Article

Practices to Improve the Sustainability of Australian Cold Storage Facilities

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Abstract: With the ever-increasing threat of climate change and global warming, ways to make energy intensive buildings, such as cold storage warehouses essential for food preservation, more sustainable need to be found. Some refrigerated warehouse owners may be unaware or unsure of the benefits obtainable from implementing sustainable practices and technologies. To search for innovations that could inform the owners and managers of cold storage warehouses about how to enhance their sustainability, convergent interviewing of subject matter experts was conducted. The resulting practices and processes were organized into a hierarchy that ranged from essential to best practices that can be implemented to improve the sustainability of refrigerated warehouses. Examples of these practices and technologies include ideal refrigeration systems, racking methods, and insulation types. To encourage the use of sustainable practices and technologies, more reporting on successful or unsuccessful applications of practices and technologies needs to be communicated. Applying change diagnostic tools such as convergent interviewing enables a practical and industry focused set of outcomes to be determined that can help drive change towards more sustainable cold storage warehouses in Australia.

Keywords: logistics; management innovation; refrigerants; Montreal protocol

1. Introduction

With a trend of rising global temperatures, accompanied by record-breaking CO2 emissions, it is becoming ever more urgent to find means of reducing climate-altering emissions [1]. To facilitate this endeavor, over 100 countries have recently communicated or adopted new Nationally Determined Contributions (NDCs) and adopted net-zero target pledges with the aim of limiting global warming [2].

One underappreciated source of global emissions, where the focus is often on energy generation, is food production and waste. Food loss and waste are important because they contribute around 8 to 10 percent of global greenhouse gas emissions [3]. In 2019, it was estimated that around one-third of all food produced was never eaten, with all of the resources, energy, and consequent emissions that went into producing that food also being wasted [3,4].

With around 40 percent of the annual food produced worldwide requiring refrigeration, cold storage is important for perishable goods such as fruit, vegetables, and meat [5–8]. Cold storage warehouses are internationally regarded as one of the best ways to store perishable goods [9]. The global expansion of cold storage facilities is important to ensure food quality is preserved [10]. The strategic positioning of post-harvest infrastructure, such as cold storage, could help preserve food after harvest and reduce food loss [11].

A lack of cold storage facilities in the vicinity of farmers can result in a loss of produce after harvest [7], and spoiled food has been assessed as leading to 420,000 deaths per year [12]. The use of refrigeration systems for food storage will help reduce food
waste and, in turn, improve the global hunger situation [13]. Hence, cold storage is an important part of reducing global emissions from food waste while also combating global hunger and improving human health outcomes. However, this focus on addressing hunger and reducing emissions is not the first time cold storage has been the focus of climate change efforts.

1.1. Cold Storage Warehouses at the Core of the Most Successful Environmental Change Ever

Although the food implications of refrigeration are substantial, historically, perhaps the most well-known environmental issues associated with refrigeration are the global warming impacts of refrigerant emissions. The use of refrigerants such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) depleted the ozone layer, allowing harmful UV radiation to more easily penetrate to the earth’s surface, contributing to a rise in global temperatures [14]. The discovery of the depletion of the ozone layer resulted in a decision to phase out the use of CFCs through mechanisms such as the ‘Montreal Protocol’ [15]. The Montreal Protocol was passed in 1987 with the aim of ending the use of ozone-depleting substances [16,17].

Initially, the Montreal Protocol called for a 50 percent reduction in the use of CFCs and some halons [15]. However, amendments to the protocol called for the total phase-out of CFCs and several HCFCs [15]. Further amendments to the protocol led to HCFCs being targeted with a total phase-out by 2029 for developed countries and 2040 for developing countries, and then HFCs were targeted with an 85% reduction in developed countries by 2036 [18].

Although the initial focus of these efforts was on refrigerants with low ozone depletion potential (ODP) values rather than low global warming potential (GWP) values [15], over time the amendments have moved from a focus almost exclusively on ODP to a growing consideration of GWP, as summarized in Table 1. In the 21st century, the focus has shifted to phasing-in refrigerants with low ODP and low GWP values [14]. Fourth-generation natural refrigerants include ammonia, hydrocarbons, and CO$_2$, which have very low or zero GWP but may have other properties, such as flammability, toxicity, or requirements for higher operating pressures, that may limit their applicability in some situations [19].

**Table 1. Refrigerant generations and their phase-outs (adapted from [18,20–22]).**

<table>
<thead>
<tr>
<th>Generation</th>
<th>Refrigerants</th>
<th>ODP/GWP</th>
<th>Phase-Out (Developed Countries)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>Chlorofluorocarbons (CFCs)</td>
<td>1/&lt;10,000</td>
<td>1995</td>
</tr>
<tr>
<td>2nd</td>
<td>Hydrochlorofluorocarbons (HCFCs)</td>
<td>0.055/&lt;3000</td>
<td>2029</td>
</tr>
<tr>
<td>3rd</td>
<td>Hydrofluorocarbons (HFCs)</td>
<td>0/&gt;1500</td>
<td>85% reduction by 2036</td>
</tr>
<tr>
<td>4th (current)</td>
<td>Hydrofluoroolefins (HFO)/Natural</td>
<td>0/&gt;150</td>
<td></td>
</tr>
</tbody>
</table>

Note: ODP = ozone depletion potential; GWP = global warming potential, expressed in CO$_2$ equivalents.

Under the Kigali Amendment, actions under the Montreal Protocol are expected to prevent the emission of up to 105 billion tons of carbon dioxide equivalent greenhouse gases, helping to avoid up to 0.5 degree Celsius of global temperature rise by 2100—a truly unparalleled contribution to climate mitigation efforts and the single largest contribution the world has made towards restraining the global temperature rise [20–22]. The Montreal Protocol is considered to be one of the most successful environmental agreements of all time [20–22].

Despite the efforts to address the Montreal Protocol and its amendments, global and Australian demand for cooling has substantially increased. For example, the total refrigerant bank (amount in use) of HFCs and HFCs in Australia, across all of the main forms of stock (e.g., stationary refrigeration, mobile air conditioning, refrigerated cold food chain, transport refrigeration, and domestic refrigeration), grew by 61 percent between 2006 and 2019 [19], despite the policies in place to phase out second and third generation refrigerants. Thus, while there are claims that the implementation of the Montreal Protocol
has been estimated to have delayed climate change by around 7 to 12 years [15], more work remains to be done to offset the climate impact of the growth in demand for refrigeration if global climate objectives are to be reached.

To address the climate impact of the growth in cooling demand in the cold storage sector, a major contributor to overall global cooling demand, refrigerant gases are only part of the solution. Many potential technological solutions exist to reduce cooling demand in cold storage warehouses, but in many cases, these are not being adopted. The slow uptake of improvements in the sustainability of cold storage may be due to a lack of knowledge on the part of cold storage companies or uncertainties as to what the best options are to reduce the impact of the growing refrigeration demand.

1.2. Drivers of Sustainability beyond Refrigerant Gases

There are a variety of drivers and possible drivers for the sustainability of cold storage warehouses. One driver is the nature of the gases in the refrigeration system, as discussed above, but other drivers include energy demand, especially due to warehouse volume and temperature, as well as insulation, flooring, the threat of frost heave, air and water infiltration, and the direct usage of greener energy sources such as solar arrays.

Cold storage warehouses are recognized as using a substantial amount of energy [23]. Among the systems driving energy usage in cold storage warehouses, the energy requirements of refrigeration systems are quite significant, consuming around 80 percent of the energy in the warehouses [6]. In broad terms, warehouse volume and the temperature set are key drivers of energy consumption for chilled storage and, more strongly, for frozen storage [24]. Studies have called for the evaluation of the energy effects of utilization, storage, and renewable energy supply in warehouses, considering the context of the facility and its characteristics [25].

Interventions to improve energy consumption could make substantial impacts on the amount of energy used, with possibly a 30% to 40% improvement through a combination of ‘optimizing store usage’, ‘repairing [existing] equipment’, and ‘retrofitting energy-efficient equipment’ [26]. Energy efficiency improvements could be obtained by investing in technology and/or by inexpensive maintenance or management practices [23].

Technologies such as racking, rack loaders, and their associated equipment are a good starting point for improving the sustainability of warehouses [27]. In turn, more advanced and comprehensive systems, such as automatic storage and retrieval systems, can optimize storage and picking processes by enabling densification, adaptability, and modularity [28].

Maintenance and operational practices also play a role, with some facilities running at an excessively low temperature, presenting an opportunity for cost-effective and straightforward temperature adjustments [26]. Yet such approaches are contested, with recent studies of the wider supply chain suggesting that lower-temperature cooling in the cold storage warehouse may lead to sustainability improvements [29]. Other operational practices, such as lot-sizing decisions and the behavior of the operators (e.g., with regard to opening doors), have received little attention, with the focus typically being on technological issues [23]. Research has been called for to investigate which and which combinations of these technologies and practices could optimize warehouse sustainability [28].

In terms of more specific improvements, addressing issues such as insulation thickness and type, age of the facility and refrigeration system, and door open times could reduce energy demand even further [24]. Table 2 summarizes the main types of insulation used in cold storage warehouses along with three of their key properties—thermal conductivity, moisture resistance, and fire safety.
Table 2. Summary of common insulation properties (Source: Authors’ summary across: [30–32]).

<table>
<thead>
<tr>
<th>Insulation Type</th>
<th>Thermal Conductivity</th>
<th>Moisture Resistance</th>
<th>Fire Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibreglass batts</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Polyisocyanurate (PIR) panels</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Expanded polystyrene (EPS) panels</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Extruded polystyrene (XPS) panels</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Mineral wool</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>High-density polyurethane (PUR) foam</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Vacuum-insulated panels</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

The most commonly used of these types of insulation is expanding foam, where the foam is the core between two polymer composite or metal skins. Foamed polyurethane, expanded polystyrene, and polyisocyanurate are created by blending chemicals in a liquid state along with foaming agents, but since 2016, the use of polystyrene for new and many existing buildings has been phased out due to fire risk concerns [33]. Despite being one of the simplest considerations, the characteristics of insulation have more complexity than may be expected, as do many of the drivers of the sustainability of cold storage warehouses.

Similarly, flooring is a fundamental component of any construction, providing the foundational structure upon which the building is assembled. Cold storage warehouses require specialized flooring solutions to ensure consistent internal conditions are unaffected by the external environment. Any compromise to the integrity of the foundation may significantly undermine the functionality and efficiency of a cold storage facility. In particular, insulating the floors of cold storage warehouses originates from a need to mitigate heat flow and prevent frost heave [33].

Frost heave occurs when a temperature gradient develops in freezing soil, and examples include deformation of embankments, pipe ruptures, and building inclination [34]. For cold storage warehouses, after several months of operation, the underside of the floor slab may reach 0°C. The increase in volume caused by the ice within porous materials such as soil displaces the ground surface through an upward movement. Structural integrity can be compromised when the slab cracks and shifts due to frost heave, which may also cause other structural members to shift, leading to devastating and costly consequences [33].

1.3. Air and Water Infiltration

Infiltration can lead to increased energy usage and moisture entry, which affect product quality. Air and water infiltration is particularly concerned with two main sources of infiltration: short intensive periods when a door is open (e.g., when transferring stock) and ongoing seepage.

There are two sets of doorways to consider: internal doorways and external doorways, as well as the use of anterooms as buffering zones between external air and water and internal areas. Minimizing door opening duration and other technologies and practices may vary depending on the location and purpose of the doorway as well as the frequency with which it is used [24].

Anterooms, also known as airlocks or vestibules, provide a physical barrier and transition area between external and internal environments [35]. The purpose of an anteroom is to buffer the thermal load and moisture content from the opening of the external door before the internal door into the cold storage warehouse is opened [36]. The smaller volume of anterooms allows them to promptly return to optimal temperatures after the external door’s operation, further safeguarding the main storage area [37]. The added layer of protection anterooms provide ensures that energy usage remains optimized, the risk of moisture intrusion is minimized, and the longevity and quality of stored products are maintained [36].

Another technology or practice that could improve the sustainability of cold storage is through the usage of renewable energy sources. For facilities that often have a large roof surface area, a key option is the use of solar (photovoltaic/PV) arrays. Similarly,
load-shifting is another technique that could impact energy usage, or at least energy costs. In a typical residential home, load-shifting could be simply setting the dishwasher to a timer around 12 p.m. or shifting clothes washer and dryer cycles during the day.

However, many of the issues raised above may be proxies for other indirect effects on sustainability. For example, the age of the building may sometimes be a proxy for whether or not solar arrays are able to be mounted on the roof. The structural design of roof-mounted solar panel arrays must be able to support the weight of the mounts and panels as well as additional loads, such as electrical systems and other attachments, and be able to withstand the associated forces from winds [38]. Many commercial buildings may lack the structural capacity to support a roof-mounted PV array of significant size due to being constructed to meet only the minimum requirements [39].

Thus, although there is recognition that cold storage warehouses are a critical area where sustainability improvements could have a large impact on climate change, the wide range of issues that may impact the sustainability of cold storage warehouses may be holding back improvement efforts. Consequently, there need to be investigations into the mix of possible practices and technologies applicable to cold storage warehouses that could lessen the extent of climate change. Such efforts to search for management innovations entail determining and choosing the best practices and technologies.

1.4. Management Innovations and Best Practices

In the face of global climate change, political and social pressures, and regulatory requirements to improve sustainability, the cold storage warehouse industry is building on earlier efforts, such as their responses to the Montreal Protocol, to continue to improve their sustainability. Large numbers of organizations in the cold storage warehouse industry want to improve their sustainability and are adopting innovations, a trend that is generating “bandwagon” pressures [40]. Those pressures are for management innovations, particularly innovation in the management practices, processes, and structures that affect day-to-day work at an operational level where observable changes take place [41].

Bandwagon pressures to improve sustainability can come from regulations, both international and national, as well as from related industry and government bodies. To find innovations that can improve their performance, such as in terms of sustainability, managers engage in a process of a search [42] to close a performance gap and, at the operational level, try to generate and implement new practices, processes, structures, or techniques [43]. Such innovations are new to the company implementing them and are typically incremental in nature [41].

Searching for management innovations often becomes a search for best practices, which usually involves investigating the internal processes of best-in-class firms, industries, or competitors to become more competitive [44]. The idea is to benchmark against other organizations so that underperforming organizations can implement such “best” practices to close a performance gap [45].

However, the term best practice is often overused or misused, and it may be the case that activities deemed to be best practices may not be [46]. For example, practices that have been adopted by a notable proportion of an industry may become a requirement of doing business in that industry but are not sufficient to provide a competitive advantage [47]. Similarly, practices that start out as best practices may enhance organizational performance for only a short period of time until competitors also implement those practices [48]. Such widespread practices may become necessary, but not sufficient, for improved organizational performance [49].

That is, there may be categories of practices ranging from the essential, commonplace and standard practices that have been widely adopted by organizations, that do not necessarily contribute to competitive advantage through to practices used by the best organizations, where the “best” practices are those that differentiate between good and bad performers [47]. Note, though, that the categorization of specific practices may change over time. For example, pursuing best practices through benchmarking may only be a way
of remaining on par with the practices adopted by other organizations [48], which then become necessary but not sufficient for superior performance (per [49]).

Efforts to represent the range or categories of practices as more of a continuum suggest that there are a variety of ‘promising’ practices that may or may not be best practices for some organizations [45]. The management innovations are new to the company implementing them [41], but they are not new to other organizations, which may be performing well. Consequently, to the organization looking at and for practices to adopt, those management innovations are only ‘promising’, not ‘best’, for a variety of reasons, including that they may need customization to the organization before the adopting organization experiences any improvements [45].

That is, searches for management innovations may surface a variety of practices and technologies that range from those that are necessary but not sufficient for high performance through to promising but unproven or less known practices. More specifically, to improve the sustainability of cold storage warehouses, organizations could benefit from the generation of practices that represent management innovations, particularly innovations in management practices, processes, and structures that affect operational activities [41]. Therefore, this study’s research question is “What practices and technologies could enhance the sustainability of cold storage warehouses?”

Although the issues outlined above are relevant to cold storage warehouses worldwide, this study focuses on the cold storage warehouse industry in Australia. Australia has some unique challenges in the cold storage industry because it is a very large country that is sparsely populated and generally has a warm climate. That is, Australia is heavily reliant on freight to move goods around the country and, particularly, on a widely distributed network of cold storage warehouses to safely store and deliver goods to market. These characteristics of the Australian cold storage industry mean that it is a huge consumer of energy, with consequently large greenhouse gas emissions. Hence, the need to improve the sustainability of this industry is critical.

2. Materials and Methods

To investigate the above research question, an inductive, action-oriented, and change-oriented method was used—convergent interviewing. Convergent interviewing is a diagnostic method that has a history of being used to inform organizational change since the 1980s [50]. Action- and change-oriented programs often generate and focus on the issues that participants have in common in order to build on that common ground [51].

In this study, the convergent interviewing process of Dick [50] was followed. The major components of convergent interviewing are the selection procedure for interviewees, the interviewing technique, the analysis of each round of interviews, and the final issue analysis [52]. An outline of this process can be seen in Figure 1.

The focus of the convergent interviewing was the research question “What practices and technologies could enhance the sustainability of cold storage warehouses?” That key question was used in each of the interviews. Next, a list of experts in the field of sustainability in cold storage warehouses was generated. The sequence of interviewees was determined, following Dick [50], by setting the first interviewee as the person who was most expert on the specific research question being examined. To determine the second interviewee, the project steering group considered who on the list was the next most expert in the field but was as different as possible from the first person. These two interviewees formed the first round of interviews, where the interviewees were the two most expert in the field and were as different as possible from each other. Continuing this process generates the subsequent sequence of interviewees in each round, with rounds continuing until no new information is received from interviewees for two rounds.
The process of convergent interviews.

The first round of interviews only asks one question (the primary research question), aiming to keep the interviewee talking for about an hour. The first round of interviews focused heavily on active listening and verbal and nonverbal cues to keep the candidate responding and to avoid leading the interview. All interviews began with this initial question across all of the rounds.

After each round, the project team analyzed the issues raised in the interviews and attempted to identify areas of agreement and disagreement among the interviewees; hence, the technique incorporates validation processes directly into the research strategy [53]. Issues arising in both interviews in a round, whether the interviewees agreed or disagreed, were part of the common results and were used to generate follow-up questions for later rounds of interviews. When both interviewees agreed on an issue, the probe question generated aimed to determine if there were circumstances when agreement may not occur. If interviewees disagreed on an issue, a probe question was generated to try to explore the reasons for the differences. Issues arising from just one interview were excluded from the analyses.

The probe questions generated after each round were designed to identify potential exceptions to the agreed-upon issues and explore differences between parties [51]. For example, the second round of interviews included probe questions such as “How can cold storage warehouses use space most efficiently?” and “What measures can be taken to limit air and water infiltration?” That is, as more interviews are conducted and additional data are collected, the interview questions are refined to highlight key insights [53]. The approach of the convergent interview is to have the interviewer intervene as little as possible to maximize the amount of time the interviewees speak.

The process is repeated until converging themes are identified [53]. Unlike many interview techniques, convergent interviews have a clear end point—when there have been two rounds of interviews with no new issues raised. The method is also considered flexible, with the subjective data obtained by it being overruled by its consistency in conver-
In this study, the team interviewed 10 candidates in five rounds. Not all of the experts interviewed were from Australia due to the niche pool of known experts for this project’s specific question, but driving motivations for innovation were construed to be similar regardless of the country of origin of the interviewees. Almost all the interviews were conducted online using Microsoft Teams or equivalent software such as Zoom. After the impacts of COVID-19, the widespread familiarity of professional workers with remote work made setting up the virtual meetings easy and efficient, as candidates were familiar with the software and had the correct setups for a successful interview.

3. Results

The interview process confirmed that being energy efficient is critical for long-term sustainability and optimizing operational costs. The experts’ insights can be condensed into two main categories: design and operations, with a secondary consideration being the considerations for new versus old buildings. The interviews revealed several considerations for cold storage warehouses, both new and existing, when trying to reduce energy consumption and emissions. The results are visually displayed in an affinity diagram (Figure 2) that shows the connections between the variables and components brought up by the experts.

![Figure 2](image_url)

**Figure 2.** A detailed affinity diagram representing the main links between issues and practices in cold storage warehouses. Note: yellow highlighted practices are those considered essential by the experts; blue highlighted practices are those that are commonly accepted in the industry but often not exploited; green highlighted practices are those deemed best practices by the experts; purple highlighted text was identified as a “possible” best practice by the experts; red connecting lines indicate possible contradictory forces.

According to the experts interviewed in this study, many possible technologies and/or innovations have the potential to improve the sustainability of cold storage warehouses. Listed from those with the potential to have the largest to the smallest room for improve-
ment, given the current state of most of the industry, these topic categories of management innovations include:

- Refrigeration systems;
- Control and automation;
- Insulation;
- Air and water infiltration;
- Maintenance, monitoring, and operational practices.

3.1. The Refrigeration System

In their discussions of refrigeration systems, two important elements were raised by the interviewees. The first was the type of refrigerant used, and the second was the refrigeration system employed.

The interviews revealed that natural refrigerants are the most commonly used in industrial refrigeration systems. This is largely a result of the Montreal Protocol, which aims to phase out high GWP and ODP refrigerants that are harmful to the environment. Ammonia was the most common type of natural refrigerant in use in cold storage warehouses. Ammonia has the benefit of being the only refrigerant, alongside water and air, with a zero GWP and ODP \[55\]. Ammonia also has favorable thermodynamic properties, allowing it to absorb more heat than competing refrigerants \[55\]. An alternative refrigerant mentioned by the interviewees was carbon dioxide (CO\(_2\)), which, unlike ammonia, is not toxic or flammable. However, CO\(_2\) has a low critical temperature, which is the temperature where a refrigerant in a gaseous state cannot be liquefied \[55\]. Therefore, refrigeration systems using CO\(_2\) as a refrigerant require high pressures, which can be expensive to design for as well as dangerous. That being said, CO\(_2\) is often used in smaller commercial refrigeration systems and is also potentially useful in the lower-temperature stage of two-stage industrial refrigeration systems, as higher pressures are not required for these systems.

In terms of the refrigeration systems raised by the interviewees, only two came up as innovative: a pumped recirculated system using liquid overfeed and a low-charge ammonia direct expansion system. Of these, the interviewees suggested that the pumped reticulated systems are the most commonly used in cold warehouses. The interviewees attributed this to the fact that they have been used for decades in industrial applications and are therefore proven to suit larger applications. However, the experts said that direct expansion (DX) systems utilizing low-charge ammonia are the way of the future, particularly because, in every aspect of their functioning, they are superior to liquid overfeed systems, although they cost more up front (Table 3).

<table>
<thead>
<tr>
<th></th>
<th>Ammonia Liquid Overfeed</th>
<th>Low-Charge Ammonia DX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>Higher</td>
<td>Capital cost</td>
</tr>
<tr>
<td>More</td>
<td>Less</td>
<td>Ongoing costs</td>
</tr>
<tr>
<td>Lower</td>
<td>Higher</td>
<td>Energy efficiency</td>
</tr>
<tr>
<td>More</td>
<td>Less</td>
<td>Emissions</td>
</tr>
<tr>
<td>Worse</td>
<td>Better</td>
<td>Safety</td>
</tr>
</tbody>
</table>

Per Table 3, low-charge ammonia DX systems are superior to ammonia liquid overfeed systems in terms of their ongoing costs, energy efficiency, emissions, and safety, but are less favorable in terms of up-front capital costs. Much of the improved performance across a range of indicators for low-charge ammonia DX systems stems from their improved energy efficiency. These DX systems tend to be more efficient than ammonia overfeed systems for two reasons. First, when operating, low-charge ammonia DX systems yield mostly vapor after the refrigerant exits the evaporator, which results in fewer energy-consuming pressure drops. Second, the absence of pumps in the DX system leads to further reductions in energy consumption compared to the ammonia liquid overfeed systems. Combined, these two
factors can lead to energy savings in the order of 15 to 30 percent per year. However, DX systems require more capital to implement due to design considerations, although the higher initial capital costs can generally be offset by energy savings in three to six years, regardless of whether they are retrofits or new systems.

Finally, low-charge ammonia systems are safer than liquid overfeed systems. One reason is that there is less ammonia in a low-charge system, and because ammonia is a toxic and flammable liquid, having less on premises lowers the risk of property damage and/or injury to workers. Given the improved qualities of low-charge ammonia DX systems across all critical measures, with the exception of upfront costs, and given the very short repayment period for these systems, it should only be a matter of time before they become the norm in the industry.

3.2. Control and Automation

Control and automation are areas where significant savings in energy use can be obtained in cold storage warehouses. The experts identified several technologies that help control and automate certain processes in refrigerated warehouses, including variable-speed drives (VSDs), sensors, automatic storage retrieval systems, and movable racking.

The first of these technologies, VSDs, can vary the output of refrigeration system components such as compressors, condenser fans, and evaporator fans. Typically, refrigeration components are sized to meet the maximum cooling demand. Using variable-speed technology allows the refrigeration system components to operate at part load when the full cooling demand is not required, thereby consuming less energy. In contrast, traditional on-off operational methods cause large spikes in energy demand when components, such as compressors, are turned on. Further, VSDs reduce the likelihood of temperature fluctuations that can occur with traditional on-off methods, which can be damaging to some products.

The next automation and control technology identified by the interviewees was sensors. Temperature sensors in the cold rooms allow warehouse operators to monitor temperature fluctuations as well as identify any spaces that are underperforming. Temperature sensors can also monitor the external insulation to help identify leaks. Hence, sensors enable the warehouse to be run more efficiently and also to identify potential problems before they seriously impact the performance of the warehouse. Sensors are also used to operate rapid roller doors to minimize the time they remain open, thereby minimizing the intrusion of higher-temperature air into the warehouse. Another application for sensors in cold storage warehouses is to control lighting systems, with sensors used to turn on lights when required and to turn them off in areas not currently being accessed. A well-designed sensor system will be run by a control system using programmable logic control (PLC) to collect inputs from multiple sensor types and execute the desired commands without the need for human intervention.

The third control and automation system identified by the experts were automatic storage and retrieval systems (ASRSs). These systems are used to move stock around cool rooms without the need for direct human intervention. There are a few significant benefits to using ASRSs, which aim to improve energy efficiency and productivity. One benefit is being able to space-rack more closely, which increases the storage volume of each cool room where this technology is utilized. Additionally, having ASRSs allows racking to increase in height, as automated forklifts can reach items that a manual forklift cannot. By increasing the height of the racking, the surface area of the building can be decreased, which improves the energy performance of the warehouse. Another benefit of ASRSs is that they do not require lighting to operate. Therefore, heat generated by lighting is minimized, which reduces energy consumption.

The final control and automation technology identified by the interviewees was movable racking. Movable racking works by having the racking slide along rails to open an aisle, which a forklift can move down to collect pallets. Traditional warehouses have an aisle between each racking section, leading to a lot of unused space. Movable racking
helps reduce the unused space by increasing the density of the racking. Being able to
move the racking allows for more storage space, which improves thermal performance and
energy efficiency. When all of these technologies are employed, there is the potential to
considerably improve the efficiency of cold storage warehouses, although they can also be
implemented independently of each other, where each will yield improvements over
classical cold storage methods.

3.3. Insulation

Cold storage warehouses operate on the principle of maintaining internal temperatures
vastly different from their external environment. Consequently, the energy consumption
and overall sustainability of cold storage warehouses are heavily reliant on quality insu-
lulation practices and technologies in walls, roofs, and floors. Inadequate or compromised
insulation poses a great risk of unnecessary and excessive air, water, and heat infiltration.
By ensuring appropriate and robust insulation is provided, cold storage warehouses are
able to drastically reduce their energy waste and maintain the consistent environment
desired for the prolonged preservation of stored goods.

Walls and roofs are directly exposed to solar radiation, and insulation is the primary
means by which the transfer of heat from the sun to the interior of the building is pre-
vented. From the interview process, polyisocyanurate (PIR) insulation emerged as the
ideal choice for cold storage walls and roofs in an Australian context due to its superior
thermal performance, as shown in Table 4. PIR insulation also excels in safety, as evidenced
by its commendable fire resistance, low smoke emissions, and minimal moisture absorp-
tion. These features not only ensure consistent insulation over time but also affirm PIR’s
superiority in terms of durability and longevity. Regarding its design and construction,
although the ideal thickness of insulation is contingent on the desired internal temperature,
external conditions, and energy efficiency targets, the experts suggested that 200–250 mm
of PIR insulation provided the optimum thickness for insulating efficiency. Beyond this
level of thickness, warehouse operators are expected to experience diminishing returns and
excessive levels of initial investment costs.

Table 4. Heat flow for insulation materials [30–33].

<table>
<thead>
<tr>
<th>Insulation Material</th>
<th>Density Kg/M³</th>
<th>“K” Value W/mK at 10 °C Mean Temp.</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral wool slabs, fiberglass</td>
<td>24–28</td>
<td>0.028</td>
<td>Only applicable to 0 °C + temperatures.</td>
</tr>
<tr>
<td>Expanded polystyrene (EPS)</td>
<td>32</td>
<td>0.036</td>
<td>Fire risks.</td>
</tr>
<tr>
<td>Polyurethane sheets</td>
<td>36 ± 2</td>
<td>0.021</td>
<td>Most common globally.</td>
</tr>
<tr>
<td>Polyisocyanurate sheets (PIR)</td>
<td>32 ± 2</td>
<td>0.021</td>
<td>Increasingly used in Australia, but more expensive than substitutes.</td>
</tr>
</tbody>
</table>

Although PIR is superior to the main alternative insulation types, many warehouses
have been built with other forms of insulation, often driven by the lower up-front cost
of those alternatives. In such cases, the only option to rectify that issue would be to
retrofit to PIR. Although this may seem like an attractive option given the benefits of
upgrading, retrofitting has some serious drawbacks when it comes to insulation. These
include the loss in time and opportunity in the period of the physical replacement of
insulation panels, losses in cooling energy during the period when the insulation is being
replaced, and the potential for stock losses if temperatures rise above safe levels during
insulation replacement. Given these limitations, it is likely that PIR will be the insulation
choice for future builds, but that legacy insulation is likely to remain in place for
buildings that were built using other forms of insulation. Given that, globally, cold storage
warehouses frequently use polyurethane as their insulation material of choice [56], with
many others using rockwool and extended/expanded polystyrene [57], it may be many
years before PIR, an essential technology, is common.
Floor insulation in a cold storage warehouse has a different objective than wall and roof insulation. For walls and roofs, the insulation protects the interior of the building from external heating. In contrast, the purpose of floor insulation is to protect the underlying ground from penetration by the cold of the building because cold penetration into underlying soils can cause frost heave, which can damage the foundation and structure of the overlying warehouse. In Australia (where the climate is warmer), frost heave occurs less frequently than in other countries; however, prevention measures still need to be installed and are essential to the proper function of warehouses. Experts identified bulging sections, warped sections, uneven spots, cracking on walls and floors, and sinking floors at the corners of warehouses as identifiers of frost heave. To prevent frost heave, the floor temperature must remain above the freezing point of water, which can be accomplished by applying low-intensity and mild heat through pipes and vents underground, applying electric resistance heaters to the underside of the floor insulation, or suspending the floor [33].

3.4. Air and Water Infiltration

To improve the efficiency and sustainability of cold storage warehouses, another important consideration raised by the interviewees was air and water infiltration. Limiting the infiltration of air and water involves consideration of internal and external doorways as well as the use of anterooms. In this study, the experts drew attention to two main entrances to consider when addressing the issue of infiltration—dock doors and anterooms—and made clear distinctions in the considerations relevant for each of the two types of entrances.

For dock doors, roller doors were recommended due to the various benefits they provide over alternatives. For example, dock doors require high-speed and frequent operation during the transportation process, and roller doors are best suited to these conditions [58]. Not only do roller doors fulfill these requirements, but they also come with the added benefit of requiring less space to function than substitutes such as vertical and sliding doors. Furthermore, due to the sheer sizing requirements of such entrances, roller doors are the most appropriate door selection for ease of installation and ongoing maintenance. The experts agreed that the most suitable type of roller door to install are rapid roller doors (RRDs). RRDs are described as a premium version of typical roller doors, further excelling in speed, insulation, safety, and durability [58]. To further minimize excessive door opening times, it is recommended to fit such doors with motion door sensors to eliminate potential sources of human error. Motion detection devices allow goods to be transferred without compromising speed and acceleration on the approach and through the doorway, thus decreasing the necessary open-door time [59]. Alternative door types, such as strip and air curtains, were disregarded as best practices by the interviewees. Strip curtains are commonly found to be perceived as a nuisance to employees, consequently inciting practices such as tying the curtains up, effectively creating a permanently open doorway. Air curtains, on the other hand, were commonly reported as being excessively energy-consuming solutions with minimal return.

In conjunction with roller doors, the experts suggested that all dock doors be fitted with a form of air seal to ensure that truck doors align seamlessly with the warehouse dock. Inflatable seals were given as the most favorable solution because they are more flexible and accommodating of differing truck sizes and misalignments to the dock doors. Moreover, substitute products, such as flap seals, are prone to being snapped and broken when backing the truck up to the dock door. The combination of roller doors and inflatable seals minimizes the risk of ambient air infiltrating the warehouse.

Finally, anterooms were identified by the interviewees as useful means to reduce air and water infiltration into cold storage warehouses. The reduced infiltration is because the anterooms are kept at intermediate temperatures (often 10–12 °C), which helps to prevent heat intrusion into cool rooms and also prevents condensation.
3.5. Monitoring, Maintenance, and Operational Practices

The final issues identified by the interviews as important to improving the sustainability and efficiency of cold storage warehouses were monitoring, maintenance, and operational practices. The practices included regular monitoring of the temperature within the temperature-regulated areas of the warehouse, which can give early warning of flaws. Temperature monitoring could be accomplished using sensors and alarms placed in appropriate locations. For example, a small leakage of CO$_2$ refrigerant could affect the cooling power and overload other components. Hence, the use of CO$_2$ sensors around the storage area is desired, typically placed towards the ground because CO$_2$ is heavier than air.

A good monitoring framework will identify many potential maintenance issues, but only if these are acted upon will the outcomes result in improved overall warehouse efficiency. However, even with adequate monitoring and rapid responses to detected problems, ongoing maintenance checks were also recommended by the interviewees. These checks typically vary based on their frequency, ranging from daily to annual checks, depending on the types of checks being performed. For example, certain checks should be performed daily, such as checks of the compressors (for oil leakage), evaporators (for ice formation), and other components relative to the type of refrigeration and temperature requirements of the cold room. Meanwhile, an example of an annual maintenance practice would be the chemical cleaning of a heat exchanger. Thermal scanning checks can be a useful method to diagnose issues with the facility, while site checks for ice and wet spots could also identify issues.

In contrast to monitoring and maintenance issues, operational practices are those behaviors that occur in the warehouse by the staff that can impact the efficiency and sustainability of a cold storage warehouse. Many of these were identified by the interviewees, and these are summarized in Table 5. All of the issues identified in Table 5 have relatively simple fixes but require a high level of awareness and training, and these issues can re-emerge if staff and management are not vigilant in ensuring that operations are as efficient as possible.

Note that the tensions that arise between the characteristics of the building (orientation, height, and surface area) and the feasibility of rooftop PV can be somewhat resolved for new buildings by the building being tall and large. That is, a tall building that is large enough to have sufficient surface area for PV resolves that tension. Existing buildings that do not have an optimized surface area to volume ratio and/or orientation can still implement PV if desired and can then rely on other practices (e.g., painted bright colors, effective insulation) to lessen any decrements in possible sustainability.
<table>
<thead>
<tr>
<th>Defect/Inefficiency</th>
<th>Explanation</th>
<th>Operational Improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaving machinery and plant idling when not in use</td>
<td>Idling machinery and plant generate heat and wastes fuel.</td>
<td>Raise awareness of plant operators, generate a culture of responsibility</td>
</tr>
<tr>
<td>Lack of routine checks and maintenance</td>
<td>Prevention methods are cost- and energy-efficient ways of stopping failures.</td>
<td>Having routine checks and fail-safe sensors allows companies to monitor and prevent critical defects prior to failure, but it needs to be embedded in the culture of the workplace</td>
</tr>
<tr>
<td>Inefficient refrigeration components (e.g., poor sequencing of compressors)</td>
<td>Components of the refrigeration system may be overworked or underworked (variable-speed drives).</td>
<td>Automation and frequent monitoring of the refrigeration system ensures the most efficient operation</td>
</tr>
<tr>
<td>Overuse of defrosting evaporators to reduce ice build-up</td>
<td>Ice buildup makes refrigeration systems function improperly.</td>
<td>Prevent ice buildup by minimizing air infiltration (condensation) and optimizing compressor usage by having sensors and timers</td>
</tr>
<tr>
<td>High infiltration and lack of door protection</td>
<td>Intermittent infiltration, often caused by heavy traffic and frequent door openings, which can account for more than 50% of the total heat load [60].</td>
<td>Mitigating heat losses can reduce the energy needed to cool the space</td>
</tr>
<tr>
<td>Inefficient storage practices</td>
<td>Unneeded movement of pallets to reach other items</td>
<td>Automated racking and/or software management tools with updated data</td>
</tr>
<tr>
<td>Cooling losses in logistics and freight (products brought in above temperature)</td>
<td>Higher product temperatures when brought into the warehouse cause strain on the refrigeration system and also cause condensation, which can lead to other problems</td>
<td>Improved cold chain logistics (communication with truck drivers and companies). Quick product movement out of the loading bay (the product is not being left there)</td>
</tr>
<tr>
<td>Control setting adjustments</td>
<td>Set points are prone to change (justifiable or not), where the adjustment may be forgotten and/or not changed back</td>
<td>Regularly check settings and restore control settings. Have communication/automation measures</td>
</tr>
</tbody>
</table>
4. Discussion

This study found many practices and technologies that can be implemented to improve the sustainability of refrigerated warehouses. The resulting management innovations were practices and processes (per [43]) organized to reflect the need to use those innovations to improve the sustainability of cold storage warehouses in Australia.

The sustainability innovations can be stratified into a hierarchy of practices and technologies, presented in Figure 3, that distinguish between the practices that are essential and those that are best, applying the considerations raised in Rodwell et al. [47] and Vedder [49]. Practices and technologies in the yellow segment of Figure 2 are those deemed essential for all refrigerated warehouses. In parallel, findings for logistics centers suggest that for those facilities with less automation (such as those at the bottom of the pyramid in Figure 2), energy consumption is driven by the characteristics of the building [25]. Most of the practices and technologies in this segment are possible to retrofit; however, a few should be considered during the design stage of the warehouse, such as building orientation, anterooms, and glycol floor heating.

![Figure 3. Hierarchy of practices and technologies for cold storage warehouses in Australia.](image)

The practices and technologies in the blue segment represent those that can be retrofitted to further improve energy efficiency and reduce emissions. These practices and technologies are often not perceived as essential. Lastly, the practices and technologies in the green segment are considered best practices. Refrigerated warehouses implementing innovations new to their organization, working from the bottom up to the next most sophisticated level of practices and technologies, will enhance their sustainability.

The text below discusses the nature and impact of the practices and technologies, organized within the categories in Figure 2, then touches on some possible practices that need further evaluation and some general observations about the need to continue making changes based on the Montreal Protocol and its amendments. The discussion of results works from the essential practices and technology, moving upward through the hierarchy.

4.1. Essential Practices and Technologies

In broad terms, the issues most directly associated with managing the energy efficiency of cold storage warehouses can be categorized into three primary areas: design and installation, maintenance, and operational practices. In terms of design and installation, thoughtful
and efficient designs should be implemented, as well as careful installation of components to avoid future defects and flaws. With newly constructed warehouses, the building orientation can be optimized. Ideally, and in best practice, the building should be positioned to minimize exposure to direct sunlight and prevailing winds, thereby decreasing cooling needs [61].

Retrofitting existing warehouses with new and improved technology is quite often a viable option to achieve higher energy efficiency. Retrofits could range from basic operational and maintenance enhancements, such as external painting (lighter colors repel more heat), to repositioning plant and equipment for more efficient material flows. Additionally, companies can either replace individual components or upgrade entire systems. For example, air strip curtains can be upgraded to rapid roller doors to minimize heat infiltration during operations, or sensor-controlled LED lights could replace other lighting alternatives with higher heat loads. Although these solutions may have high upfront costs, the payback periods are relatively short due to the amount of savings arising from these minor improvements [26].

Effective maintenance is essential for the optimal operation of every component within a cold storage warehouse. Routine maintenance practices are more effective than reactive maintenance.

The energy consumption and overall sustainability of cold storage warehouses are heavily reliant on quality insulation practices and technologies. The benefits provided by PIR sandwich panels for wall insulation go beyond mere thermal resistance and were strongly recommended by the experts.

The issues that floor insulation must face differ from those of the walls and roofs. Unlike walls and roofs, floors face consistent ground temperatures that might be warmer than what is required internally [34]. Moreover, the issues of ground moisture and potential frost heave pose a real threat to the structural integrity of the concrete foundation slab on which the warehouse resides [33]. A delineation arising from the results was that chilled storage rooms were not required to have insulated flooring, but insulated flooring is essential in frozen storage areas. The most important way to prevent frost heave is through the use of underfloor heating, particularly glycol.

Managing air and water infiltration is important for cold storage warehouses and can be addressed by focusing on high-quality doors such as RRDs for cold storage entrances and the appropriate use of anterooms.

Typical roller doors were adequate for external entrances such as dock doors, but the challenges associated with docking bays [58] may be addressed by aligning the floor level of the unloading bay with the bed of the transportation trucks, as well as the strategic placement of frequently accessed doors, considering their proximity to delivery trucks and easy access routes for forklifts, which can further reduce the open-door time duration [59]. Finally, the use of inflatable seals can maximize protection against infiltration of air and moisture at docking doors.

For anterooms, a further improvement is to integrate desiccant systems in some anterooms to actively reduce the air’s moisture content [36]. Even well-designed anterooms can face challenges, especially with respect to the potential lack of discipline of employees using anterooms in practice. For example, some employees may view anterooms as a nuisance and may keep anteroom doors permanently open, completely diminishing the value of anterooms [37]. Therefore, training plays a crucial role in communicating the importance of the anterooms to the proper operation of the warehouse. Warehouse owners and managers can also use automated tools, such as traffic lights or indicators, that can guide personnel to ensure that only one door is operational at any given moment [37].

The above are examples of basic, essential practices for enhancing the sustainability of cold storage warehouses. The next set of practices and technologies that this research surfaced are accepted by experts as being helpful in improving sustainability but have not been as widely implemented or exploited as they perhaps should be.
4.2. Accepted but Not Exploited Innovations

Perhaps the next key step forward in sustainability improvements for cold storage warehouses would be for them to begin using accepted innovations that are not widely exploited. Using ammonia as a refrigerant is a key example of a well-proven innovation that should be more widely used. Perhaps one reason why cold storage warehouses may be continuing to use HFCs, in the absence of regulatory forcing, is that some refrigeration systems using HFCs cannot be easily retrofitted with ammonia because ammonia is incompatible with some materials, such as copper, commonly used in HFC lines [62]. Such barriers to implementation may contribute to owners hesitating to update technology, leaving some warehouses to fall behind in an ever-changing industry.

For those warehouses that do use ammonia, another issue of concern is which system they use. The findings of this study are consistent with other studies that suggest low-charge ammonia DX systems are more efficient than pumped recirculated liquid overfeed systems [63]. However, the uptake of low-charge ammonia DX systems is slow, and liquid overfeed systems are still predominantly used for industrial-scale applications. The slow uptake is unusual since low-charge ammonia DX systems are superior in nearly all aspects to recirculated liquid overfeed systems outside of the upfront cost. Thus, it appears that upfront capital costs, with less consideration of ongoing costs and sustainability, are the primary obstacle to the slow uptake of low-charge ammonia DX systems.

A further reason for the slow uptake of low-charge ammonia systems may also be a lack of knowledge surrounding the higher energy efficiency of low-charge ammonia DX systems. That knowledge gap indicates that there is not enough exposure to or acceptance of new industry technology trends.

In terms of accepted but not exploited technologies such as PV systems, two particular circumstances may explain some of the hesitancy for the take-up of solar systems—the potentially inadequate structural supports of existing warehouses and situations where the cold storage company leases the warehouse from a third party. In circumstances where the cold storage company is renting a warehouse, there are few incentives for the warehouse owner to install solar panels because they are not responsible for ongoing energy costs. However, there are several ways in which warehouse owners who are not cold storage operators could benefit from the addition of solar panels to their roofs. First, they could invest in solar panels and sell the energy to their tenants. Second, they could enter PPAs (power purchase agreements) with third-party solar developers for lower energy costs and minimal risk. Finally, they could simply lease rooftop space to the warehouse operators for another form of warehouse revenue.

4.3. Best Practices

Many of the best practices and technologies were to do with control and automation, usually after the warehouse has implemented many of the practices and technologies that are lower in the hierarchy. The sustainability best practices for cold storage warehouses included advanced automation such as movable racking, with ASRSs, VSDs, thermal scanners, and low-charge ammonia DX refrigeration systems.

Most warehouses implement the technologies mentioned that help control warehouse processes, such as VSDs, sensors, and PLCs. However, warehouses that do not use these technologies may be unaware of the benefits they can receive, such as the energy savings that can be achieved by implementing variable-speed technology [64]. Perhaps warehouses that do not need strict temperature set points cannot justify the cost of installing VSDs. However, the increased availability of VSDs along with declining costs should see VSDs implemented in more refrigeration systems.

The use of technology such as ASRSs is possible in existing warehouses; however, it is easier to implement in new warehouses, because new warehouses can be designed specifically for the use of ASRSs. In contrast, existing warehouses would require racking to be repositioned and upgraded to cater for ASRSs. Nevertheless, retrofitting existing warehouses with ASRSs would still improve their energy efficiency and productivity.
A possible best practice (per [45]) that may one day be more widely tested and accepted is the use of electricity demand response and load shifting. More testing and evaluation of the best ways to do this practice, perhaps more so for frozen foods in well-insulated buildings with solar panels, needs to be done.

Load shifting is a strategy for managing electricity demand by relocating consumption from high-demand periods to times when demand is lower in such a way that is not detrimental due to the thermal inertia of the product. Warehouses with larger volumes of product may therefore have greater potential returns for applying demand response techniques. Furthermore, lower temperatures (such as those of frozen foods) may present a stronger demand response potential than cooled products, such as fruit and vegetables [65].

Air and products may rise in temperature during a period with a higher set temperature, hence the need for regulation and monitoring during the process in order to not spoil products. However, the risk of food quality and safety degradation means that most industrial frozen food warehouses refuse to use demand response. There may be circumstances where peak load shifting may be more beneficial, such as when the warehouse has solar panels, but ultimately, more studies are needed to further analyze the parameters under which load shifting may be viable and present less of a risk to the stored products.

Further, battery and solar energy storage are becoming commonplace in residential applications but are much rarer in cold storage warehouses, possibly because batteries usually do not meet the substantial energy demands of cold storage warehouses. If more efficient panel technology emerges, battery systems may become viable or useful for cold storage warehouses.

In terms of more general issues in improving the sustainability of cold storage warehouses, it is notable that despite the success of the Montreal Protocol and its amendments, there is still quite a lot more that could be done in managing refrigerant gases. For example, ammonia is recommended above and is increasingly used in refrigerated warehouses because it has great thermodynamic properties as well as zero GWP and ODP. However, there are still some warehouses using synthetic refrigerants such as HFCs with high GWP values, which is a concern when such refrigerants leak, causing substantial global warming impacts [23]. The continued use of less environmentally friendly refrigerants could be a result of governments not being strict enough with phasing out the use of HFCs. For example, Australia is phasing down the use of HFCs by 85 percent by 2036 [66], leaving warehouses to continue to use HFCs in the meantime and also suggesting that some HFCs will still be in use after that date. Since policies are significant drivers for technology change, governments need to make more of an effort to phase out HFC use [55], which could help move more cold storage facilities to use ammonia as a refrigerant.

4.4. Limitations

Perhaps the main limitation of the above findings is that they were based in Australia, a developed country, although international experts from other (developed) countries were also involved. Note, though, that the cold storage warehouse industry in Australia is very fragmented, and many organizations in Australia’s cold storage industry could usefully implement the practices and technologies emphasized above. However, the above hierarchy of practices could enable cold storage warehouses by informing them of the practices and technologies to implement at their level and work through to the next higher level and the higher level after that, irrespective of the development of their home economy. The larger discriminator across the practices and technologies is in terms of whether they are being applied for a new site or are to be retrofitted to an existing site.

Furthermore, the practices categorized in this study were the actionable practices and technologies in common that the experts recommended for cold storage warehouses specifically. Recent studies have suggested that if the wider supply chain is considered, then lower-temperature cooling in the cold storage warehouse may lead to sustainability improvements across the cold chain, at least until green electricity-powered trucks become more common [29]. Yet that consideration is not incompatible with the potential of the
improvements suggested in this study. Cold storage warehouse facilities that implement increasingly sophisticated practices from those in Figure 2 will improve their sustainability, and even with the temperature set lower, they could be more sustainable for them and the wider cold chain than they otherwise would be.

5. Conclusions

With the ever-increasing threat of climate change and global warming, we must find new ways to make energy intensive buildings, such as cold storage warehouses (per [23]), that are essential infrastructure for food preservation, more sustainable. Therefore, encouraging searches for practices and technologies that enhance the sustainability of cold storage warehouses is crucial in the battle against climate change and global warming.

The resulting management innovations, consisting of specific practices and processes (per [43]), were delineated in this study to inform cold storage organizations’ search for practices that can improve their sustainability. There are many practices and technologies that can be implemented to improve the sustainability of refrigerated warehouses. The practices and technologies were organized into a hierarchy that ranged from essential to best practices, applying the differences in practices and technologies suggested by Rodwell et al. [47] and Vedder [49]. Essential practices and technologies should be implemented by all refrigerated warehouses, whereas best practices may be implemented depending on budget and whether a warehouse is new. Some refrigerated warehouse owners may be unaware or unsure of the benefits obtainable from implementing sustainable practices and technologies. To encourage the use of sustainable practices and technologies, more reporting on successful or unsuccessful applications of practices and technologies needs to be communicated across the industry.

Also note that the practices and technologies in Figure 2 improve the sustainability of cold storage warehouses now, but they are not static and may change over time. That is, the practices and their categorization may change over time, requiring a continuing search for management innovation.

Author Contributions: Conceptualization, A.M., G.M., K.B., J.R. and S.R.; methodology, J.R.; formal analysis, A.M., G.M. and J.R.; investigation, A.M. and G.M.; writing—original draft preparation, A.M., G.M. and K.B.; writing—review and editing, J.R. and S.R.; supervision, J.R. and S.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by Swinburne University of Technology, Human Research Ethics Committee 20226678-10905.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data is contained within the article.

Acknowledgments: The authors would like to thank T.H. for research assistance.

Conflicts of Interest: The authors declare no conflicts of interest.

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