Final report

The cost of manipulating temperature within the meat supply chain

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Abstract

The red meat supply chain is complicated and product is stored and transported at different temperatures. A Federal Government funded study estimated that cold chain deficiencies result in 3.5% losses which equates to $0.14 billion pa in sheep meat (26 ktpa) and $0.42 billion pa for beef and veal (78 ktpa). A recent report estimated a saving of $3.6 million pa for a single domestic supply chain if the UTAS/MLA shelf life model was used to design the logistics, due to the reduction in waste. However, it assumed that all temperatures remain the same. This project provides industry the costs and benefits of changing temperature within the meat supply chain, so that both shelf life and the cost of temperature control can be balanced. A key output of the project is a user friendly model with the option to change key parameters that impact the $ / tonne cost for keeping meat cold at temperatures between -24 to -12 ^{o}C for frozen products and -2 to 10 ^{o}C for fresh product. To model the cost of the keeping product cold, use this link https://myenergy.tech/cold-chain-cost-calculator/ .

Executive summary

Background

The red meat supply chain is complicated, and product is stored and transported at different temperatures. A Federal Government funded study estimated that cold chain deficiencies result in 3.5% losses which equates to $0.14 billion pa in sheep meat (26 ktpa) and $0.42 billion pa for beef and veal (78 ktpa). A recent report estimated a saving of $3.6 million pa for a single domestic supply chain if the UTAS/MLA shelf life model was used to design the logistics, due to the reduction in waste. However, it assumed that all temperatures remain the same.

Objectives

The project presents the findings of a comparative analysis of the costs of each stage in the red meat supply chain. The results of this project are to be used for exploration cold chain improvements to extend shelf life and to determine any significant impacts such as dramatic increases in energy cost or use. This project will inform industry of the comparative cost and benefits of changing temperature for individual segments within the meat supply chain to control shelf life or the cost of frozen meat.

Methodology

Using the coefficient of performance (CoP) values for a typical refrigeration loop, and indicative values for power at five refrigerated stages in the red meat supply chain, the following costs of cooling were calculated as $ per kilowatt-hour ($/kWh) of cooling. For this analysis, the accuracy of the CoP at a specific target temperature associated with the performance and operation of the cold store infrastructure is more important than the actual technology type that is used. The detailed thermodynamic modelling was used to create an interactive EXCEL model of the supply chain taking the cost to run the cooling system as well as losses from the containment system due to conductive, convective and entry way openings (i.e. how efficient the storage infrastructure is at preventing energy from entering the storage system).

Results/key findings

The output of the project consists of a simple (MS Excel) model with options to select key variable parameters that impact the $ / tonne cost for keeping meat cold at different locations at temperatures between -24 to 10^{o}C, throughout the cold chain at processor facilities versus other segments.

For vertically integrated cold chains, where the operator has control over large stationary refrigeration plant as well as distributed storage, trucking, shipping, or other freight modes, changes to the supply chain can be made to take advantage of higher efficiency or lower power costs to reduce overall supply chain costs. A large refrigeration plant at a processor can take advantage of lower power costs and higher efficiency. Large refrigeration systems can take advantage of their higher COP to chill product to a lower temperature with the remaining stages in the supply chain maintaining a target temperature band, reducing the cooling load on these lower COP, higher cost of cooling stages.

Benefits to industry

Combining an understanding of how temperature control in the supply chain affects both the shelf life of chilled meat, and the costs of achieving that temperature, at various points in the supply chain, allows processors and product owners optimise both shelf life and refrigeration costs, for each supply chain. The relative costs and shelf life loss through sea freight against air freight is a case where the use of these models together can help exporters optimise make better decisions about how to transport product.

There are numerous ways that processors can improve their practices in refrigeration systems and practices, and in tracking their product through supply chains

Future research and recommendations

As an extension of this project, we recommend further work with cold chain operators to investigate the impact and cost of holding product at a different temperature relative to waste.

Where changing the refrigeration temperature is not feasible, the following is recommended to improve refrigeration performance and reduce costs.

- Red meat processors running a covered anaerobic lagoon (CAL) and flaring biogas should investigate biogas generation to reduce the large baseload power demand (kVA) and volume (kWh) from refrigeration, making considerable savings on power and cooling costs
- Variable speed drives (VSDs) on refrigeration system compressors
- De-superheaters to deliver hot water and ease pressure on the site boiler
- Dry coolers and adiabatic coolers to condense the refrigerant while reducing cooling water costs

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1. Background

Review of Previous Works

Meat and Livestock Australia. (2020) *Managing the cold chain and shelf life of chilled vacuum packed beef and sheep meat.* Meat and Livestock Australia.

MLA has identified in the previous project *Managing the cold chain and shelf life of chilled vacuum packed beef and sheep meat* the anecdotal evidence that Australian vacuum packaged primals had longer storage lives in commerce compared with product from competing countries. The evidence for achieving the long shelf life of Australian beef and sheep meats is discussed in MLA publication, *Shelf life of Australian red meat (2nd edition).* With storage temperature of -0.5°C vacuumed beef primals can achieve 160 days and lamb achieve 90 days.

The key types of export packaging and transport modes that were identified in this report

1. Carcass / vacuum packed primals / boxed beef air freighted to destination
2. Vacuum packed primals / primal cuts / boxed beef transported by sea freight
3. Retail ready vacuum skin packed (VSP) via air freight.

Temperature by far has the highest impact of overall shelf life of product. For every 1 degree the rate of shelf life decreased by about 30%. Controlling temperature gives the best insurance for a long shelf life. A short period of temperature abuse may not have a significant impact on your product - you can work this out with the help of the Shelf life prediction tool. The tool is described in *Shelf life of Australian red meat* and can be used to predict remaining shelf life providing you know the TVC at packing and the time:temperature record during storage. Once these parameters are entered into the model and either the lamb or beef is selected, predictions for TVCs and days remaining until detection of a strong odor on opening the pack can be predicted.

An example of the data plot collected by USB logging of temperature within the supply chain is presented below (Figure 1). This temperature plot is not separated into cold chain segments, so it must be assumed that spikes are during loading and unloading.

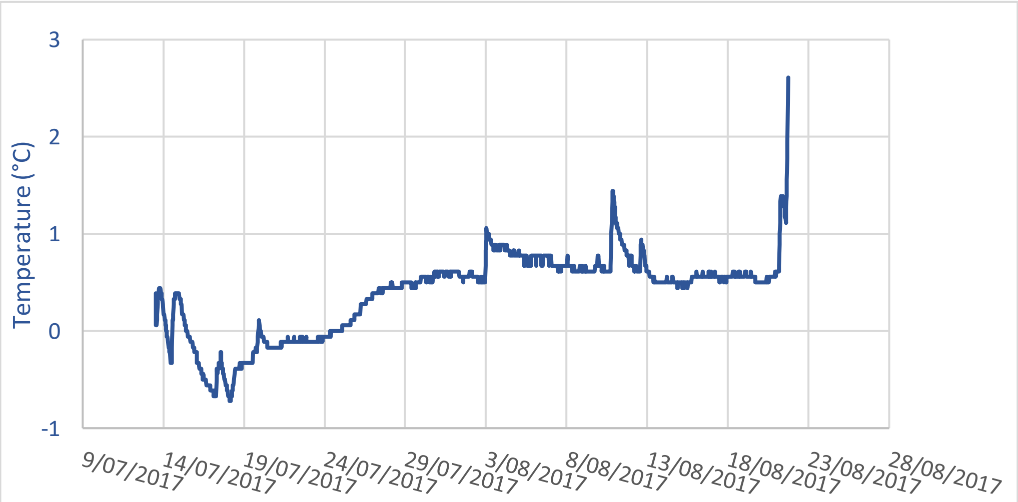


Figure 1: Example of cold chain temperature logger data, MLA 2020

More detailed real-time logging can allow the temperature plot to be broken into different events in the supply chain, as shown below for a "good trip" to the Middle East, with product leaving the processor at 2 ^{o}C, and arriving at the final port 30 days later at -1 ^{o}C, with further cooling while in transit (Figure 2).

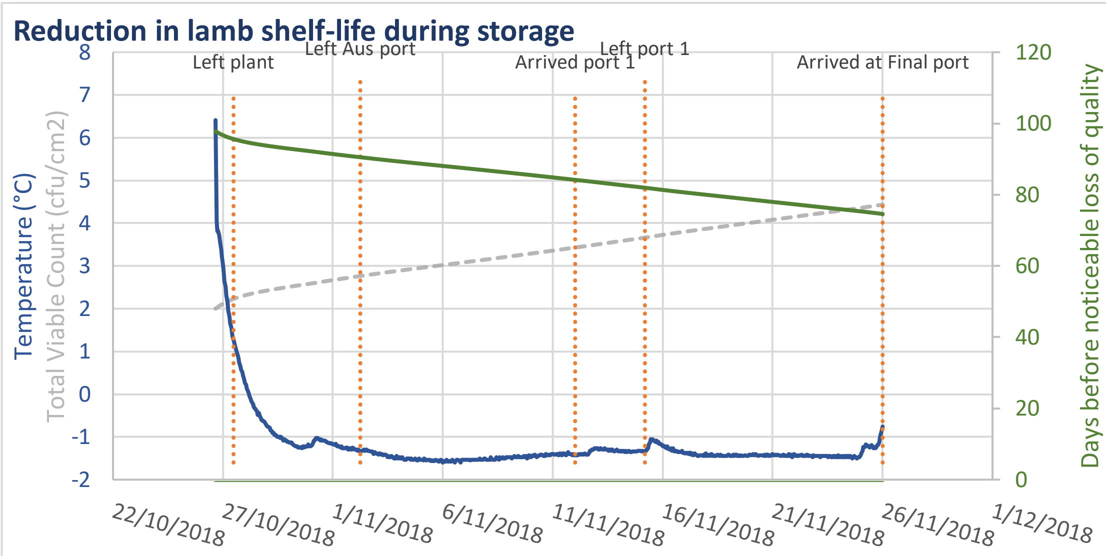


Figure 2: Good shipment to the Middle East, MLA 2020

Figure 3 below suggests that the most common target temperature during shipping to the Middle East is -1 ^{o}C, supporting the temperature plot in Figure 2 where this maximum temperature is maintained while in transit. This is later used to inform the pre-set value in the cold chain model.

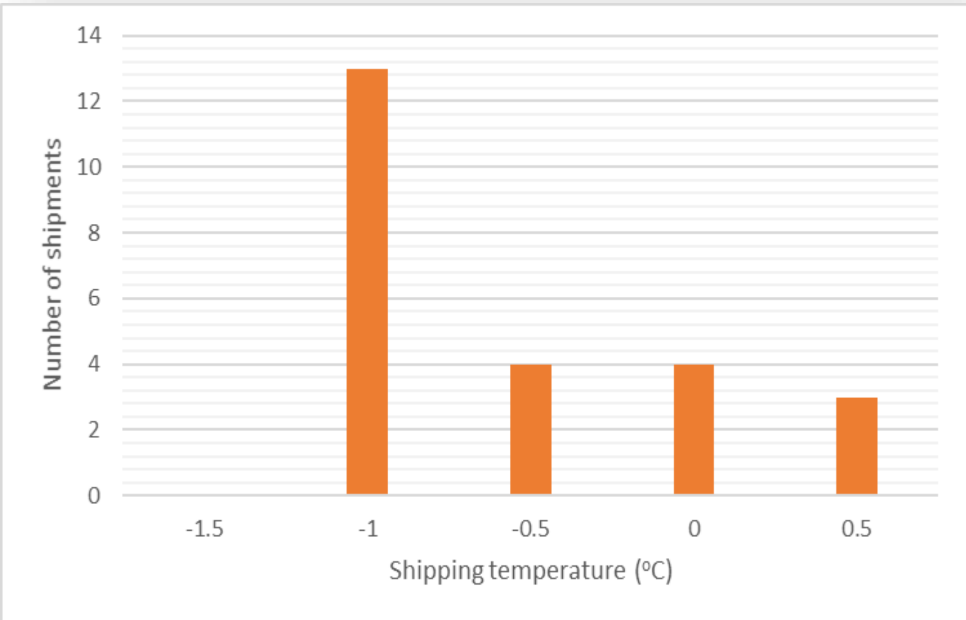


Figure 3: Average shipping temperatures to Dubai, showing -1 ^{o}C most common, MLA 2020

An example of a “bad trip” where there is greater storage time between arriving at and leaving port 1 is shown below. This storage time was estimated to reduce the shelf life by half compared to a good trip (Figure 4).

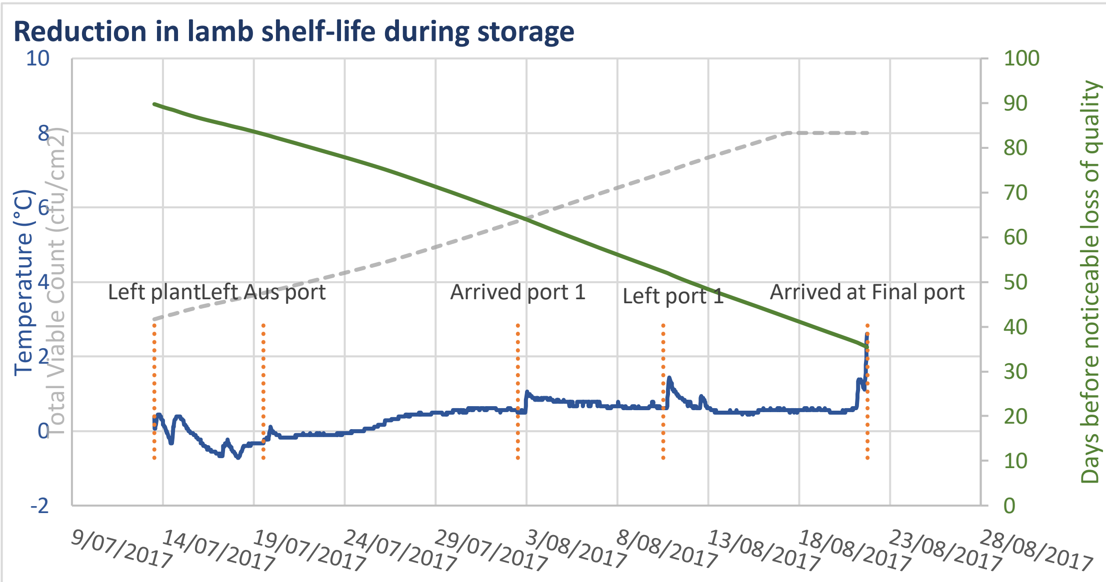


Figure 4: Bad shipment to the Middle East, MLA 2020

A good example of air freight to Asia is shown in Figure 5 below

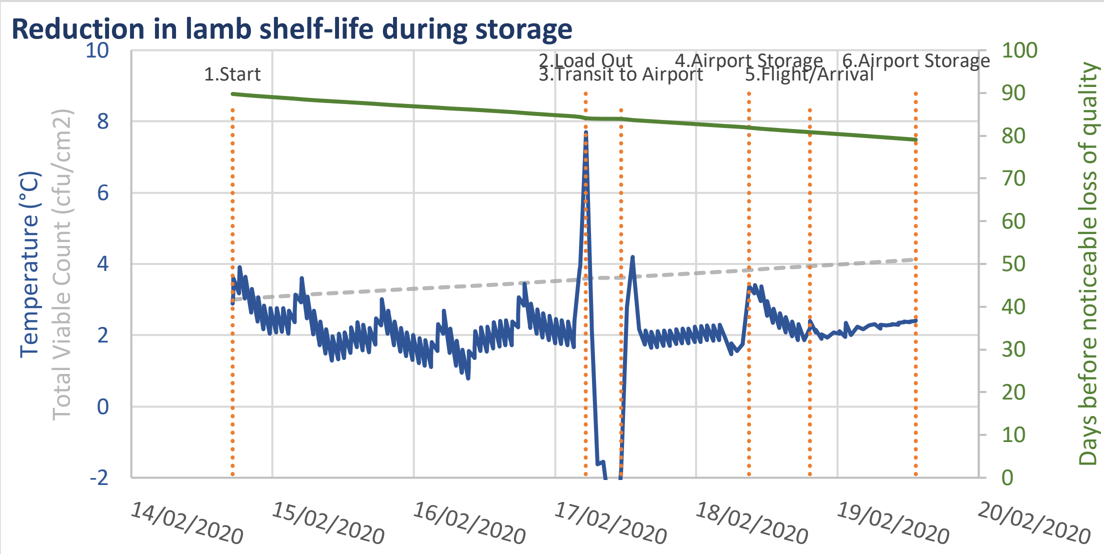


Figure 5: Good air freight to Asia, MLA 2020

To mitigate the costly impacts of issues during air freight, it is recommended to ensure the product reaches the freight forwarder at a sufficiently low temperature and dry ice is used during transit. An example of the temperature over the domestic supply chain is shown below (Figure 6).

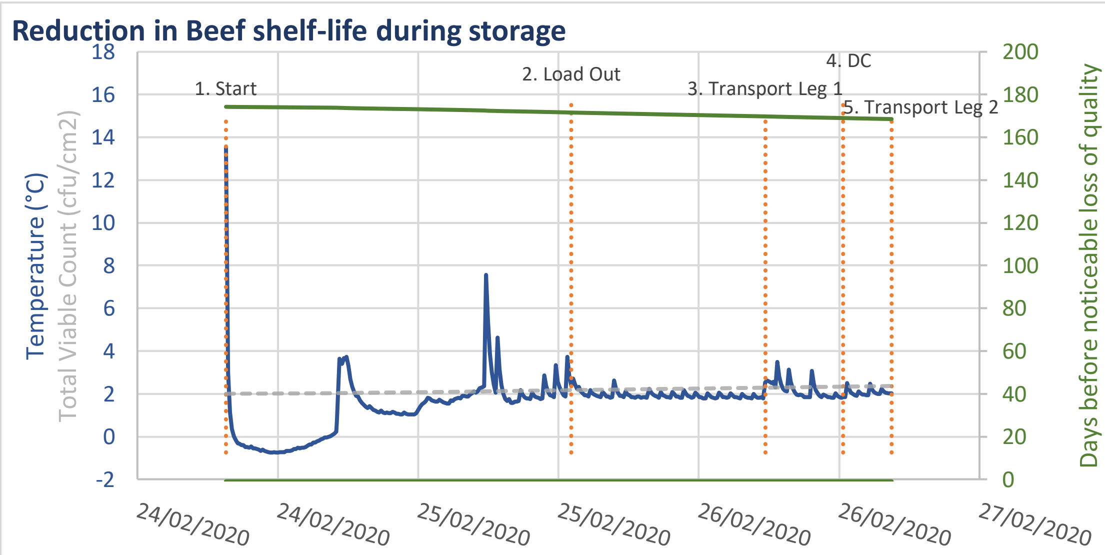


Figure 6: Domestic supply chain good example, MLA 2020

Realistic temperature targets are given in Table 1 below

Table 1: Current domestic temperature thresholds at processor, distribution centre, retail, and transport legs, MLA 2020

	Temperature threshold		
Supply Chain Legs	Green (Recommended)	Amber (Needs attention)	Red (Urgent attention)
Abattoir & Processor (value adder)	-1 to 2 ^{0}C	2.1 to 5 ^{0}C	5.1 ^{0}C or higher
DC	2 to 5 ^{0}C	5.1 to 7 ^{0}C	7.1 ^{0}C or higher
Retail Store	3 to 7 ^{0}C	7.1 to 9 ^{0}C	9.1 ^{0}C or higher
Transport legs	2 to 5 ^{0}C	5.1 to 7 ^{0}C	7.1 ^{0}C or higher

Realistic storage and transit times at each element of the supply chain that are used to inform the pre-set values in the developed model are given below in Figure 7 and Figure 8. The 4 ^{0}C temperature range is the current practice, with others being scenarios to inform shelf life estimates.

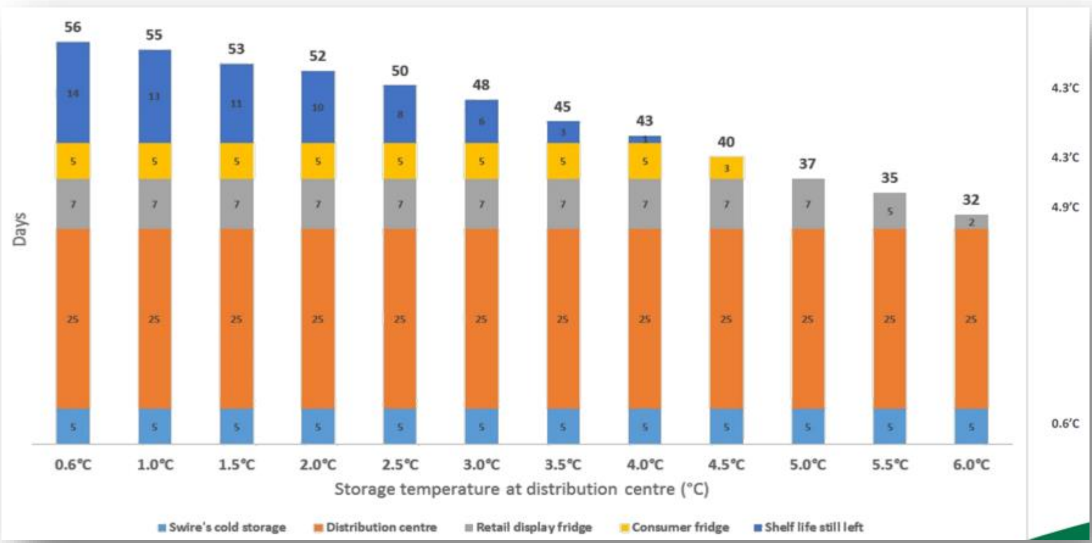


Figure 3: Storage temperature and storage time at processor, distribution centre, retail and consumer fridge, with remaining shelf life, MLA 2020

Figure 4: Dubai shipping time, showing 34-38 days most common transit time, MLA 2020

Sea freight is reported at approximately one fifth the cost of air freight, with the disadvantage of the common perception of less shelf life on arrival due to longer transit time. However, the difference is shelf life may be insignificant (at about 7 – 10 days max.) and not justified by the increased transport cost. Interestingly, a typical 34 day shipping journey at 0 ^{o}C has a longer shelf life than a 4 day air journey (80 vs 69 days), possible due to a greater number of loading and unloading handlings during the journey.

Expert Group. (2020) *A study of waste in the cold food chain and opportunities for improvement.* Department of Agriculture, Water, and the Environment & Refrigerants Australia

This report identifies and quantifies the impact of food waste in the cold chain attributable to breaks and deficiencies at 3.5% of the annual production of meat (155,000 tonnes) worth $670 million. Also, the greenhouse gas emission impact from food waste attributed to sub-par refrigeration technology, practices, and processes is estimated as 7 Mt CO_2 equivalent in 2018, or 1.3% of Australia's total. The total direct and indirect emissions from operating the cold chain are estimated at 18.9 Mt CO_2 equivalent.

This source recommends chilled red meat stored as cold as possible to maximise the storage period and that a temperature of -1°C to 0°C is desirable and practical. Optimal storage temperatures of the majority of fresh meats listed in the *Best Practice Guide for Energy Efficient Walk-in Cold-Rooms* (Australian Institute of Refrigeration Air conditioning and Heating [AIRAH]) range from -2°C to 1°C with a relative humidity above 85%, whereas the temperature range of supermarket and food retail meat cases is -1°C to 4°C (M0 temperature class defined in *ISO 23953, Refrigerated Display Cabinets).*

The Red Meat Advisory Council has developed a 10-year strategic plan that encompasses supply chain efficiency and integrity including waste management. No hard data of loss and waste rates is available (RMAC 2018). This study found meat waste in the supply chain was around 13% and in the absence of hard data, it is assumed that a quarter of this waste is attributed to sub-par refrigeration equipment, practices and processes.

Project Scope

The area for exploration in this project is the cost of storing product colder to extend shelf life and are there any significant impacts such as dramatic increase in energy use. This project will inform industry of the cost and benefits of changing temperature for individual segments within the meat supply chain to control shelf life or the cost of frozen meat. The output of the project will consist of a simple (e.g. MS Excel) model with options to select key variable parameters that impact the $/tonne cost for keeping meat cold at different locations at temperatures between -2 to 10 ^{o}C, throughout the cold chain at processor facilities versus other segments.

The project will also include a modelling the cost for keeping export product at frozen temperatures in the supply chain over the range of -12 to -24 ^{o}C, the information on frozen supply chain and cost of storage will be valuable when we complete the frozen shelf life project, which will give us an indication of the feasibility to store product at -24 vs -12 ^{o}C.

Refrigeration in the Red Meat Industry

The initial chilling of carcasses is the most important step in the cold-chain process for preserving meat (McNeil, McPhial and Macfarlane, 1991). Immediately after slaughter, the temperature of animal carcasses is around 40°C, hence rapid chilling of carcasses to inhibit the growth of bacteria is an important hazard control point (Zhang et al., 2019). Slow chilling allows carcasses to enter rigor at higher temperatures, such as 12 to 35°C as defined by Meat Standards Australia.

Red Meat Processors (RMPs) require freezing (also called chilling) capacity for boning rooms, plate freezers, cold store, dehumidification and other lower temperature facilities. Taking an ammonia circuit as an example, the below freezing temperatures are often achieved via two stage compression (ammonia has a saturation temperature of -33^{o}C at atmospheric pressure). High stage heat rejection is routinely achieved via evaporative condensers (i.e. evap towers), often fitted with variable speed fans to maintain the head pressure set-point. Oil cooling heat rejection for both high stage and low stage compressors is routinely achieved via cooling towers. Liquid ammonia is then pump to evaporators at various areas within the plant, then evaporates to provide cooling capacity.

For cooling (rather than freezing / chilling) single stage ammonia screws compressors are often employed for carcass chillers and space cooling (i.e. air conditioning).

Previous studies have found approximately 44% of power for refrigeration is attributed to the freezing requirements, with 56% for carcass cooling and air conditioning (see MLA report P.PIP.0363, 2014). The KPI for refrigeration is total energy consumption per kg Hot Standard Carcass weight reported as 0.29 kWh/kg. Up to 80% of cooling is for carcass cooling and freezing. The remaining 20% is for space cooling / air con, removing heat from equipment and lighting, and inefficiencies (e.g. open doors; poor insulation).

Refrigeration systems are the largest user of electricity in meat processing plants and can make up between 15-30% of total energy consumption. Larger, central ammonia systems are greater than 30% more efficient than smaller, distributed freon systems. However, the lower the desired temperature, the more expensive the refrigeration on a $/GJ of cooling basis as both the capital and operating costs increase.

2. Objectives

1. Work with MLA to identify common cold chain journey of carton meat including domestic chilled, frozen export shipping, and frozen export air cargo product.
2. Write a report that summarises the modelling results and discusses:
   - Impact of energy on costs as well as other impacts.
   - Alternative systems to recover energy.
   - Any potential research or changes to the supply chain for maximum efficiency e.g. processor utilises a high efficiency system for initial chill to a low temperature with supply chain maintaining target temperature / temperature band width.
3. Create a simple (e.g. Excel) model with options (e.g. drop downs) to select key variable parameters that impact the $ / tonne cost for:
   - keeping meat cold at different locations at different temperatures throughout the cold chain (i.e. processing plant, truck, ship, plane, warehouse, retail). i.e. cost for storing between -2.0^{o}C to 10.0^{o}C at processor site versus other options in order to maintain / increase shelf life.
   - Frozen supply chain over the range of -24 to -12^{o}C.

3. Methodology

Refrigeration Background Thermodynamics

Refrigerators transfer heat from a low temperature region to a higher temperature one, going against the basic thermodynamic principle of heat flowing from higher to lower temperature. Thus, mechanical work is required to drive this cycle. The most common refrigeration cycle is the vapour compression refrigeration cycle, where the working fluid (refrigerant) is alternately compressed, requiring work, vaporised, absorbing heat, and condensed, dumping heat.

The basic refrigeration cycle, with the phases of the refrigeration shown as L-liquid and V-vapour is shown below in Figure 9, with the thermodynamic T-s and P-h diagrams shown in Figure 10.

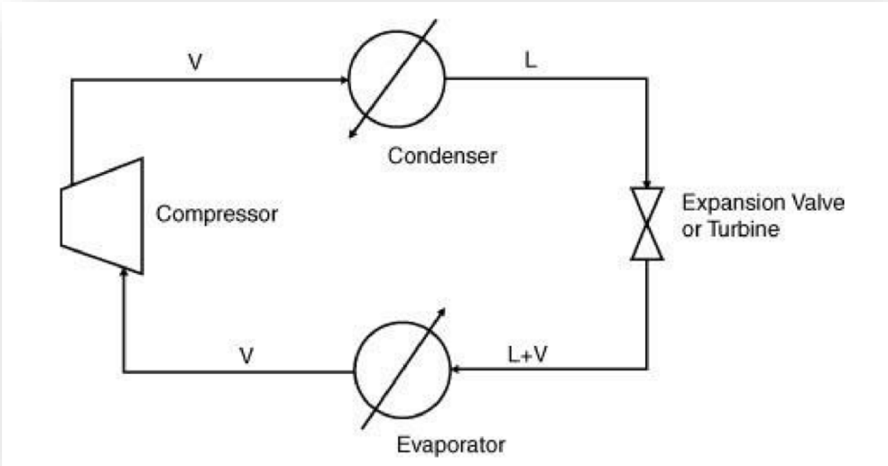


Figure 5: Basic 4 stage refrigeration cycle

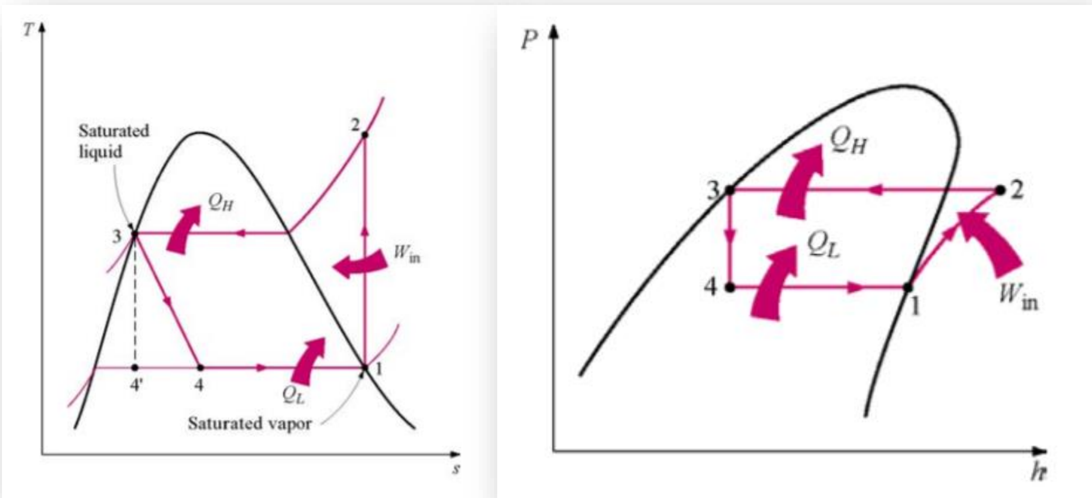


Figure 6: Temperature-entropy (T-s) and Pressure-enthalpy (P-h) diagram of Figure 1 (Cengel and Boles, 2011)

For an ideal refrigeration cycle[1] where the four processes and conditions are (Cengel and Boles, 2011)

1 – 2: Isentropic compression. Entering as saturated vapour and exiting as superheated vapour
2 – 3: Constant pressure heat rejection to surroundings in condenser. Exiting as saturated liquid
3 – 4: Throttling in expansion valve. Exiting as low vapour fraction mixture with saturated liquid
4 – 1: Constant pressure heat absorption in evaporator. Exits as saturated vapour and returns to compressor

[1] Note that the actual vapour compression cycle differs from the ideal due to irreversibilities in components caused primarily by fluid friction causing pressure drops and heat transfer to or from the surroundings. For the purposes of this indicative study, it is not necessary to consider the actual vapour compression cycle, as the exact cost of cooling is highly specific to individual systems. Relative costs of cooling are presented here.

The Coefficient of Performance (COP) is a measure of the usable cooling energy per work input and is represented on the P-h diagram as

$$COP = \frac{Q_L}{W}$$

$$= \frac{Q_L}{Q_H - Q_L}$$

$$= \frac{1}{\frac{T_H}{T_L} - 1}$$

Note that COP is not equal to efficiency and is usually greater than 1, with a higher COP better than a lower COP. It can then be seen that ideal COP depends primarily on the high temperature where heat is rejected in the condenser, and the low temperature in the refrigerated space. COP then decreases as the ratio of T_H to T_L increases, i.e. refrigerating to lower temperatures.

Modelling

A refrigeration loop was modelled using the COFE chemical flowsheet simulation program[2]. The temperature ranges of interest for product are:

- Chilled (Vacuum packed): -2 to +10 ^oC.
- Frozen: -24 to -12 ^oC.

Generally, the target temperature is 3 to 5 ^oC higher than the refrigerant fluid temperature, hence the model considered:

- Chilled loop: -7 to +5. Outlet pressure of compressor: 10.1 barg.
- Frozen: -29 to -17. Outlet pressure of compressor: 15.0 barg.

Ammonia is routinely used in the refrigeration systems at RMPs. It occurs naturally, is readily available in pure form from industrial gas suppliers, has an ozone depletion of zero and a global warming potential of less than 1, is low cost and can absorb large amounts of heat as it evaporates. Its main drawbacks are toxicity and flammability. It is noted that ammonia has a saturation temperature of -33 ^oC at atmospheric pressure, hence, to achieve lower temperatures a two stage ethylene/propylene two stage system could be considered, noting that this would be at a higher capex, Op Ex and hence higher overall $/GJ. It is appreciated that in practice an ammonia loop for freezing may normally employ a two stage compression, however, to enable some comparison between the systems, both loops were modelled as single stage compression.

- Isentropic efficiency of screw compressor: 78%
- Mechanical and other losses: 4%
- Overall efficiency: 74%

22.5 WET BULB. dT approach assumed at 5 ^oC. Outlet from condenser modelled at 28.05 ^oC. The outlet temperature from the de-superheater is optimised to ensure that no condensate forms in the desuperheater i.e. at 14.662 Bara this means 318 ^oK (44.85 ^oC).

[2] https://www.cocosimulator.org/

To add to the realism of the model:

- kPa pressure drop is allowed for in each unit operation of de-superheater, condenser, and cooling.
- 74% overall compressor efficiency.

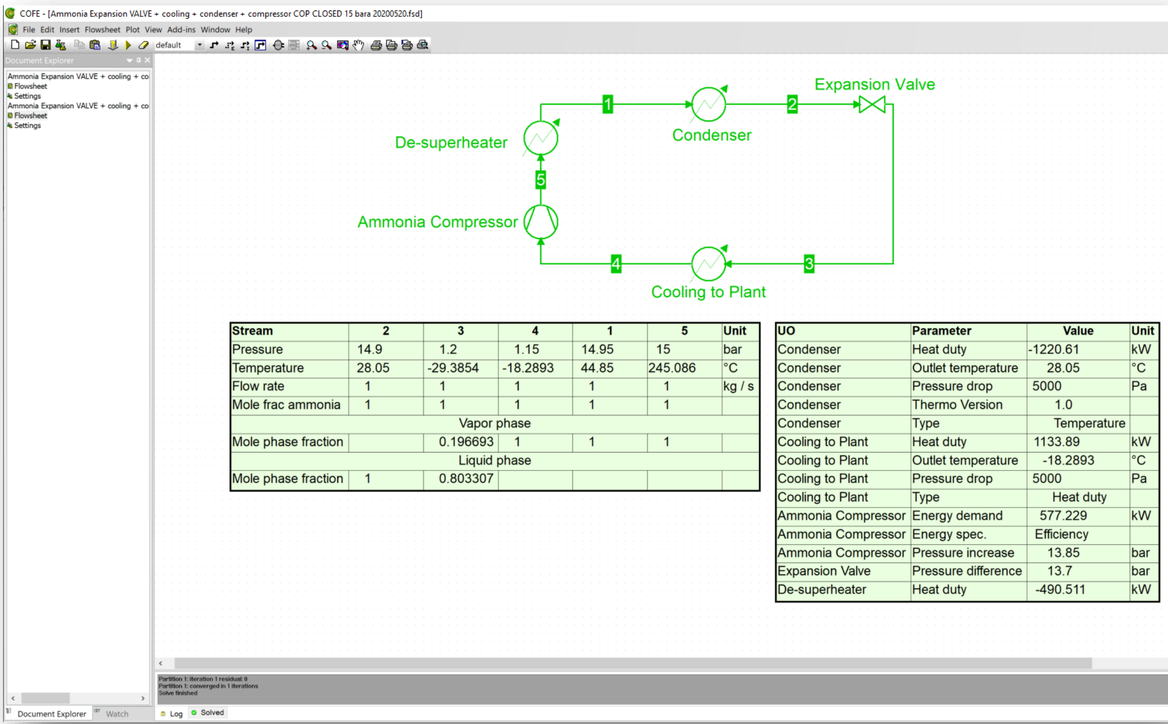
Ammonia compressors routinely operate at 100 to 250 psig (7.9 – 18.2 bara; ~17 barg is a common upper pressure). Exits regulator at 75 – 80 psi (6.2 - 6.5).

Compressor suction side pressure target is approx. 25 to 30 psi (2.7-3 bar).

Freezing – Higher compressor pressure: 15.0 bara

Cooling – Lower compressor pressure: 10.1 bara

Water cooling towers used for evaporative condensing, with ratio of 13.31 MW of cooling for 55 kWe fan and motor load[3]. Generally, warm water recovery at RMPs with render condensate has minimal economic value. The desuperheater for the cooling is in the range of 45 – 97 °C for 1 to 122 kWt respectively, hence the economic viability of heat recovery is limited. For the freezing loop the desuperheater is in the range of 160 – 245 °C for 328 to 491 kWt respectively, hence there may be economic value in recovering sterilization water (at, say, 90 to 95 °C) to off-set steam from the boiler to raise sterilization water. Hence, the desuperheater is only considered for the freezing loop, and not the cooling loop. The modelled process flow diagram with stream and unit operation tables is shown in Figure 11.



Stream	2	3	4	1	5	Unit
Pressure	14.9	1.2	1.15	14.95	15	bar
Temperature	28.05	-29.3854	-18.2893	44.85	245.086	°C
Flow rate	1	1	1	1	1	kg / s
Mole frac ammonia	1	1	1	1	1	
Vapor phase						
Mole phase fraction		0.196693	1	1	1	
Liquid phase						
Mole phase fraction	1	0.803307				

UO	Parameter	Value	Unit
Condenser	Heat duty	-1220.61	kW
Condenser	Outlet temperature	28.05	°C
Condenser	Pressure drop	5000	Pa
Condenser	Thermo Version	1.0	
Condenser	Type	Temperature	
Cooling to Plant	Heat duty	1133.89	kW
Cooling to Plant	Outlet temperature	-18.2893	°C
Cooling to Plant	Pressure drop	5000	Pa
Cooling to Plant	Type	Heat duty	
Ammonia Compressor	Energy demand	577.229	kW
Ammonia Compressor	Energy spec.	Efficiency	
Ammonia Compressor	Pressure increase	13.85	bar
Expansion Valve	Pressure difference	13.7	bar
De-superheater	Heat duty	-490.511	kW

Figure 7: COFE CAPE OPEN flowsheet

[3] Based on Qld wet bulb.

The domestic vacuum packed cooling circuit results are presented in Figure 12.

Refrigerant Temp.	dP	Compressor	Cooling water	Cooling water load	Evap Heat load	De-superheater	COP	COP with cooling water load
oC	Bara	kWe	kWt	kWe	kWt	kWt		
- 7.0	6.9	225.5	1,238.1	5.1	1,133.9	122.1	5.0	4.9
- 6.2	6.8	219.2	1,238.1	5.1	1,133.9	122.1	5.2	5.0
- 3.1	6.4	193.8	1,238.1	5.1	1,133.9	89.7	5.9	5.7
- 0.2	6.0	171.8	1,238.1	5.1	1,133.9	67.6	6.6	6.4
2.5	5.6	152.4	1,238.1	5.1	1,133.9	48.2	7.4	7.2
5.0	5.2	135.6	1,238.1	5.1	1,133.9	32.2	8.4	8.1

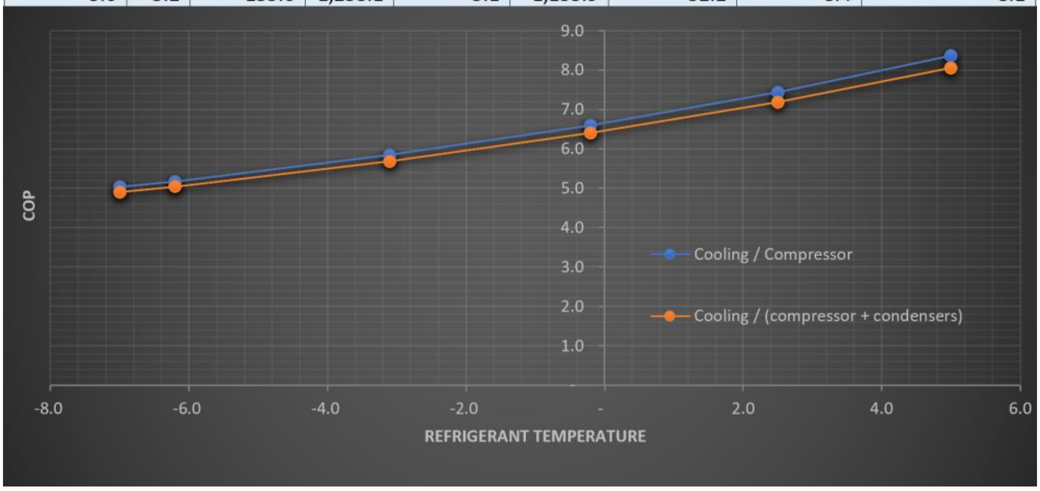


Figure 8: Cooling circuit modelling results

The export product freezing circuit results are presented in Figure 13.

Evap outlet Temp.	dP	Compressor	Cooling water	Power load for cooling	Evap Heat load	De-superheater	COP	COP with cooling water load	COP with cooling water load and de-superheater
oC	Bara	kWe	kWt	kWe	kWt	kWt			
- 12.0	12.3	362.9	1,220.6	5.0	1,133.9	328.3	3.1	1.6	4.0
- 14.6	12.6	390.7	1,220.6	5.0	1,133.9	328.3	2.9	1.5	3.7
- 16.8	12.8	415.0	1,220.6	5.0	1,133.9	341.5	2.7	1.5	3.5
- 18.0	12.9	428.2	1,220.6	5.0	1,133.9	341.5	2.6	1.5	3.4
- 19.0	13.0	442.3	1,220.6	5.0	1,133.9	355.6	2.6	1.4	3.3
- 20.4	13.1	457.4	1,220.6	5.0	1,133.9	370.7	2.5	1.4	3.3
- 23.1	13.3	490.9	1,220.6	5.0	1,133.9	404.2	2.3	1.3	3.1
- 26.1	13.5	530.2	1,220.6	5.0	1,133.9	443.5	2.1	1.3	2.9
- 29.4	13.7	577.2	1,220.6	5.0	1,133.9	490.5	2.0	1.2	2.8

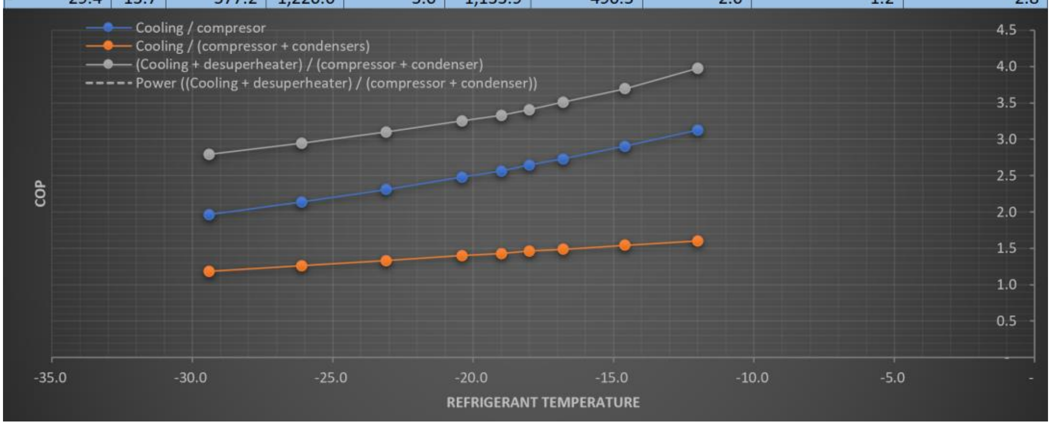


Figure 9: Freezing circuit modelling results

Comparing the COP over the two temperature ranges is shown in Figure 14.

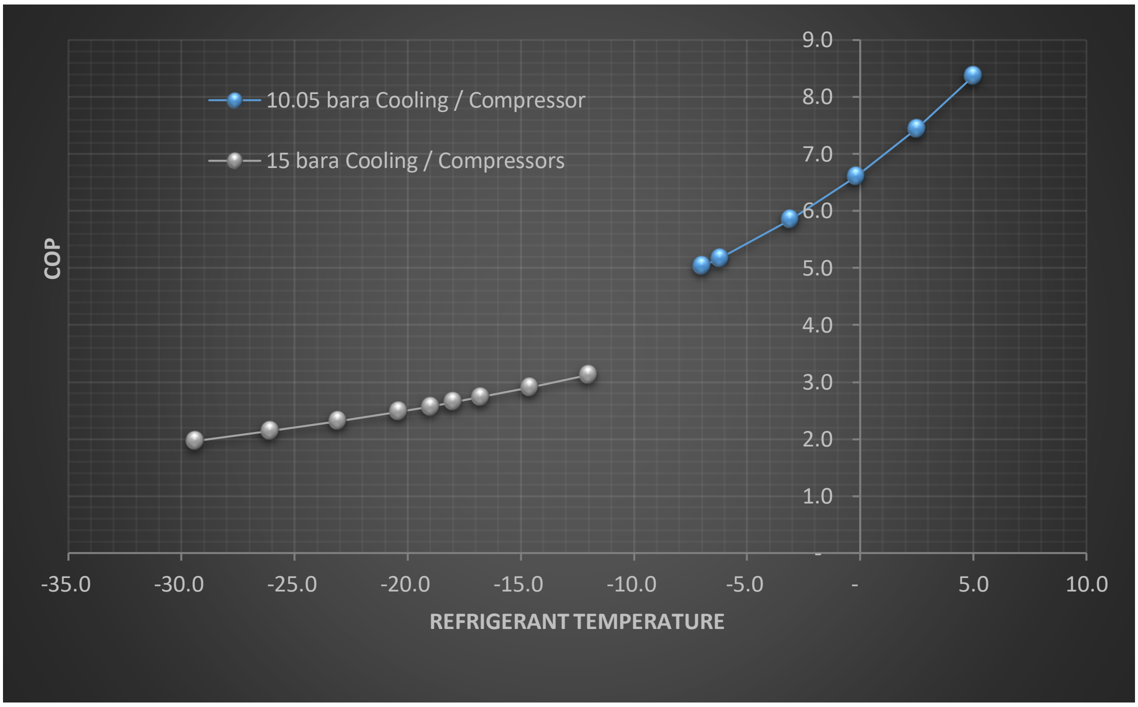


Figure 10: COP vs refrigerant temperature over chilled and frozen range

4. Results

Effect of Temperature on Cooling Cost

Using the COP values[4] calculated in Figures 12 and 13 and indicative values for power at five refrigerated stages in the red meat supply chain, the following costs of cooling were calculated.

[4] Inclusive of cooling water load of 5.1 kWe

	$ / kWh indicative
Warehouse	0.19
Retail	0.24
Ship	0.35
Truck	0.40
Plane	0.80

				Cost of Cooling $ / kWh				
	Target Temp [degC]	Refrigerant Temp [degC]	COP	Warehouse	Retail	Ship	Truck	Plane
Frozen	-24	-29	1.2	$ 0.158	$ 0.200	$ 0.292	$ 0.333	$ 0.667
	-21	-26	1.26	$ 0.151	$ 0.190	$ 0.278	$ 0.317	$ 0.635
	-18	-23	1.33	$ 0.143	$ 0.180	$ 0.263	$ 0.301	$ 0.602
	-15	-20	1.4	$ 0.136	$ 0.171	$ 0.250	$ 0.286	$ 0.571
	-14	-19	1.43	$ 0.133	$ 0.168	$ 0.245	$ 0.280	$ 0.559
	-13	-18	1.46	$ 0.130	$ 0.164	$ 0.240	$ 0.274	$ 0.548
	-12	-17	1.49	$ 0.128	$ 0.161	$ 0.235	$ 0.268	$ 0.537
	-10	-15	1.54	$ 0.123	$ 0.156	$ 0.227	$ 0.260	$ 0.519
Chilled	-2	-7	4.9	$ 0.039	$ 0.049	$ 0.071	$ 0.082	$ 0.163
	-1	-6	5.0	$ 0.038	$ 0.048	$ 0.070	$ 0.080	$ 0.160
	0	-5	5.2	$ 0.036	$ 0.046	$ 0.067	$ 0.076	$ 0.153
	2	-3	5.7	$ 0.033	$ 0.042	$ 0.061	$ 0.070	$ 0.140
	5	0	6.4	$ 0.030	$ 0.038	$ 0.055	$ 0.063	$ 0.125
	10	5	8.1	$ 0.023	$ 0.030	$ 0.043	$ 0.049	$ 0.099

Figure 11: Indicative cost of cooling analysis

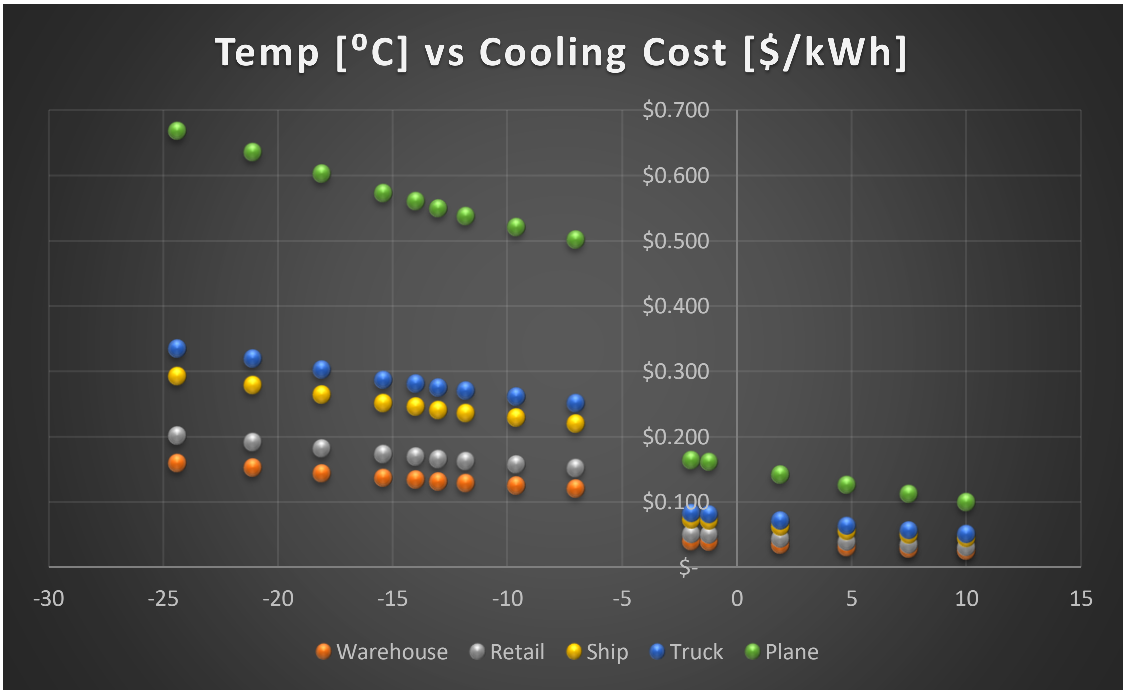


Figure 12: Target temp [°C] of refrigeration vs cost of cooling [$/kWh]

The formula for calculating cost of cooling is

$$Cost\ of\ Cooling = \frac{Electricity\ Cost}{COP}$$

Thus, it can be seen that at a given target temperature and COP, the cost of cooling is directly proportional to the cost of electricity delivered to the compressor. The cost of cooling can then be improved by:

- Minimising electricity cost
    - Switching to renewable sources, such as solar PV or generation engines running on biogas
    - Improving site power factor
    - Improving equipment voltage optimisation
- Maximising COP
    - Minimise work input *W*
        - Compressor maintenance, oil leaks, motor function
        - Check seals to ensure no ambient hot air entering refrigerated space
        - Ensure doors are not left open unnecessarily
        - Consider a variable speed drive to run compressor proportionately to amount of product to be cooled
    - Maximise heat absorbed Q_L
        - Set temperatures as near to food safety standard limits, as the greater the difference between T_L and T_H, the lower the COP
        - Keep the space full
        - Insulate refrigerant pipes to prevent absorbing ambient heat and maintain insulation

Supply Chain Cost of Cooling Calculator

The key variable parameters influencing the overall $/tonne cost for refrigerating meat along the supply chain include

- Cost of electrical power for:
    - Processor
    - Trucking
    - Shipping
    - Warehouse
    - Retail
- Target temperature
    - Affects COP and cost of maintaining temperature – refrigerator insulation and seal efficiency losses
- Payload in trucks and shipping containers
    - Assumed 30% packing density (Food Science Australia, 2005) equivalent to 330 kg per cubic metre
- Quality of refrigerated container seals and insulation
- Frequency of opening and closing container, warehouse, and retail refrigerator doors
- Time in transit or storage, particularly for high cost refrigeration e.g. shipping
- For air cargo, the cost of dry ice.

As shown below in Figure 18, the initial chill at the processing plant involves the removal of sensible heat from the initial carcass temperature of 38 to 0 ^{o}C[5], latent heat of fusion while the meat freezes at 0 ^{o}C[6] (American Meat Science Association, 2017), then supercooling below 0 ^{o}C to the target temperature[7], absorbing sensible heat. Further along the supply chain, where temperatures are

[5] Meat cp above freezing 2.85 kJ/kg.K

[6] Assumed at 250 kJ/kg from 75% meat moisture of water hf 333.55 kJ/kg

[7] Meat cp below freezing 2.01 kJ/kg

maintained below or above 0 ^oC, this involves only the removal of sensible heat. Losses are calculated as the sum of convective and conductive losses, heat transferred by the movement of fluid and through objects in contact with a temperature differential, respectively, while in transit and storage.

The list of assumptions behind this calculator is as follows:

- Ambient temperature
  - Trucking and storage in warehouse 25 ^oC
  - Shipping 15 ^oC
  - Retail 20 ^oC
- Average transit speed
  - Truck 60 km/h
  - Shipping 40 km/h
- Trucked in refrigerated B double
- Shipped in refrigerated 40 ft containers
- 30% packing density in truck and shipping container
  - 25 t payload
- 5% packing density in retail refrigerator
- Storing 3 trucks' worth in warehouse
- Meat water content 75%
- Starting carcass temperature of 38.5 ^oC
- Assumed insulation and seal quality
  - Trucking low efficiency, 6% losses
  - Shipping medium efficiency, 3.5% losses
  - Warehouse door frequently opening, 30% losses
  - Retail door constantly opening, 50% losses

Refinements to the draft tool made after presenting the draft to MLA include

- Amending processor storage time to 10 days to reflect time product is aged
- Increasing time on retail shelf up to 10 days at 2 – 5 ^oC
- Including an additional value adder between the warehouse and retail stage built off the processor algorithm
- Including an option for dry ice as the refrigerator during shipping
- Basic greenhouse gas emissions calculation

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Refrigeration Supply Chain Cost of Cooling Model

Processor

Product Target Temperature [°C]	-2
% of time run on solar PV	0%
Cost of Cooling [$/kWh]	$ 0.033
Cost to achieve Target Temp [$/tonne]	$ 2.67
Days in Storage	10
Losses due to periodic openings	10%
Cost to maintain Target Temp [$/tonne]	$ 35.02

Trucking

Product Target Temperature [°C]	-2
Hours in Transit	6
Cost of Cooling [$/kWh]	$ 0.082
Losses due to periodic openings	5.0%
Cost to maintain Target Temp [$/tonne]	$ 14.78

Shipping / Plane Cargo

Product Target Temperature [°C]	-1	
Cooling Medium	Refrigeration	
Days in Transit	0	If product not shipped, put zero here
Cost of Cooling [$/kWh]	$ 0.177	
Losses due to periodic openings	1%	
Cost to maintain Target Temp [$/tonne]	$ -	

Warehouse

Product Target Temperature [°C]	-1
% of time run on solar PV	20%
Days in Storage	10
Cost of Cooling [$/kWh]	$ 0.032
Losses due to periodic openings	30%
Cost to maintain Target Temp [$/tonne]	$ 40.71

Value Adder

Product Target Temperature [°C]	-1
% of time run on solar PV	20%
Cost of Cooling [$/kWh]	$ 0.032
Cost to achieve Target Temp [$/tonne]	$ 2.54
Days in Storage	10
Losses due to periodic openings	10%
Cost to maintain Target Temp [$/tonne]	$ 33.61

Retail

Product Target Temperature [°C]	3
% of time run on solar PV	20%
Days Stored Until Sold	7
Cost of Cooling [$/kWh]	$ 0.034
Losses due to periodic openings / continuous opening	50%
Cost to maintain Target Temp [$/tonne]	$ 253.2

Cost to Maintain Target Temperature

Production [tonnes per annum]	100,000
Supply Chain Cooling Cost [$/tonne]	$ 382.5
Supply Chain Cooling Cost [$ per annum]	$ 38,248,643

Percentage contribution of cold chain costs:

Processor	9.9%
Trucking	3.9%
Shipping / Plane Cargo	0.0%
Warehouse	10.6%
Value Adder	9.5%
Retail	66.2%

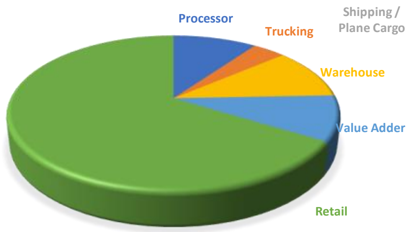

Figure 13: Supply chain cost of cooling calculator tool – "Chilled Domestic" scenario

The primary impact on the total supply chain cooling cost is whether a product is shipped (i.e. domestic or export product) and time spent in transit. Shipping at -1 ^{0}C for an 18 day shipping time, or the estimated time to ship from Brisbane to Tokyo, adds an additional cost of $1,622.9 / tonne. Changing the processing initial carcass chill temperature from -12 to -24 ^{0}C changes the cost of cooling from $55.5 to $76.38 per tonne.

Dry ice as a cooling medium is very expensive compared to vapour compression refrigeration cycles, with the latent heat of sublimation from solid to gas, then sensible heating from the sublimation temperature of -78.5 ^{0}

C to an assumed air cargo temperature of 0 ^{0}C calculated at 0.229 kWh cooling per kg, or $10.95 / kWh at an assumed bulk purchase or manufacturing cost of $2.50 per kg. For an equivalent distance as an 18 day ship journey, dry ice only appears viable at plane journeys of 8 or fewer hours, or other situations where cargo payload and volume is critical.

This tool will be published in MS Excel form on the MLA website, available for download and use. Where additional budget is not required for contingency, this can be built into www.myenergy.tech as an online module.

Frozen and Chilled Export and Domestic Vacuum Packed Product Scenarios

Frozen Export Product Shipped

This scenario is summarised in the below table and Figure 18.

Supply Chain	Storage / Transit Time	Product Target Temperature
Processor	10 days	-18
Trucking	6 hours	-12
Shipping	34 days	-18
Warehouse	7 days	-18
Value Adding	7 days	2
Retail	7 days	5

Percentage contribution of cold chain costs:

Processor	0.9%
Trucking	0.3%
Shipping	95.7%
Warehouse	0.9%
Value Adder	0.2%
Retail	1.9%

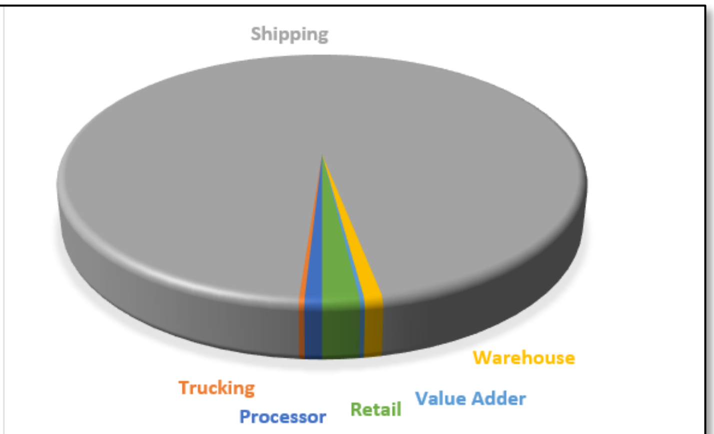

Figure 14: Frozen export shipped product scenario

The extended shipping time vastly dominates the cost of cooling in this supply chain, as is expected for a refrigeration system run on marine fuel oil.

Frozen Export Product Air Freight with Dry Ice

Supply Chain	Storage / Transit Time	Product Target Temperature
Processor	10 days	-24
Trucking	6 hours	-12
Plane	2 days	-24
Warehouse	7 days	-24
Value Adding	7 days	2
Retail	7 days	5

Percentage contribution of cold chain costs:

Processor	8.2%
Trucking	2.0%
Plane Cargo	66.1%
Warehouse	8.7%
Value Adder	1.9%
Retail	13.1%

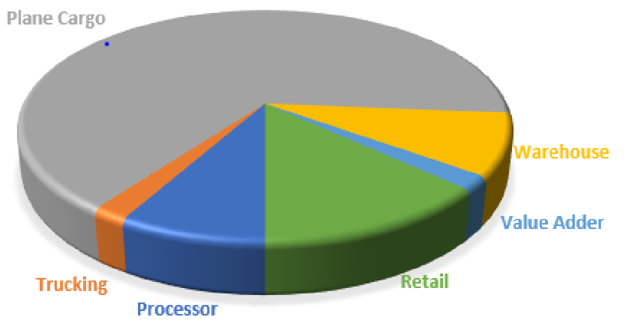

Figure 15: Frozen export product air freight with dry ice scenario

The cost of dry ice dominates the total supply chain refrigeration cost, with the critical variable being time spent in air transit. The threshold time of approximately 8 hours gives parity to the $ / tonne cooling cost in shipping.

Chilled Export Product Shipped

Supply Chain	Storage / Transit Time	Product Target Temperature
Processor	10 days	-2
Trucking	6 hours	-1
Shipping	34 days	-2
Warehouse	7 days	-2
Value Adding	7 days	2
Retail	7 days	5

Percentage contribution of cold chain costs:

Processor	0.9%
Trucking	0.4%
Shipping	90.6%
Warehouse	1.0%
Value Adder	0.5%
Retail	6.6%

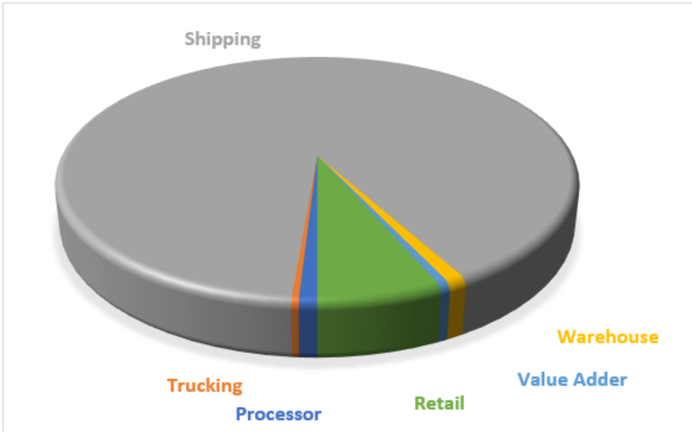

Figure 16: Chilled export product shipped scenario

Chilled product being shipped, e.g. maintaining a higher permissible target temperature during shipping of -2 rather than -18 reduces the shipping costs to $3,346.5 from $12,148.5 / tonne.

Domestic Vacuum Packed Product

Supply Chain	Storage / Transit Time	Product Target Temperature
Processor	20 days	-2
Trucking	6 hours	-1
Shipping	NA	NA
Warehouse	30 days	4
Value Adding	7 days	2
Retail	7 days	5

Percentage contribution of cold chain costs:

Processor	14.3%
Trucking	3.7%
Shipping / Plane Cargo	0.0%
Warehouse	21.8%
Value Adder	4.2%
Retail	56.0%

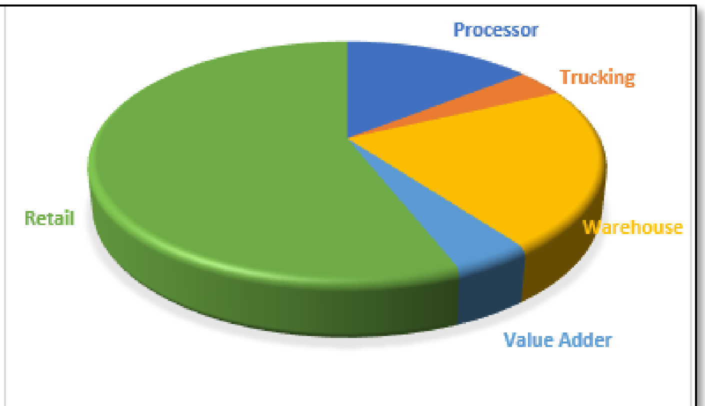

Figure 17: Domestic vacuum packed product scenario

Using storage times suggested to extend product shelf life in the scenario shown above in Figure 21 shows that without international transit by shipping or air freight, supply chain cost is dominated by the inefficiencies of retail refrigeration, followed by the large storage time in the warehouse and processor. The lowest hanging fruit of in this supply chain to reduce costs is thus investing in closed display cases rather than open cases, significantly reducing convective losses while on display.

4.1 Key findings

For vertically integrated cold chains, where the operator has control over large stationary refrigeration plant as well as distributed storage, trucking, shipping, or other freight modes, changes to the supply chain can be made to take advantage of higher efficiency or lower power costs to reduce overall supply chain costs. A large refrigeration plant at a processor can take advantage of lower power costs and higher efficiency. Large refrigeration systems can take advantage of their higher COP to chill product to a lower temperature with the remaining stages in the supply chain maintaining a target temperature band, reducing the cooling load on these lower COP, higher cost of cooling stages.

For exported product, whether shipped or air freighted, the cost of marine fuel oil-fired refrigeration systems and dry ice respectively vastly dominates the total supply chain cost. Parity is achieved between the shipped and air freighted specific cost of cooling at transit times of around eight hours. Above this with all other factors equal, shipping provides a more cost effective transit method, with air freight tending to be better suited to shorter journeys or under conditions where dry ice can be procured very cheaply, or transit time is of critical importance.

For domestic product, supply chain cost is dominated by the inefficiencies of retail refrigeration, followed by the large storage time in the warehouse and processor. The lowest hanging fruit of in this supply chain to reduce costs is thus investing in closed display cases rather than open cases, significantly reducing convective losses while on display.

At a given target temperature and COP, the cost of cooling is directly proportional to the cost of electricity delivered to the compressor. The cost of cooling can then be improved by:

- Minimising electricity cost
    - Switching to renewable sources, such as solar PV or generation engines running on biogas
    - Improving site power factor
    - Improving equipment voltage optimisation
- Maximising COP
    - Minimise work input W
        - Compressor maintenance, oil leaks, motor function
        - Check seals to ensure no ambient hot air entering refrigerated space
        - Ensure doors are not left open unnecessarily
        - Consider a variable speed drive to run compressor proportionately to amount of product to be cooled
    - Maximise heat absorbed Q_L
        - Set temperatures as near to food safety standard limits, as the greater the difference between T_L and T_H, the lower the COP
        - Keep the space full
        - Insulate refrigerant pipes to prevent absorbing ambient heat and maintain insulation

Opportunities for best practice improvements (Expert Group, 2020)

- Improve traceability throughout cold chain
    - Better record keeping identifying critical control points and monitoring temperature, relative humidity, shock, and movements
    - Correct use of thermometers and evidence collecting

    - Monitoring of refrigerated transport
    - Use of time temperature integrators
- Improve equipment and insulation standards
    - Refrigerated spaces including walk in cold rooms, cold storage facilities, and loading
    - Best practice guides for design, installation, commissioning, and maintenance
    - Measuring interior and exterior temperatures, with specified maximum K coefficient of thermal conductivity
    - Registering refrigerated trucks under unique class, with inspections to check compliance to agreed standards, consider mandatory standards in extension of *AS 4982:2003 R2016: Thermal performance of refrigerated transport equipment, specification, and testing*. Currently a voluntary standard and thus ineffective
- Refrigeration systems to work effectively, well maintained, easy to operate, easy to interrogate in person and remotely, and understood by all users along supply chain
- Training and educational materials more widely available
- Improved processes to address the key commonly observed failures identified by the Australian Food Cold Chain Council focus group
    - Lack of suitable training and materials for training
    - Absence of process for goods handling or insufficient or inadequate process
    - Lack of ability to verify a process has been maintained
    - No means of identifying process failure
    - Failure to understand and/or properly implement process
    - Lack of product traceability
    - Lack of validation of prior process
    - Overloading trailer
    - Incompatible mixed loads
    - Incorrect segregation
    - Lack of regular cleaning
    - Incorrect or absence of pre-chilling
    - Poor packing, stacking, or wrapping
    - Operational pressures that force mixed loads
    - Poor demand forecasting leading to over supply
    - Excessive transit distances
    - HACCP
    - Incorrect pre-loading temperature
    - Badly designed loading docks, delays, weather exposure
    - Training specific to equipment
    - Lack of validation of equipment
    - Poor airflow in trailer and packaging
    - Lack of appropriate equipment where and when needed
    - Poor container repair
    - Poor maintenance
    - Equipment age
    - Poor air distribution in refrigerated space
    - Poor trailer mapping
- Greater use of vacuum packaging and freezing to improve shelf life
- Refrigeration display cases with doors to ensure temperatures uniformly maintained and reduce losses due to meat discolouration, extend shelf life

5. Conclusion and recommendations

It can be concluded that as temperature increases, particularly in the domestic vacuum packed temperature range of -2 to 10°C, the COP increases non-linearly, with proportionate savings in cooling cost, however will impact on product quality as temperature increases. A balance between the 2 will be dependent on storage time and feasibility of lowering the temperature.

We recommend further work with cold chain operators to investigate the impact and cost of holding product at a different temperature relative to waste and cold chain operators to review Alternative Systems to Recover Energy in the appendix to reduce cost.

6. References

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7. Appendix

Alternative Systems to Recover Energy

De-Superheaters

De-superheaters can be installed between the compressor and condenser and function on heating water or another process fluid with the waste sensible heat that is rejected from the superheated (i.e. heated above its vaporisation temperature) refrigerant prior to being condensed in the condenser, dumping latent heat. The refrigerant then exits the de-superheater a few degrees above its condensation temperature, with the heated water approaching the inlet refrigerant temperature. A de-superheater improves on the heat transfer efficiency in the condenser as the temperature pinch – the minimum temperature difference between the hot fluid and cold fluid is avoided, as the temperature remains constant in the condenser as latent heat is lost – see Figure 22.

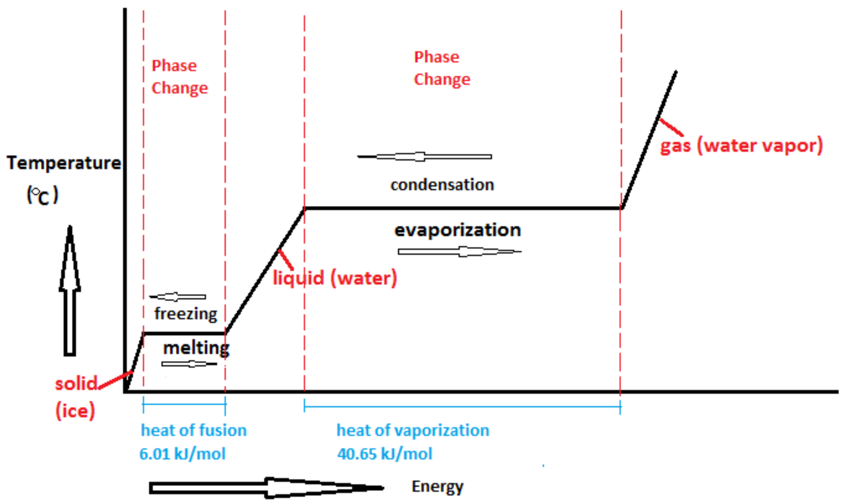

Figure 18: Diagram of latent and sensible heat, showing temperature constant at phase change

The value in water heated in a de-superheater can relieve pressure on a site's boiler, particularly at the beginning and end of shifts, and changeover between shifts when the demand for hot water for cleaning, hand washing, and sterilisation is highest. Estimates of the value[8] in harnessing the available de-superheater energy calculated in Figure 23 below.

[8] For a coal boiler with a thermal energy price of $5/GJ, running a refrigeration system 24 hrs per day for 330 days per annum

			De-superheater		
	Target Temp [degC]	Refrigerant Temp [degC]	[kWt]	[GJ pa]	$ pa
Frozen	-24.4	-29.4	490.5	13985.1	$69,926
	-21.1	-26.1	443.5	12645.1	$63,225
	-18.1	-23.1	404.2	11524.6	$57,623
	-15.4	-20.4	370.7	10569.4	$52,847
	-14	-19	355.6	10138.9	$50,694
	-13	-18	341.5	9736.8	$48,684
	-11.8	-16.8	341.5	9736.8	$48,684
	-9.6	-14.6	328.3	9360.5	$46,802
Chilled	-2	-7	122.073	3480.5	$17,403
	-1.2	-6.2	122.073	3480.5	$17,403
	1.9	-3.1	89.65	2556.1	$12,781
	4.8	-0.2	67.6	1927.4	$9,637
	7.5	2.5	48.23	1375.1	$6,876
	10	5	32.22	918.7	$4,593

Figure 19: Value in recovered energy from de-superheater across frozen and chilled temperature range

Innovative Condenser Cooling

All Energy Pty Ltd has previously analysed innovative industrial cooling options in extensive detail, with options considered including open loop evaporative cooling, closed loop evaporative cooling, dry cooling, adiabatic cooling, and heat exchange with a large body of water e.g. evaporation ponds, rivers, dams, etc.

Evaporative Cooling – Open Loop

An example quote and schematic for an open loop cooling tower is shown below. The operation of open loop cooling towers is relatively simple, with hot cooling water sprayed against cool dry air in counterflow. A portion of the hot cooling water is evaporated and discharged as hot saturated air, rejecting latent heat from the cooled water returned to the process. The primary drawback to the simplicity of this plant is the potential for microbial and mineral contamination, requiring additional opex for cleaning and chemical dosing. A portion of makeup water is required in the cooling water stream, adding to high water consumption.

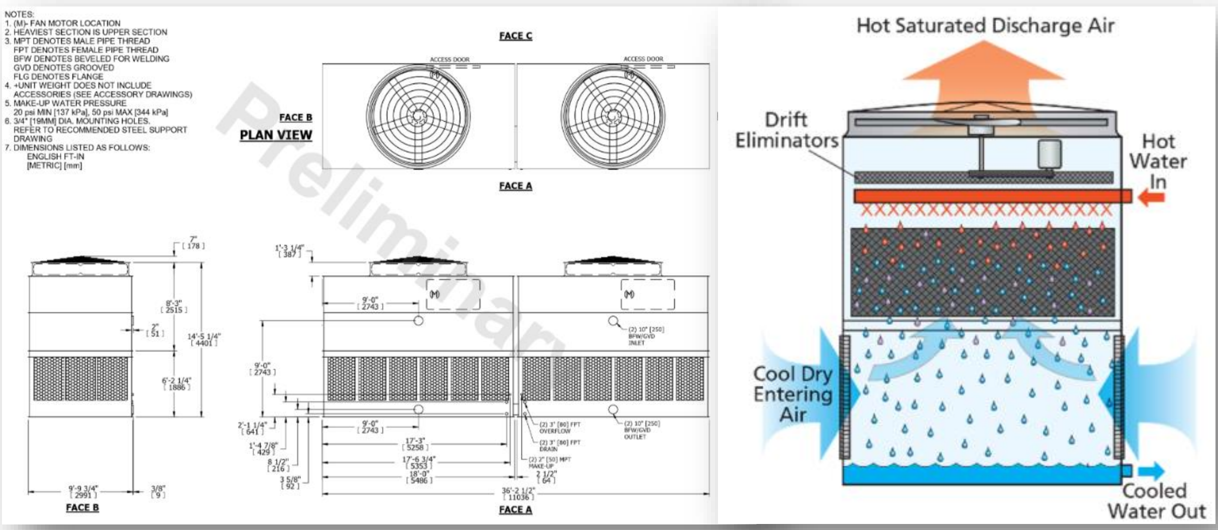

Figure 20: Example quote and schematic for an open loop evaporative cooler, EvapCo 2019

Evaporative Cooling – Closed Loop

A simplified schematic of a closed loop cooling tower is shown below. The principle of operation is based on a non-contact heat exchange with the cooling water from the electrolysers flowing through the cooling tower, with spray water and cool dry air introduced in a counterflow operation. Hot saturated air is discharged, while latent heat is absorbed from the cooling water. The primary benefit of a closed loop tower is the minimised potential for microbial or mineral contamination of the cooling water, reducing the need for cleaning of cooling water lines and chemical dosing. The material of construction is SS316 with nitrile rubber gaskets.

Dry Coolers

To mitigate the issue of water availability, the option of dry cooling was explored. Dry cooling refers to a method of rejecting sensible heat from a fluid using little to no water, hence the name "dry cooling". Provided that the cooling fluid is able to be accepted at a temperature with a sufficient dT from the ambient dry bulb temperature, dry cooling may be an attractive option for most of the year. During the hottest days of the year, where the ambient dry bulb temperature exceeds 35 °C, the use of evaporative pads may be required during these times. An additional quote was received for "adiabatic cooling" where heat is rejected through the expansion of air.

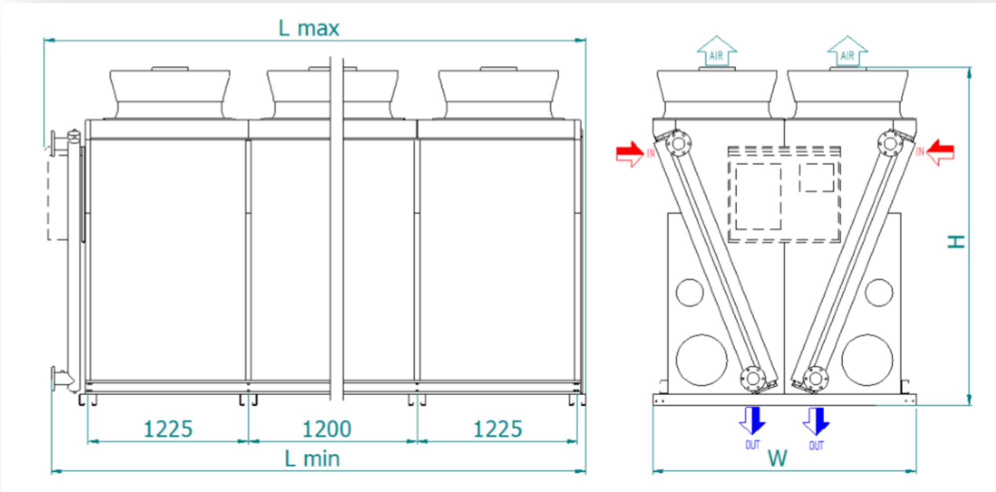

Figure 21: Example schematic of dry cooler with pads, suitable to 35 °C, UAP 2019

Adiabatic Cooling

Adiabatic cooling systems function similarly to dry cooling systems, but with the incorporation of pre-cooling pads; running water over pre-cooling pads and drawing air through the pads depresses the dry bulb of the incoming air. Adiabatic systems are highly effective in hot, dry environments, while using less water than traditional evaporative units. Adiabatic units also deliver the required cooling capacity in a smaller footprint and/or lower fan motor horsepower than a completely dry cooler/condenser.

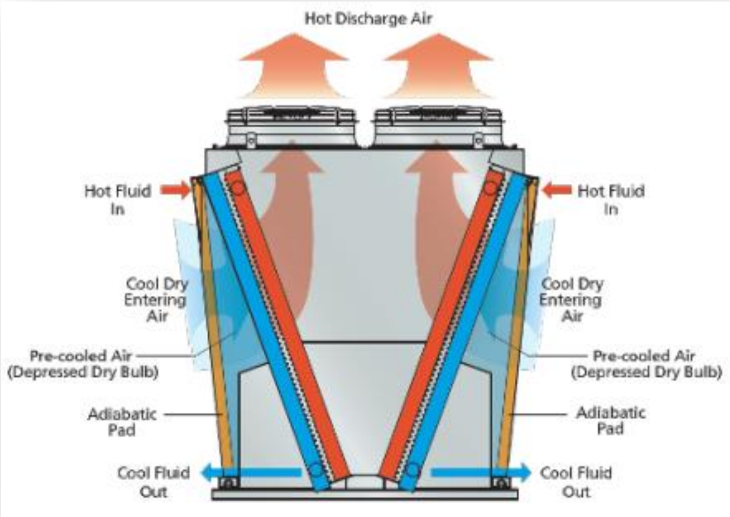

Figure 22: Example quote and schematic for adiabatic cooling, EvapCo 2019

Heat Exchange with Large Water Body

Large bodies of water (e.g. evaporation ponds, dams, water treatment ponds) may be a convenient source of cooling water, requiring pumping, piping, and heat exchange plant. An image of a suitable heat exchanger is given below. For RMPs, a specific example could be making use of WWTP holding ponds as a heat sink to reduce the power and water costs associated with an evaporative cooling system or dry coolers.

Figure 23: Plate and frame heat exchanger suitable for cooling process fluid using large volumes of water as a heat sink, Alfa Laval 2019

The cost and feasibility of this option is dominated by the requirement of piping (supply and return loops), excavation, installation, and backfill; rather than the cost of the heat exchanger.

Indicative Cost of Cooling Comparison

As seen below, the need for water dominates the eventual Levelised Cost of Cooling (LCoC; or the cost of cooling over the life of the plant taking all CapEx and OpEx into account), hence dry cooling should be investigated further as this cost becomes prohibitive when water is scarce. The price paid per kL of water is another critical determinant of the feasibility of cooling towers and the evaporation pond, so should be definitively priced on a plant specific basis.

Table 2: Indicative cost of cooling comparison. LCoC: Levelised Cost of cooling, in units of Megawatts hours of cooling (MWhc).

#	Cooling Technology	Option	LCoC [$/MWhc]
1	Adiabatic cooler (dry cooler with moistened cooling pads)	Cooling closed loop fluid from 50°C to 40°C	$2.43
2	Plate and frame heat exchanger with water transfer pump	Evap pond HX, pump, and piping – 4 in parallel	$2.94
3	Dry cooler	Cooling closed loop fluid from 50°C to 40°C	$3.31
4	Evaporative Cooling Tower	Open loop ID counterflow cooling tower (cooling from 60°C to 50°C)	$10.97
5	Evaporative Cooling Tower	Open loop ID counterflow cooling tower (cooling from 50°C to 40°C)	$10.99

It should be noted that the above **indicative** analysis was modelled for a scenario where low power from a large solar PV array, biogas engine or off-peak power was utilised with water costed at approximately $4.50 / kL. The feasibility of the above cooling options will depend on the specific site energy and water costs, however the analysis reflects the trend in the Australian RMI and industry as a whole for greater utilisation of lower cost power via solar PV in line with cost and emissions reduction goals while also operating under increasing water utility costs. As the cost of water increases further, options with minimal water consumption such as heat exchangers, dry coolers and adiabatic cooling will become more attractive compared to evaporative cooling towers.

Innovative Supply Chain Efficiency Gains

For vertically integrated cold chains, where the operator has control over large stationary refrigeration plant as well as distributed storage, trucking, shipping, or other freight modes, changes to the supply chain can be made to take advantage of higher efficiency or lower power costs to reduce overall supply chain costs. A large refrigeration plant at a processor can take advantage of lower power costs and higher efficiency from:

- Biogas generation or solar PV (permitted by large available land on site)
- De-superheaters
- Turbines

- Variable speed drives
- Voltage optimisation
- Power factor correction
- Single or multi-stage, absorption, or cascade refrigeration systems
- Different choice of refrigerants
- More frequent maintenance schedules

Large refrigeration systems can take advantage of their higher COP to chill product to a lower temperature with the remaining stages in the supply chain maintaining a target temperature band, reducing the cooling load on these lower COP, higher cost of cooling stages.