Sustainable action for a better tomorrow

KPHI Decarbonisation Workstream 1

Use of natural refrigerants for replacement or new refrigeration systems.

Final Report

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Executive Summary

Workstream 1 of the Kiwifruit Post-Harvest Industry (KPHI) Decarbonisation Programme focused on completing a review of natural refrigerant alternatives to replace the use of high-GWP synthetic refrigerants.

The aim of the study was to establish typical replacement scenarios and then review the most likely natural alternatives for each of these. To address this aim, the report is structured as follows, with each section examining a key aspect of the analysis:

- Section 1 provides report background and definition of scope etc.
- Section 2 reviews the natural refrigerant options and typical system architectures.
- Section 3 explores the technical and practical considerations around the adoption of natural refrigerants.
- Section 4 presents indicative cost comparisons for different natural solutions for small, medium, and large coolstore applications.
- Section 5 presents the main replacement scenarios and evaluates the pros and cons of the natural refrigerant options against these.
- Section 6 provides a summary of findings and recommendations.

Right now, there are commercially viable natural refrigerant solutions for all KPHI applications. These solutions can permanently address the emissions concerns associated with the extensive use of high GWP synthetic refrigerants within the industry. However, no single natural refrigerant offers a silver bullet solution, each having benefits and drawbacks that need to be weighed against the individual requirements of the site and business.

Key findings from this work include the following:

- Technology is changing quickly in this space, with new products entering the market (e.g., hydrocarbon packaged chillers) and other sectors demonstrating the viable use of natural refrigerants for applications previously considered out of reach (e.g., the widespread roll-out of CO_2 for the supermarket industry).
- Opex (both energy and maintenance) represents a considerable portion of the total levelised cost of cooling, stressing a need for consideration of energy efficiency when reviewing natural refrigerant options.
- Historical concerns with CO_2 systems and its compatibility to the seasonal demands from the KPHI have been addressed.
- The benefits of large, centralised plant were not obvious, based on the data supplied – requires site by site consideration of coolstore layouts, spacing, and load diversity.

What is the likely solution for existing coolstores?

- Driven by pragmatics, it is most likely that adoption of natural refrigerants for existing coolstores will involve an interim solution whereby coolstores are converted to glycol reticulation and the existing plant is retained and operated on drop-in replacement refrigerants. Natural refrigerants would then be adopted for the compressor plant either at the end of the existing plant life, or when capital allowed. This approach:

  - Dramatically reduces synthetic refrigerant charge immediately
  - Extends the operational life of the coolstore
  - Future proofs the plant for conversion to natural refrigerants, with options for different refrigerants kept open

What is the likely solution for new coolstores?

- It is anticipated that all new coolstores would be built to use natural refrigerants.
- Lowest levelised cost of cooling are expected for either direct expansion CO_2 or ammonia glycol systems.
- It is important for KPHI operators to ensure defrost loads and glycol ancillary power loads are considered when comparing energy demands as these can be considerable.

1. Background

1.1 KPHI Decarbonisation Programme

Kiwifruit is the biggest horticulture industry in New Zealand, and New Zealand is the largest global exporter of kiwifruit by a wide margin. The industry faces headwinds to decarbonise with the main challenges being transport and cool storage.

The Kiwifruit Post-Harvest Industry (KPHI) working group is carrying out a programme of work, with support from MPI's Primary Sector Growth Fund (PSGF), to help address the cool storage decarbonisation challenge. The work aims to equip the New Zealand KPHI (and other related industries) with the required knowledge to determine the most cost-effective options to reduce greenhouse gas emissions liability at their sites.

The programme constitutes four workstreams as follows:

1. Use of natural refrigerants for new or replacement refrigeration systems.
2. Replacement of high Global Warming Potential (GWP) refrigerants with lower GWP refrigerants for existing systems.
3. Refrigerant leak mitigation and minimisation.
4. Programme management including stakeholder engagement, communication, knowledge sharing and administration.

1.2 Workstream 1

Workstream 1 involves completing a review of the natural refrigerant alternatives that are available for replacement refrigeration systems in KPHI businesses. The review considers both solutions for retrofitting existing coolstores as well as new coolstore scenarios.

1.3 Background

Surveys conducted by DETA of the New Zealand kiwifruit post-harvest industry, capturing 97% of the industry by market share, indicated widespread use of high GWP refrigerants. At the time, total refrigerant emissions liability was 176,110 tCO_2e. In addition to the emissions liability, the industry faces challenges from the phase down of the legacy HFC refrigerants and subsequent considerable increases in refrigerant costs. Combined, these influences are driving the industry to review low-GWP natural refrigerant alternatives.

1.4 Objective

The objectives of the report are to:

- Review the natural refrigerant alternatives.
- Establish typical replacement scenarios.
- Carry out system impact and financial assessment on the various scenario and option combinations.
- Develop recommendations of which refrigerants and systems are most appropriate, and in which context one option might be preferred over another

1.5 Scope

The scope of this current report is limited to the exploration of natural refrigerant options. The work does not consider synthetic refrigerant alternatives or drop-in replacements other than presenting this as an interim, enabling solution, or to provide benchmarking information around system costs etc.

The refrigeration requirements of each stakeholder in the KPHI are different and bespoke. This report attempts to provide broad advice and use representative scenarios to provide a fact based, objective reference.

1.6 Key Industry Engagement

To help inform this report, DETA engaged directly with various industry stakeholders, including equipment suppliers, refrigeration contractors, and end users.

It should be noted that the material compiled within is an independent compilation, including consideration of available literature and standards as well as the information and anecdotes provided by these stakeholders.

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2. Refrigerants

2.1 Historical Usage Timeline

The following high-level timeline illustrates the evolution of refrigerants since the inception of vapour compression refrigeration systems.

Pre-1930s: Natural Refrigerants

- **Common refrigerants**: ammonia (NH_3, R717), carbon dioxide (CO_2, R744), hydrocarbons (R290, R600a), sulphur dioxide (SO_2), methyl chloride (CH_3Cl).
- **Drivers**: they were the only options available.
- **Problems**: toxicity (NH_3, SO_2, CH_3Cl), flammability (HCs), very high pressures (CO_2), leading to safety incidents.

1930s–1980s: Rise of Synthetics (CFCs/HCFCs)

- **Key innovation**: invention of CFCs (R12, R11) by GM & DuPont in 1928. Later HCFCs (R22, R123).
- **Drivers**: safety concerns and desire for non-toxic, non-flammable, chemically stable, easy to use.
- **Problems discovered later**: ozone depletion (CFCs/HCFCs), very high GWP.

1987–2000s: Ozone Crisis & CFC/HCFC Phase-Out

- **Key event**: Montreal Protocol (1987).
- **Drivers**: scientific consensus on hole in ozone layer led to mandated phase-out of CFCs, then HCFCs.
- **Replacements**: HFCs (e.g., R134a, R404A, R410A) introduced as "ozone-safe" alternatives.

2000s–Present: Climate Concerns & HFC Phase-Down

- **Problems**: HFCs have very high GWPs (hundreds to thousands).
- **Drivers**: Kyoto Protocol, EU F-Gas regulations, Kigali Amendment (2016) leading to global phase-down of HFCs.
- **Replacements**:
  - **HFOs (e.g., R1234yf, R1234ze)** - low GWP synthetics, mildly flammable.
  - **Natural refrigerants return**: CO_2 in supermarkets/heat pumps, ammonia in industry, hydrocarbons in domestic fridges and small systems, water and air in niche applications.

Current & Future outlook:

- **Trend**: increased efficiency, reduced climate impacts, and safety balance.
- **Main drivers**: Kigali HFC phase-down, net-zero policies, energy efficiency standards.
- **Outlook**: strong growth in naturals (CO_2, NH_3, hydrocarbons) with ongoing innovation in system design to mitigate flammability/toxicity risks. There is also growth expected in the adoption of HFOs, but long-term use is uncertain due to their breakdown to "forever chemicals" in the atmosphere (refer to Appendix B for more information).

2.2 Natural Options

According to an industry wide survey undertaken in 2024[1], approximately 95% of the refrigeration systems in the New Zealand KPHI currently use fluorinated refrigerants (HCFCs, HFCs and blends including HFOs), collectively representing a total emissions liability of 176,110 tCO_2e. By contrast, there were only 20 low GWP (<150) systems, consisting of 12 ammonia systems, 7 propylene, and 1 HFO, with a collective emissions liability of 1 tCO_2e.

Natural refrigerants present alternatives to synthetic refrigerants which can be adopted to mitigate global warming concerns. They are referred to as natural as they are substances which occur in nature, and include ammonia, carbon dioxide, hydrocarbons, and water. Table 1 summarises the main natural refrigerants and their key properties.

Table 1. Summary of the main natural refrigerants and their key properties.

Refrigerant	Chemical Name	Chemical Formula	ASHRAE Class[2]	GWP	ODP	Boiling Point (°C)	Saturation Pressure @ 25°C (bar)
R717	Ammonia	NH_3	B2L (toxic, mildly flammable)	0	0	-33.3	~10 bar
R744	Carbon Dioxide	CO_2	A1 (non-toxic, non-flammable)	1	0	-78.5	~64 bar
R290	Propane	C_3H_8	A3 (highly flammable)	~3	0	-42.1	~8.4 bar
R600a	Isobutane	C_4H_{10} (iso)	A3 (highly flammable)	~3	0	-11.7	~2.1 bar
R1270	Propylene	C_3H_6	A3 (highly flammable)	~2	0	-47.7	~9 bar
R718	Water	H_2O	A1 (non-toxic, non-flammable)	0	0	100	0.03 bar

2.2.1 Ammonia

Ammonia is a colourless gas at atmospheric pressure with zero GWP and ODP. It is widely used as an industrial refrigerant because it has inherently high energy performance, excellent thermodynamic properties (e.g., high latent heat – large amounts of energy in phase change, high volumetric cooling capacity – the cooling energy per unit volume of refrigerant), and high thermal conductivity. It is also readily available and relatively low cost.

The main drawback with ammonia is its toxicity at high concentrations (>300 ppm). Ammonia also has a flammability range of 15 to 34 per cent by volume in air, and a Lower Explosion Limit of 150,000 ppm, which is well above easily detectable levels, and orders-of-magnitude above accepted levels of occupational health exposure of less than 50 ppm.

Ammonia has a pungent odour which allows for easy human detection even at very low concentrations (~5 ppm), which helps mitigate potential harm from exposure. Due to its toxicity, use of ammonia is regulated by WorkSafe New Zealand, with continuous ammonia gas detection and alarm systems required for machinery rooms and enclosed spaces. Machinery rooms must

[1] Xlabs Refrigerant Team, Kiwifruit Post-Harvest Refrigeration Survey Report, 2024
[2] Refer to Appendix A for additional information on ASHRAE Refrigerant Safety Classifications

have mechanical ventilation to remove leaked ammonia and secondary containment (bunding) may be required around vessels to manage liquid spills.

2.2.2 Carbon Dioxide

Carbon dioxide (CO_2) has been used as a refrigerant since the 1860's. CO_2 offers highly desirable traits including low toxicity, non-flammability, zero ozone depletion potential and a global warming potential of 1. However, carbon dioxide has some unique temperature/pressure characteristics, including an unusually low critical temperature of 31.1°C. This means that condensing needs to take place at very high pressures of up to ~90 bar, which is as much as 10 times higher than those required for alternative systems (e.g., ammonia and HFCs).

In warm ambient conditions rejecting heat requires the system to operate in transcritical (or supercritical) mode (i.e., no condensing, just gas cooling). The temperature glide associated with gas cooling in transcritical operation can offer advantageous characteristics for heating applications – giving rise to the development of CO_2 heat pumps – however, for refrigeration systems this comes with an efficiency penalty (COP of ~2.4 for transcritical vs. >6 for subcritical). It is important to note that in New Zealand and for the KPHI specifically, the amount of time for which the ambient conditions during the season require transcritical operation is very limited and consideration should be given to the average seasonal efficiency.

Earlier CO_2 systems were often used in a cascade arrangement with a synthetic refrigerant used to condense the CO_2. This allowed the condensing temperature, and importantly pressures, to remain below the safe limits of the equipment. However, when the cooling load was not required and the CO2 system was switched off, the secondary synthetic system was still required to cool the CO2 condenser to prevent pressures in the system rising, consuming energy even when the coolstore is off.

This is no longer a problem, as modern CO_2 systems utilise equipment that is rated for 120 bar pressure to accommodate the inherently high pressures of the CO_2 in high ambient conditions. They also incorporate Pressure Relief Valves (PRV) to safely vent refrigerant in the event of a rapid pressure increase following a power outage or system shut off.

Advances in valves and controls have improved the ability for CO_2 systems to regulate coolstore air temperatures. This has also led to reduced icing and defrost requirements.

2.2.3 Hydrocarbons

The hydrocarbons most commonly used as refrigerants are ethane (known as R170), propane (R290), butane (R600), isobutane (R600a) and propylene (R1270). All hydrocarbons have zero ODP and very low GWP of around 3. Hydrocarbons are compatible with almost all refrigeration system lubricants and can be used as drop-in replacements for some systems designed for a fluorocarbon refrigerant. Hydrocarbon refrigerants are used globally in millions of domestic refrigerators.

The primary drawback for hydrocarbon refrigerants is their high flammability. To combat this risk, refrigerant charge limits are strictly controlled by Australian and New Zealand Standards, such as

AS/NZS 5149. For this reason, hydrocarbon refrigerants are not well suited to direct expansion coolstore applications and will be limited to use with secondary refrigerants such as glycol (see section 2.3.2). Hydrocarbon systems also have relatively low efficiency (i.e., Coefficient of Performance – COP) compared to either ammonia or CO_2, which means they consume more energy to deliver comparable cooling.

However, packaged hydrocarbon refrigeration systems are beginning to enter the market. Construction techniques such as welded fittings and extruded or swept bends are being used to minimise potential for leaks. Whilst the capacity of these units is currently much smaller than synthetic or other natural alternatives (~30 kWr), they are expected to eventually reach 350 kWr and offer a legitimate alternative.

2.2.4 Water

Water is also technically considered a natural refrigerant and has had renewed interest because it is non-toxic, non-flammable, low cost, and abundant. Water is used in higher temperature absorption chiller systems, where it is used as the refrigerant in combination with lithium bromide as the absorbent. However, the unique thermophysical properties of water (e.g., very low saturation pressure, high boiling point) mean that applications in vapour compression refrigeration cycles are challenging. To achieve liquid conditions at useful temperatures for chilling applications, operating suction pressures need to approach zero bar absolute (i.e., perfect vacuum), which makes it very hard to prevent contamination from air and dust ingress. Secondly, water vapour is extremely low density compared to other refrigerants. This means that compressors need to be able to handle very large volume flow rates. For this reason, it is unlikely water-based refrigeration systems will ever be a viable option for the KPHI.

2.3 System Architecture

2.3.1 Direct Expansion (DX)

Direct expansion (DX) refers to a design where the refrigerant is piped to the evaporator and is expanded directly into the evaporator coils inside the coolstores. From here, the refrigerant absorbs heat and changes phase from liquid to vapor inside the coil thereby cooling the air passing over the coils. Most synthetic refrigerant systems in the KPHI utilise direct expansion (DX) architecture. A simplified schematic of this architecture is shown in Figure 1.

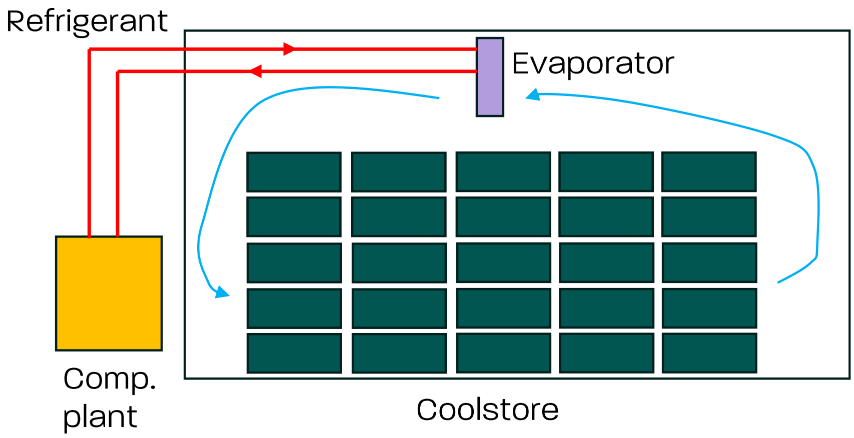

Figure 1. Schematic representation of direct expansion (DX) architecture.

Advantages of DX systems include:

- **Simplicity** – avoid need for secondary refrigerants and additional heat transfer steps.
- **Efficiency** – direct heat transfer between the refrigerant and the coolstore air allows for higher saturated suction pressures (i.e., refrigerant liquid temperatures) compared to indirect systems (e.g., glycol) for the same primary refrigerant. Additionally, DX systems do not require secondary refrigerant pumps with their additional power consumption.
- **Smaller evaporators** – latent heat of phase change for refrigerants are much higher than the specific heat capacity of non-phase change secondary refrigerants (e.g., glycol). This means DX evaporators require less surface area than secondary refrigerant unit coolers.
- **Greater responsiveness** – DX evaporators can respond more quickly than secondary refrigerant systems to rapid load changes. This is due to there being less thermal mass in these systems.

Disadvantages of DX systems include:

- **Greater refrigerant charge** – additional refrigerant volume is required due to the volume contained within the reticulated piping and evaporators. This represents greater refrigerant cost and emissions liability.
- **Increased risk of refrigerant leaks** – the additional lengths of refrigerant piping plus greater number of valves and evaporators requiring connections increases the potential for refrigerant leaks. Furthermore, the presence of refrigerants within the coolstore pose additional risk of leakage caused by accidental damage from mobile plant such as forklifts.
- **Risks from exposure to refrigerants** – The presence of refrigerants within internal occupied spaces creates safety risks from the potential leakages of refrigerants (risks from flammable, toxic or hazardous substances).

Based on these trade-offs, CO_2 is the only natural refrigerant suitable for use with a DX system architecture.

2.3.2 Secondary Refrigerants

In secondary refrigerant systems, the primary refrigerant is confined to a central chiller and heat rejection system. The primary refrigerant cools a secondary fluid, most commonly an aqueous solution of water and glycol (ethylene glycol or propylene glycol), which is then pumped to the cooling coils (referred to as "unit coolers") that are mounted inside the coolstores. A simplified schematic of this architecture is shown in Figure 2

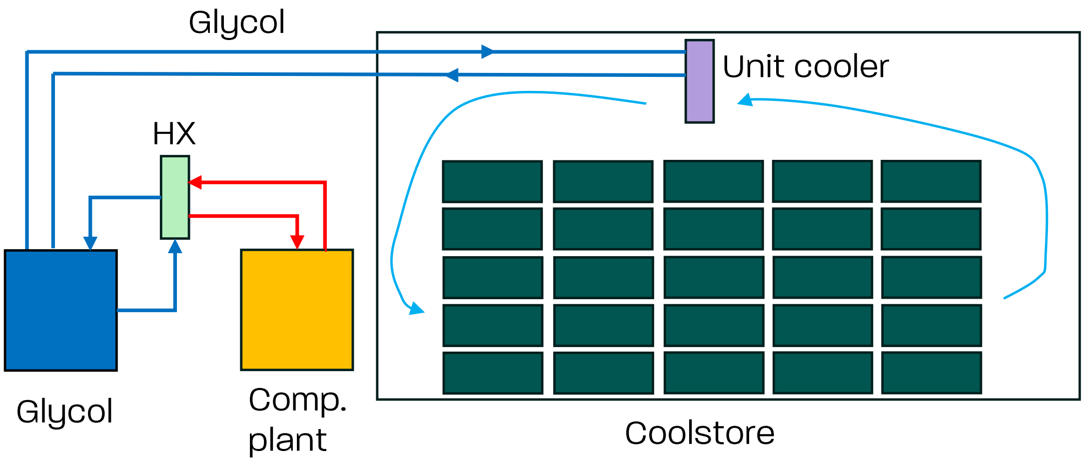

Figure 2. Schematic representation of secondary refrigerant (glycol) architecture.

Advantages of secondary refrigerant systems include:

- **Reduced refrigerant charge** – avoiding circulating the primary refrigerant throughout the entire system reduces the refrigerant charge. This reduces emissions and replacement cost liability.
- **Easier distribution of cooling over long distances** – allows for larger, more efficient centralised refrigeration plant servicing multiple coolstores.
- **Improved safety** – reduced risks from exposure to hazardous refrigerants in occupied spaces.
- **Simpler plant maintenance** – maintenance of the primary refrigerant system is limited to a centralised, easily accessible plant.
- **Increased plant life** – the larger capacity systems often enable the use of heavier-duty plant, which typically has longer operational lifespans than lighter duty equipment.
- **Greater ability for humidity control** – secondary refrigerant unit coolers allow for very accurate control of air temperatures within the coolstore (control of air temperatures to within +/- 0.1°C of setpoint is quoted by refrigeration contractors). This can enable coil temperatures to be set slightly above the freezing point, thereby largely avoiding frost formation. This can avoid the removal of water vapour from the coolstore air, helping to retain high humidity and aid with kiwifruit quality.
- **Reduced defrost energy consumption** – the improved temperature control and avoidance of frost formation (above) can lead to much reduced defrost requirements.

Disadvantages of secondary refrigerant systems include:

- **Additional costs** – The requirement for additional equipment such as glycol storage tanks (chilled and warm), circulation pumps, refrigerant/glycol heat exchangers, glycol reticulation piping (commonly stainless steel), and unit coolers (typically more expensive than DX evaporators) all add capital costs.

- **Reduced primary refrigerant energy efficiency** – the primary refrigerant is required to operate at lower temperatures than on a DX system to enable transfer of heat from the glycol. This reduces the efficiency of the compressor (COP) and leads to additional electricity use.
- **Additional ancillary energy loads** – additional pumping power is required to circulate the secondary refrigerant. Total electrical demand should be considered when comparing systems, not just the demands of the compressor plant.
- **Installation costs can be higher** – due to the additional equipment.

These trade-offs make secondary systems well-suited for large facilities, multi-zone cooling, or applications where refrigerant safety and charge reduction are priorities. This includes retrofit applications where secondary refrigerants can be adopted to remove reticulation of HFC refrigerants within coolstores, whilst retaining the existing compressor plant.

3. System Replacement Considerations

There are many factors to consider when evaluating which natural refrigerant system may be best suited for a KPHI coolstore. This section summarises some of these by broad classification.

3.1 Technical Considerations

3.1.1 Coolstore Strength

Glycol unit coolers are considerably larger and heavier than the equivalent cooling capacity DX evaporator, driven by the requirement for more surface area on the coils. Furthermore, glycol reticulation piping is heavier than piping supplying synthetic refrigerants as it is larger diameter and generally made from stainless steel rather than copper. The additional loading from this equipment needs to be considered. Some existing coolstores hang or support piping directly from the insulated panels. In these situations, the loading may exceed allowable levels and require additional steel structures to support adding cost, complexity and time to a project.

3.1.2 Hazards

Adoption of hydrocarbon refrigerants can introduce new flammability hazards to a site. To mitigate this, hydrocarbon systems are limited in charge and should be installed in well-ventilated plant rooms fitted with leak detection systems, or outside/open air environments.

Ammonia refrigeration systems pose risks of toxicity, flammability, environmental harm, and mechanical failure, which are managed through engineered controls such as leak detection, ventilation, shunt trips, pressure relief, and robust system design, alongside administrative measures like emergency planning, restricted access, and operator training.

CO_2 refrigeration systems present hazards including very high operating pressures, the risk of rapid gas release, and asphyxiation in confined spaces. These risks are mitigated through pressure-rated components, over-pressure detection and relief devices, adequate ventilation, continuous leak detection, and strict maintenance and operational procedures. The rapid adoption of CO_2 systems in the supermarket industry demonstrates that, when properly designed and managed, these risks can be effectively controlled.

3.1.3 Energy Efficiency

The lifetime operational energy costs of a coolstore refrigeration system far outweigh the initial capital costs of the hardware. For this reason, it is essential to pay attention to the energy efficiency of the system, considering not just the compressor plant COP, but the energy demand of all ancillary equipment (such as glycol circulation pumps, heat rejection system fan loads, and defrost loads).

3.2 Practical Considerations

Practical considerations influencing a decision regarding the adoption of a particular natural refrigerant include the following:

3.2.1 Equipment Selection

- **Plant architecture:** Natural refrigerants generally favour specific architectures (e.g., ammonia and hydrocarbons are only suited to secondary refrigerant configurations). If the existing plant is DX then it is important to assess coolstore structural strength when considering retrofitting a secondary refrigerant loop due to the additional weight. If the existing plant uses a secondary refrigerant, then conversion of the synthetic refrigeration to naturals is relatively easy.
- **Safety & ventilation constraints:** Evaluation of plant room ventilation, construction type (note: ammonia plant rooms should be constructed from fireproof materials such as concrete), and distance to neighbouring buildings help determine suitability of ammonia or hydrocarbons (flammable/toxic). If ventilation is inadequate, a plant room upgrade or new plant room may be required.
- **Refrigerant charge minimisation:** Adoption of air-cooled condensers for ammonia systems provides an opportunity to further reduce the required quantity of refrigerant, as these heat exchangers hold less volume of liquid ammonia than traditional evaporative condensers. However, heat rejection using air-cooled condensers is less efficient than evaporative condensers as it requires a higher ammonia temperature/pressure. This should be considered when reviewing the benefits of the reduced emissions liability.

3.2.2 Cost

- **Capital costs:** Capital cost remains one of the most significant considerations for both retrofit (existing coolstore) or new systems (new coolstore). Decisions made around refrigerant selection for a retrofit situation will be done in the context of extending the useable life of the coolstore. Converting an existing DX coolstore will commonly require complete replacement of the evaporators (if retaining the DX architecture) or installation of fit-for-purpose unit coolers if converting to a secondary refrigerant system. Both will involve considerable cost, which in some cases can be many times that of the compressor plant costs.
- **Operating costs & energy efficiency:** Natural refrigerants can be more efficient than synthetic refrigerants, depending on climate and system choice. Transcritical CO_2 has penalties in warm climates but strong performance in cool climates, ammonia is very efficient for low-temp, hydrocarbon systems tend to have relatively poor efficiency. It is important to evaluate seasonal COPs and electricity tariffs and understand plant utilisation.
- **Soft costs:** Other costs to be mindful of include site staff training, emergency planning, increased insurance premiums (or lower premiums if risk reduced), downtime during conversion, and contractor availability for ongoing maintenance.

3.2.3 Leak Detection and Spill Containment

- **Bunding:** For ammonia systems, bunding is often required around large outdoor vessels or liquid receivers to contain potential liquid leaks and prevent environmental contamination. This is particularly true for installations in rural sites without access to trade waste.

- **Spill containment:** Ammonia is water-soluble and toxic to aquatic life, so spill containment is a key safety and environmental control measure.
- **Gas-release mitigation**: For hazardous gases design safe venting paths, automatic ventilation, and fixed gas detection tied to alarms and shutdowns. For hydrocarbons, limit sources of ignition and ensure fire-fighting water management (runoff containment).

3.2.4 Resource Consent & Regulatory Considerations

- **Resource consent is site-specific:** Coolstores themselves may be a permitted activity in some district plans; however, major changes to hazardous-substance storage, tank works, noise, odour, or building alterations can trigger resource consent under the Resource Management Act and district plan. A full plant replacement that changes the risk profile (e.g., adding large ammonia tanks, new bunded areas, or new flammable storage) often requires council notification, consent or at least a pre-application discussion.
- **Hazardous-substance controls & approvals**: WorkSafe/Hazardous Substances legislation and local council rules govern storage, handling, and bunding. New national measures (product stewardship for synthetic refrigerants) and industry training expectations are evolving. Factor in compliance and reporting obligations.
- **Insurance & emergency response:** Notify insurers/Fire Service as required. Some consent processes require an emergency response plan and proof of staff training and equipment.
- **Synthetic refrigerant phase down:** Concerns about the breakdown of HFO refrigerants into "forever chemicals" (PFAS – see Appendix B) is likely to lead to the eventual phase down of fluorinated refrigerants. This would lead to supply constraints for moderate GWP synthetic refrigerants that are blended HFC/HFOs adopted as interim solutions to address emission reduction (most relevant in the context of drop-in replacement refrigerants used in conjunction with a conversion to a secondary refrigerant architecture). The risk and potential costs associated with this phase out should be considered.

3.2.5 Other Operational & Safety Items

- **Training & certification:** technicians must be trained for the chosen refrigerant. Industry bodies and WorkSafe guidance list training expectations.
- **Maintenance regime changes:** daily checks, leak detection, and planned preventive maintenance differ between refrigerants. Upgrade maintenance systems to track new tasks.
- **Contractor capacity:** ensure local service providers have experience with the chosen natural refrigerant or factor travel and training into cost and lead times.
- **Emergency planning**: update emergency response and medical arrangements (ammonia inhalation response, CO_2 asphyxiation protocols and hydrocarbon fire plans).

4. System Cost Comparison

Attempts to characterise natural refrigerant system costs are based on the following scenarios:

- Small system (200 – 275 kWr capacity) – indicative of a single coolstore load
- Medium system (420 – 480 kWr capacity) – indicative of 2 coolstores load
- Large system (880 – 1000 kWr capacity) – indicative of around 4 coolstores load.

This classification is supported by data obtained from survey of the industry's existing coolstores completed by DETA in 2024.

4.1 Limitations and Intended Use

The levelised cost of cooling analysis presented herein is intended as a comparative assessment tool only. The results are inherently sensitive to assumed capital costs, financing parameters, utilisation profiles, electricity pricing, and annualised performance (COP). In particular, capital cost data for natural refrigerant systems are often project-specific, non-standardised, and commercially confidential, requiring the use of indicative or benchmarked values. As such, the analysis does not represent a definitive or universally applicable cost outcome for any specific installation. Rather, it provides a structured framework to compare technology pathways under a consistent set of assumptions. Actual project economics will vary depending on site conditions, load characteristics, integration complexity, regulatory requirements, and procurement context.

4.2 Levelised Cost of Cooling

Figure 3 & Figure 4 present the estimated capital cost and average lifetime cost of cooling, respectively, for a range of different refrigerant solutions. Pricing and estimated COPs for these systems were based on data and estimates provided by equipment suppliers and refrigeration contractors. Whilst care has been taken to present like-for-like comparisons, it should be noted that due to the fundamental differences between the systems, this is a very difficult task. As a result, the capex and opex figures presented should be viewed as comparative only. Each site will have nuance that requires individualised consideration, and expert advice should be sought to fully appreciate likely costs.

4.2.1 Key Assumptions:

- Electricity costs are taken as $0.2 / kWh, inclusive of all energy and network components.
- Capital costs are based on figures supplied by contractors/suppliers and are considered as installed total project costs inclusive of compressors, heat rejection, evaporators/unit coolers, piping, pumps, valves & instrumentation.
- All systems assume new evaporators/unit coolers
- Electrical costs are assumed to be 10% of installed plant costs (excludes capacity upgrades).
- No allowance has been made for civil works as these items are situation dependent[3].

[3] Note: Ammonia systems, for example, typically require much more substantial plant rooms.

- No costs for refrigerant replacement/purchase have been included. As refrigerant costs for naturals are very low compared to synthetics, this is a minor omission.
- Assumed system annual runtime of 4,380 hours (50% of year).
- Refrigeration system utilisation is assumed as equivalent to 60% average name plate capacity over the annual runtime.
- Maintenance costs taken as 1% of total project capital cost for all refrigerants, except for large scale ammonia systems, which was taken as 2%.
- COPs are based on data supplied by contractors and equipment OEMs. Refer to Appendix C for a summary.
- Discount rate = 10%
- Levelised cost is calculated over a 25-year period (life span of all systems was taken as 15 yrs, except ammonia, which was assigned a working life of 25 years).
    - Assumed 40% of initial capital outlay required at 15-year mark (e.g., compressor replacement) for non-ammonia systems.
- Glycol pumping loads are included and based on data provided by contractors.

More detail describing the calculation methodology is presented in Appendix D.

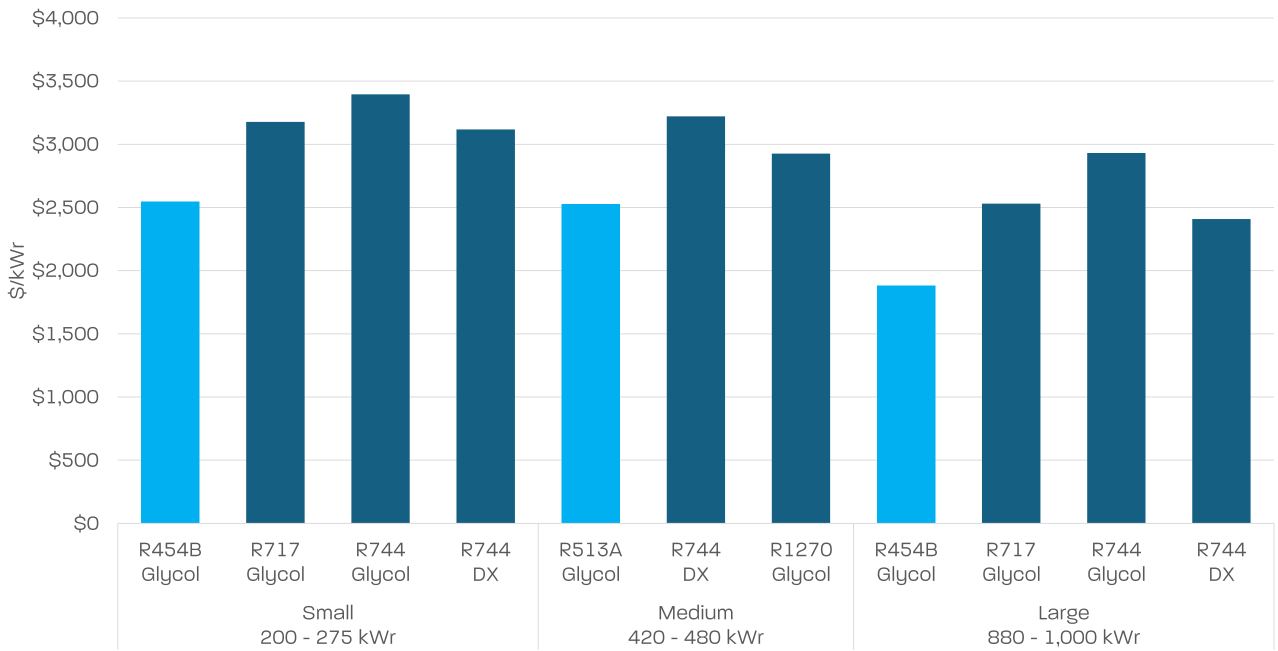

Figure 3. Capital cost by system type and size, expressed as $/kWr (i.e., per unit of cooling capacity). Light blue bars represent synthetic refrigerant systems, shown here for comparison.

For convenience,

R717 = Ammonia
R744 = Carbon dioxide
R1270 = Propylene
R454B & R513A = Synthetics

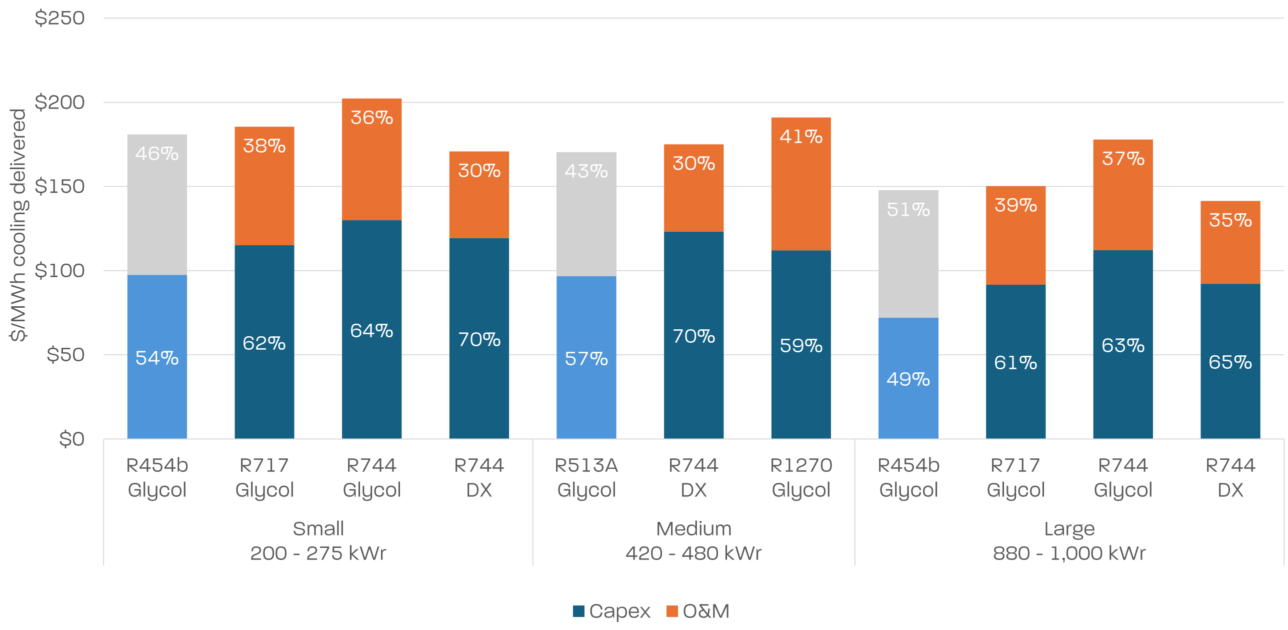

Figure 4. Levelised cost of cooling ($/MWh) for different refrigerant systems, separated into levelised fixed costs (i.e., capital) and levelised variable costs (i.e., Opex) components.

4.2.2 Key Observations:

- **All natural options are viable and relatively close in levelised cost compared to synthetic refrigerants (within ~10% for small and medium, ~17% for large).**
- Which refrigerant is best is based on preference and dependent on the individual site constraints and priorities.
- For all systems, opex represent a large fraction of the total levelised costs of operation.
    - This emphasises the importance of considering the energy efficiency of the solution when reviewing different options.
- Natural refrigerant systems have higher capital costs, but average lifetime costs of cooling are generally comparable to synthetic systems for all system sizes. This excludes the cost of refrigerant purchase and top-ups over the system life (less for naturals than synthetics).
- Across all ranges of system size, CO_2 DX systems provided the lowest levelised cost of cooling over the 25-year period for the natural options. For medium sized systems, the synthetic example provided (R513A) is similar in levelised cost to CO_2 DX.
- Ammonia glycol systems were the next lowest levelised cost option, and very similar to CO_2 DX. The marginally higher upfront capex costs for ammonia systems are countered by the longer anticipated life span of the equipment.
- Increased utilisation or runtime will increase the relative benefit of the natural systems.
- Ammonia systems are expected to have much higher maintenance costs than other systems, although evidence to support this is anecdotal.
- The single propylene system for which we could obtain pricing indicated lower initial project capital compared to CO_2 DX, but a higher levelised cost of cooling.
    - At the time of writing no pricing information could be obtained for butane or propane chiller systems.

5. Replacement Scenarios

5.1 Retrofit an Existing Coolstore

Approximately 95% of the surveyed refrigeration systems in the New Zealand KPHI currently use fluorinated refrigerants (HCFCs, HFCs and blends including HFOs). These systems are generally direct expansion (DX) systems with relatively large volumes of refrigerant, representing considerable refrigerant cost and carbon emission liability (see section 2.2). Furthermore, operation of HFC plant represents a potential risk to operational continuity, as access to replacement refrigerant, particularly in the event of a major leakage event, will become increasingly difficult and costly as the phase down progresses.

Options to address this liability and reduce emissions include:

1. Utilise drop-in refrigerant replacements – retain the existing DX system
2. Utilise drop-in refrigerant replacements – convert to glycol reticulation
3. Install NEW synthetic refrigerant plant – retain the existing DX system
4. Replace existing HFC plant with NEW natural refrigerant plant, Including replacement of evaporators with either glycol unit coolers or CO2 DX evaporators

Error! Reference source not found. summarises the pros and cons of each of these options.

Table 2. Pros and cons related to coolstore natural refrigerant retrofit options.

Option	Description	Pros	Cons	Solution Longevity
1	Utilise drop-in refrigerants – retain the existing DX system	- Lowest capital cost - Availability of refrigerant	- Large refrigerant charge - Relatively high refrigerant cost - Adoption of HFO/HFC blends (e.g., R449A) mean exposure to future phase out - HFO/HFC blends also lead to PFAS "forever chemicals" - Possible reduction in system efficiency (may be mitigated using electronic valves at greater cost) - Old refrigeration equipment retained - Refrigerant still reticulated through coolstore with associated risk of leaks	Interim only
2	Utilise drop-in refrigerants – convert to glycol reticulation	- Reduced primary refrigerant charge - Lower capital cost than full conversion to naturals - Allows the "sweating" of existing refrigeration assets - replace at end-of-life - Eliminates refrigerant from coolstore spaces reducing likelihood of refrigerant leaks	- Adoption of HFO/HFC blends (e.g., R449a) mean exposure to future phase out. - HFO/HFC blends also lead to PFAS "forever chemicals" - Moderate emissions risk from drop-in refrigerant leaks	Interim with future proofing
3	Install NEW synthetic refrigerant plant – retain the existing DX system	- Small capex savings with synthetic packaged chiller units, relative to natural options	- High refrigerant charge - High refrigerant costs - Adoption of HFO/HFC blends (e.g., R513A) mean exposure to future phase out - HFO/HFC blends also lead to PFAS "forever chemicals" - Refrigerant still reticulated through coolstore with associated risk of leaks	Interim only
4	Replace existing HFC plant with NEW natural refrigerant plant	- Lowest cooling costs - Lowest refrigerant costs - Eliminated emissions risks - Greater produce quality control	- Highest upfront costs - Potential for introduction of new hazardous material	Permanent

5.1.1 Drop-in Refrigerants - An Interim Solution

Based on the pros and cons presented above, utilising drop-in refrigerant replacements (such as R449A in place of R404A), with or without converting the coolstore to reticulated glycol, is a pragmatic interim measure (Option 1 or Option 2). It is generally assumed that the design intent of the coolstore will remain unchanged with these changes (e.g., operational characteristics and product packing configuration).

This enables a dramatic reduction of refrigerant charge (some contractors noting a 10-fold reduction in refrigerant charge possible, depending on system size), whilst the implementation of glycol in the coolstores brings additional benefits. These include greater control of humidity within the coolstore which translates to better product quality control and potentially reduced losses.

Removal of the refrigerant reticulation from the coolstores also reduces the potential for refrigerant leaks (reduced piping, evaporators, valves, bends, joints etc.).

Converting to glycol also future proofs these elements of the system and allows the site to adopt a natural refrigerant plant solution later when capital permits, or when regulations or refrigeration supply challenges force a change. This has the benefits of reducing the required capex, allowing the business to direct these funds towards expansion and construction of new coolstores to cater for business growth.

However, based on the likely phasing down of blended synthetic refrigerants containing HFOs (see Appendix B), use of drop-in refrigerants are not considered a long-term solution.

5.1.2 Naturals - The Permanent Solution

Full retrofit of natural refrigerants to existing coolstores represents a permanent solution. However, this brings the highest up-front cost, with notionally no change to the productivity of the coolstore. There is potential to leverage efficiency benefits of merging individual coolstore refrigeration systems together into a larger centralised natural system (e.g., CO_2 or Ammonia over glycol), with reduced nameplate capacity due to the diversity of cooling demand across coolstores. However, it is important to understand seasonal cooling loads well to maximise this benefit and de-risk potential under sizing.

For these reasons, it is expected that full natural retrofit would be less commonly adopted than the utilisation of drop-in refrigerants

5.1.3 Repurposing HFC Evaporators as Glycol Unit Coolers

Some KPHI operators and refrigeration contractors raised the potential for the repurposing of existing evaporators to glycol unit coolers. The objective is to avoid the costs associated with installing new fit-for-purpose glycol unit coolers.

Simplistically, the conversion involves removing the refrigerant expansion valve and distribution header and upgrading these with larger equivalents that are suited to the distribution of glycol. Supply piping from the chilled glycol storage tanks to each evaporator would need to be upgraded to accommodate the higher volume flow rates required. However, in some instances the refrigerant suction line (originally returning refrigerant vapour to the compressor) can be repurposed for glycol, saving some costs.

However, there are some fundamental challenges with this concept. Heat transfer to glycol within the unit cooler is sensible only (i.e., no phase change). As the specific heat capacity is much lower than the latent heat of vaporisation of refrigerants, transferring equivalent heat requires much larger surface areas and/or larger temperature differences between the coil outer surface and liquid within the coils. Surface area cannot be varied and is limited by the available coil surface area of the original evaporator. Increasing the temperature difference requires the glycol temperature to be reduced, which requires lower refrigerant saturated suction pressures and leads to lower COP (more energy consumption).

For this reason, a reduction in capacity of the evaporator is expected, if a conversion is possible. KPHI operators should therefore explore these issues with contractors proposing this method to fully understand capacity and plant efficiency impacts, such that an informed decision can be made as to the merits of the potential capex savings.

5.2 New Coolstores

In the context of seeking reduced emissions liability, improved cooling performance, and reduced operating costs, refrigeration systems for new coolstores should all be natural in future.

Options for natural systems centre on the different refrigerants and the system architecture. Table 3 summarises the pros and cons of these options.

Table 3. Pros and cons related to new coolstore natural refrigerant options.

Option	Description	Pros	Cons	Suitability
1	Synthetic	- Well understood - Potentially low capex - Reasonable efficiency	- High refrigerant costs - High emissions liability - Adoption of HFO/HFC blends (e.g., R513A) mean exposure to future phase out - For DX systems, refrigerant still reticulated through coolstore with associated risk of leaks	Unjustifiable
2	HC - Glycol	- Small skid-based units, easy to install - Low maintenance - Minor capex benefit over CO2 or NH3	- Higher opex than CO2/NH3 (lower efficiency) - Limited cooling capacity avialable - Flammability risks - Only suited to glycol/secondary refrigerant architecture	Moderate
3	CO_2 - DX	- Lowest operating costs - Lower capex than glycol systems - Low cost, abundant refrigerant - High seasonal efficiency/aligns with cooling requirement - Well suited to all system sizes	- Reduced performance in hot ambient conditions (transcritical operation) - Less effective humidy control than gycol systems	High
4	CO_2 - Glycol	- Low operating costs - Low cost, abundant refrigerant - High seasonal efficiency/aligns with cooling requirement - Good humidty control - Elimination of refrigerant in coolstore	- Reduced performance in hot ambient conditions - Higher energy costs than DX systems - Higher capex than DX systems	High
5	Ammonia - Glycol	- Low operating costs - Low cost, abundant refrigerant - Good humidty control - Very long service life	- Highest capital costs - Introduction of hazardous material - Additional personnel training etc. - Higher maintenance costs	High

5.3 Key Questions to Ask When Assessing Options

1. What is the remaining serviceable life of the coolstore?
    - Understanding this will frame the investment priority (long-term or interim solution?)
2. What is the realistic utilisation of the coolstore?
    - Reduced utilisation will impact ROI – may bias towards an interim solution with a lower capital cost.
3. Does the site already use ammonia?
    - If so, then ammonia may be an obvious consideration.
    - If not, are we willing to introduce a hazardous material?
4. Can the coolstore structure support the weight of glycol piping and unit coolers?
    - Will any additional structural supports be required?
    - If so, how much cost and time will this add?
5. What is the expected plant efficiency (COP) for design conditions (worst case) AND anticipated conditions (site based annual data)?
    - Ensure energy demands for ancillary loads are included.
6. Can existing evaporators be repurposed as glycol unit coolers?
    - What is the reduction in cooling capacity and will this impact coolstore operations?
    - Is the capital cost saving justified?

6. Summary & Recommendations

Right now, there are commercially viable natural refrigerant solutions for KPHI coolstore applications. These solutions can permanently address the emissions concerns associated with the extensive use of high GWP synthetic refrigerants within the industry. However, no single natural refrigerant offers a perfect solution, each having benefits and drawbacks that need to be weighed against the individual requirements of the site and business.

Key findings from this work include the following:

- Technology is changing quickly in this space, with new products entering the market (e.g., hydrocarbon packaged chillers) and other sectors demonstrating the viable use of natural refrigerants for applications previously considered out of reach (e.g., the widespread roll-out of CO_2 for the supermarket industry).
- Opex (both energy and maintenance) represents a considerable portion of total levelised cost of cooling, stressing a need for consideration of energy efficiency when reviewing natural refrigerant options.
- Historical concerns with CO_2 systems and its compatibility to the season demands from the KPHI have been addressed.
- The benefits of large, centralised plant was not obvious, based on the data supplied – requires site by site consideration of coolstore layouts, spacing, and load diversity.

What is the likely solution for existing coolstores?

- Driven by pragmatics, it is most likely that adoption of natural refrigerants for existing coolstores will involve an interim solution whereby coolstores are converted to glycol reticulation and the existing plant is retained and operated on drop-in replacement refrigerants. Natural refrigerants would then be adopted for the compressor plant either at the end of the existing plant life, or when capital allowed. This approach:
  - Dramatically reduces synthetic refrigerant charge immediately.
  - Extends the operational life of the coolstore.
  - Future proofs the plant for conversion to natural refrigerants, with options for different refrigerants kept open.

What is the likely solution for new coolstores?

- It is anticipated that all new coolstores would be built to use natural refrigerants.
- Lowest levelised cost of cooling are expected for either direct expansion CO_2 or ammonia glycol systems.
- It is important for KPHI operators to ensure glycol ancillary power loads are considered when comparing energy demands as these can be considerable.

Appendix A: Refrigerant Hazard Classifications

ASHRAE Standard 34 assigns an identifying reference letter and number to each refrigerant to classify it according to the hazard involved in its use. The capital letter designates a toxicity class based on allowable exposure, while the numeral denotes flammability. See Figure 5below.

ASHRAE recently updated the safety classification matrix to include a new flammability subclass 2L, for flammability class 2 refrigerants that burn very slowly.

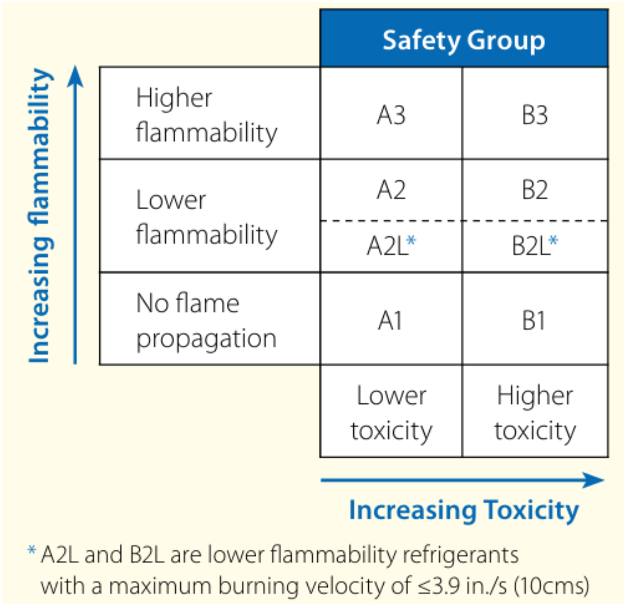

Figure 5. ASHRAE Standard 34 – Refrigerant safety group classifications.

Appendix B: HFO's and Environmental Concerns

B.1 Hydrofluoroolefins (HFOs)

Hydrofluoroolefins (HFOs) are flourinated gases (F-gases) developed as synthetic alternatives to Hydrofluorocarbon (HFC) refrigerants. HFOs and other unsaturated halocarbons such as HCFOs and HBFOs contain a double carbon-carbon bond, which is not present in previous generation F-gases such as HFCs and HCFCs. This makes them highly reactive, causing them to break down rapidly in the environment.

Consumption of hydrofluoroolefins (HFOs) and hydrochlorofluoroolefins (HCFOs) in the U.S. is projected to more than double by 2030, reaching approximately 106,000 metric tons – up from around 40,000 metric tons in 2021 (Environmental Invitagation Agency (EIA), *Persistent Problems*, July 2025).

The continued uptake of HFOs is generally encouraged by the idea that they are sustainable products with low GWP (typically less than 1) and low ODP values.

At surface value, these properties appear very attractive. However, atmospheric breakdown of many common HFOs and some other F-gases results in the formation of trifluoroacetic acid (TFA), which is an ultrashort chain per- and polyfluoroalkyl substance (PFAS).

B.2 PFAS – Forever Chemicals

Per- and polyfluoroalkyl substances (PFAS) are a class of more than 9,000 anthropogenic chemicals with diverse applications due to their unique properties like water and grease resistance and high stability. They are used in a wide range of products, including food packaging, firefighting foams, textiles, non-stick cookware, and personal care items. They are, or they degrade into, substances which are chemically stable and thus remain in the environment for very long periods of time, giving rise to their common description as "forever chemicals".

B.3 HFO phase down

TFA and other PFAS chemicals are highly persistent in the environment, and some are bio-accumulative and toxic. In response to these concerns there is growing momentum, led by the European Union, toward tightening regulations around F-gases, suggesting an eventual phase down of HFOs is likely.

Businesses looking at refrigerant options that address GWP concerns with existing synthetic refrigerants should be mindful of the known ecological impacts of synthetic drop-in replacements or proposed synthetic alternative systems utilising HFO refrigerants.

Appendix C: Refrigerant COP Summary

Table 4. Assumed seasonal average COP for different refrigerants.

System	Size	Avg. COP
R454B Glycol	small	3.46
R717 Glycol	small	4.46
R744 Glycol	small	4.47
R744 Glycol	small	4.47
R744 DX	small	4.81
R513A Glycol	medium	3.81
R744 DX	medium	4.81
R1270 Glycol	medium	3.55
R454B Glycol	large	3.46
R717 Glycol	large	5.17
R744 Glycol	large	4.47
R744 DX	large	4.81

Appendix D: Levelised Cost of Refrigeration (LCOR) Methodology

The Levelised Cost of Refrigeration (LCOR) represents the unit cost of delivering cooling over the life of a refrigeration asset, expressed in $/MWh$_{(cooling)}$. It annualises capital expenditure and combines this with annual operating costs, divided by the annual cooling delivered.

D.4 Calculation Framework

$$\mathrm{LCOR} = LFC + LVC$$

Where:

LFC = Levelised Fixed Cost ($/MWh$_{(cooling)}$)

LVC = Levelised Variable Cost ($/MWh$_{(cooling)}$)

D.5 Parameter Definitions

Total Installed Cost (TIC) – The full capital cost required to deliver the refrigeration system, including:

- Major equipment (compressors, evaporators, condensers, controls)
- Mechanical and electrical installation
- Piping, insulation and structural works
- Engineering, commissioning and contingency

Fixed Charge Rate (FCR) - The Fixed Charge Rate converts upfront capital into an equivalent annualised cost. It reflects:

- Cost of capital (WACC)
- Asset life
- Financing assumptions
- Insurance and fixed O&M (where applicable)

The standard capital recovery formulation is:

$$FCR = \frac{r(1+r)^n}{(1+r)^n - 1}$$

Where:

r= real discount rate

n= asset life (years)

Annual Cooling Delivered (Q_{annual}) - The total useful cooling provided over one year:

$$Q_{annual} = \text{Cooling Capacity (kW)} \times \text{Operating Hours (h/yr)}$$

Levelised Fixed Cost (LFC) - captures the capital intensity of the system and its utilisation (load factor).

$$LFC = \frac{TIC \times FCR}{Q_{annual}}$$

Levelised Variable Cost (LVC)

$$LVC = \frac{C_{electricity} + C_{varibale\ O\&M}}{Q_{annual}}$$

$$C_{electricity} = \frac{Q_{annual}}{COP_{annual}} \times P_{elec}$$

Therefore:

$$LVC \approx \frac{P_{elec}}{COP_{annual}} + \frac{C_{varibale\ O\&M}}{Q_{annual}}$$

Where:

COP_{annual}= annual average coefficient of performance

P_{elec}= electricity price ($/MWh$_e$)

$C_{varibale\ O\&M}$= annual maintenance costs

Final Expression

$$\boxed{LCOR = \frac{TIC \times FCR}{Q_{annual}} + \frac{P_{elec}}{COP_{annual}} + \frac{C_{other}}{Q_{annual}}}$$

D.6 Interpretation

LCOR is primarily influenced by:

- Capital intensity (TIC)
- Asset life and discount rate (FCR)
- System utilisation (Q_{annual})
- Annual average COP
- Electricity price

This methodology enables consistent comparison between refrigeration technologies, system designs, and operating strategies on a lifecycle cost basis.