector at different scales.

Table 1 compares a few properties of CO_2 with other refrigerants.

Table 1. Comparison of a few properties of CO_2 (R744) with other refrigerants.

Refrigerant	Hydrofluoro-carbons (HFCs)	Hydrofluoro-olefins (HFOs)	Ammonia (R717)	CO_2 (R744)
Greenhouse warming potential	>1300	<1	0	1
Toxicity				
Flammability				
Refrigerant cost				
System cost				
Long term viability				

Among the distinct properties of CO_2 are its high operating pressure and considerably low critical point compared to other refrigerants. The former requires use of pipes and equipment with better mechanical resistance but results in better heat transfer within smaller pipework and heat exchangers. The latter, however, makes operation of the system less efficient in hot ambient conditions. The system is required to operate in a mode referred to as transcritical operation. The limitations of the transcritical mode of operation have been overcome in several ways, such as incorporating parallel compression or multi ejectors, as well as precooling of air supplied to the gas cooler (Belusko, et al., 2019). In summary, use of CO_2 as a refrigerant is growing, with it replacing synthetic refrigerants in many sectors.

Light industrial and commercial refrigeration applications including supermarkets, commercial cold storage and warehouses are rapidly moving towards replacing their plants with transcritical CO_2 systems.

Hence, for the purpose of this study we have considered CO_2 as the primary refrigerant of the cooling plant with integrated PCM ESS.

1.5 Sensible heat transfer versus latent heat transfer

An HTF is an intermediary liquid or gas that enables the cooling or heating effect generated by the plant to be transferred to the demand or storage. The HTF is pumped through a loop technically referred to as a secondary refrigerant loop. For instance, a chilled water loop is a means of transferring the heat from individual air handling units in a building to the chillers. The primary refrigerant in the chillers could be an HFC, Ammonia or CO_2.

There are two types of heat transfer fluids:

1. **Sensible** or **single-phase** heat transfer is when the fluid temperature varies while transferring the energy. For instance, in a chilled water loop, water is chilled to 6°C by the chiller. It is pumped through a closed loop to the air handling coils where it cools the air as its temperature is raised to 12°C. It then flows back to the chiller to be cooled again and the loop continues. Other examples of sensible HTFs are glycols or Dynalene.

   In this report, such HTFs will be referred to as single-phase or sensible HTFs.

2. **Latent** or **two-phase** heat transfer is when the temperature of the medium remains constant, but it goes through a phase change during the energy transfer, thanks to the volatility of the medium. For instance, when liquid ammonia is pumped to wine tank jackets, it evaporates by absorbing the heat from the product. A mixture of the vapor and liquid ammonia will return to the plant where the vapor is condensed back to liquid while being chilled by the plant and the loop continues. Two-phase HTFs will

usually be the same as the primary refrigerant in a plant; though this is not always the case. CO_2, ammonia and water (steam) are all examples of two-phase HTFs.

In this report, such HTFs will be referred to as two-phase or volatile HTFs.

Refrigerants such as CO_2 and ammonia have a large latent heat capacity that makes them an attractive primary refrigerant but also a suitable HTF. Compared to single-phase HTFs, pumping a small amount of a two-phase refrigerant will enable a higher heat transfer rate. Consequently, the size and cost of pipework and equipment required for systems with two-phase HTFs are lower than for single-phase fluids. Furthermore, having to pump a smaller volume of the refrigerant will require less input energy, resulting in lower operating cost for the systems. A study on supermarket refrigeration (Karampour & Sawalha, 2018) conducted by the Royal Institute of Technology in Sweden has established that supermarkets operating with pumped CO_2 as a heat transfer fluid are 12–17% more efficient than with a direct expansion transcritical CO_2 system, depending on the ambient condition.

In the next section of the report, we will establish the performance improvements of replacing the single-phase (sensible) HTF with CO_2 as a two-phase (volatile) HTF in the integration of PCM ESS.

1.6 Coefficient of performance

Coefficient of Performance (COP) is a measure of efficiency defined as the amount of useful energy delivered by a system divided by the input electrical energy. In other words, the higher the COP of a system the higher the efficiency as less input energy is required for the same amount of energy delivered.

For a refrigeration plant, the **COP of cooling** is the amount of cooling energy the compressors can deliver divided by their input electrical energy.

For a plant integrated with PCM ESS, in addition to the COP of cooling, COP of charge and COP of discharge are defined to evaluate the overall performance of the system.

- COP of charge is the amount of energy stored in the PCM ESS divided by the input electrical energy required to achieve that.
- COP of discharge is the amount of energy delivered by the PCM ESS divided by the input electrical energy required to achieve that.

2 Performance of PCM energy storage with CO_2 versus Dynalene as the HTF

2.1 Drawbacks of current PCM ESS

As explained in Section 1.3, integration of PCM ESS with a refrigeration system will require a secondary refrigerant loop, which comes with additional energy losses and limitations:

- Coupled with PCM ESS, the refrigeration system should operate at a lower suction temperature resulting in a lower COP of charge.
- The pumping power required for heat transfer is an inevitable additional power consumption. Minimising this power will increase the savings of integrating PCM ESS with a plant.
- In several applications, implementation of a secondary refrigerant loop is not feasible because of space limitation as well as cost of implementation.

While the existing setup of PCM ESS can reduce the overall cost of energy for consumers, improving on any of the above-mentioned performance deficiencies not only makes the investment more attractive for existing end users by increasing the savings, it also expands the range of industries that can benefit from PCM ESS as a means of reducing peak demand and overall energy costs. In the following sub-sections, we will address each of the above-mentioned penalties and evaluate the improvements that can be achieved if CO_2 is used as the HTF.

2.2 Integrated system efficiency

We will use an example to show how the integration of PCM ESS will reduce the COP of the original plant and how the use of volatile HTF will improve the COP of the integrated system.

At a dairy, the produced milk should be cooled and maintained at 3°C after production. The cooling system is a transcritical CO_2 chiller.

Configuration 1—Refrigeration plant directly meeting the cooling load. In order to cool the milk directly with CO_2, the Saturated Suction Pressure (SST) setpoint will be –1°C.

Configuration 2—Refrigeration plant meeting the cooling load through a secondary heat transfer loop. In this case the temperature of the HTF should be about –1°C to cool the milk down to 3°C. The SST should therefore be set to –5°C.

The 4°C reduction in the SST of the refrigeration system caused by converting a direct expansion system to a secondary loop refrigeration system, leads to the system efficiency reducing by about 13%. It also means that a larger system is required to meet the same capacity. This accounts for the efficiency penalty initiated by the introduction of a secondary refrigerant loop for integration of PCM ESS. It is also the main reason behind industries moving to direct refrigeration instead of using secondary refrigerant loops. This will be elaborated in Section 2.4.

Following is how replacing the single-phase HTF with the primary refrigerant can impact the efficiency of the PCM ESS.

Configuration 3—For a system with integrated PCM ESS, the temperature of the single-phase HTF should be no more than −1°C to cool the milk down to 3°C. The melting (freezing) temperature of the PCM should be lower to be able to cool the HTF down to −1°C during discharge. Let us consider PCM-6 developed by our team at UniSA.

During the charge cycle, in order to freeze PCM-6, the temperature of the HTF should be −9°C or less, which requires an SST setpoint of about −13°C.

Configuration 4—For the same system, if we replace the single-phase HTF with the primary refrigerant CO_2, the SST will remain the same as the HTF temperature of −9°C.

For every degree higher SST, the capacity of the refrigeration system will be increased by about 3%. This adds up to 12% improvement in the efficiency of the refrigeration plant during charge.

In other words, a smaller system with less input power can meet the same charging requirement. Or with the same system and same input power, we could store more energy in the same period of time.

In Appendix A we have demonstrated the evaluation of compressor input power at the above configurations to support the argument.

2.3 Pumping power and heat transfer

Using the model created in MATLAB as a part of this project, we have compared the performance of a PCM ESS operating with Dynalene as a single-phase HTF with that of a PCM ESS operating with CO_2 as a two-phase HTF.

The simulations show that the pumping power of a PCM ESS operating with CO_2 as the primary refrigerant and the HTF is significantly lower than that of the same PCM ESS system with Dynalene HC30 as the HTF.

We have also established that a higher heat transfer rate can be achieved through the same overall PCM ESS tank size when the single-phase HTF is replaced by CO_2. As a result, lower charging times will be expected.

Finally, through multiple iterations we have reconfigured a coil that can fit in the same size tank with slightly higher storage capacity (Appendix B).

The overall layouts of the two models are illustrated in this section in addition to the results of the study. The calculations and principles behind the model are thoroughly explained in Appendix B of this report.

The study compares two different phase change material (PCM) tank models built using MATLAB to simulate the charging and discharging phase for Dynalene HC30 and CO_2 as heat transfer fluid (HTF). In both models CO_2 is the primary refrigerant.

2.3.1 Model 1: Single-phase secondary refrigerant

As shown in Figures 3 and 4, in the conventional layout CO_2 is the primary refrigerant cooling the HTF (in this case Dynalene HC30) to be pumped through the PCM ESS coil as well as the load heat exchanger. The heat transfer between the HTF and PCM is sensible only. The difference between the inlet temperature and outlet temperature of the PCM coil is the main indicator of the amount of energy absorbed/released by the storage.

For instance, in this case study, a PCM that freezes and melts at −6°C (PCM-6) is used, which is suitable for medium temperature applications such as cooling of milk at a dairy. During the charge cycle, the temperature of the HTF is −9°C; consequently the SST of the CO_2 evaporator is −12°C (Figure 3).

During the discharge cycle, PCM melting at −6°C will deliver −2°C HTF to the load (Figure 4).

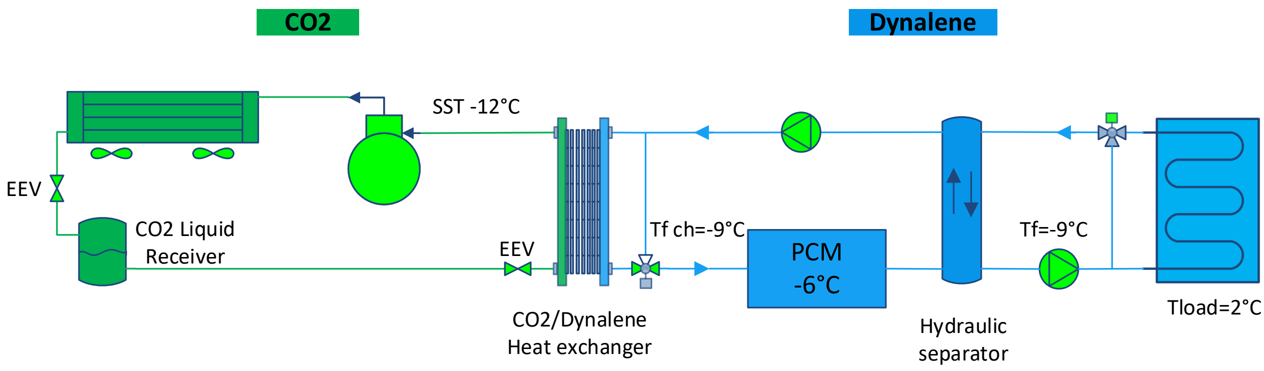

Figure 3. PCM ESS refrigeration circuit with CO_2 as primary and Dynalene as secondary refrigerant (charge cycle).

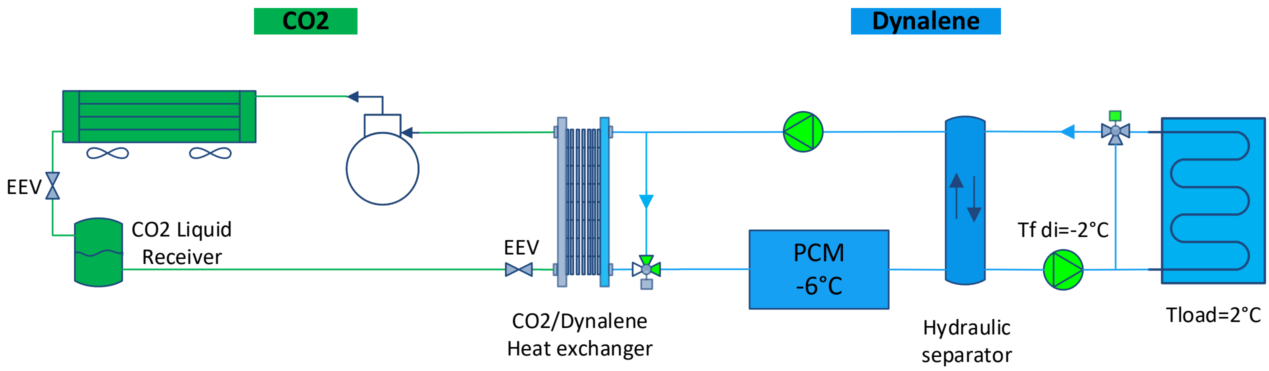

Figure 4. PCM ESS refrigeration circuit with CO_2 as primary and Dynalene as secondary refrigerant (discharge cycle).

2.3.2 Model 2: Volatile secondary refrigerant

In this model the heat transfer between the PCM and the HTF (liquid CO_2) is attained through latent heat as the HTF vaporises or condenses when it passes through the PCM tank. Since this is a latent heat exchange, there would be no change in temperature of the HTF along the tubes of the coil. The controlled variable in this case is the input mass vapour quality $\mathbf{x_{vap}}$ while the mass vapour quality at the outlet is the main indicator for energy transfer.

In this study, we suggest pumping CO_2 at −8°C and 27 bar (g)through PCM-6 for the charge cycle (Figure 5). For discharge, the pressure will be set to 32 bar (g), which will allow −6°C ice to condense CO_2 at −2°C and return to the liquid receiver (Figure 6).

A circulation ratio of 2:1 is considered. By calculating the heat transfer through the PCM coil, the mass flow rate of the pumped liquid (x = 0) can be determined based on the expected quality at the outlet, to be used for the calculation of the required pumping energy.

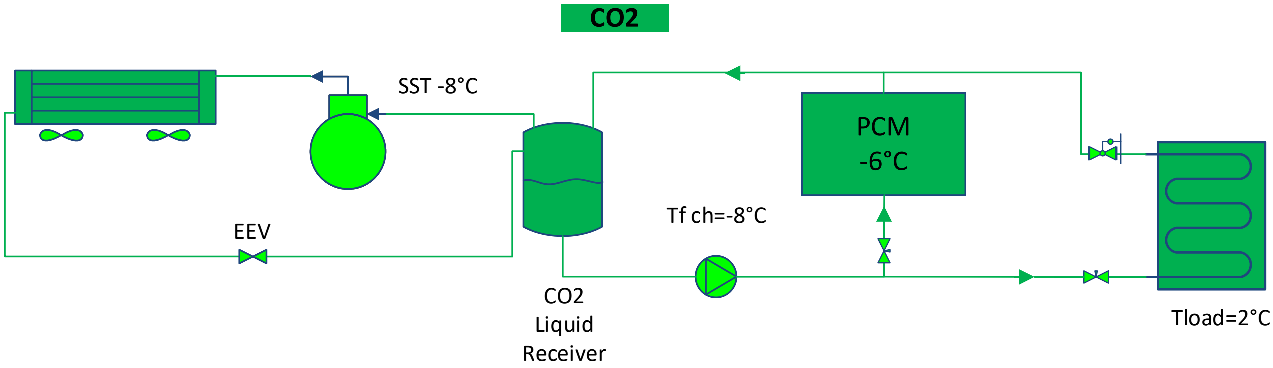

Figure 5. Refrigeration circuit with CO_2 as primary and secondary refrigerant (charge cycle).

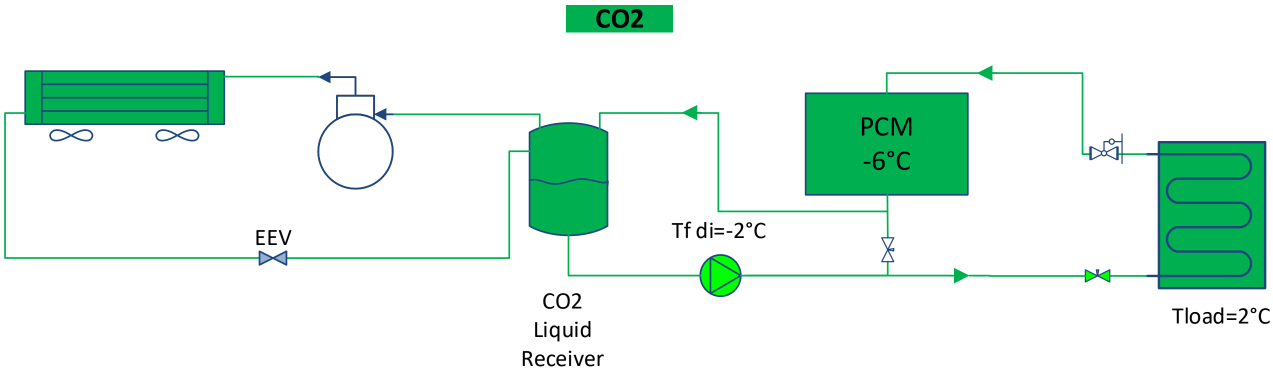

Figure 6. Refrigeration circuit with CO_2 as primary and secondary refrigerant (discharge cycle).

2.3.3 Outcome 1: Lower pumping power requirement

The pressure drop for single-phase-flow is a function of volume flow rate as well as other fluid properties such as density and viscosity. Change of these properties with respect to temperature is negligible. Thus, for a constant volume flow rate taken through the process, the pressure-drop and consequently hydraulic power remain constant.

The pressure drop for two-phase-flow varies in time since the mass vapour quality at the output varies together with the heat transfer rate. The Friedel correlation is applied for the calculation of the pressure drop for two-phase-flow at different vapour qualities for charge and discharge processes (Tahery & Ehterami, 2011).

The pressure drop of a two-phase flow is higher than the pressure-drop of a single-phase flow in a pipe of the same diameter at the same mass flow rate. However, since the desired heat transfer rate can be achieved with a significantly lower mass flow rate of a volatile secondary compared to a single-phase fluid, the pressure drop is significantly lower for the same thermal energy transfer rate. Figure 7 shows the correlation of heat transfer (thermal power) in a single tube pass with the required hydraulic power for the two different models. It can be observed that to achieve the same thermal power transfer, the required hydraulic power in the case of a two-phase flow is significantly lower than that of a single-phase mix.

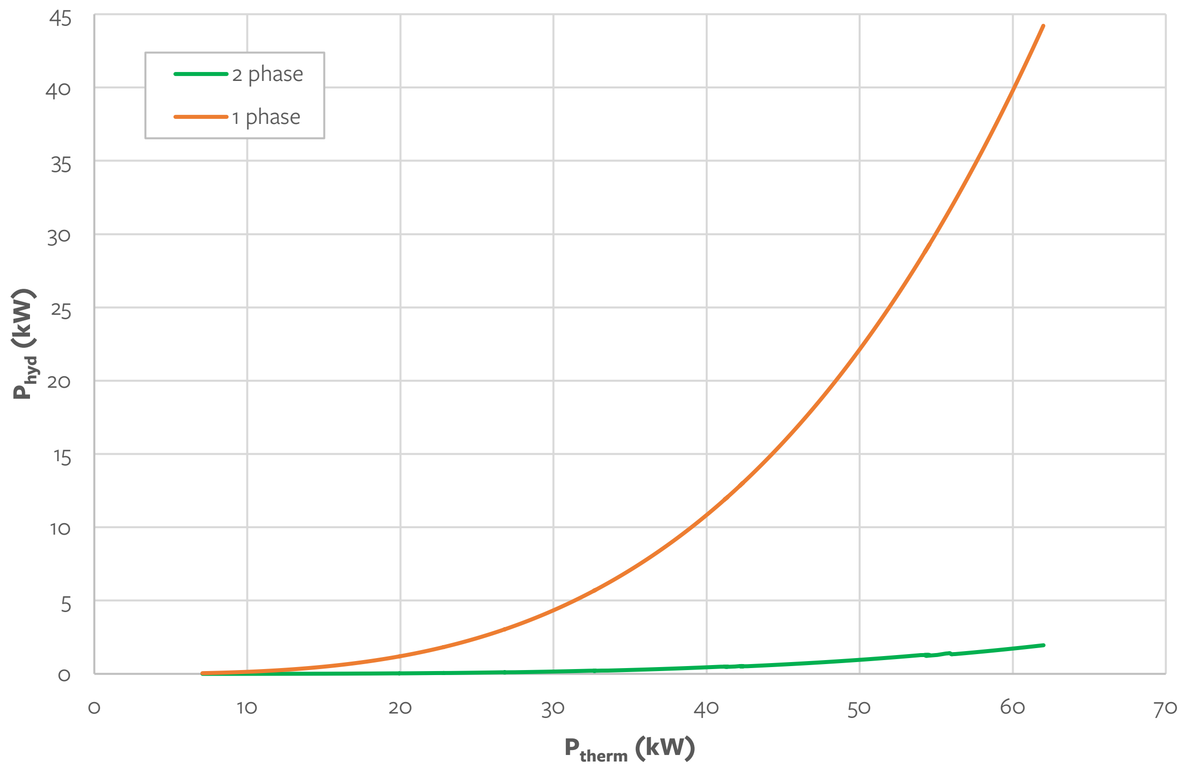

Figure 7. Correlation between thermal energy and hydraulic energy.

2.3.4 Outcome 2: Improved heat transfer

The overall heat transfer ratio between the HTF and the PCM is a function of the thermal resistance of the PCM and tube material in addition to the HTF flow inside the coil. The thermal behaviour of the pipe material is always constant. Thermal resistance of the PCM varies throughout the charge and discharge process relative to the volume of frozen/melted PCM formed on the tube. Therefore, the principal variable for the time loop is the amount of transformed PCM accumulated around the pipe. Depending on the thickness of this PCM layer, the thermal resistance of the PCM varies, monotonically increasing during both charging and discharging. Consequently, the heat transfer rate varies for each time step.

The heat transfer rate is calculated using ε-NTU method as the temperature of the fluid varies as it passes through the PCM tank.

The heat transfer coefficient of the two-phase mix is calculated using the correlation of Gungor and Winterton (1986) for small time steps based on the resistance of the PCM layer for that time step.

Variation of energy transfer with respect to volume flow rate is calculated for the same pipe layout for two phase flow and single-phase flow. It is evident from the result shown on Figure 8 that a target heat transfer rate can be achieved with a significantly lower volume flow rate of the volatile secondary compared to a conventional HTF.

Through the simulations we have established that not only the require pumping energy to charge and discharge a PCM ESS will be significantly lower when CO_2 is used as the HTF, but also a higher heat transfer rate can be achieved. This means that COP of discharge will significantly increase, resulting in improvement in the response of the integrated system at the peak demand period. In addition, a higher heat transfer rate allows better utilisation of the low-cost energy with the asset. The study demonstrated across Sections 3 and 4 puts a value on these improvements.

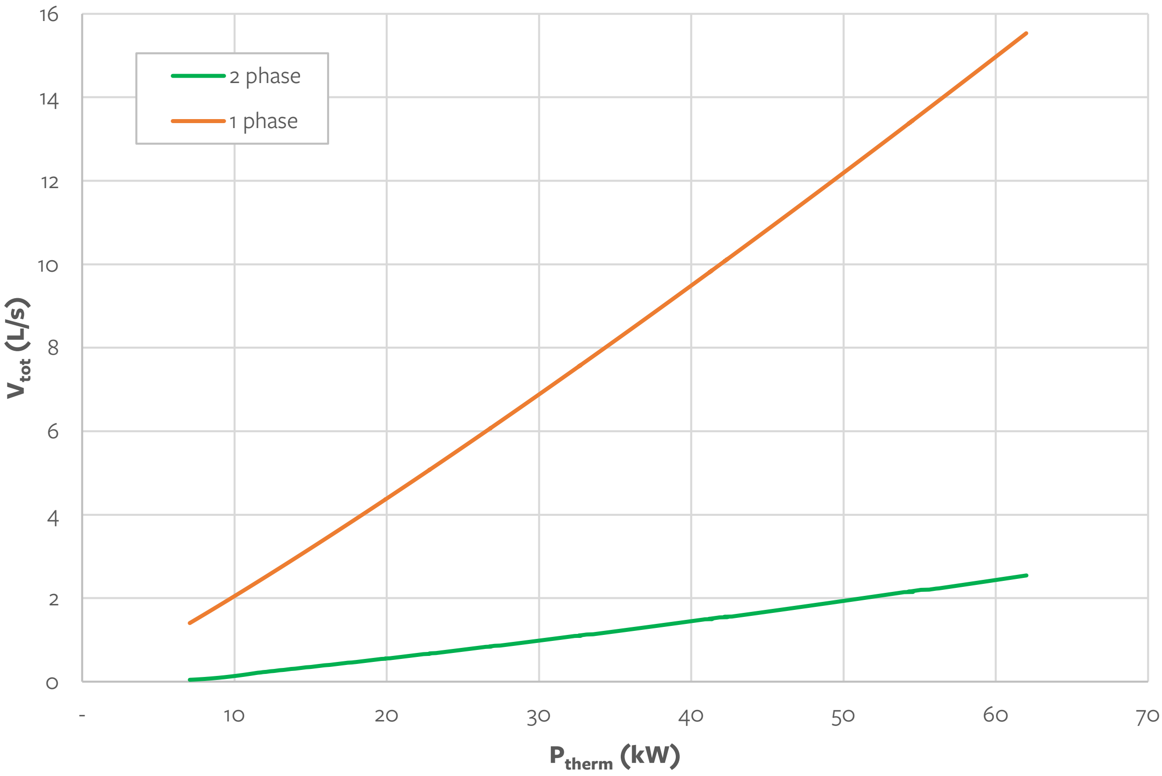

Figure 8. Correlation between thermal energy and volume flow rate for two-phase-flow GW86 and single-phase-flow.

2.4 Feasibility of implementation

As explained in Section 2.2, refrigeration plants with an integrated secondary loop have an efficiency disadvantage compared to systems with direct refrigeration. Consequently, in many applications where the presence of the primary refrigerant in the proximity of the cooling demand does not raise safety issues, the latter has become the dominant layout. For instance, in supermarkets, the use of a glycol loop is obsolete and direct expansion evaporators operating with the primary refrigerant are used in all cool rooms, freezers, and display cases. On the contrary, in an industrial processing plant where ammonia is the primary refrigerant, a glycol loop is in place to transfer the required cooling into processing rooms or cool rooms to eliminate the presence of the toxic and flammable refrigerant in occupied spaces.

Since supermarkets are predominantly equipped with pumped or direct transcritical CO_2 refrigeration systems, integration of PCM ESS with their existing system is not practical. Consequently, for the industry to reduce its carbon footprint by maximising the utilisation of renewable energy, PCM ESS using CO_2 as the HTF is the only practical option.

Introducing the new PCM ESS to such applications will enable such industries to reduce their peak demand in addition to energy cost saving, thanks to shifting the load to off-peak hours. In addition, it will make rooftop solar and PPAs a more viable option for such industries.

3 Case study: Milk cooling plant with integrated PCM ESS

A new refrigeration plant installed by Glaciem Cooling with integrated PCM ESS at Misty Downs Dairy was selected for evaluation of the expected improvements in the performance of our new concept.

Misty Downs Dairy is located close to a creek on Cleland Gully Road at Mount Compass South Australia. There is a capacity to milk up to 250 cows twice a day. This number varies throughout the year during calving season and can be as low as 150 cows. Every cow produces up to about 25 litres of milk on average every day. The total volume of milk produced per day is 3000–6500 litres.

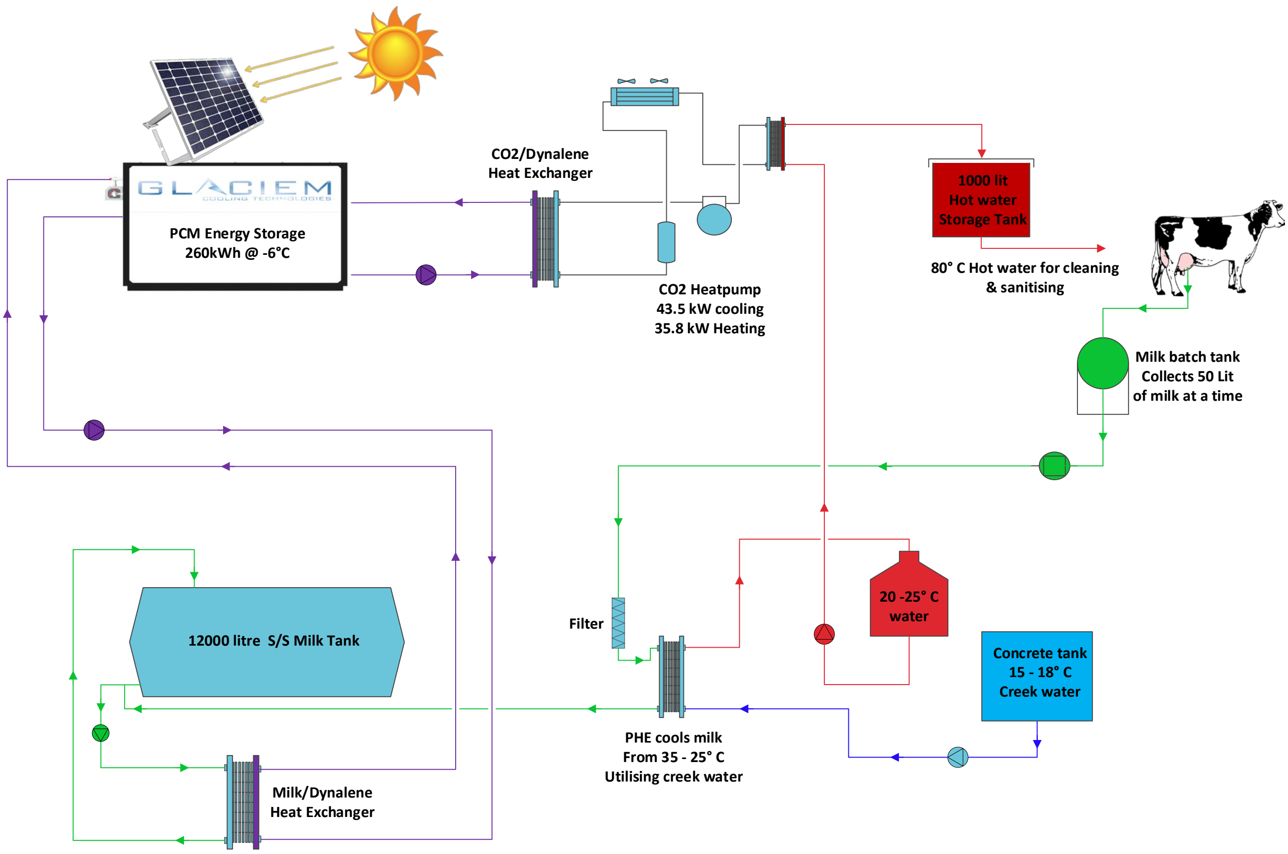

Figure 9. Overall layout of milk cooling plant at Misty Downs Dairy.

Glaciem Cooling installed a prototype rapid milk cooling and chilled milk storage plant on the site. The system included a CO_2 heat pump, PCM thermal storage, hot water storage and PV solar panels. The system demonstrated the ability to use renewable energy and natural refrigerants to efficiently and cost-effectively deliver advancements in milk production. The ability to rapidly use stored energy allows for timely cooling of milk. In conjunction with an ability to provide security from interruptions in the electrical grid for the storage of milk, the system has successfully increased the quality of milk.

Figure 10 demonstrates the timing of the two milking processes and the cleaning processes at Misty downs. VAT CIP can take place any time between the morning and afternoon milking depending on when the milk is transferred to a production facility. Each milking period can be up to 3 hours and varies depending on the number of cows. The electricity tariffs for the entity charges a lower price during off peak hours. Availability of solar energy is highlighted on the diagram as well.

Table 2. Specifications of the refrigeration system at Misty Downs Dairy.

Misty Downs specifications	Value	Units
Milk storage vat volume	12,000	L
Daily milk production	3,000–6,500	L
Number of cows	150-250	cows
Refrigeration cooling capacity	43.5	kW
Heat pump heating capacity	35.8	kW
PCM charging capacity	42	kW
PCM tank charge capacity	260	kWh
PCM tank discharge rate Capacity	42	kW
Hot water storage temperature	80	°C
Daily water heating load	60.7	kWh
Stored hot water	800	L
Typical daily hot water usage	700	L
Milk starting temp	35	°C
Milk cooled temp	4	°C
Milk cooling time (old)	2–3	h
Milk cooling time (new)	Instant to 8°C	
	20 min to 4°C	
Installed solar system capacity	20	kW
Solar system output—average	80	kWh/day
Solar system output—max Summer	130	kWh/day
Daily cooling load	249.3	kWh
Old milking cooling length	3–4	h
New milk cooling length	Instantaneously	

Water heaters are timed to heat the water twice a day one of which occurs during off-peak for lower cost of energy. Milking equipment is cleaned with a combination of cold water, hot water and detergents after each milking. The amount of hot water used at each cleaning is up to 200 litres. Milk is taken from the vat every day between the morning and afternoon milking. After the milk is taken, the vat will be washed automatically in five stages. Two of these stages require about 200 litres of hot water.

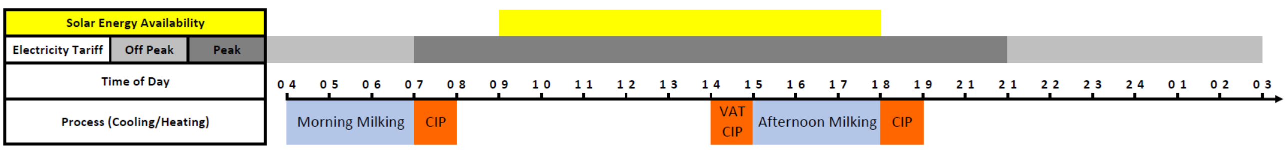

Figure 10. Milking and equipment wash down schedule at Misty Downs Dairy.

3.1 PCM ESS integration

The excess solar each day is stored as thermal energy in the PCM tank and is used to reduce electrical power consumption during non-daylight hours. The capacity of the store changed daily with fluctuations in daily solar irradiance and therefore electricity production. Days of high solar electricity production aided in increasing the energy store in the PCM tank. On days where the solar electricity production was low, the system was able to use the stored capacity from previous days. Figure 11 shows the State of Charge (SoC, %) of the PCM tank over a four-day period. The red and green boxes illustrate periods of tank discharging and charging respectively.

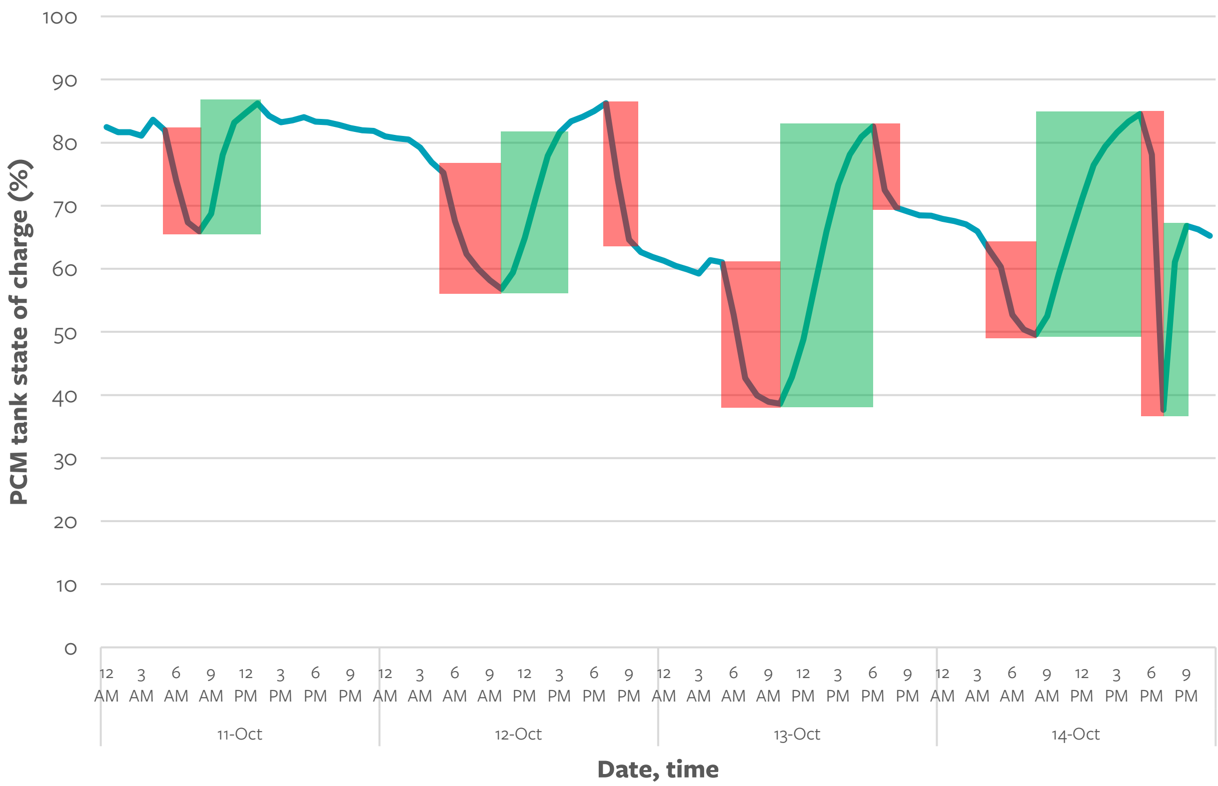

Figure 11. PCM tank state of charge over a four-day period.

3.2 Electrical power time shift

The system was able to shift the electrical power time of use. Figure 12 below illustrates the effective transition of electrical consumption. The refrigeration system was activated during solar electrical power production to charge the PCM thermal energy store (purple). This stored energy was discharged during the two daily milking processes (yellow). A further heating cycle occurred each morning, taking advantage of off-peak electricity prices to ensure hot water during the morning CIP. The stored energy in the tank was utilised to maintain the milk at 3°C (grey) throughout the night without the need to energise the compressor.

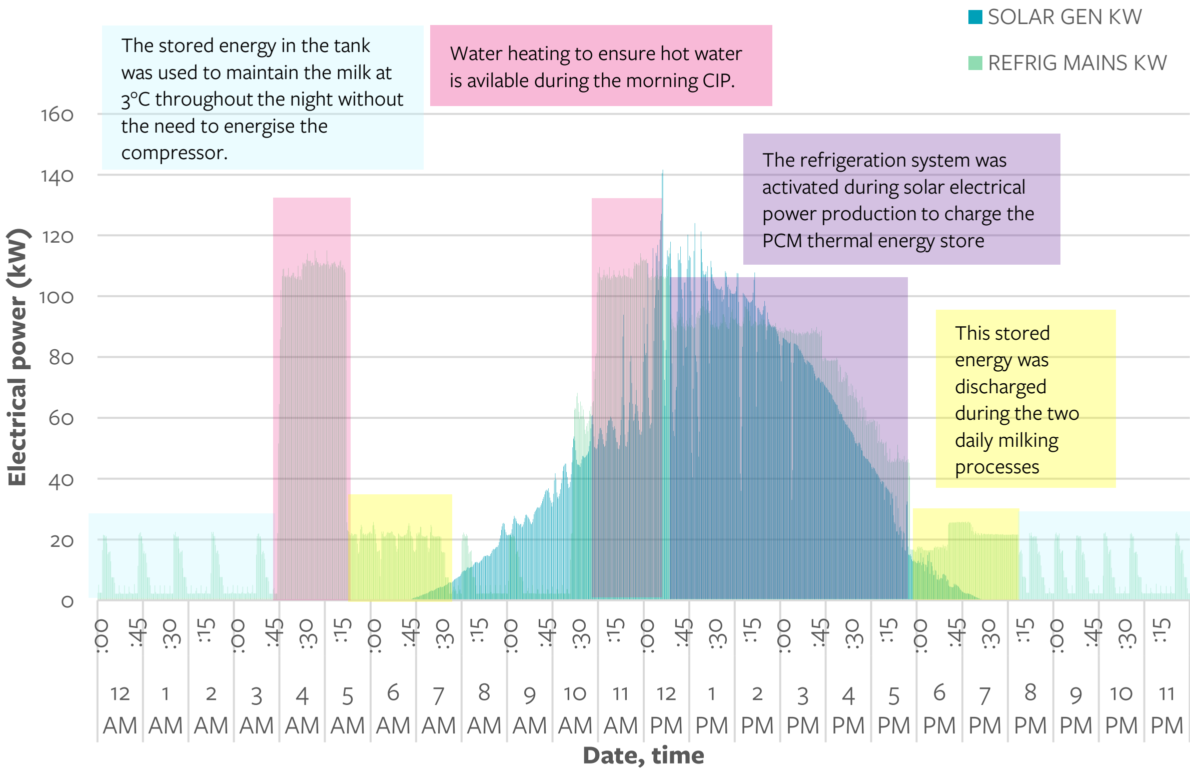

Figure 12. Typical daily refrigeration power consumption versus solar power production (based on data for 13 October 2020).

3.3 Validation of MATLAB model—Dairy monitored data

The monitored data from the dairy was consistent with the results evaluated using the model produced to represent the performance of PCM ESS with Dynalene as HTF. The MATLAB model has the attributes of the Dairy PCM system. Coil size, tube spacing, and fluids heat transfer properties were all inputted to the model.

The validity of the predicted heat transfer performance by the model during charge and discharge using Dynalene as the HTF was proven when compared to the monitored data. The charge rate and the outlet temperature of the Dynalene loop on the outlet of the PCM tank are good indicators to demonstrate the validity of the model. Comparisons of these parameters, Figure 13 and Figure 14, show that the model has an acceptable level of accuracy.

The output of the model of the CO_2 as an HTF was compared to the Dynalene-as-HTF model. The main difference between the two models is the approach to the heat transfer calculations from the HTF. The modelling of the heat transfer through the PCM and tank along with the storage capacity remain the same for both models. Figure 15 and Figure 16 illustrate the relative performance of the Dynalene HTF and CO_2 HTF models.

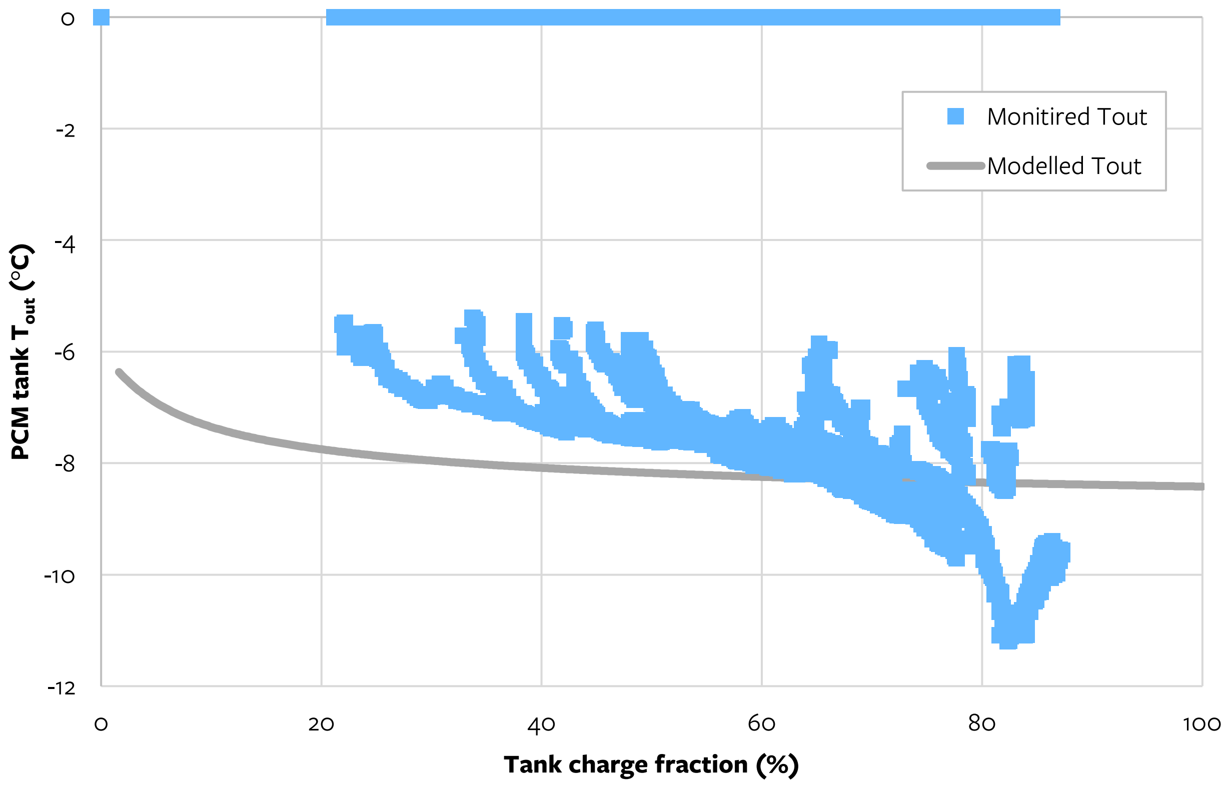

Figure 13. Dynalene loop PCM outlet temperature versus charge percentage.

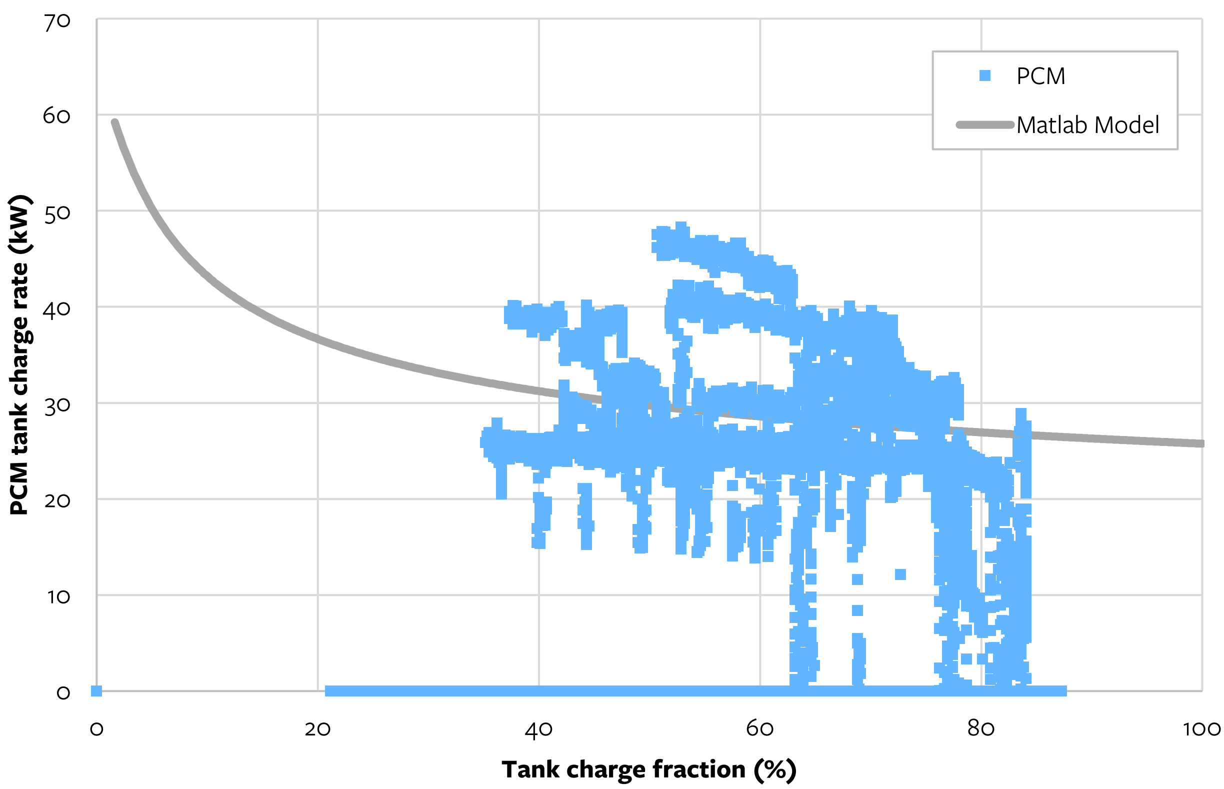

Figure 14. PCM ESS charge rate versus charge percentage.

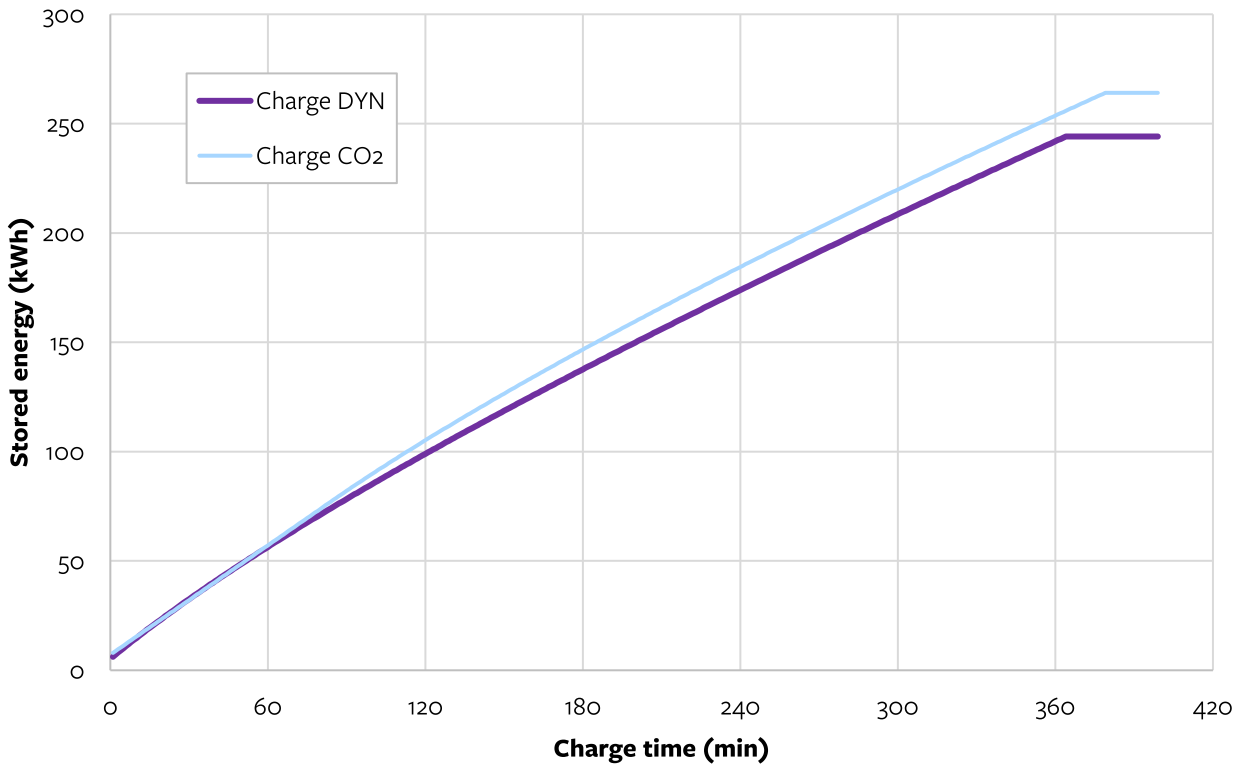

Figure 15. PCM tank stored energy versus charge time for Dynalene HTF and CO_2 HTF.

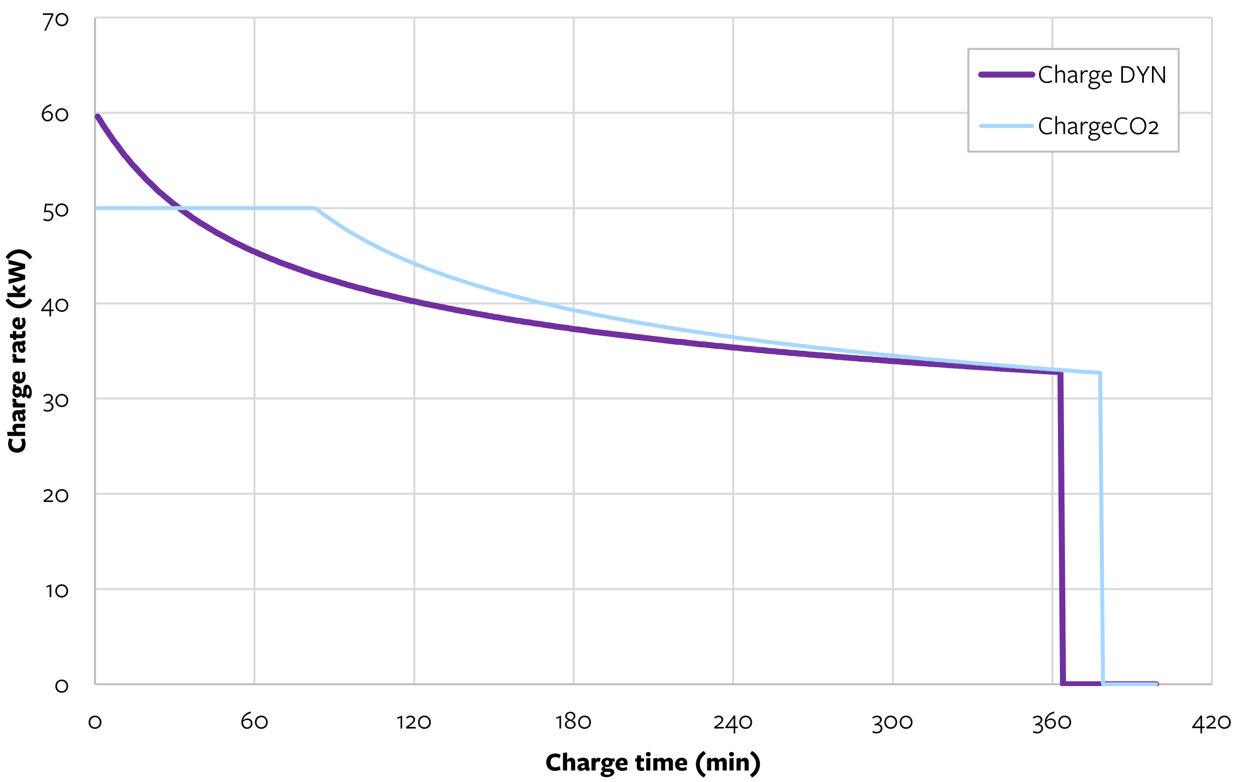

Figure 16. PCM tank stored energy versus charge time for Dynalene HTF and CO_2 HTF.

4 Concept design of PCM ESS with CO_2 as HTF for Misty Downs Dairy

4.1 Old system versus new system concept

The concept design of the existing refrigeration system at Misty downs is demonstrated in Figure 17 and Figure 18 during charge and discharge modes, respectively. The system consists of a heat pump chiller that interacts with the milk and the PCM ESS through a secondary refrigerant loop with Dynalene HC-30 as the HTF.

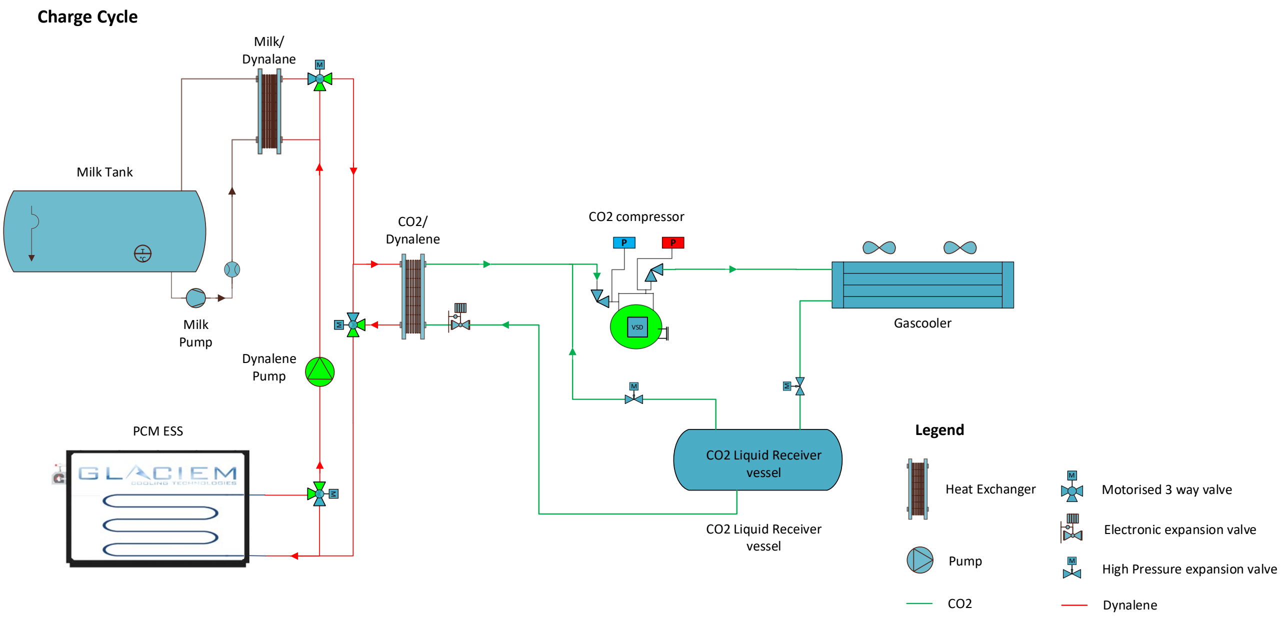

Figure 17. Misty Downs existing refrigeration plant layout in charge mode.

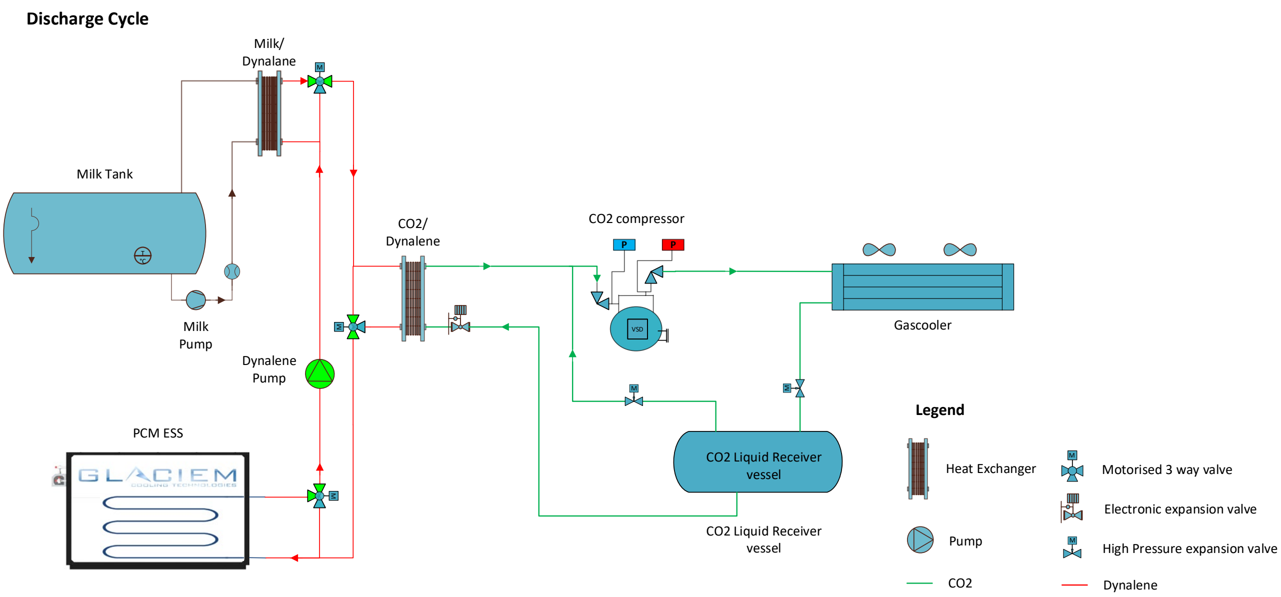

Figure 18. Misty Downs existing refrigeration plant layout in discharge mode.

The new concept design of the refrigeration system with integrated PCM ESS using CO_2 as the HTF is shown on Figure 19 and Figure 20 for charge and discharge cycles, respectively.

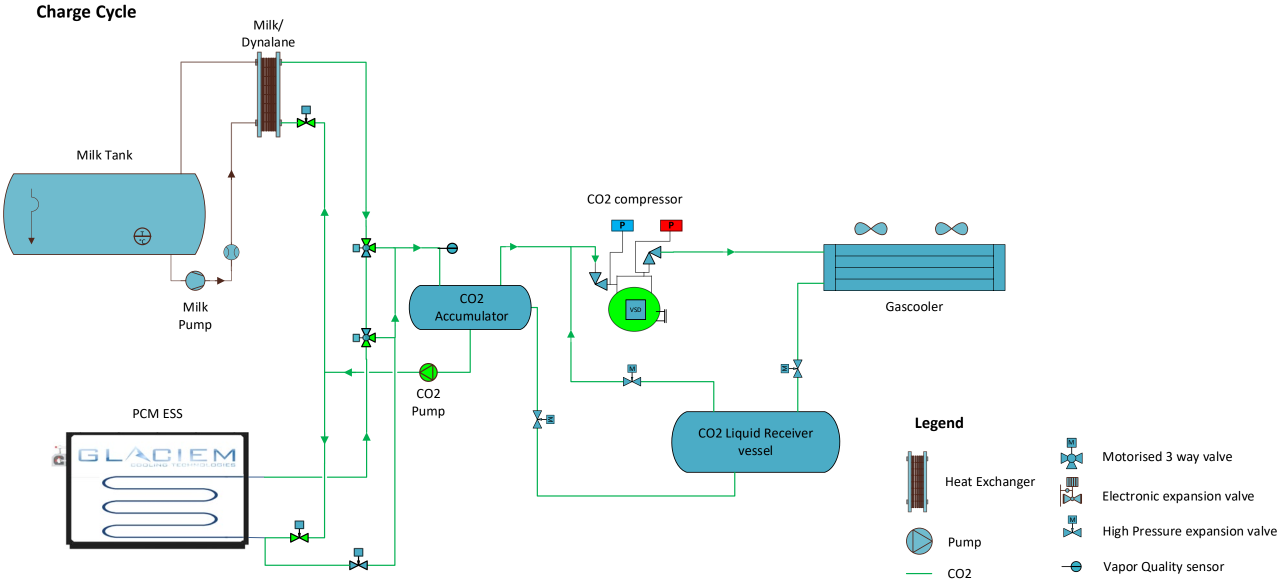

Figure 19. Misty Downs plant layout with CO_2 as HTF in charge mode.

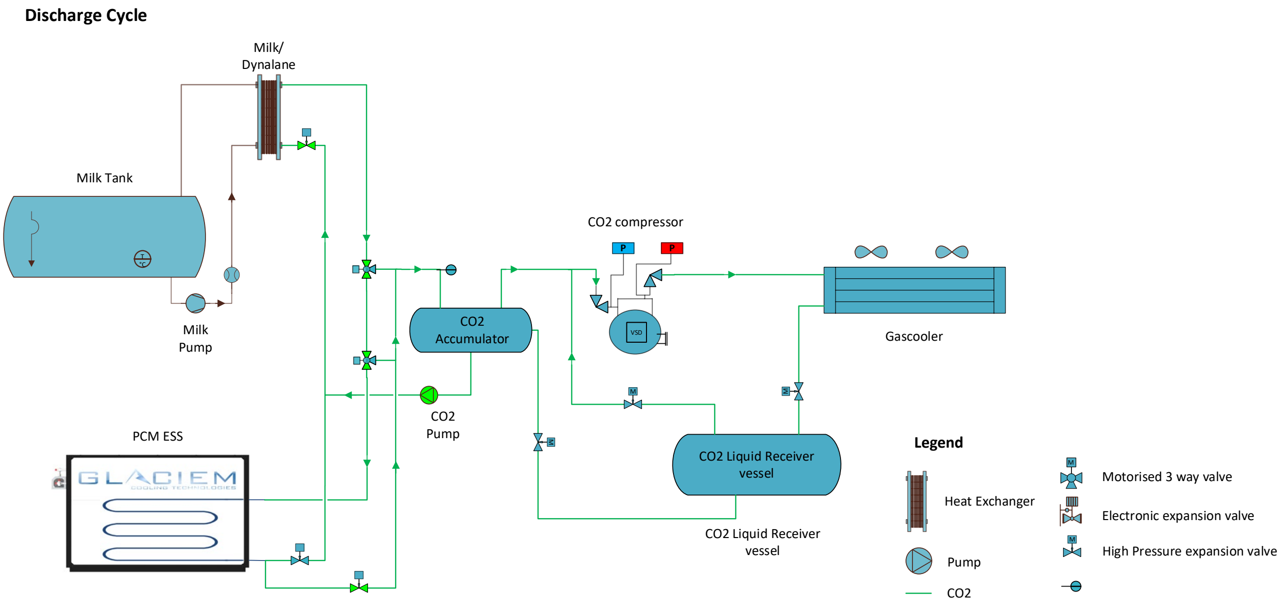

Figure 20. Misty Downs plant layout with CO_2 as HTF in discharge mode.

4.2 System components

The main component of the new design is the coil inside the PCM tank. Considering the calculated improvements and to have a fair comparison, the new coil is designed such that it fits in the existing PCM tank. We have specified the same heat pump/chiller that is currently operating at Misty Downs Dairy. The main variations across the two systems include:

- CO_2 high pressure pump instead of Dynalene pump
- CO_2 Dynalene evaporator is eliminated
- Dynalene/milk heat exchanger is replaced by a CO_2/milk heat exchanger
- three-way valves on Dynalene loop are replaced by high pressure three-way and two-way valves suitable for CO_2
- pipe work from plumbing copper is changed to K65 (suitable for high pressure) tubes at smaller sizes
- all of the instruments remain the same and are included in the heat pump cost except for a vapour quality sensor required for controlling the feed ratio.

All of the components are selected according to the coil specifications. Figure 21 shows the new coil design that has been quoted by Modine, a European manufacturer of evaporator coils. The designed coil consists of two separate coils of 14 rows and 12 passes, which are combined in a staggered layout to achieve the desired tube spacing.

The major components for the two systems are listed in Table 3 and Table 4, including their prices.

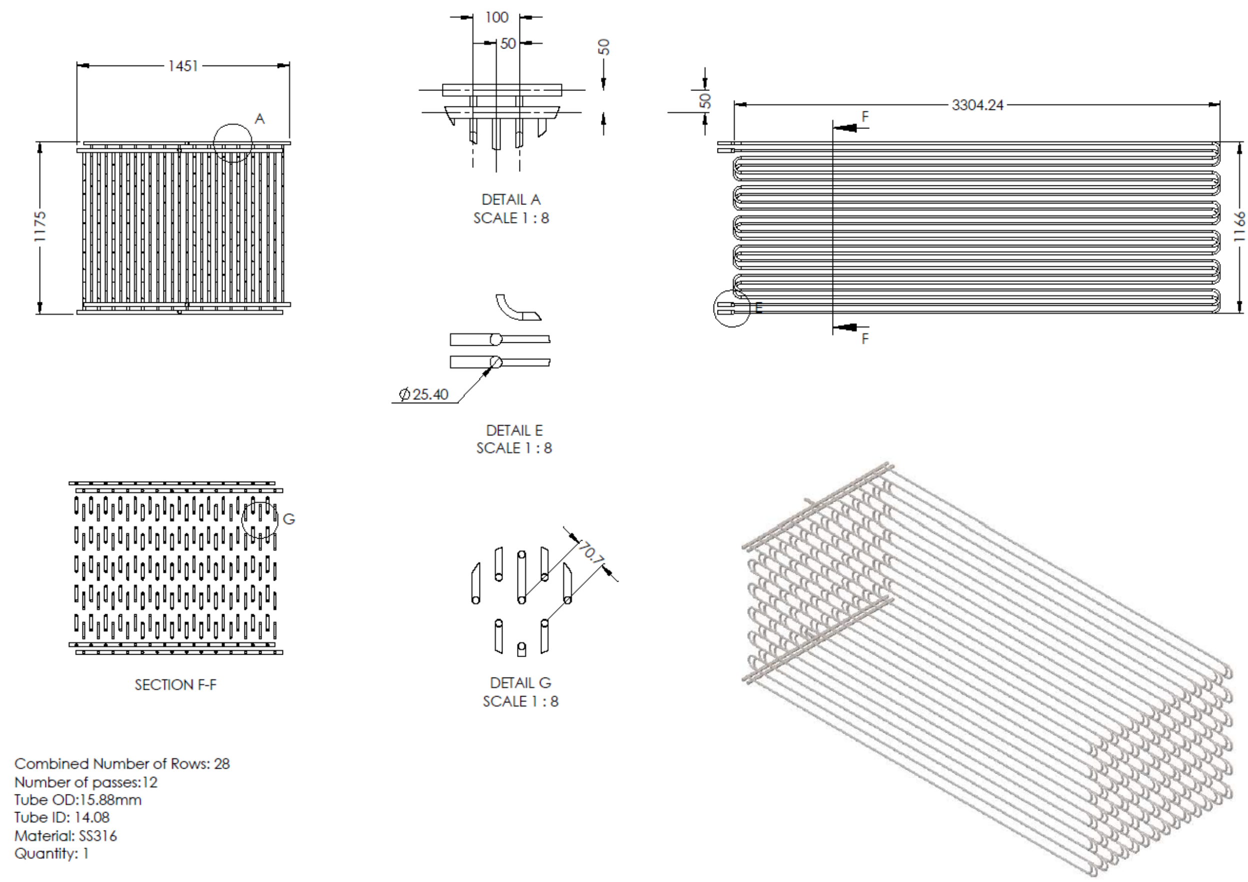

Figure 21. High pressure evaporator coil for CO_2.

Table 3. Equipment schedule for existing refrigeration plant at Misty Downs.

Component schedule Dynalene secondary loop			
Equipment/valve	**Specification**	**Qty**	**Price**
			($)
PCM ESS tank	Build and material	1	20,000.00
PCM ESS coil	304 stainless steel 16 bar rated	1	13,889.00
Co_2 heat pump chiller	40 kW	1	45,000.00
Dynalane/CO_2 heat exchanger	Swep F250ASHx54/1P-NSC-H	1	2,300.00
Milk/Dynalene heat exchanger	WA HX	1	3,500.00
Dynalene pump	Grundfos CRIE 15-2	1	3,250.00
Motorised three-way ball valve	Belimo 2″ three-way valve + actuator	3	1,500.00
Pipe work and fittings	Standard copper pipe	N/A	6,500.00
Total			**95,939.00**

Table 4. Equipment schedule for the new concept design at Misty Downs.

Equipment/valve	Specification	Qty	Price
			($)
PCM ESS tank	Build and material	1	20,000.00
PCM ESS coil	304 stainless steel 60 bar rated	1	13,314.00
CO_2 heat pump chiller	40 kW	1	45,000.00
CO_2/milk heat exchanger		1	5,000.00
CO_2 liquid pump	Hysave 860-SS-080-VSD-EA-K65	1	3,680.00
CO_2 accumulator vessel		1	5,500.00
Motorised 3 CO_2 three-way ball valve	Refrigerant high-pressure three-way valve 7/8″ with actuator	2	960.00
Motorized 3 CO_2 two-way ball valve	Refrigerant high-Pressure two-way valve 7/8″ with actuator	2	864.00
Vapor quality control sensor	For 7/8″ copper + cable	1	568.70
Pipework and fittings	K65 copper tube and fittings	N/A	5,500.00
Total			**100,386.70**

The cost of implementation of the new system is 4.6% higher than the cost of the original system. Essentially, the capital cost savings returned by eliminating the secondary loop components, is cancelled out by the extra cost of incorporating a pumped CO_2 system.

4.3 Performance comparison

An economic analysis of the operating cost of converting the existing Dynalene-based PCM ESS at the dairy to the new CO_2-based configuration has been performed.

For simplicity, several assumptions were made about the site and the operation of the refrigeration system. These assumptions include:

- The 20-kW solar system (as installed at the dairy) is solely used in conjunction with the refrigeration plant; i.e. all non-refrigeration loads are ignored.
- The operating schedule remains the same as monitored in the past. Efficiency gains for pumping power and compressor efficiency are considered but the ability to store more energy thanks to the increased compressor capacity or cooling at different times was not considered.
- Energy savings are based on the installed solar and refrigeration components.

Monitored data from the period between August 2020 and August 2021 was used to establish a baseline electrical load. The monitored electrical data for compressor power, pumping power, control power, refrigeration mains power and solar power was disaggregated.

The cost of electricity was determined, based on the electricity tariffs associated with the site, as shown in Table 5.

Table 5. Dairy electricity tariff structure.

Charge	Charge (incl GST)
Peak usage	44.602 c/kWh
Off-peak usage	28.025 c/kWh
Solar feed-in	8.0 c/kWh (decreased to 6.0 c/kWh in 2021)
Supply charge	98.747 c/day

The cost–benefit of the proposed system was calculated by modifying the electrical power consumption of the pumps, compressors and condensing unit based on the performance characteristics calculated in this case study and presented in Appendix A and B.

The grid electrical energy consumption based on the electricity price was calculated for each month to demonstrate savings trends.

Figure 22 illustrates the potential electrical energy savings using CO_2 as a secondary HFT through the PCM ESS. By providing cooling directly to the PCM without a sensible secondary fluid, the refrigeration system can operate at a higher efficiency. The use of the charging cycle during high solar power input results in lower-cost charging. The reduction in pumping power thanks to the higher heat transfer rate of the two-phase flow, reduces the electrical power consumption throughout the charge and discharge period. Considerable cost savings are recognised during discharge periods, which usually occur during high electricity price periods.

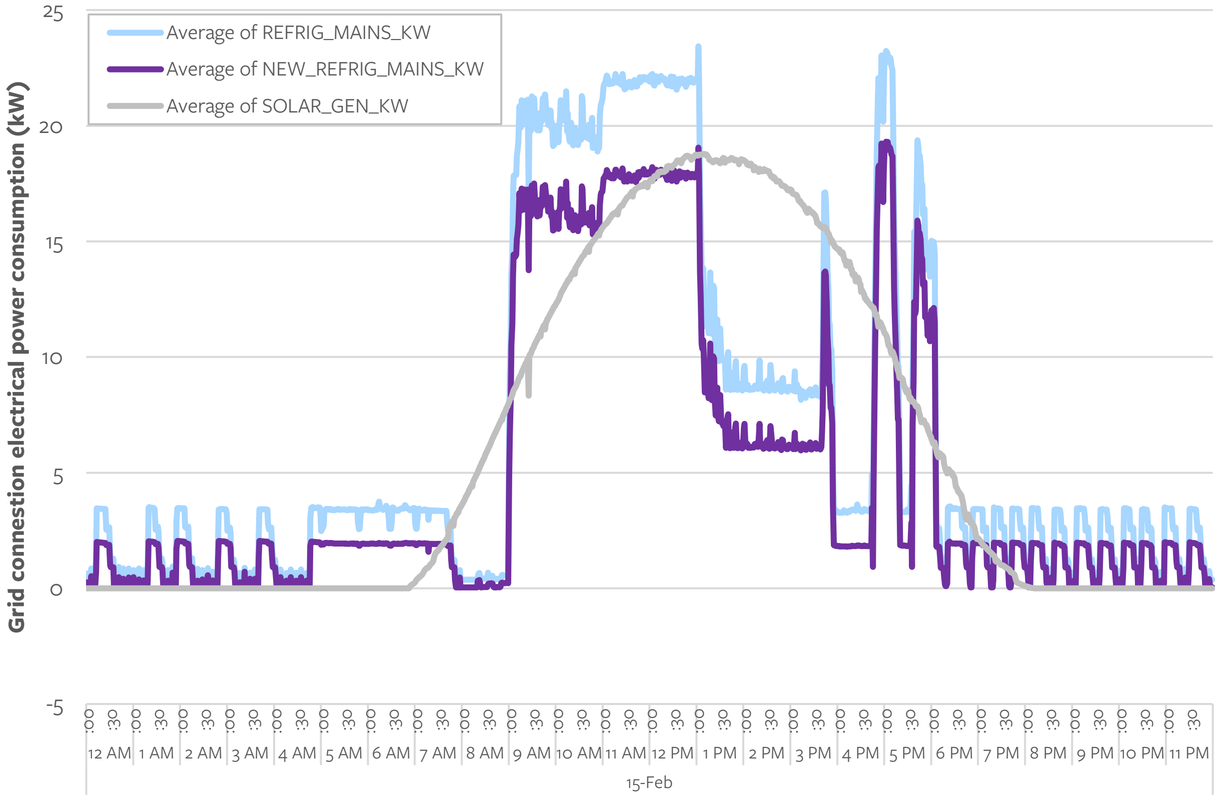

Figure 22. Electrical power consumption of original (Dynalene-based) versus proposed (CO_2-based) system for 15 February 2021.

The timing and the size of loads are critical to the daily electrical power cost. Figure 23 shows that there are significant financial savings obtained by charging during solar electricity production, thanks to the lower consumption of peak-price power.

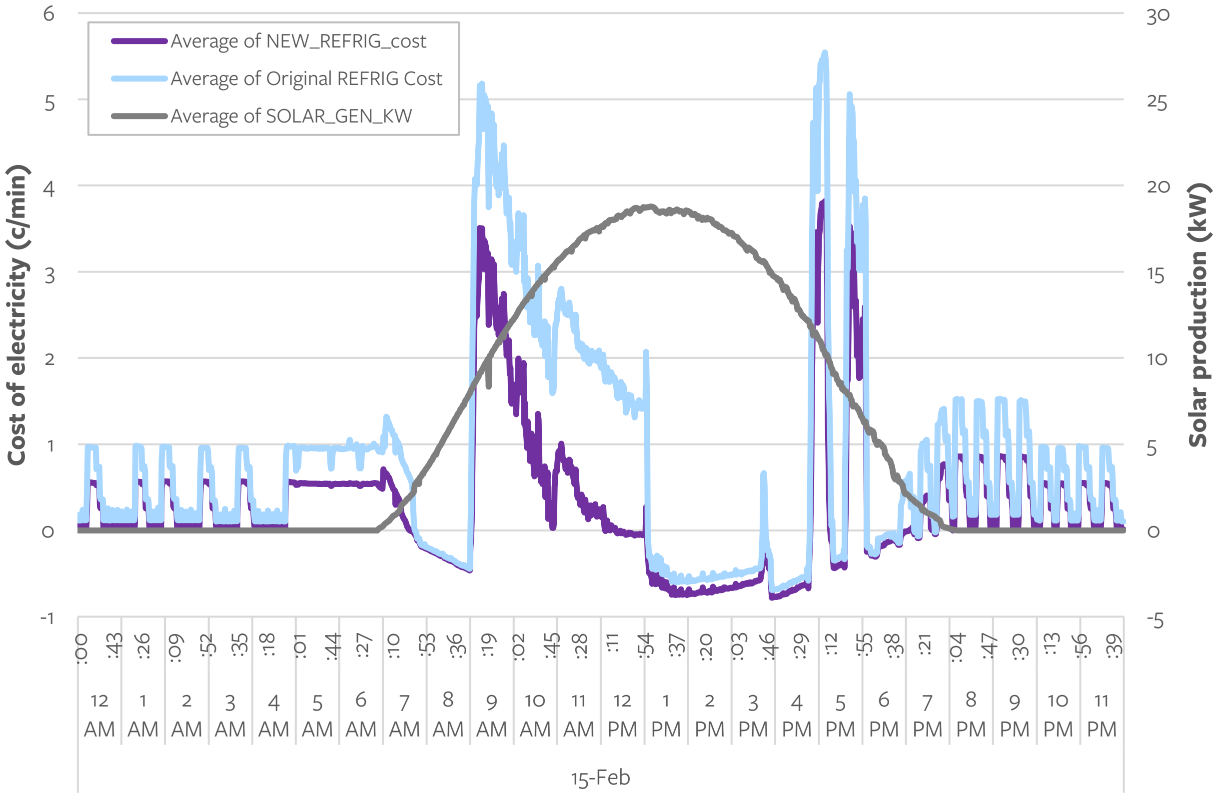

Figure 23. Power cost comparison for 15 February 2021.

Figure 24 and Figure 25 compare the yearly trends for both electrical power usage and electricity costs for the existing system and the proposed system.

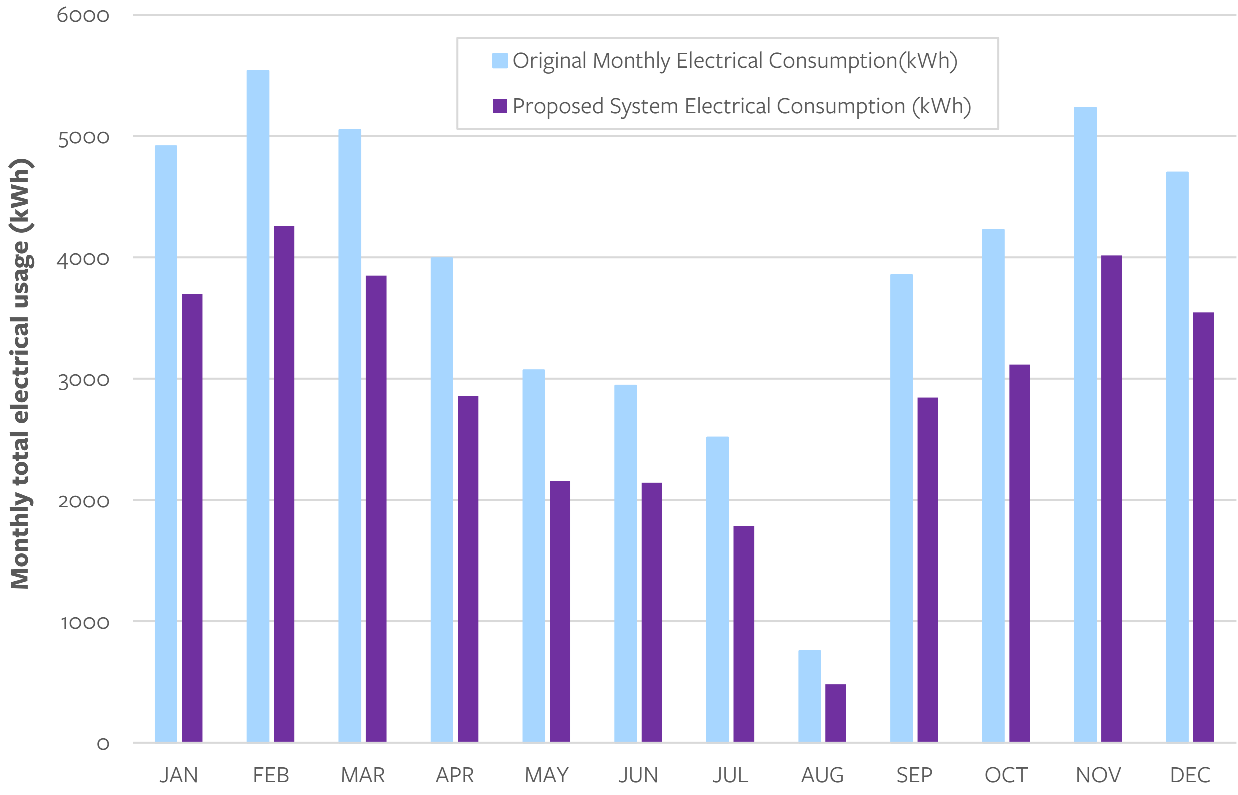

Figure 24. Monthly electricity usage of original (Dynalene-based) versus proposed (CO_2-based) system.

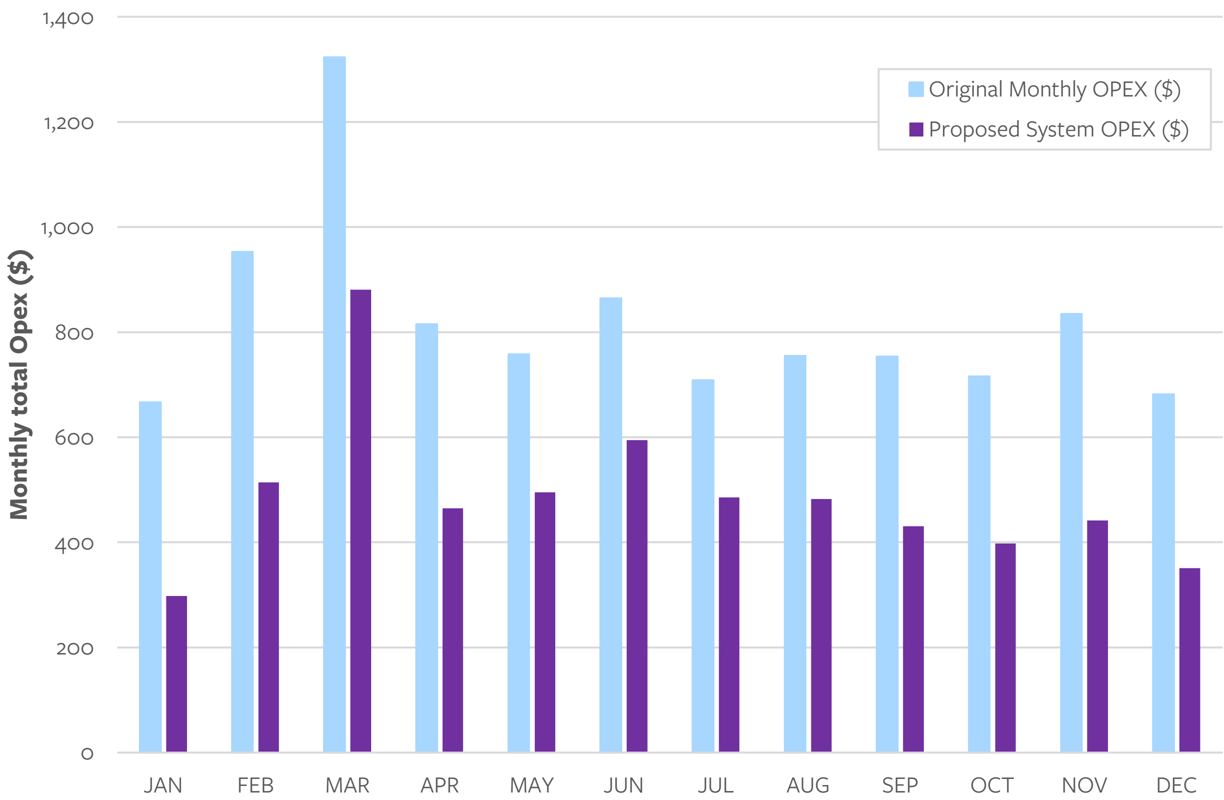

Figure 25. Monthly operating costs of original (Dynalene-based) versus proposed (CO_2-based) system.

It is observed that the electrical power consumption will be reduced by 26% throughout the year. There is little variation in the percentage of saved energy from month to month. The average reduction in the purchase cost of the energy will be 41%. The reduction in electrical cost was greater in summer months. The increased solar output of the PV system in summer was able to meet the whole refrigeration system's energy requirements more often in these months. Table 6 provides the annual operating costs and electrical consumption with the expected electrical and cost reductions.

Table 6. Annualised statistics.

	Operating cost	Grid electrical consumption
	($)	(kWh)
Original system	9,823	46,794
Proposed system	5,836	34,764
% reduction	41%	26%
Saving	**3,990**	**12,029**

4.4 Payback period and annual saving

The increase in the cost of implementation of the PCM ESS with CO_2 as an HTF is minimal (4.6%), accounting for $4,447 above the cost of the existing system. An annual operating cost saving of $3,990 means that the payback period for the additional capital expenditure is 1.1 years. Over 10 years of ownership, there is a $35,424 cost benefit for using CO_2 as the HTF above Dynalene for the PCM ESS systems.

Table 7. Payback and long-term ownership costs.

	Dynalene HTF PCM ESS	CO_2 HTF PCM ESS
Purchase cost	$95,939	$100,386
Annual operating cost	$9823	$5836
Payback period		1.1 years
10-year ownership cost	$194,178	$158,754

5 Conclusion and future steps

5.1 Conclusion

Within a collaborative project conducted by the University of South Australia and Glaciem Cooling Technologies supported by the RACE for Business program, we have introduced a new way of integrating PCM ESS with processes involving cooling, as a means of flexing their energy consumption. Through a desktop study verified by actual data acquired from an existing cooling plant at a commercial dairy, we have demonstrated the improvements of our proposed layout compared to the conventional PCM ESS.

Within this report we have demonstrated the expected savings returned by incorporating the new technology for integration of PCM ESS at an existing commercial application. The collected data from the refrigeration system of a dairy with integrated PCM ESS is used as a baseline and the cost savings returned by implementing the new design is evaluated. We have identified that the energy cost savings justify the slight increase in the cost of implementation of the new system. We have established that the implementation of the new system will return $3,990 of cost savings annually compared to the conventional PCM ESS. These savings make the integration of PCM ESS a more viable strategy to enable load flexing for power consumers across the HVAC-R sector. Considering the scale of energy consumption by the HVAC-R sector, deployment of this technology across the sector is going to alleviate the stress on power network by reducing the export of non-synchronous generation by power consumers. Moreover, this improvement will be a considerable step towards achieving net zero emissions.

5.2 Future steps

We identified that supermarkets which operate on transcritical CO_2 refrigeration systems with liquid CO_2 as the HTF across the store are more efficient than those operating on transcritical CO_2 systems with direct expansion evaporators (Karampour, et al., 2017). For such systems, integration of PCM ESS requires lower capital expenditure and will return maximum saving based on the demonstrated improvements compared to the conventional PCM ESS.

By evaluating the peak demand reduction and energy cost savings for a typical supermarket integrated with the new PCM ESS as well as rooftop solar, we can build a compelling investment opportunity for the sector.

Having eliminated the essence of the sensible HTF, it is now possible to have a higher melting/freezing temperature to meet the load at 3°C. Referring to Configuration 4, explained in Section 2.2, during discharge even if the temperature of PCM is −2°C there will be enough temperature difference to have effective cooling at 3°C. To freeze a PCM at −2°C, the compressors can operate at −5°C SST. Therefore, it is possible to have a higher COP of charge. As a result, the same storage capacity can be achieved by a smaller refrigeration system resulting in lower cost of implementation with less input energy required.

Consequently, developing a PCM that is stable at −2°C will further enhance the improvements that have already been demonstrated.

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