Leaks, maintenance and emissions: Refrigeration and air conditioning equipment

Prepared for the Department of Agriculture, Water and the Environment

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1 Executive summary

This project assessed the potential for improvements to maintenance regimes on refrigeration and air conditioning (RAC) equipment to deliver meaningful reductions in electricity use, refrigerant leaks and indirect emissions. As a major cross-cutting technology, present in all sectors of the economy RAC equipment was estimated to produce more than 11% of Australia's annual greenhouse gas emissions in 2019.[1]

An extensive survey of the international literature on common faults in RAC equipment was conducted and revealed a range of potentially large energy saving, leak reduction and emissions reduction opportunities.

The study confirms that there are a limited number of common faults reported across large stocks of RAC equipment that result in the great majority of energy penalties and refrigerant leaks.

An energy penalty is defined as electricity consumed by a piece of equipment, over and above the optimal electricity consumption levels of the equipment, as a result of poor installation and/or operating conditions.

These are the most common faults responsible for the largest portion of energy penalties and refrigerant leaks across the stocks of both refrigeration and air conditioning equipment:

- Sub-optimal refrigerant charge (over or undercharge, refrigerant leakage).
- Dirty condensers and mechanical issues (fouling, faulty fan).
- Dirty evaporators and mechanical issues (fouling, ice-up, obstructions, faulty fan).
- System capacity (no heat load calculation, disconnect between owner and designer, safety margins) and mismatched components.
- Control systems, sensors and wiring issues.
- Poor equipment location.
- Liquid line issues (including restrictions).
- Degraded and contaminated refrigerant.
- Minimal or no documentation (installation, commissioning baseline data, operation, maintenance).
- Excessive heat load (applies only to refrigeration).
- Airflow: Air distribution, duct sizing, dampers and fans (applies only to air conditioning).
- Airflow: Filters (applies only to air conditioning).
- Duct insulation and leakage (applies only to air conditioning).

These common faults occur across most equipment segments. A large majority of these faults are related to maintenance or can be addressed by routine maintenance. These common faults are discussed in detail in *Section 4*.

The most commonly recurring fault in commercial refrigeration and air conditioning equipment, is refrigerant undercharge - which is directly related to refrigerant leakage. Refrigerant undercharge results in significant ongoing energy penalties, as discussed in detail in *Section 3*.

Possibly the single most important measure to improve RAC equipment performance is to eliminate leaks of refrigerant gas. Apart from reducing direct emissions, ensuring equipment is operating on an optimal refrigerant charge delivers the additional benefit of reducing electricity use and electricity-related greenhouse gas emissions. However, there are important differences in how the opportunities in those two broad classes of technology might be addressed.

A significant finding is that by establishing a few important installation and maintenance practices as routine activities, there is the potential to capture large electricity savings across a wide variety of equipment formats. Equipment formats that are considered most prospective for delivering electricity savings are tabulated below.

Table 1: Technology Format Opportunity Table.

Technology format	Opportunity at installation	Opportunity for leak minimisation	Opportunity for maintenance	Emission benefit (Direct and indirect)
Small AC (Self contained)	No	None identified	No	Minimal
Small AC (Non-ducted)	Yes	Some	Some	Yes
Ducted AC (Split and package) and light commercial AC	Yes	Commercial only - manual every 6 to 12 months (incl. ducted systems upwards)	Yes, mostly commercial only	Yes
Central plant (Chillers)	Yes	Manual every 6 to 12 months with auto on larger systems	Yes	Yes
Self-contained equipment	Some types	Mostly none - manual every 12 months on larger systems	Yes, some types (for example, harsh applications only, etc.)	Minimal, some types can be identified
Remote condensing units	Yes	Manual every 6 to 12 months with auto on larger systems	Yes	Yes
Supermarket	Yes	Automatic leak detection	Yes	Yes, mostly independents
Central plant (Cold storage and process)	Yes	Automatic leak detection	Yes	Yes, only regulated refrigerants are within scope

AC = Air Conditioner

Leading contracting businesses in the heating, ventilation, air conditioning and refrigeration (HVAC&R) industry have long term data collections at various levels of sophistication that could be used to validate the prevalence, against the severity, of common faults and potentially calculate the cost-benefits of particular practices with a reasonable degree of accuracy.

The project outcomes also include an extensive bibliography of recent research findings and programs addressing the energy efficiency of RAC equipment. This report and the project findings provide a basis on which to target further work to validate the costs and benefits of various possible policy approaches and active measures.

2 Introduction

This report explores opportunities to reduce emissions from refrigerant leaks and unnecessary electricity consumption due to faults in the installation, operation and maintenance of stationary refrigeration and air conditioning equipment.

In most modern economies refrigeration and air conditioning equipment is one of the largest, if not the single largest consumer of electricity. This fact, coupled with the high GWPs of the majority of refrigerants in use, puts this nearly ubiquitous technology at the focus of measures aimed at slowing impacts of climate change.

In 2016 a global phase down of hydrofluorocarbon (HFC) manufacture and imports was agreed under the Kigali amendment to the Montreal Protocol. HFCs are a suite of synthetic greenhouse gases (SGGs) that are very effective and long-lasting thermal media, and at present, the most common refrigerants used globally. This 'technological forcing', driven by international treaty and national regulation, is a major step towards reducing the overall environmental impact of RAC systems.

However, the overall climate impact of emissions of refrigerants to atmosphere are dwarfed by the energy-related emissions from the electricity that powers the billions of pieces of RAC equipment around the world.

The Expert Group estimated that, in Australia, losses of refrigerant from operating RAC equipment was responsible for approximately 1.2% of national emissions in 2019. However, in that year RAC equipment was estimated to consume more than 24% of all electricity generated in the economy, resulting in a combined total of direct and indirect emissions of 61.28 million tonnes carbon dioxide equivalent (Mt CO_2e) or approximately 11.5% of national emissions.[1]

Table 2: Direct and in-direct emissions from RAC equipment in Mt CO_2e in Australia 2019.

	Direct emissions (Mt CO_2e)	In-direct emissions (Mt CO_2e)	Total emissions (1) (Mt CO_2e)
Stationary AC	2.43	28.56	30.98
Mobile AC	1.40	2.94	4.34
Refrigerated cold food chain	3.16	15.80	18.96
Domestic refrigeration	0.03	6.97	7.00
Total	6.56	54.27	61.28

(Source: Cold Hard Facts 2020)[1]

Notes:

1. Excludes end-of-life emissions.
2. Sum of values in table do not add up to totals due to rounding.

There are hundreds of different RAC equipment formats in the economy, ranging from countertop portable refrigerators to huge air conditioning systems that condition buildings the size of airport terminals. Nearly all RAC equipment, irrespective of the equipment format, have common operational requirements. They all need sufficient air flow across heat exchange surfaces to transfer heat. Most RAC equipment employ common mechanical elements, such as the compressor that compresses and recirculates the refrigerant and the expansion device used to help create the cooling effect through heat exchangers.

The common features in this very broad class of equipment create opportunities to identify and apply remedial actions that could deliver efficiency improvements and reduce electricity consumption at a scale that is meaningful to the environment and the national energy economy.

2.1 *Scope and method*

The primary objective of this project was to identify the main causes of refrigerant leaks, energy inefficiency, the contribution that refrigerant leaks and sub-optimal refrigerant charges make to inefficient operation, and opportunities for energy savings across the stock of stationary RAC equipment in the economy. Heat pump equipment were also considered as part of the research, the very large majority of air conditioners are heat pumps due to their ability to deliver both heating and cooling. Other types of heat pumps include pool heaters, domestic and commercial hot water heat pumps and heat pump clothes dryers. These types of heat pumps were excluded as they are either small sealed systems, or there are relatively small stocks of this type of larger equipment employed.

The review aimed to identify all relevant prior research into the most common causes of refrigerant leaks and energy inefficiencies, or *energy penalties*, in RAC equipment.

An energy penalty is defined as electricity consumption by a piece of equipment, over and above the designed consumption levels of the equipment, as a result of poor installation and/or operating conditions.

To provide a basis on which to assess these opportunities, this study first examined two main propositions:

1. There are common 'faults', including refrigerant leaks, across large stocks of RAC equipment that result in the great majority of energy inefficiencies incurred.
2. There is sufficient commonality of RAC equipment components and design that establishing a few important practices as routine activities, such as regular cleaning of coils and condensers, has the potential to reduce refrigerant leaks and deliver large electricity savings across a wide variety of equipment formats.

The first phase of the study involved undertaking a wide-ranging Australian and international literature review.

The global literature review was conducted by a team of experts with extensive experience across the RAC industry from equipment design to the complexities of industry supply lines, and fundamentals of installation and maintenance of equipment of all sizes.

The desktop research started with the exploration of several key terms and variations including:

- Refrigerant leakage: Detection and optimisation;
- Optimal refrigerant charge: Nominal refrigerant charge, measurement, verification;
- Faults: Various types and levels including building, HVAC, refrigeration, air conditioning and heat pump (RACHP), compressor and component;
- Fouling: Condenser, evaporator, filter and refrigerant dryer;
- AC, heating, ventilation and air conditioning and refrigeration (HVAC&R) – commissioning, recommissioning, optimisation, total equivalent warming impact (TEWI) and life-cycle climate performance (LCCP);
- Poor building performance: HVAC&R systems;
- Automated fault detection and diagnosis, metering, monitoring, maintenance, internet of things (IoT) and software as a service (SaaS); and,
- Maintenance, encompassing air conditioning, refrigeration, energy efficiency, leak minimisation and smart maintenance.

The research covered Australia and other regions including New Zealand, North America, the European Union, Japan, Singapore and Hong Kong. These broad geographies and economies were selected because they have similar technical and economic characteristics as Australia, have minimum energy performance standards (MEPS) or equipment energy efficiency labelling and standards in place, they employ similar training/trade skills competence regimes, and exhibit similar levels of market penetration of leading product types.

Reports collected were scanned for the research focus and findings, and then rated by relevance to the scope of this project as either high, medium or low. Highly relevant reports were reviewed in more detail.

Commonly reported faults, including refrigerant leaks, and causes of energy penalties were assessed to determine whether they were applicable to RAC equipment overall, or across large parts of the stock of equipment. From this work a list (refer *Tables 4* and *5*) was created of those common faults that had the potential to produce large energy penalties across significant stocks of equipment.

In parallel, the major classes of RAC equipment were characterised to identify those stocks that are more likely to present economic and addressable opportunities for reductions in refrigerant leaks and in electricity use. This involved, for instance, identifying those equipment segments that were the largest electricity users, and that might deliver the largest economic returns to equipment owners with better maintenance.

These reviews established a matrix of equipment types (refer *Appendix A1: Technology format: Opportunity table*) that were judged as being the most likely areas in which economic and addressable opportunities for electricity savings could be found.

The literature search looked for reports that investigated or quantified the effect of addressing the refrigerant leaks and other commonly identified faults. A particular area of interest was hard data from studies into the energy penalties caused by sub-optimal refrigerant charges.

Losses of refrigerant to air in Australia were reported as being responsible for approximately 6.56 Mt CO_2e in 2019.[1] These losses represent only 1.2% of the entire Australian National Greenhouse Gas Inventory for the year. However, if large stocks of equipment are consuming more electricity than they should be, because of refrigerant losses, this compounds the total environmental warming impact of the synthetic greenhouse gas emissions by increasing energy related emissions. Essentially the question is:

'How much of the energy related emissions created by vapour compression refrigerating systems can be attributed to equipment operating with sub-optimal charges?'

While some data was identified that is relevant to this question, more research is needed to substantiate the estimates of additional emissions that have been made. But in short, the answer is yes, some large stocks in high electricity consuming segments of RAC equipment use more electricity than they should. This occurs as a result of operating with less than optimal refrigerant charge which produces significantly more energy related emissions than if they were operating on optimal refrigerant charge.

While achieving an accurate calculation of the energy penalty incurred over large stocks of equipment as a result of sub-optimal charges is worthy of investigation, possibly the more important question is, '*How much of this energy penalty can be practically avoided?*'.

2.2 *Why does it matter?*

The implications of the fact that cooling services are consuming more than a fifth of all the electricity generated in Australia is still not widely appreciated.

Electricity production is the largest single source of greenhouse gas emissions in the Australian economy, producing 34% of all emissions in the year ending December 2019.[2]

Cooling demand is temperature driven to a great extent. This is most directly the case with air conditioning working to deliver comfort conditions in buildings but also for commercial and industrial refrigeration of all types, even though those applications are more likely to employ effective insulation.

The increasing range of temperatures experienced with climate change, and the longer periods of high temperatures being recorded, means there will be more days when RAC equipment is working harder, and for longer durations. When RAC equipment is working harder, losses of refrigerant gas increase. Hotter component temperatures soften seals, harder working equipment vibrates more, connections loosen, and equipment life overall is reduced by wear and tear. When refrigerant charges fall, RAC equipment must work even harder to circulate the remaining refrigerant to transfer heat, consuming ever more electricity right when the electricity networks are under most pressure.

In most Australian cities, the peak demand on the electricity supply system also triggers higher prices charged to commercial equipment owners. In commercial buildings peak demand charges can be as much as 50% of total electricity charges in the summer months.

Cold Hard Facts 2020 estimated that total energy related greenhouse gas emissions of RAC equipment in Australia was 54.27 Mt CO_2e, more than 8 times greater than the greenhouse gas emissions due to direct emissions of refrigerants (6.56 Mt CO_2e). However, it is the interaction between all these elements at the core of our electro-technical economy on hot days that increases peak demand on electricity supply when the grid is at its most strained.

These feedback loops in the national electricity infrastructure underline why the energy efficiency of RAC equipment and systems is such an important focus for policy makers and business leaders.

The life-cycle assessment methodologies (TEWI, LCCP, etc.) that are applied to RAC systems account for direct emissions due to refrigerant leakage to atmosphere.[3] However, they do not account for the increase in electricity consumption, and resulting increase of indirect emissions, associated with systems that are operating with reduced refrigerant charge or other common faults resulting in energy penalties.

2.3 *Previous review of leak reduction strategy and maintenance activities*

The *Assessment of environmental impacts from the Ozone Protection and Synthetic Greenhouse Gas Management Act 1989* study undertaken in 2015 considered a wide range of emission reduction opportunities, two of which relate to this project:[4]

1. A leak reduction strategy involving leak inspection routines and automatic leak detection on certain classes of commercial RAC equipment from 2017 to 2030 was estimated to be able to avoid the equivalent of 8.5 Mt CO_2e (0.15 Mt CO_2e ozone depleting substances (ODS)/8.32 Mt CO_2e synthetic greenhouse gases (SGGs)) in direct emissions as compared to business as usual, and deliver indirect emissions savings as a result of improved efficiency of 4.7 Mt CO_2e.
2. Maintenance activities on certain classes of commercial RAC equipment from 2017 to 2030 delivering indirect emissions savings as a result of improved efficiency of 38.1 Mt CO_2e.

   The maintenance practices proposed were consistent with the International Organization for Standardization's (ISO), ISO 5149-4: '*Refrigerating systems and heat pumps - Safety and environmental requirements - Part 4: Operation, maintenance, repair and recovery*', and include, as examples of highly effective and simple preventative maintenance program elements interventions such as:

   a) Regular inspection and cleaning of air filters, or replacement if required.

   b) Regular inspection and clearing of the surfaces of condensers, evaporators, fans blades and fan guards.

   c) Improved containment practices on equipment connections, hoses, pipes and accessories.

   d) Regular inspection and repairs improving vapour sealing of cold rooms by replacing door gaskets and sealing of insulation to minimise ambient air/moisture ingress to the refrigerated space.

As the technicians employed for the proposed activities would be capable of carrying out all suggested work, and as many of the equipment types were very similar, the maintenance activities could simultaneously support the delivery of the leak reduction strategy.

At the time of that study, the authors' estimates of potential electricity savings and reductions of indirect emissions was consciously conservative, applied to relatively limited stocks of equipment, and using flat estimates of electricity savings of just 10%.

The International Institute of Refrigeration (IOR) provided a global estimate that 'Better optimisation, monitoring, and maintenance of cooling equipment has the potential to save 30 giga tonnes (Gt) of CO_2e emissions by 2050, contributing a further 38% of savings on those delivered through the planned phase down of high GWP refrigerants agreed at Kigali.' The IOR estimates optimisation, monitoring and maintenance can reduce total greenhouse gas emissions by 13%.[5]

2.4 *Equipment types targeted for efficiency improvements*

Not all RAC applications and equipment types have readily addressable opportunities for efficiency improvements. With more than an estimated 50 million individual pieces of RAC equipment employed in the Australian economy, any practical approach to identifying addressable and economic opportunities must first determine what attributes an equipment segment must have in order to potentially present an economically attractive opportunity for improved efficiency.

These attributes include:

- Equipment stocks that incorporate large individual pieces of equipment that on their own are significant electricity consumers;
- Equipment types that are 'mission critical', i.e. for them to malfunction or perform poorly risks economic loss;
- Equipment types that are more likely to leak refrigerant or be subject to common component faults;
- Equipment that is more likely to have a maintenance regime or be subject to monitoring and maintenance at some level by technically skilled personnel; and,
- Equipment designs that present easy opportunities for improvements that could potentially be delivered by low skilled personnel.

The inventory of RAC equipment in Australia, as modelled for the Cold Hard Facts research series, was screened to identify the segments that exhibit all or some of these attributes. *Appendix A1: Technology format: Opportunity table* provides a summary of the main equipment segments and identifies where opportunities for improved installation, leak minimisation or maintenance practices could deliver emissions savings.

The results tabulated below, represent the broad equipment segments where the largest opportunities are expected to be found.

Table 3: Stocks and electricity consumption of larger energy using segments of RAC equipment in 2019.

	2019 Stock	Electricity consumption (GWh/yr)	
		Residential	Commercial
Stationary AC			
Split AC (Non-ducted)	10,665,000	5,700	3,500
Ducted AC (Split and package) and light commercial AC	2,797,000	5,100	10,100
Central plant (Chillers)	25,300	0	11,700
Commercial refrigeration (CR)			
Self-contained equipment	1,375,000	0	6,800
Remote condensing units	350,000	0	7,300
Central plant (Supermarkets and other)	4,200	0	>4,000

(Source: Cold Hard Facts 2020)[1]

An immediate outcome of the process of seeking addressable opportunities for energy savings, was the identification of some RAC equipment segments, that for various reasons, explained below, have largely been excluded from further study at this time.

These segments include:

- Domestic refrigeration;
- Small self-contained AC including window/wall units and portable AC;
- Transport refrigeration;
- Cold storage and process applications operating on ammonia;
- Small mobile air conditioning (MAC) includes air conditioning equipment in passenger vehicles, light commercial vehicles, trucks and commuter buses; and,
- Large MAC includes air conditioning equipment in a diverse range of registered, unregistered and off-road vehicles, such as: larger buses and coaches; locomotives, passenger trains and trams; recreational vehicles and caravans; boats and pleasure craft; aircraft systems; mobile cranes; combine harvesters; and road construction equipment.

These segments have mainly been excluded because of one or more of the following reasons:

1. The individual pieces of equipment involved contain very small refrigerant charges, often less than a few hundred grams, and individually consume small quantities of electricity.
2. The stock of equipment has largely migrated to a low or zero GWP refrigerant (in the case of domestic and portable refrigerators and freezers both 1 and 2 apply).
3. It was considered unlikely that any compelling economic or environmental benefit could be captured by changes to installation or maintenance procedures of the stock of equipment.
4. The stock of equipment is of a specialised nature, there are relatively small stocks of this type of equipment employed, or it is most likely to be maintained regularly by competent engineering personnel due to the mission critical nature of the equipment or the specialised application.

3 Common faults

3.1 The common faults

This report aimed to identify all relevant prior research into the most common causes of refrigerant leaks, energy inefficiencies, or energy penalties, in RAC equipment. In the review many studies and meta studies were discovered listing common installation and maintenance related faults found in these systems. Although there are many similarities between the common faults found on both refrigeration and air conditioning systems there were also some significant differences. The common faults are listed in *Tables 4* and *5* below and a detailed explanation of each fault is provided in *Section 4* (including literature references).

3.1.1 Stationary air conditioning specific faults

The effective and efficient performance of reverse cycle air conditioning systems is ultimately determined by having sufficient 'refrigeration capacity' (i.e. heating and cooling), combined with effective 'air flows' via the air delivery system (i.e. registers, ductwork, air reticulation and zoning), and following the relevant technical standards and 'Good Practice' design (i.e. heat load calculations and product selection), installation, commissioning and maintenance guidelines.

All the main installation and operational faults identified in *Table 4* can be attributed to either inadequate refrigeration capacity, inadequate air flow, not following good practice guidelines, or a combination of all the above.

Table 4: Common faults in air conditioning equipment and systems.

Fault		Split AC (Non-ducted)	Ducted AC (Split and package)	Central Plant (Chillers)	Installation related fault	Maintenance related fault	Opportunity/ priority	Section
1	Refrigerant (sub-optimal charge, over or undercharge, refrigerant leakage)	Y	Y	Y	Y	Y	1	4.1 and 4.2
2	Airflow: Air distribution, duct sizing, dampers and fans	N	Y	Y	Y	S	1	4.11.1
3	Airflow: Filters	Y	Y	Y	N	Y	1	4.11.2
4	Control systems, sensors, and wiring issues	N	Y	Y	Y	Y	1	4.6
5	Condenser issues (fouling, faulty fan)	Y	Y	Y	S	Y	2	4.3
6	Evaporator fouling	Y	Y	Y	N	Y	2	4.4
7	System capacity (no heat load, disconnect between owner and designer, safety margins) and mismatched components	N	Y	Y	Y	N	2	4.5
8	Refrigerant health and non-condensables	S	Y	Y	Y	Y	3	4.9
9	Poor equipment location	N	Y	S	Y	N	3	4.7
10	Duct insulation and leakage	N	Y	Y	Y	N	3	4.11.3
11	Liquid line issues (including restrictions)	S	Y	Y	Y	Y	4	4.8
12	Minimal documentation (i.e. installation, commissioning baseline data, operation, maintenance)	Y	Y	Y	Y	Y	4	4.10

Notes:

S = Some applications or circumstances.

The building fabric and thermal and air sealing performance of the building is a significant driver of HVAC energy consumption. However, these aspects are considered a market failure rather than a fault and are discussed in *Section 5*.

3.1.2 Commercial refrigeration specific faults

The effective and efficient performance of commercial refrigeration systems is similarly determined by having sufficient refrigeration capacity and effective heat exchange mechanisms as well as appropriate controls and correct component sizing and location.

Table 5 provides a list of the common installation and operational faults specific to commercial refrigeration, the majority of which relate to not following good practice guidelines.

Table 5: Common faults in commercial refrigeration equipment and systems.

Fault		Self-contained	Remote condensing units	Central plant	Installation related fault	Maintenance related fault	Opportunity/ priority	Section
1	Refrigerant (sub-optimal charge, over or undercharge, refrigerant leakage)	N	Y	Y	Y	Y	1	4.1 and 4.2
2	Condenser issues (fouling, faulty fan)	Y	Y	Y	S	Y	1	4.3
3	Excessive heat load	N	Y	Y	Y	Y	1	4.12.1
4	Evaporator issues (fouling, ice-up, obstructions, faulty fan)	S	Y	Y	N	Y	2	4.4
5	System capacity (no heat load, disconnect between owner and designer, safety margins) and mismatched components	N	Y	N	Y	N	2	4.5
6	Control systems, sensors and wiring issues	N	Y	Y	Y	S	3	4.6
7	Poor equipment location	S	Y	S	Y	N	3	4.7
8	Liquid line issues (including restrictions)	N	Y	Y	Y	Y	4	4.8
9	Refrigerant health and non-condensables	N	Y	Y	Y	Y	4	4.9
10	Minimal documentation (i.e. installation, commissioning baseline data, operation, maintenance)	N	Y	Y	Y	Y	4	4.10

S = Some applications or circumstances.

As can be seen from *Tables 4* and *5* there are a range of technical faults that commonly occur across all equipment/stock sectors and a large majority of these faults are related to maintenance or can be addressed by routine maintenance.

3.2 *How common and how bad: Prevalence and severity*

A fault or problem that is reported as common, is a fault that has been referred to in numerous studies and text. As a result of the universal use of some elements of RAC equipment design (for example use of refrigerants, condenser coils and compressors) prevalent faults are often the same across different equipment types, and across the two broad applications of refrigeration and stationary air conditioning.

However, when considering the effect of a commonly reported fault, or problem, across large stocks of equipment, it is not enough just to understand how often it occurs but also its prevalence and severity. It is both the *prevalence*, and the *severity* of a problem that is important in understanding the resulting energy penalty.

There is a tendency in any industry, to report more often on instances where faults are severe, where they drastically impact the operation of equipment. This reporting of severe impacts suggests that certain faults can cause equipment to operate at a fraction of design capacity, or in the worst instances, fail altogether. However, that does not answer the question of how often a common fault can result in a severe impact. Even if a commonly reported fault can cause severe malfunctions, under performance and energy penalties, it does not mean that it always does, or that it does so immediately.

One way of scaling severity is based on which faults can cause equipment failure or severe malfunction, as opposed to reduced performance. For instance, a compressor failure is catastrophic, whereas the fouling of the condenser by dust, lint and grime, while allowing the equipment to continue to operate can drastically erode performance. That approach however does not support an analysis focused on assessing the energy penalty of a fault. Compressor failure brings electricity consumption to a very sudden halt.

Another approach to assessing severity is understanding the degree to which a fault could degrade performance and increase electricity consumption, without causing total equipment failure. Using this measure, condenser fouling has a much higher probability of causing a major energy penalty as compared to catastrophic compressor failure. Even minor faults can be cumulatively significant if they occur within a large installed base of equipment.

The following sections of this Chapter explore the above approaches to identify the scale of energy penalties that common faults can produce. However, in the absence of significant samples of hard data from the field, these approaches can only provide indications of the energy penalty of a fault or set of faults, or conversely the energy opportunity of repairing them.

3.3 *Prevalence*

In terms of prevalence, the faults that are reported in the literature as common in all stocks of RAC equipment selected for this study are listed below. These are the faults that can occur in most refrigeration and air conditioning vapour compression system and likely to be the most prevalent faults across several equipment segments. For equipment not regularly maintained, it can be expected that the equipment will develop faults and performance degrade over time, depending on a range of environmental factors.

Most prevalent faults across all RAC equipment segments within scope, the common faults, are:

- Sub-optimal refrigerant charge (undercharge most common);
- Condenser fouling and restricted airflow;
- Evaporator fouling and restricted airflow;
- Refrigerant contamination, degradation, fractionation, non-condensables and flow;
- Control system faults; and,
- System sizing and equipment location.

Refer to *Section 4* for a detailed explanation and analysis of these common faults.

3.4 *Severity*

For this study the severity of the faults was considered from two aspects:

1. The magnitude of the fault (fault level) – How intense is the fault on a defined scale? Fault level is generally defined as a percentage, such as the percentage refrigerant undercharge, the percentage airflow reduction, the percentage fouling of heat exchanger surfaces, as applicable.
2. The performance impact of the fault at various fault levels (fault impact) – In this case, for energy penalties - defined by the percentage reduction in system coefficient of performance (COP) at a specific fault level.

Therefore, one can consider 'Fault Severity' as being the product of 'Fault Level' x 'Fault Impact'.

For individual faults the relationship between fault level versus fault impact (energy consumption) can be represented by curves, such as those shown in *Section 3.6* for refrigerant charge faults. Several studies have developed similar curves for other fault types.[7]

3.5 *Energy penalty or opportunity*

The potential energy penalty or energy saving opportunity presented by each fault type across a stock of equipment can be assessed by the relationship between 'Fault Prevalence' x 'Fault Severity'.

Energy Penalty = Fault Prevalence x (Fault Level x Fault Impact)

Therefore, Energy Penalty = Fault Prevalence x Fault Severity

In the context of this report fault impacts have been researched and are relatively well understood.

The two main variables with the greatest uncertainty when assessing energy penalty are: fault prevalence and fault level, i.e. the distribution of these faults across the various RAC stock segments and the severity of the occurrence.

Note that there are also non-energy impacts associated with faults, for example compliance, safety, productivity, comfort, and service life of equipment. Increased electricity use and increased direct and indirect emissions are not the only negative outcome created by common RAC faults.

Refer to *Section 4* for a detailed discussion on the prevalence, energy penalty and drivers of common faults.

Multiple simultaneous faults

The effect of having several individual equipment faults occurring on a system simultaneously should be considered when assessing the impact of common faults on RAC equipment. In some situations, particularly in the absence of a maintenance program, systems will experience more than one of these equipment faults which compound the performance degradation that results. The likelihood of multiple faults occurring is higher for new systems that are not properly installed or commissioned and for existing systems that are not regularly maintained.

Modelling of double faults has shown the energy penalty of some fault pairs is not related and little changes relative to the single fault condition. However, for other fault pairs, the energy penalty for the double fault condition can be multiplied.[6]

In the absence of detailed bench and field testing, the extent of fault compounding can only be broadly estimated. The component energy penalty of individual equipment faults versus the system energy penalty of multiple simultaneous equipment faults is evidenced in:

- Laboratory tests on equipment that report equipment energy increases/performance reductions;
- Surveys on systems and buildings that report whole building energy increases/savings; and,
- Modelling of system in buildings that estimate whole building lifecycle energy increases/savings.

Several different methodologies have been used to estimate the aggregate energy penalty of RAC faults or RAC maintenance across regions or sectors.[8, 9, 10, 5] Most of these models generate outputs by employing broad assumptions that are themselves based on limited hard data.

Some hard data on the effect of individual faults was discovered during the literature survey[13, 11, 14, 12] such as the effect of sub-optimal charges of refrigerant modelled on its own for certain equipment types using some limited test data.

The other common faults listed and their effect on electricity consumption in particular segments, and potential opportunities to address these problems are explored in more detail in *Section 4*.

Addressable faults

Some faults tend to build up over time. These faults include incorrect refrigerant charge, dirty filters, fouled evaporators and condensers, refrigerant contamination, and inappropriate changes to control settings. These faults can be easily addressed and corrected by routine good practice maintenance and monitoring techniques.

Other faults are related to the original design and installation of the system. These faults include undersized ductwork, leaking ductwork, mis-sized or mis-matched equipment, incorrect location or poor equipment control. These faults tend to be more difficult to address as they cannot be corrected by maintenance alone, and require optimisation, recommissioning or upgrade to repair the fault or reduce the energy penalty.

Owner versus user motivation is another factor in fault resolution. Without providing a persuasive economic argument or identifying compelling alternative benefits to change behaviour some stakeholder groups will not act on a fault, even after it has been identified.[15] In some scenarios there can be a split-incentive disconnect between those paying for the fault correction and those benefitting from the improved performance and lower operating costs.

Technology changes

A further issue to consider is the rate of innovation across the industry. Modern RAC equipment now utilise microchannel technology, speed controllable compressors, fans and pumps, electronic sensors and components, advanced controls, new refrigerant types and digital communications abilities which can all improve system COP. The industry is innovative, competitive and technology is constantly improving. Modern equipment has progressively been designed to operate more efficiently with components and refrigerant charges optimised.

This has several implications:

- New equipment is less likely to leak than legacy equipment;
- New equipment is more likely to be more energy efficient than existing equipment;
- New equipment is more likely to be easier to integrate into a system and accurately control; and,
- Optimised new equipment and components *may be* more susceptible to individual component level faults. For example, due to the more refined designs and closely matched component capacities, a fault that might have caused older styles of equipment to simply run harder, consuming more electricity, may in some instance in new equipment designs cause an automatic alarm, and even a shut down.

The replacement of old equipment with modern typically reduces power consumption and refrigerant losses. However, modern equipment and components may be more susceptible to performance degradation from lack of maintenance or refrigerant leakage when compared to older, less optimised systems.

Modern equipment typically has an optimised or critical refrigerant charge, optimised speed (frequency) controlled compressors, advanced surface heat exchangers (i.e. micro-channel), and intelligent electronic sensors and controls. By design there is minimal ‘spare capacity’ in the system, which relies on the correct optimal performance of each component to meet its tested/rated performance capabilities. Therefore, the specific fault responses for modern equipment may be different to the responses for older generation equipment, and maintenance may be even more important for high/super-high efficiency equipment to allow them to achieve their full operational potential.

Conversely the new capabilities of modern technology, such as wireless monitoring, automatic fault detection and diagnosis and cloud-based machine-learning algorithms can facilitate, flag and optimise the maintenance delivery process.

3.6 *Sources and causes of mechanical refrigerant losses*

The main types of direct emissions from RAC equipment in general, are:

- Losses during installation.
- Gradual leaks during normal operation.
- Catastrophic losses during normal operation.
- Losses during equipment service and maintenance.
- Losses at end of equipment life.

Refrigerant emissions in Australia, Sources, causes and remedies, 2010 provides detailed insights into the sources and causes of mechanical refrigerant losses.[16] Sources of leaks can be broadly defined by the location/component at which the leak occurs. Causes of leaks can be thought of as system design/performance characteristics, or workplace practices, that increase the likelihood of leaks – often through accelerating the degradation and eventual failure of components.

The 2010 study surveyed over 150 refrigeration technicians and contracting businesses involved in installing, servicing and repairing refrigeration equipment. Participants were asked to nominate and comment on the major sources and causes of leaks they had encountered or repaired over the previous 12 to 24 months.

The results of the survey are provided in *Figures 2* and *3*.

These results are also reflected in international studies on the causes and sources of refrigerant leakage in commercial refrigeration, including findings from the USA Environment Protection Agency Greenhill program[17, 18] a UK study of two supermarket chains[28] and the European Real Zero work.[20, 21]

There are many potential leak locations, especially on larger systems that have numerous joints, valves and compressors. If leakage is slow it can go unnoticed for long periods and result in direct emissions, poor refrigeration plant performance and a significant energy penalty due to long hours of operation of an undercharged system.

Sources of refrigerant leaks

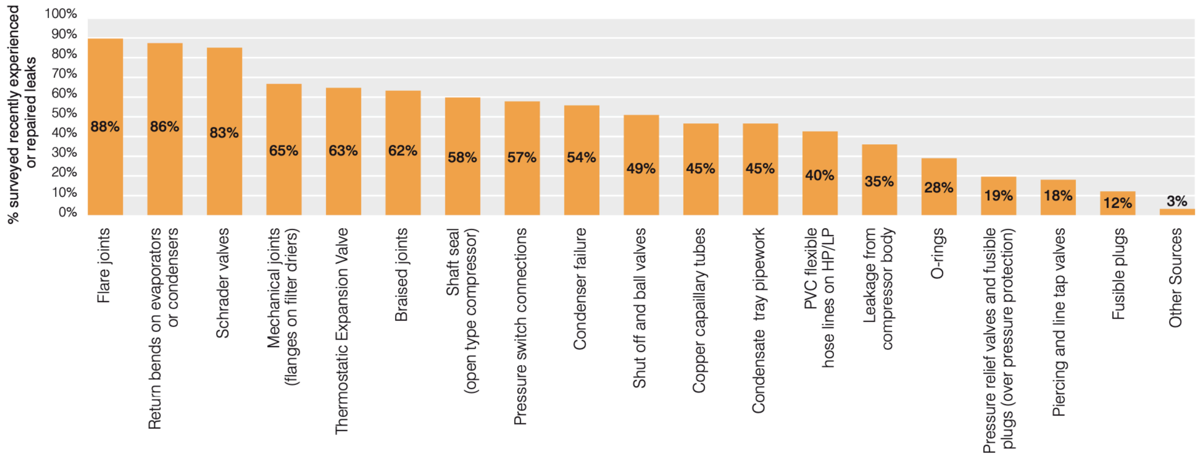


Figure 1: Sources of refrigerant leaks identified by refrigeration technicians and contracting businesses.

(Source: Refrigerant emissions in Australia, Sources, causes and remedies, 2010, now the Department of Agriculture, Water and the Environment)[16]

Key causes of leaks

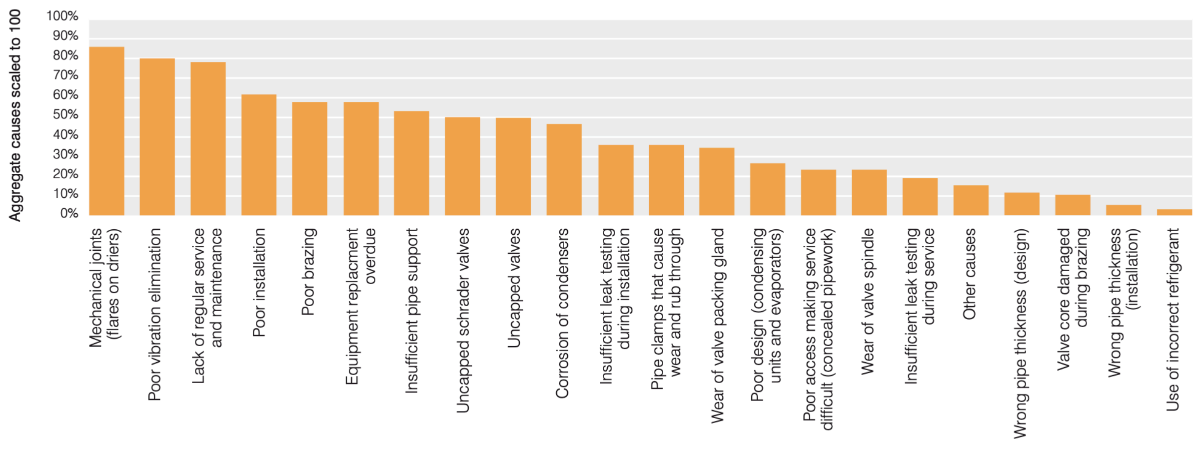


Figure 2: Key causes of refrigerant leaks observed by refrigeration technicians and contracting businesses.

(Source: Refrigerant emissions in Australia, Sources, causes and remedies, 2010, now the Department of Agriculture, Water and the Environment)[16]

Notes:

1. Survey respondents were asked to number the most common causes of leaks from 1 to 10 from a list of 20 possible causes. Survey results were used to create a comparative score for each cause listed and the scores were then scaled against 100 in the chart above.

3.7 *Energy penalty of sub-optimal refrigerant charges*

3.7.1 Studies on energy penalty of sub-optimal charges

There is currently limited hard data available on the energy penalties incurred from operating on sub-optimal refrigerant charges, sufficient evidence was discovered to demonstrate that across stocks of large, hardworking equipment, sub-optimal charges are cumulatively incurring significant electricity costs for equipment owners and the community.

These costs, coupled with the direct and indirect emissions that result, suggest a strong case can already be made for exploring all options for low cost internet enabled automatic leak detection systems for application in some equipment classes.

The research found several meta studies and a dozen research papers that contained system performance curves (COP, EER) at different refrigerant charge levels, for stationary RAC and mobile AC equipment.

The general observations of the research are:

- All systems show an efficiency impact when undercharged.
- The severity of the energy penalty depends on the type of system, ancillaries and the extent of under or overcharge (i.e. percentage of optimal).
- Performance significantly declines below 60% of optimal charge to the extent it might be expected to prompt a service call.
- There is less impact with air conditioners in heating mode than in cooling mode.
- Systems with receivers react differently and the expansion device used (fixed orifice, thermostatic, electronic) influences the efficiency impact.
- With respect to overcharging, some types of air conditioning equipment appear to be relatively unaffected from 100 to 120% of charge. Refrigeration equipment appear to be more affected by overcharge than air conditioning equipment.

Sections 4.1 and *4.2* provide details on over or undercharge faults including definitions, relevant equipment types, causes, fault level drivers and discussion on system impacts.

Figure 3 shows the aggregated performance curves of air conditioning systems from a meta-analysis of 25 studies on performance variables of air conditioners and heat pumps.

Air conditioners and heat pumps

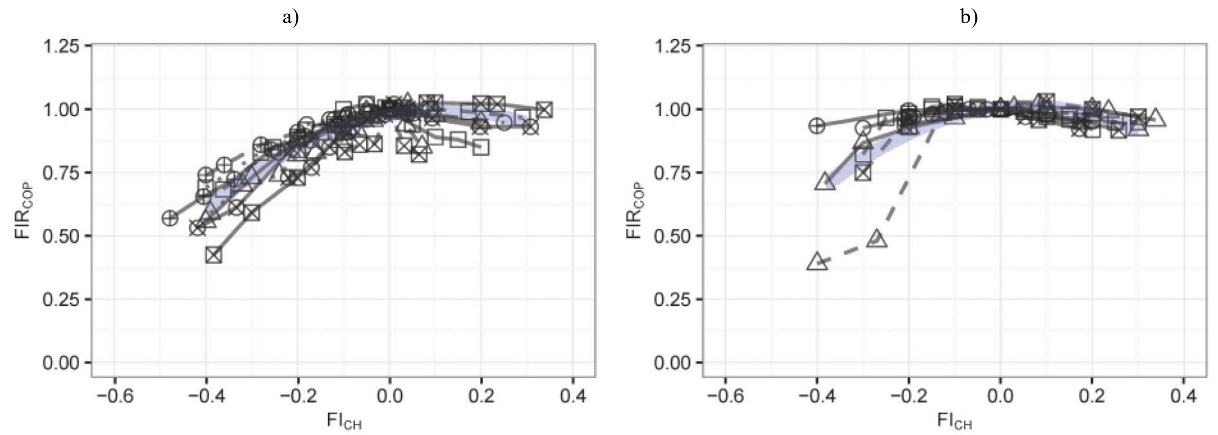


Figure 3: Meta-analysis of energy penalty versus refrigerant charge variation.

(Source: Mehrabi, M., & Yuill, D., Generalised effects of refrigerant charge on normalised performance variables of air conditioners and heat pumps, International Journal of Refrigeration, 2017, pages 367–384)[83]

Notes:

1. x axis: FI_{CH} - 'Fault Intensity Charge': normalised charge amounts (FI_{CH} -0.4 = 60% of optimal charge). y axis: FIR_{COP} - normalised Fault Index Coefficient of Performance.
2. a) systems have fixed orifice expansion devices (FXO), and b) systems use thermostatic expansion valves (TXV). TXVs are intended to reduce system sensitivity to charge level, so the results from FXO and TXV equipped systems are shown separately.
3. These analyses confirm that it is reasonable to use these generalised relationships to model the effect of refrigerant charge variation.

Figure 4 provides the results from the tests undertaken by CSIRO Energy for Buildings Division in Newcastle in 2020 on a 9 kW split ducted system.[13]

Ducted split air conditioning system

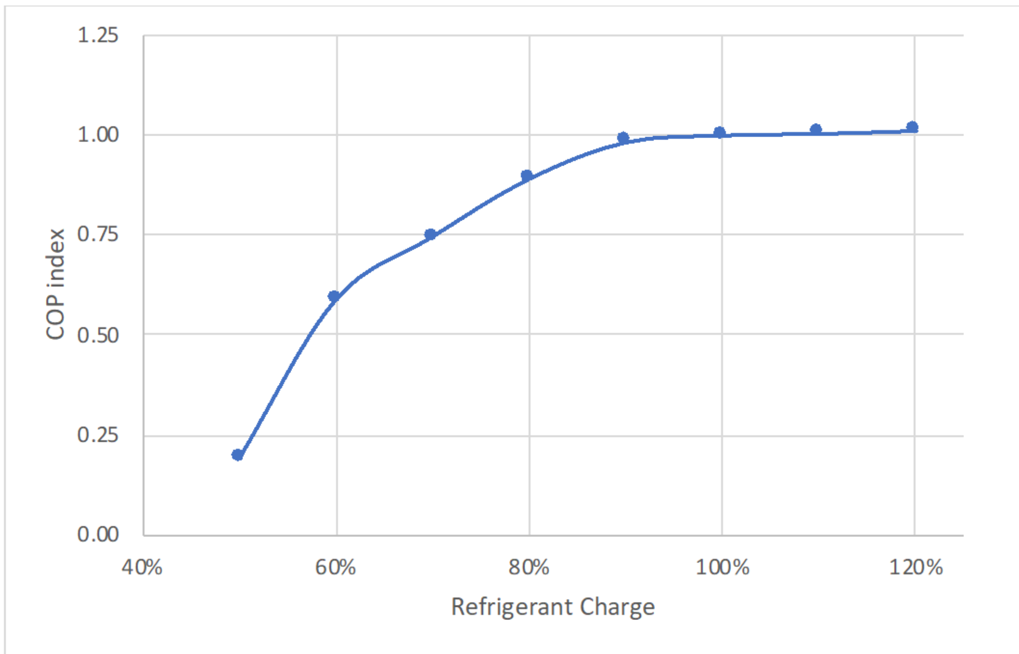


Figure 4: Energy penalty versus refrigerant charge curve of 9 kW ducted split system.

(Source: CSIRO Energy for Buildings Division in Newcastle, 2020)[13]

Notes:

1. This shape of this curve is consistent with meta-analysis shown above in *Figure 3*.

Figure 5 shows a curve based on tests undertaken by the School of Energy and Mechanical Engineering, Nanjing Normal University in 2017 of a walk-in cool room with a remote condensing unit with a nominal cooling capacity of 6.5 kW operating on HFC-404A.[14]

Commercial refrigeration system with remote condenser

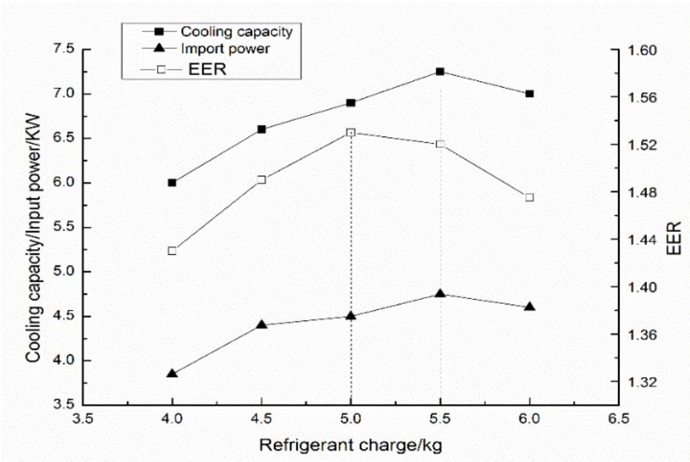


Figure 5: Energy penalty curve of walk-in cold room with a remote condensing unit with a cooling capacity of 6.5 kW operating on HFC-404A.

(Source: Hu et al, School of Energy and Mechanical Engineering, Nanjing Normal University, 2017)[14]

Notes:

1. Optimal charge: 5 to 5.35 kg of HFC-404A at 32°C ambient.
2. Operating conditions: ambient temperature 32°C, evaporation temperature, compressor suction temperature 18°C, condensation temperature is 45°C and the sub-cooling in condensation outlet is 5°C.
3. Compressor type: Danfoss scroll compressor, model: MLZ038 with a cooling capacity of 10,320 watts at an evaporating temperature of -5°C.
4. Coefficient of performance varied from around 1.43 at 80% of charge to 1.53 at optimal charge.

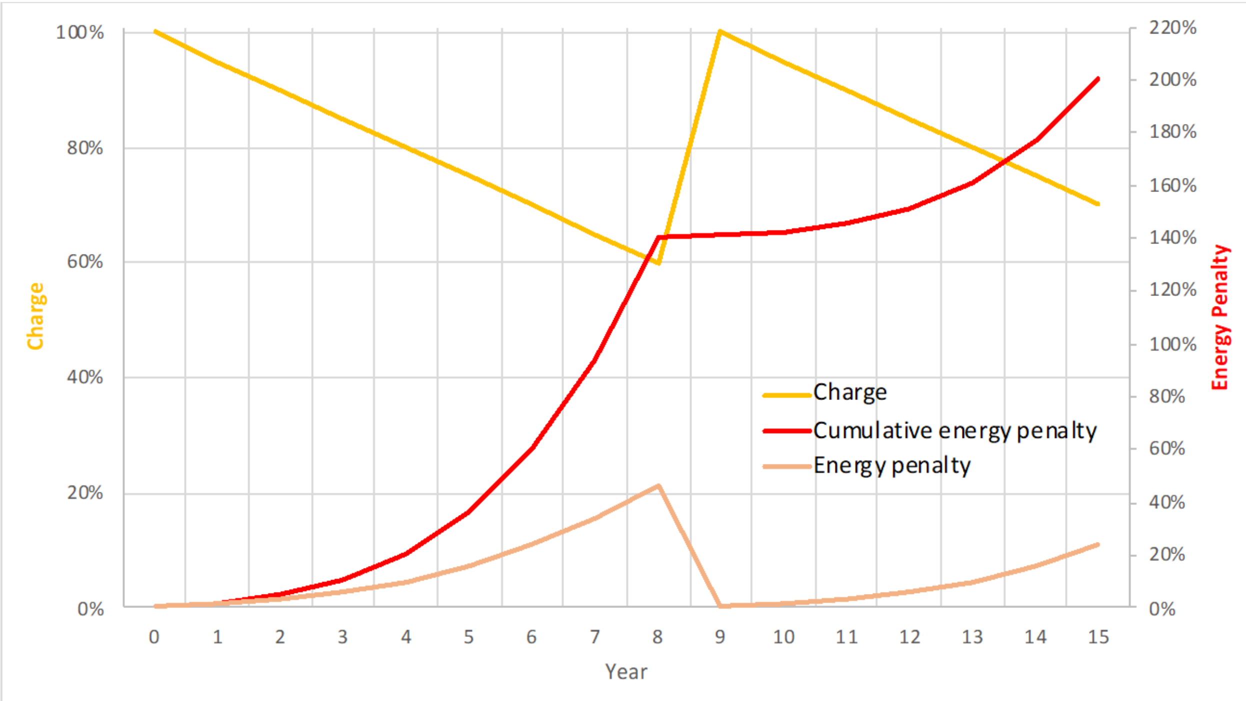
Further testing is required to provide more evidence to gain a better understanding of the energy penalty created by sub-optimal charges in a wider variety of equipment types, in different sizes of equipment of the same type, and in different circumstances.

3.7.2 Modelling of the energy penalty of sub-optimal charges

An energy penalty calculator was developed to model the severity of the energy penalty for different applications and criteria. The calculator inputs include the annual leak rate as a percentage of optimal charge, the percentage of pre-charge, a trigger point where the refrigerant charge is replenished, equipment lifespan and applies the energy penalty curve to calculate the annual and cumulative energy penalty of the lifespan of the equipment.

Figure 6 provides a model of a modern ducted split air conditioning system that exhibits a cumulative penalty of 200% over a 15 year lifespan.

Ducted split air conditioning system



Note: cumulative penalty is shown as a % of one year's energy consumption.

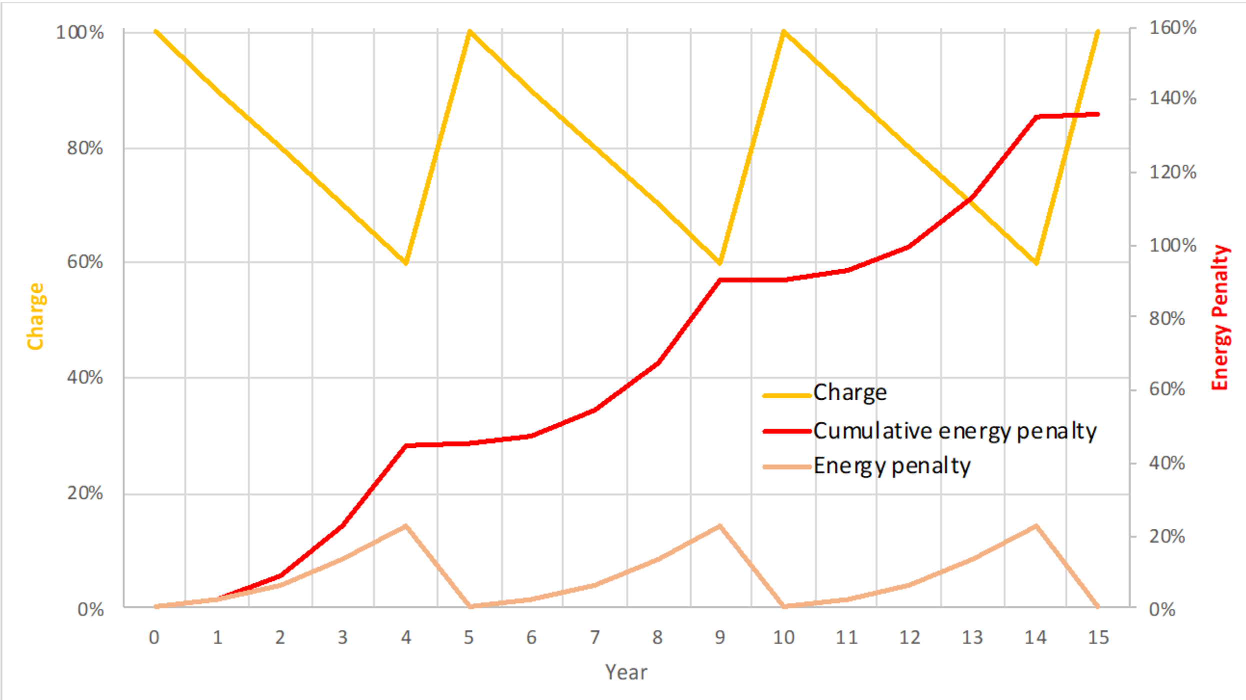
Figure 6: Energy penalty versus refrigerant charge of a ducted split air conditioning system.

Assumptions:

1. Annual leak rate: 5% of charge.
2. System pre-charge: 0%, assumes optimal charge of 100%.
3. System recharged if it falls below: 60% of charge.
4. No service cycle, other than system recharge.
5. Lifespan: 15 years.
6. Energy penalty curve: CSIRO Energy for Buildings Division in Newcastle, 2020 (refer *Figure 4*).

Figure 7 provides a model of a commercial refrigeration system with a leak rate of 10% per annum that shows a cumulative energy penalty of 130% over a 15 year lifespan.

Commercial refrigeration system with remote condenser



Note: cumulative penalty is shown as a % of one year's energy consumption.

Figure 7: Energy penalty versus refrigerant charge of a commercial refrigeration system with remote condenser.

Assumptions:

1. Annual leak rate: 10% of charge.
2. System pre-charge: 0%, assumes optimal charge of 100%.
3. System recharged if it falls below: 60% of charge.
4. No service cycle, other than system recharge.
5. Lifespan: 15 years.
6. Energy penalty curve: Hu et al, Nanjing Normal University, 2017 (refer *Figure 5*).

4 Common faults detailed

The following sections tabulate the effects of, and remedies for, the dozen leading causes of energy penalties in RAC equipment.

A few of the faults listed are specific to stationary air conditioning systems, some caused by the process of equipment selection, others by situational and locational issues, often created at installation. However, all listed faults are expected to be reasonably prevalent with the potential to severely degrade performance and increase energy consumption.

Most importantly, all these faults are addressable and, when repaired or avoided, have potential to reduce and or eliminate refrigerant leaks, deliver electricity savings and meaningful economic returns compared to the effort and investment required to remedy them.

4.1 *Refrigerant: Undercharge*

Definition	Less refrigerant charge than the optimal (critical) charge for the system.
Equipment types	All RAC equipment, less relevant to self-contained equipment as they are charged with optimal charge in factory and have lower leak rates.
Cause: Installation	Improper charge on installation, poor quality installation, incorrect/no commissioning.
Cause: Operational	Refrigerant leakage over time from valves, joints/connectors, equipment seals, corrosion and component failure, vibration; improper re-charge following repair. For most systems refrigerant undercharge over time is inevitable without regular maintenance.
Fault level drivers	Quality of installation, complexity of system charge calculation, approach to refrigerant management, approach to maintenance, time.
System impacts	The cooling capacity of a vapour compression refrigerating system will increase with the increase of refrigerant charge up to an optimal level. Further increment of refrigerant charge deteriorates the cooling capacity of the system. The extent of the deterioration of capacity and efficiency depends on the RAC equipment type: a split AC has minimal impact up to 120% of optimal. A low charge will give a high superheat and the sub-cooling value decreases, the average refrigerant density, the evaporating temperature, and the refrigerant mass flow rate from the compressor drop. The increased pressure ratio across the compressor leads to a reducing refrigeration effect and a reducing COP. The split temperature (return air minus supply air) trends down and suction temperature trends up. Significant deterioration of performance (40% or more) occurs on all RAC equipment types at around 60% of optimal charge.
Comments	Efficiency penalty appears consistent across a range of evaporating/condensing temperatures. Whether the system has a receiver or whether system components act as a refrigerant receiver can explain many of the variances in system impact between -10% and -25% fault levels. The equipment design aspects that affect this include the relative sizes of the evaporator, condenser and compressor, and the length of refrigerant lines. The undercharge or refrigerant leakage fault can be detected by a compressor power reduction and an increase in the supply air temperature.
Prevalence	Probably the most common RAC equipment technology fault across all sectors with the greatest impact in terms of efficiency penalty for cooling systems. Easily correctable. Air conditioning systems are more likely to have a critical charge than refrigeration systems.

Energy penalty	All systems show an efficiency impact when undercharged. The severity of the energy penalty depends on the type of the system, ancillaries and the extent of undercharge (i.e. % of optimal). Less impact in heating mode than in cooling mode. Systems with receivers react differently and the expansion device used (fixed orifice, thermostatic, electronic) influences the efficiency impact. Refer to *Section 3.7* for further details on a range of curves illustrating energy penalty versus refrigerant charge.
Potential solutions	Leak detection measures similar to EU F-gas regulations based on CO_2e equipment charge. Inspection for refrigerant leakage or automatic leak detection on central systems, checking charge physically, checking charge by diagnosing system performance, automated fault detection and diagnosis (AFDD) for refrigerant undercharge.
Examples	A study of 13,000 air conditioners installed on residential and commercial buildings in 2002 found improper refrigerant charge in 57% of all systems. A survey study involving 55,000 units in 2004 reported that 60% of commercial air conditioners and 62% of residential air conditioners had incorrect refrigerant charge. In a survey study of 4,168 new and existing split, package, and heat pumps in 2004 found 2% of the tested units had improper refrigerant charge.[6] A review of 503 commercial roof top units found refrigerant charge issues in 46% of units.[24]
	An analysis of the potential energy impact of common faults in small commercial buildings[9] estimated the prevalence of systems with non-standard refrigerant charge as 42% in refrigeration systems and roof top air conditioners and 77% in split system AC.
	A summary of other American studies[22] notes that correcting refrigerant charge in chillers can typically save up to 20% energy used, and in roof top ducted air conditioners up to 15% energy used.
	In 2011, a meta-analysis of new and existing commercial building faults[23] estimated that improper refrigerant charge cost the US economy $700 million/year. A more recent 2017 analysis[9] has estimated that nonstandard refrigerant charge costs the US economy $587 million/year.
	A study on supermarket equipment characteristics[25] found refrigerant charge issues on 36% of all systems and is the most common fault encountered.
Examples	Refer *Section 3.6* for further details on the range of curves illustrating energy penalty versus refrigerant charge.
References	6, 9, 22, 23, 24, 25

4.2 *Refrigerant: Overcharge*

Definition	More refrigerant charge than the optimal (critical) charge for the system.
Equipment types	All RAC equipment, less relevant to self-contained equipment as they are charged with optimal charge in factory.
Cause: Installation	Improper charge on installation, incorrect/no commissioning.
Cause: Operational	Improper re-charge following repair, misdiagnosis of undercharge fault leading to addition of excess refrigerant to a correctly charged system.
Fault level drivers	Quality of installation/repair, approach to refrigerant management.

System impacts	The compression work (power) continuously increases with the refrigerant charge. An overcharge will give a low superheat along with a higher compression ratio (refer undercharge for further explanation).
Comments	The refrigerant overcharge fault can be detected by an increase in the compressor power and a reduction in the supply air temperature.
Prevalence	High prevalence in non-ducted split systems that are typically pre-charged with 10 or 15 metres of pre-charge pipe length (and some suppliers as much as 30 metres). The most common application is where the outdoor unit and indoor units are positioned “back to back” requiring only 3 metres of pre-charge pipe length. In this application the additional charge can range from 10% to as much as 30% of optimal depending on the equipment supplier. Less prevalent in other RAC equipment.
Energy penalty	Less impact than with refrigerant undercharge. Less impact in heating mode than in cooling mode.
Potential solutions	Checking charge physically, diagnosing system performance, AFDD – overcharge.
Examples	Many of the examples listed in *4.1 Refrigerant: Undercharge* include a small percentage of refrigerant overcharge. Refrigerant overcharge is not as prevalent a fault as refrigerant undercharge (due to refrigerant leakage).
Examples	An American study[6] of residential ducted air conditioning showed the heat pump using 10% to 16% more energy when overcharged by 30%. In an analysis of heat pump installation practices (heating only) 10% of units were found overcharged and 8% found undercharged.[27]
Special case	MEPS/Energy Labelling test results can be affected by refrigerant charge miscalculation as the length of refrigerant piping used in the tests is not consistent between countries. It varies from 5 metres to 7.5 metres, and could cause a change in EER of 1% to 3%.[26]
References	6, 26, 27

4.3 *Condenser fouling*

Definition	Build-up of material on condenser heat exchange surfaces affecting heat exchange efficiency and air flow for air cooled condensers.
Equipment types	All RAC equipment within scope. The large majority of RAC equipment have air cooled condensers however condenser fouling applies to air cooled and water-cooled condensers (see special case).
Cause: Installation	Poor location near contamination source, fouling or damage during installation, incorrect/no commissioning.
Cause: Operational	Local contamination source, lack of inspection and cleaning, located in a corrosive environment (e.g. near coast) leading to fin/tube corrosion.
Fault level drivers	Level of local air contamination, physical characteristic of heat exchanger, approach to maintenance and time.
System impacts	Increase in the condensing and evaporating pressure, sub-cooling decreases with increased fault intensity. Power consumed by the compressor increases due to increased pressure ratio. Power consumed by the fan increases or airflow rate reduces.

Comments	The fault level is highly variable, dependent largely on local air quality levels. A condenser in a low dust environment that is exposed to weather may only suffer low levels of fouling. Condensers located near vegetation or high dust locations (indoors, near roads or construction, or rural) can suffer high levels of fouling and consequently high efficiency impacts. The nature of the fouling contaminant (dust, leaves, detritus, grease, lint) will influence the impact (i.e. energy penalty percentage and time). The fault can be identified by a reduction in airflow or increase in pressure drop across the heat exchanger.
Prevalence	Very high, 5 years after installation with no maintenance. More prevalent in commercial refrigeration applications with high foot traffic including self-contained refrigeration units in commercial applications.
Energy penalty	AC: Ranges from 0% to 40% per annum for an air-cooled condenser that is 50% blocked and from zero to 35% per annum for a water-cooled chiller condenser that has fouled tubes. CR: Ranges from 0% to 90% per annum for an air-cooled condenser that is totally clogged. Medium case scenario 15% per annum.
Potential solutions	Maintenance: Inspection and cleaning of the coil, measuring pressure drop across coil, automated fault detection and diagnosis (AFDD) for coil fouling and post installation protective coating.
Examples	AC: A meta study of previous condenser fouling fault research produced a series of normalised curves to illustrate the reduction in COP in a generalised format. Most studies, which did not investigate beyond a 50% condenser blockage/fault level, showed a 40% change in COP/energy penalty in cooling mode for a 50% blocked condenser fault.[7]
	RAC: Several research organisations and start-up companies including LiquiGlide, SLIPS Technologies, and Nelumbo have developed advanced surface coatings that repel water (ice) and other materials better than current technologies. Coatings can be sprayed onto existing heat exchangers in the field or applied to new heat exchangers at the factory. The efficacy of post-installation field-applied solutions has been questioned due to the difficulty in coating non-visible surfaces of the heat exchanger.[28] Nelumbo (who have partnered with Danfoss) projects up to 20% energy efficiency improvement in new refrigeration and air conditioning applications with their technology.[29]
	CR: Self-contained: The PG&E Food Service Technology Center, an unbiased energy-efficiency research program funded by California utility customers conducted several tests of single and double glass door merchandisers and storage cabinets in 2015. The study found energy consumption can increase by up to 90% with dirty coils.[30, 31] Dust and lint can limit the condensers ability to reject heat and is particularly relevant with bottom mounted condensing units when placed in locations on carpet (e.g. airports).
Special case	The internal fouling of chilled water condensers in (water-cooled) chillers can also cause an energy penalty. Research has shown that a 0.8 mm scale build-up in condenser tubes can increase energy consumption by as much as 35%. Applying a water treatment program to keep condenser tubes clean can generate 15% savings for eliminating microbes, 10% to 20% more if scale and iron deposits are present. 35% savings or more are possible in extreme fouling cases.[22]
References	7, 22, 28, 29, 30, 31

4.4 *Evaporator issues*

Definition	Evaporator issues includes fouling, ice-up, obstructions or faulty fan. Fouling is the build-up of material on evaporator heat exchange surfaces affecting heat exchange efficiency and air flow.
Equipment types	All RAC equipment within scope.
Cause: Installation	AC: Incorrect air filter, damage during installation and incorrect/no commissioning. CR: Damage during installation, poor installation practices (cases not level, drains not trapped etc) and incorrect/no commissioning.
Cause: Operational	AC: No/Poor filter, failed filter, lack of inspection and cleaning, and constantly wetted surfaces. CR: One fan of multiple fan evaporator failed, lack of inspection and cleaning, incorrect control adjustments, defrost issues, blocked or iced over drains. Food retail applications where prices labels, packaging or produce can affect the evaporator and evaporator fan discharge.
Fault level drivers	Level of local air contamination, physical characteristic of heat exchanger, approach to maintenance and time.
System impacts	System resistance increases, fan power increases or air volume flow reduces. Superheat value decreases and sub-cooling value decreases with reduced evaporator airflow. The heat exchanger (evaporator) is less efficient. In air conditioning system the airflow energy penalty from fouled evaporators is generally significantly larger than the heat exchanger penalty.[32] With refrigeration systems with multiple evaporator fans the system can continue to operate inefficiently with partial air flow which can impact product quality and customer satisfaction. Reduced airflow can lead to ice ups and eventual compressor failure.
Comments	With AC the coil cleaning method is important, and the method should not push contaminants further into the coil or damage the fins. Microchannel coils react differently to fouling than flat fin coils. In some cases, early fault levels (light contamination) of fouling can reduce the air resistance of microchannel heat exchanger fins (although the heat exchange efficiency is also reduced) resulting in increased energy efficiency. The contrary is true of flat fin coils where early fouling can improve the heat exchange but also increase resistance to air. In all cases the effect of fouling on system performance tend to be quite small until medium and high levels of fouling are encountered.[33]
Prevalence	5 years after installation with no maintenance, high.
Energy penalty	AC: Ranges from 0% to 10% per annum for an evaporator that is 50% clogged. RAC: Medium case scenario 5% to 10% per annum.
Potential solutions	AC: Maintenance: Inspection and cleaning of the coil, measuring pressure drop across coil and automated fault detection and diagnosis (AFDD) for coil fouling. CR: Maintenance: Inspection and cleaning of the coil.
Examples	A meta study of previous evaporator heat transfer fault research produced a series of normalised curves that to illustrate the reduction in COP in a generalised format. Most studies, which did not investigate beyond a 60% evaporator blockage/fault level, showed a 5% to 15% change in COP/energy penalty in cooling mode for a 50% blocked evaporator fault.[7]
Special case	Research by the US Lawrence Berkeley National Laboratory into the energy implications of coil fouling almost two decades ago showed that typical coils foul enough to double

	evaporator pressure drop (at constant air flow) in about 7.5 years. The energy impacts can be much greater for marginal systems or extreme conditions and can have a significant impact on peak electricity demand.[34]
References	7, 32, 33, 34

4.5 *System capacity: Over or undersizing*

Definition	AC: Oversizing of commercial air conditioning as a risk management practice or due to overly conservative load estimation and undersizing of residential air conditioning as a cost cutting measure or due to an inaccurate load estimation. CR: Sizing and installing equipment for peak load plus a safety factor.
Equipment types	Whilst oversizing can occur in other RAC, it is particularly common with commercial AC specified by consultants and medium sized CR with remote condensers.
Cause: Installation	AC: Over application of safety factors and over conservative design assumptions during design development leading to oversized system components. CR: Inadequate design, lack of communication and understanding of actual design loads.
Cause: Operational	N.A.
Fault level drivers	AC: Standard industry practices. More stringent building codes and better insulation are reducing building cooling loads, but industry continues using traditional load estimation practices, leading to oversizing. Undersizing of residential air conditioning as a cost cutting measure or due to an inaccurate load estimation. CR: Standard industry practices.
System impacts	AC: Oversized systems do not operate at their design capacity and will cycle more frequently than systems sized to better match actual loads. Although oversizing inefficiencies are compensated for using inverter capacity control and variable speed drives the oversizing of commercial air conditioning equipment will tend to mask the performance degradation due to common system faults. Oversized systems will operate for longer under fault degradation and at a higher energy penalty than right sized systems. Undersizing means inverter systems are potentially operating at full output, instead of optimising the output resulting in increased energy consumption. Whilst this can be an issue with large space chillers that may have an optimal operating range it is less common. CR: Oversizing the compressor selection can result in unnecessary energy use and can shorten the life of the compressor. On cooler days or low load conditions, the compressor capacity will significantly exceed the evaporator load, causing the compressor to start/stop frequently, which can affect compressor reliability, temperature control and refrigeration efficiency. An oversized compressor not only consumes more energy but can have other side effects such as lower evaporating temperature; this in turn can result in evaporator icing and drying of unpacked produce, which can affect food quality.
Comments	AC: The main drivers of oversizing are design engineers seeking to guarantee thermal comfort at the peak design condition and even beyond, i.e. a worst-case design approach. Split incentives exist between designers, developers, and owners. The main cost impacts are plant capital costs (purchase and installation) however the energy penalty for oversizing occurs for every year of plant life and is difficult and expensive to correct. CR: Generally, refrigeration systems with remote condensing units are designed for fixed capacity to achieve a cooling capacity based on the calculated maximum demand at the design ambient temperature. In reality, the system may only be operating at this maximum

	load point for a small portion of its operating life. In addition, a refrigeration load can vary significantly during a 24-hour period. For example, a product may require a rapid pull down to prevent spoilage, then be frozen slowly to prevent damage and then chilled to a storage temperature in a specific time. The application of capacity control methods to refrigeration systems offers the potential for substantial energy savings. Variable-capacity technology can assist in satisfying a range of capacity requirements. An energy penalty occurs with equipment on/off controls and is not considered an issue with variable-flow refrigeration system with capacity control capability.
Prevalence	AC: Oversizing occurs in most commercial applications, but the extent varies widely. CR: Very high, occurs in most applications with remote condensing units.
Energy penalty	AC: Medium case scenario 5% per annum. CR: Medium case scenario 5% to 10% per annum.
Potential solutions	AC: Review of design approach to AC sizing; rules of thumb, more accurate occupancy and internal load data, apply integrated design process, improved approach to commissioning and maintenance. Note that all best practice design guides recommend an accurate load estimation calculation as the starting point for any air conditioning design. NatHERS software and other load estimation tools could be improved to better estimate correct heating and cooling loads for new highly insulated well sealed homes. CR: Incentives for variable-capacity technology. Best practice design (heat load calculations). Certificate of compliance requiring heat load calculation. Better communication between owner and designer to understand requirements and reduce heat load safety margins.
Examples	Surveys of commercial air conditioning installations regularly find evidence of system or component oversizing.[35, 36, 37, 9] Conversely studies of small residential heat pump installations regularly find evidence of system or component undersizing.[10, 27]
References	9, 10, 27, 35, 36, 37

4.6 *Controls, sensors and wiring issues*

Definition	RAC Systems: Relates to inadequate or incorrect controls software and hardware that leads to incorrect monitoring and control of the system and incorrect wiring leading to power losses in larger three-phase equipment. CR: Remote primarily relates to common industry use of basic controls and electric defrost timers (see special case).
Equipment types	All RAC except self-contained and stand-alone equipment (i.e. split and packed systems with dedicated AC controllers).
Cause: Installation	Poor specification and installation of sensors, controls and wiring, overly complex control systems, poor quality controls, lack of controls interoperability (requiring gateways), lack of commissioning, lack of operator training and education at handover.
Cause: Operational	Ad-hoc approach to system operation, management and maintenance, lack of operator understanding of controls and monitoring (complex systems), frequent ad-hoc changes to control settings (temperature, airflow) in response to comfort complaints or to compensate for system operational issues, lack of controls maintenance.

Fault level drivers	Lowest-cost purchasing, poor control system specification, absence of commissioning of control systems. Poor approach and processes for setting, adjusting, and testing RAC control software and hardware. Poor approach to maintenance.
System impacts	Controls and the associated components are essentially the brains or thinking parts of an RAC system. Sensors tell the systems what is happening (inputs) and controls and the associated algorithms tell the system what to do (outputs). Any inaccuracy in the sensor or operator inputs will lead to incorrect outputs (instructions) from the system. These common control system errors lead to increased energy consumption because the system works harder and for longer than is needed to meet the load or end user requirement.
Comments	AC: This fault covers a broad range of operational errors in air conditioning systems and, when grouped together, often represent the most prevalent fault type in commercial building air conditioning (in both un-commissioned new buildings and poorly maintained existing buildings). Faults under this category include: ▪ Improper controls hardware installation (e.g. temperature/humidity sensors exposed to direct sunlight). ▪ Improper controls setup/commissioning. ▪ Software programming errors, including schedule errors. ▪ Control component failure or degradation.
Prevalence	AC: In surveys of commercial buildings, inadequate or inappropriate controls software and hardware is repeatedly the most common fault encountered.[23] In a survey of roof top ducted air conditioners over 50% of units had control issues including economy cycle (65%), thermostats (58%) and sensors (20%).[24]
Energy penalty	AC: From 0% to 60% energy savings for existing buildings. AC: Medium case: 10% system energy use.
Potential solutions	AC: It is difficult to identify poor operation or control of systems during a standard maintenance inspection, monitoring of trend data is generally required. Monitoring of system performance or energy consumption over time provides better insights. Building or system re-commissioning, retro-commissioning, and tuning methodologies are all potential cost-effective solutions to energy penalties associated with non-commissioned or non-performing control systems. Rating tools such as National Australian Built Environment Rating System (NABERS) Energy or Calculating Cool[38] require energy use of HVAC to be monitored and managed over time. Some jurisdictions in the USA have mandated periodic building tuning processes for large building HVAC[39], which focusses on monitoring and controls.
Examples	AC: Inadequate or inappropriate controls software and hardware was the most common fault encountered in an analysis of the commissioning records of 643 buildings in the USA.[23] A separate literature review and survey of small commercial buildings prioritised the top 20 faults, 8 of which were HVAC controls related.[9] In an American study best practices in building operations (HVAC maintenance and control) were shown to reduce energy use by 10% to 20% across all climate zones. In contrast, bad practices in this area can increase energy use by 30% to 60%.[40]
Examples	AC: In a European study six out of the top eight Energy Conservation Opportunities (ECOs) identified were based on fixing or improving controls, showing the importance of HVAC control and operator understanding of the systems in achieving efficient energy operation.[42]
Examples	CR: A study of supermarket refrigeration systems found control system problems (leading to system failure) in around 25% of systems surveyed.[25]

Special case	CR: Remote: Walk-in cold room control types can vary from basic on-off control thermostats and an electric defrost timer to advanced control solutions with smart or demand defrost. Electronic controllers offer numerous options for energy-efficient control of all the components in a walk-in cold room from the evaporator to the door. Modern advanced control solutions can reduce energy consumption by up to 40% compared to the basic systems that dominate this industry sector.[41]
References	23, 24, 25, 9, 38, 39, 40, 41, 42

4.7 *Poor equipment location*

Definition	Poorly located condensing units that restrict the performance of the condenser.
Equipment types	RAC with remote condensers and cooling towers.
Cause: Installation	Not following manufacturers installation and best practice guidelines regarding placement of condensing units. Inadequate clearance between condenser face and wall. Position multiple RAC units so that the air discharge of one unit is into the condenser air intake of another. Installation of condensing unit in non-ventilated, enclosed space such as in a carpark, roof cavity or above the cold room. The condenser coil (air inlet) should not be west-facing or north-facing. Ideally, south-facing is best, followed by east, unless severity of prevailing winds is a significant factor. Site or owner may impose limitations.
Cause: Operational	Allowing new equipment to be installed too close to existing equipment.
Fault level drivers	Not following manufacturers or best practice installation guidelines, site limitations. Local planning regulations that encourage enclosing heat rejection condensers to reduce visual impact, causing air recirculation, reduced heat rejection and increased energy use.
System impacts	AC: Multiple condensers or cooling towers recirculating airflows (discharge to intake) reducing heat transfer efficiency and creating a heat island effect.[43] CR: Poorly located condensing units restrict the performance of the condenser is essentially making the condenser smaller relative to the equipment design. The industry standard is to achieve 14 KTD (i.e. temperature difference in degrees Kelvin between the condenser air on temperature and leaving refrigerant saturation temperature). Loose around 2% to 3% efficiency for every degree change in KTD. Larger sized condensers can achieve 5 KTD to 10 KTD and a system with 5 KTD can use 25% to 35% less power.
Comments	Roof mounted, south-facing coil (air inlet) condensers with good air flow and no opportunity for recirculation is ideal. Consider shading with west-facing or north-facing condensers. Select a condenser location to minimise the refrigeration pipe lengths; longer distances require more refrigerant to pump around the circuit, resulting in greater energy consumption.
Prevalence	AC: Common in split systems in commercial air conditioning, where multiple systems are installed on a single site.

	CR: Very high, occurs in most applications.
Energy penalty	Ranges from 0% to 40% per annum for an air-cooled condenser that is significantly restricted or not able to perform as designed due to recirculation of warm air back into the condenser air inlet. Medium case scenario 5% to 10% per annum.
Potential solutions	Improved information and awareness of the lifetime energy penalty for poorly equipment location. Training of architects. Contractor training. Ventilation for equipment in enclosed buildings or confined spaces. Best practice installation.
Examples	AC: AIRAH DA17 Best practice guide for cooling towers[44] recommends that towers are located so they are protected from wind, direct sunlight penetration and are located to avoid interference with other towers and recirculation caused by surroundings or enclosures.
Examples	CR: Sustainability Victoria undertook benchmarking study of 50 refrigeration systems with remote condensing units across 43 sites in 2018. This study showed examples of several poorly installed condensing units and measured the temperature difference across the condenser of a unit located in a confined space at 21 KTD. This equates to an energy penalty of around 40% compared to a unit operating at 5 KTD.[45, 46]
Special case	AC: Access for maintenance is also a common problem for high wall mounted or roof mounted condenser plant. If the plant cannot be safely and cost effectively accessed, it will not be maintained. CR: The placement of the evaporator(s) is an important consideration for the efficient operation of the walk-in cold rooms, as improper placement can lead to wasted energy and performance issues.
References	43, 44, 45, 46

4.8 *Liquid line issues*

Definition	Liquid line issues mean restrictions in the refrigerant pipeline and associated components (expansion valves, filters) that increase resistance and will starve the evaporator of the correct amount of refrigerant. There are several issues covered by this fault including incorrect pipe sizing, poor commissioning such as not setting up superheats on the thermal expansion value (TEV), referred to by industry as “TEV out of a box”, and issues with liquid line components, e.g. when particles accumulate within and block the refrigerant filter in the refrigerant circuit.
Equipment types	All RAC, except self-contained equipment.
Cause: Installation	Incorrect component selection/installation, incorrect refrigerant line sizing, poor jointing techniques leaving residue inside the pipework, incorrect/no commissioning.
Cause: Operational	Damage to pipework, ad-hoc adjustments, alterations, not replacing the filter dryer on a regular basis and at least every time a system is opened to atmosphere (to replace the compressor, TEV, etc.).
Fault level drivers	Low quality of installation, non-standard approach to commissioning, poor quality of maintenance.

System impacts	Liquid line restrictions or the accumulation of particles in filters increases the flow resistance of the refrigerant circuit and the pressure difference across the compressor. It also reduces the evaporating temperature and leads to lower cooling capacity and efficiency. Not setting up the TEV correctly can result in efficiency losses for the entire lifetime of the equipment.
Comments	It is important to note that TEVs are refrigerant-specific valves and if a system is retrofitted to a new refrigerant the TEV should be either replaced or in some instances the same TEV can be used with the superheat readjusted according to manufacturer's instructions.
Prevalence	More common in complex systems with longer pipe runs but can occur in any system. More common in large AC and chillers that may have unmaintained filter/driers. CR: Not setting up the TEV has been standard industry practice and prevalence is high.[47]
Energy penalty	AC: From 0% to a 15% loss in operating efficiency for a 30% increase in the pressure difference between the condenser outlet and evaporator inlet. Medium case 15% increase in pressure difference for a 5% energy penalty.
Potential solutions	Training on liquid line sizing and setting up TEV. Understanding the lifetime penalty of poor practices. Maintenance: Scheduled replacement of refrigerant filters, inspection of the system for restrictions, checking by diagnosing system performance, automated fault detection device (AFDD) for liquid-line restrictions.
Examples	AC: Study of a roof top unit showed a 5.1% decrease in COP for a 15% increase in liquid line resistance.[48] A meta study of previous liquid line fault research produced a series of normalised curves to illustrate the reduction in COP in a generalised format. The few studies that have investigated this fault did not investigate beyond a 50% fault level. The research showed a 15% loss in operating efficiency for a 30% increase in pressure difference.[7]
Special case	The AIRAH NSW OEH HVAC Optimisation Guide published in 2015[49] estimates that retrofitting AC compressors with electronic expansion valves (EEV) as opposed to mechanical can save up to 15% of energy consumed by the compressor.
References	7, 47, 48, 49

4.9 *Refrigerant health and non-condensables*

Definition	Air is the most common non-condensable in vapour compression systems and cannot be condensed like refrigerant vapours. Fractionation is the change in the circulating refrigerant composition relative to the normal composition. Refrigerant blend compositions are referenced in ANSI/ASHRAE Standard 34 and acceptable levels of contaminants (purity levels) are specified in AHRI 700 Specifications for refrigerants.[50]
Equipment types	RAC central systems and equipment with remote condensers.
Cause: Installation	System not properly evacuated including failure to fully evacuate the inert gases used during transport or leak testing. Air and other contaminants enter the system during installation or charging.

	Oil contamination in chiller refrigerant. Blends charged from vapour port can cause fractionation. Blends should always be charged from liquid port.
Cause: Operational	Lack of maintenance of refrigerant filters. Fractionation of zeotropic blends (two or more component refrigerants with different boiling points) due to refrigerant leakage. Air and contaminants entering system during maintenance or charging. Wear and tear, compressor burn out or works on the system can result in contaminants in the system.
Fault level drivers	Poor practices when undertaking works, use of zeotropic blends.
System impacts	When an RAC unit is not properly evacuated prior to being charged with refrigerant, the unit runs with a mixture of air and refrigerant. The air is non-condensable and is typically trapped in the high-pressure vapour downstream of the compressor, and the pressure difference across the compressor and the compressor power consumption exceeds the normal level resulting in a decline in efficiency. The emergence of blends, makes it more complex for technicians going forward. Both incorrect set-up during retrofit or leakage causing a change in composition can result in an energy penalty. During leak events, higher pressure components of the zeotropic blend may leak first, changing refrigerant composition and resulting in an energy penalty. With incorrect expansion valve adjustment and composition change two things can happen. First, the liquid may not vaporise before reaching the compressor, which can cause inefficiency and lead to compressor damage. Second, the blend may completely boil part way through the evaporator, leading to a loss of efficiency.
Comments	Blended HFC and hydrofluoroolefins (HFO) refrigerants, made by mixing several refrigerants together in specific proportions to create the desired operating characteristics, can behave differently to single-component refrigerants. Single component refrigerants and azeotropic blends evaporate or condense at constant temperature in a constant pressure process. For zeotropic blends, the temperature varies between dew (saturated vapour) temperature and bubble (saturated liquid) points in a constant pressure process. ASHRAE classifies blends as azeotropic (R500 series) and zeotropic (R400 series). Some zeotropic blends can fractionate when leaking from systems while in a superheated or subcooled condition, which will alter the refrigerant's overall composition and energy performance. Where a leak of fractionated refrigerant has occurred, the entire refrigerant charge may need to be recovered and replaced with virgin blend refrigerant to ensure the correct blend ratio (and hence system performance) is maintained. This can be an expensive maintenance practice, especially for central plants such as chillers or supermarket systems. The fractionation effect is dependent on the extent of temperature glide of the refrigerant blend.[84]
Prevalence	The prevalence of non-condensable gases and contaminants in refrigerant is medium. Fractionation is not that prevalent at present however the emergence of many HFO/HFC zeotropic blends could lead to higher prevalence in leaky systems.
Energy penalty	AC: Chillers: From 0% to a 20% loss in chiller efficiency for 10% oil contamination in the refrigerant. For split systems and packaged air-conditioners from 0% to 7.5% loss in efficiency for 20% contamination with non-condensable gas.
Potential solutions	Improved maintenance practices such as:

	Refrigerant health check and test for non-condensable gases. Refrigerant charge reclamation to remove-clean-replace the existing refrigerant in a one-time process. Use of a purging system that cleans the circulating refrigerant on an ongoing basis.
Examples	Cheung and Braun (2015) estimated 60% non-condensable gas entrainment can result in 0.7% increased whole building energy (approximately 9% cooling energy increase).[51]
Examples	Laboratory testing of split system air conditioners has shown that even a mild amount of non-condensables produces a 7.5% reduction in sensible EER.[52]
Examples	AIRAH DA19[53] recommends periodic testing of oil quality and refrigerant quality for chillers.
Potential solutions	Test kits are available to undertake a refrigerant health check (i.e. purity, composition, moisture, acidity, residue, chloride and oil analysis) and test for non-condensable gases.[54] This is an analytical product that allows technicians and end users to sample the working fluids (refrigerant and oil) within an operating HVAC&R system and receive analysis that will help inform their maintenance/troubleshooting process. Some major end users have made testing prior to and after works a requirement for contractors undertaking rectification works to ensure best practice is undertaken. Ensuring purity of the refrigerant in turn protects the working life of the equipment and ensures more efficient operation.
References	50, 51, 52, 53, 54, 84

4.10 *Minimal documentation*

Definition	Inadequate as-installed documentation, lack of a performance benchmark or commissioning baseline data, lack of operation and maintenance manuals, and poor operator training and understanding of the system.
Equipment types	All RAC equipment excluding self-contained commercial refrigeration and non-ducted split systems.
Cause: Installation	Lack of specification for as-installed/as-built and operation and maintenance documentation, lack of commissioning/baseline testing, system documentation and baseline performance testing records not provided.
Cause: Operational	Documentation and records not managed correctly, not used, not updated with changes, not understood.
Fault level drivers	Least cost purchasing, poor approach to commissioning and handover, poor approach to maintenance.
System impacts	Without knowing the design intent, the control strategies, the final installed equipment layout and the initial baseline performance data, and without adequate operation and maintenance knowledge and training the energy impacts can be high.
Comments	This is a compounding fault that is typically found in poorly specified, low cost, low quality, non-commissioned and poorly maintained systems. It is difficult to separate the impact of this fault from the impact of other faults as they tend to occur simultaneously.
Prevalence	AC: Although not the focus of specific research the anecdotal evidence is clear that this fault is common. Documentation is either never provided, is provided and is lost, is not updated, is of very low quality, or is too complex to be useful to the operator. Similarly, the level of operator and instruction training provided at a typical air conditioning handover is extremely limited. CR: This fault is very prevalent with refrigeration systems with condensing units, and many central refrigeration systems. Process refrigeration applications in manufacturing are more inclined to be documented.
Energy penalty	AC: 5% to 20% impact on operational energy for poorly documented and poorly understood systems. CR: Can vary significantly depending on the system or end users. Medium case scenario is 5% to 10% per annum.
Potential solutions	Best practice approach to procurement, commissioning and operation. Including record keeping and updating of system documentation with changes in the maintenance services contract. A building/system logbook. Digital solutions that allow records and documentation to be more easily stored, updated and accessed when required by technical service providers.
Examples	The Calculating Cool HVAC rating tool[38] requires the documentation characteristics of the HVAC system to be evaluated, with a higher rating awarded to systems that are well documented including: ▪ A complete set of as-built documentation; ▪ Project specific manuals for operation and maintenance; ▪ A document that captures operational issues; and, ▪ A process that communicates the energy efficiency strategies specific to the HVAC system to relevant stakeholders.

Examples	Almost all good practice guides[55, 56, 62] require that appropriate documentation and operation and maintenance information be provided with the system. AIRAH DA19[53] provides a detailed summary of what should be included, formats, etc. All commissioning guides[58, 59] also require that appropriate operator instruction and training is delivered to ensure continued optimal system operation to the design intent.
Examples	AC: A survey of HVAC contractors in New York[60] reported that 49% of the systems that they inspected/maintained (installed by others) suffered from poor quality installation.
Examples	CR: Unlike air conditioning, refrigeration equipment typically does not come with installation or operation guidelines. They are considered a custom design, and documentation is the responsibility of the installer, consequently no or minimal documentation is provided to the contractor or end user (i.e. installation, commissioning, operation, maintenance). The extent of the documentation may typically include equipment data sheets and the controller operator manual.[47]
Special case	HVAC Optimisation: 'Maintaining accurate and reliable documentation on how the HVAC systems should function will assist in benchmarking and identifying/diagnosing problems that may contribute to unsatisfactory operating performance. Clear, complete, up-to-date as-installed drawings, operating manuals, functional descriptions, maintenance procedures, checklists and logbooks expedite the optimisation process'.[49]
References	38, 47, 49, 53, 55, 56, 58, 59, 60, 62

4.11 *Specific to air conditioning*

4.11.1 Airflow: Air distribution/duct sizing, dampers and fans

Definition	Characteristics of air distribution system resulting in actual air flows below the design airflow or the rated airflow range for the equipment.
Equipment types	Ducted AC (split and packaged) and central air conditioning (chillers).
Cause: Installation	Improper duct sizing, poor fan connection/installation, incorrectly sized or installed dampers, incorrect/no commissioning.
Cause: Operational	Ad-hoc adjustments, alterations, penetrations.
Fault level drivers	Poor quality of installation, non-standard approach to commissioning.
System impacts	Air distribution system resistance increases, fan power increases or air volume flow reduces, and the refrigeration system (evaporator) heat exchange is less efficient.
Comments	Inefficient ductwork is a system fault that is designed into the system at installation stage. Systems that do not meet the minimum airflow requirements will not operate at their designed efficiency level. Fans work harder and refrigeration systems do not reach their operation potential. It is not uncommon for a ductwork system in a commercial application to be re-used even when air conditioning systems are replaced or upgraded. The energy penalty occurs for the life of the system and is most impactful at periods of peak load.
Prevalence	Sub-optimal air delivery systems are relatively common, and prevalence is considered medium to high.

Energy penalty	Range from zero energy penalty for a well designed and installed air delivery system to 25% impact where the system is significantly compromised. Medium case scenario is 5% to 10% per annum.
Potential solutions	The installing technician should always check the evaporator airflow rate, and airflows of each outlet against the intended design. Initial inspection and diagnosis of airflow issues, documenting solutions and correction of poorly designed and installed ductwork, and re-balance air quantities. Duct plan a mandatory requirement of Certificate of Compliance. Best Practice Guidelines: Design/install, system balancing/commissioning. Training and accreditation program for designers and duct fixers.
Examples	An extensive review commissioned by the California Energy Commission Evidence-based Design and Operations Research Program in 2011 comparing the impact of design, operation, and tenant behaviour on building energy performance concluded the selection of HVAC system type, air distribution type, equipment and duct sizing, system efficiency, ventilation damper settings and control strategies are all controlled by the HVAC system designer and have a huge impact on the energy use of the building. Best practices in the building envelope, lighting and HVAC design can lead to 50% energy consumption savings, and worst practices can lead to a 60% to 210% increase.[40] Field surveys of ducted air conditioning systems consistently find low airflow (indoor or evaporator airflow) as the first or second most common HVAC installation fault.[6, 23, 24, 27, 36, 70]
Special case	Prolonged lack of maintenance to ductwork air distribution systems can lead to energy penalties from faulty (volume control and outdoor air) dampers and soiled ductwork components due to poor HVAC hygiene.
Special case	A study by the US Department of Commerce, National Institute of Standards Technology in 2014 found most field methods for determining refrigerant charge provide inaccurate results if the air conditioner is operating below the nominal airflow rate.[6]
References	6, 23, 24, 27, 36, 40, 70

4.11.2 Airflow: Filters

Definition	Characteristics of air filter resulting in actual air flows below the design airflow or the rated airflow range for the equipment.
Equipment types	Non ducted split AC, ducted AC (split and packaged).
Cause: Installation	Filter efficiency too high for the application, poor filter installation (resulting in air bypass).
Cause: Operational	Filter fouling over time, resulting in reduced airflow or air bypass. Replacement of an existing filter with a higher efficiency filter during service.
Fault level drivers	Quality/type of filter, level of local air contamination, approach to maintenance, time.
System impacts	This fault decreases the evaporator saturation temperature, which decreases overall cooling capacity, sensible heat ratio (SHR), and the coefficient of performance (COP). As the resistance of the filter rises the fan will either reduce airflow or increase power to retain the airflow. Severely overloaded filters can blow-out and lose all function.

Comments	The rate of filter fouling will depend on the efficiency of the filter and the characteristics of the air contaminants (dust loading) passing through it. Filter fouling affects energy efficiency, and a fouled filter may also present a microbial control indoor air quality (IAQ) health risk.
Prevalence	Medium case scenario is reached after 6 months without maintenance.
Energy penalty	Impact varies depending on the performance of the fan (fan curve), all fans will increase power with increased system resistance. Medium case scenario is 5% to 10% per annum.
Potential solutions	Modern low pressure-drop high energy-efficient filters are available that can provide an immediate performance uplift when replacing a poorly designed filtration system.[61] Periodic inspection and cleaning/replacement of filter as necessary, measuring pressure drop across filter, automated fault detection and diagnosis (AFDD) for filter resistance.
Examples	Comprehensive building studies have shown that filter maintenance is typically not carried out in 25%[23] to 40%[42] of buildings. Regular filter inspection and maintenance is recommended by every air-conditioner manufacturer and all HVAC maintenance best practice guides,[55, 56, 62] and minimum maintenance standards AS/NZS 3666.2.[63]
Special case	Kitchen exhaust filters are installed on kitchen exhaust systems when the exhaust air is contaminated with steam, grease and smoke from cooking processes. Depending on the type of filter, as grease builds up the resistance increases and fan power increases. Inspection and cleaning of grease filters is a regulated activity.[57, 64]
References	23, 42, 55, 56, 57, 61, 62, 63, 64

4.11.3 Duct insulation and leakage

Definition	System efficiency losses due to conditioned air leaking from the air distribution ductwork or excessive thermal losses from uninsulated or under insulated ductwork and connectors, commonly referred to as branch take offs (BTOs).
Equipment types	Ducted AC, includes split and packaged systems, and central air conditioning (i.e. chillers).
Cause: Installation	Poor specification of duct sealing requirements. Poor quality duct manufacture and installation. Low R-value/thickness of insulation used and poor installation of insulation. Insufficient roof/cavity space to follow good practice (i.e. bend radius, constrictions, etc.) or install compliant ductwork (i.e. NCC minimum required R-value). Poor commissioning and verification processes.
Cause: Operational	Lack of maintenance of dampers and equipment connections, damage and degradation to ductwork/insulation systems, vermin.
Fault level drivers	Least cost purchasing, poor approach to duct sealing, testing and commissioning. No regulatory requirement for verification testing.
System impacts	Insufficient thermal insulation R-value increases heat losses from the air distribution system which increases system energy consumption. In poorly sealed ducts, the effect of leakage can be considerable. Individual workmanship is the greatest variable. Leakage from the supply duct will reduce the capacity of the system to meet the load (chillers and cooling towers and fans will work harder) and increase power consumption, ducts can sweat (condensation) at leakage points and if not adequately insulated. Leakage into the return air duct adds to the plant load.

Comments	Duct leakage faults are very difficult and/or expensive to rectify post installation, particularly for insulated ductwork systems. The energy penalty can exist for the entire service life of the cooling equipment and potentially be re-used when equipment is upgraded or replaced.
Prevalence	Duct leakage is a frequently encountered issue in building surveys.[6, 9, 23, 36] In Australia duct leakages ranging from 5% to 30% have been found.[65] Independent thermal performance testing of nine flexible duct specimens sourced from the marketplace found the R value of all nine products tested was less than the declared thermal performance of insulation.[66]
Energy penalty	It is not unreasonable that a modest 5% leakage rate could add 10% or 15% to operating energy.[67] Testing has found on average a 10% leakage rate. Leakage rate of 5% adds up to 17% to supply fan energy. At 10% leakage the extra fan energy is 37%.[65] Poorly insulated flexible ductwork contributes to excessive energy use and unnecessary generation of greenhouse gases. The default factor for most heat load calculators for duct gain or losses is 10%. Medium case: 5% per annum.
Potential solutions	This fault is best addressed at the installation and acceptance stage. Improved ductwork specification that includes verification testing. AS 4254.1[85] should be updated to address R-value compliance issues for flexible ductwork. Mandating AS 4254.2[86] duct leak testing protocols. Requirement for heat load calculation and duct plan as a certificate of compliance. Accredited training of duct fixers.
Examples	A study of variable air volume (VAV) systems in large commercial buildings in California calculated that, compared to 'tight' duct systems (2.5% leakage), systems with 10% leakage had annual HVAC system operating costs 9% to 18% higher, while those with 5% leakage used 2% to 5% more energy.[68]
Special case	The NCC limits this through AS 4254.2:2012[86]; Clause 2.2.4 Air Leakage which limits leakage to 5% at 125% of design pressure. A system that meets this can be expected to leak less than 3%. NCC references sealing requirements but does not require sealing to be validated by ductwork testing.
References	6, 9, 23, 36, 65, 66, 67, 68, 85, 86

4.12 *Specific to commercial refrigeration*

4.12.1 Excessive heat load

Definition	The refrigeration system load for a walk-in cold room is made up of the following sources of heat gain: ▪ Transmission load (heat gain through walls, floors and ceiling). ▪ Air change load (Heat gain from air infiltrating from outside and adjoining spaces through doors and other openings). ▪ Product load. ▪ Internal and system related loads. Excessive heat loads are mostly transmission and air change loads.
Equipment types	Commercial refrigeration, mostly walk-in cold rooms with remote condensing units, as well as centralised refrigeration systems.
Cause:	Poor selection of thermal insulation properties of walk-in cold rooms (WIC) enclosure.

Installation	A full vapour seal of the WIC is important with all penetrations (pipework, electrical) correctly sealed as well as joins of insulation panels, types of doors and door gaskets. Type of glazing on windows and doors. No doors on refrigeration display cases.
Cause: Operational	Heat infiltration through the WIC enclosure due to doors left open by operator. Unreported damage to thermal insulation and air sealing elements of the enclosure (e.g. forklift impact). Inefficient interaction between HVAC and refrigeration systems.
Fault level drivers	Operator issues (i.e. leaving door open), lack of understanding of energy penalty.
System impacts	Additional heat loads the refrigeration equipment must remove to achieve the desired set point. The system operates for longer periods and consumes more energy to achieve the conditions required to chill or freeze the product.
Comments	Automatic rapid roller doors, spring hinged doors, or other method of minimising infiltration when doors are open such as strip doors. Alarms can assist if not ignored or disabled. Fan cut-off switches when doors are open.
Prevalence	Excessive heat load is very prevalent with walk-in cold rooms. The main causes are doors left open, poor vapour seals and poor-quality thermal insulation on WIC structures. It is very common to have a poor level of insulation in the WIC structure. And the majority of medium temperature food retail (i.e. dairy, meat, produce and liquor) uses open display cases without doors.
Energy penalty	Air infiltration typically accounts for around 30% of the heat load[41] and leaving the WIC door open for extended periods (up to 8 hours per day) can consume significant amounts of un-necessary energy. A refrigeration display case with doors, typically consumes 40% to 75% less energy than a similar sized open display case.
Potential solutions	Best practice installation (enclosure and system) and operation., e.g. AIRAH DA12 [70], IPCA code of practice,[69] etc. Education on impact of cost associated with leaving WIC door open. Application of automatic closers and door open alarms. Communication for end users such as operator guide and maintenance guide to remind end users of their obligations under AS/NZS 5149 Part 4: 2016[87] and how to operate and maintain WICs efficiently. Minimum standard thermal insulation for cold rooms in Australia in NCC equivalent to standard practice in EU and USA.
Examples	Study of an independent supermarket located in regional Victoria logged the period the door of the main cold room was open and found to be up to 8 hours some days.[47] In hospitality applications cooks leaving WIC doors open to provide cooling in hot kitchens.[47]
	In 2015 the Energy Efficiency & Conservation Authority (ECCA) of NZ conducted trial, retrofitting 25 meters of medium temperature open display cases with doors at a Countdown store in Pukekohe South, Auckland. The study found a 42% saving at the cases.[71] Advanced Refrigeration Technologies, an Australian manufacturer of doors with very high thermal efficiency claim savings of 75%.[72]
References	41, 47, 69, 70, 71, 72, 87

5 Market failures, commissioning and maintenance

5.1 *Least cost purchasing and information failure*

One of the significant drivers of energy inefficiency and the proliferation of common faults in refrigeration and air conditioning systems in Australia is the *least cost* approach to procurement that is prevalent in the Australian RAC market and throughout the construction industries.

The construction and RAC industries are highly competitive, with tender processes designed to rate different procurement options or different providers largely based on relative cost, with the least cost solution most often selected. In many projects this reflects the split incentives that exist between the developer/designer, who looks to achieve lowest capital costs, and the owner/operator who would benefit from a lowest life-cycle cost approach, even at the expense of a higher initial capital cost. As less expensive equipment and lower quality systems tend to be lower performing and require more maintenance it also suggests that least cost purchasing can drive excessive energy consumption in RAC systems.

Least cost building construction practices do not build to best practice or good quality standards but rather build to meet minimum compliance standards. Least cost can refer to both equipment and practitioners (designers and contractors) and both can have an influence on system quality. The quality and integration of different building elements generally suffers, resulting in low quality buildings with poor sealing and low thermal performance.

Systems that are procured on a least cost basis can employ low quality minimum performance equipment, poor workmanship and quality assurance, poor system monitoring and control, and lack of system documentation and operator training and understanding. These tendencies in the Australian market can be compounded by an absence of an integrated approach to commissioning.

The 2018 study by AIRAH, *Walk-in cool room and freezer research project: Barriers to energy efficiency* found this issue was very prevalent with procurement and construction of walk-in cold rooms.[47] The research concluded that information failure, split incentives and least cost purchasing were the primary reasons for energy inefficiency. The issue is magnified in this equipment segment as many of the purchasers are small to medium enterprises (SMEs), there are no minimum efficiency standards on the equipment or WIC structure (i.e. unlike the majority of other building structures regulated by the National Construction Code (NCC)), and in most States and Territories there are no requirements for specific skills except a refrigerant handling licence when installing equipment that requires charging with refrigerant.

The significant information failure in this process occurs when equipment and building owners do not make purchasing decisions based on the total cost of ownership (TCO). This very powerful piece of information allows rapid comparisons of the cost of capital plus energy consumption over a period of ownership of equipment of a building (or the period of tenancy in a building). Having the ability to easily compare the TCO of different purchasing decisions would change buyer decisions for those for whom the additional capital was available to pay for higher efficiency equipment or building designs and accrue the life-of-equipment or tenancy/ownership savings.

5.2 *Commissioning failure*

The process of commissioning RAC equipment incorporates design and construction reviews, static pre-commissioning activities, setting to work, balancing and adjustment, performance testing, demonstration and issuing of a detailed report upon completion. One of the difficulties with commissioning is the lack of industry-wide agreements on the definition, application and scope.

The intent of proper commissioning is to discover and rectify design and installation faults and control system errors that ensure the system can perform to achieve its design intent. One of the most important aspects of system commissioning is the provision of baseline information to inform the ongoing operation and maintenance/tuning approach, and to apply fault detection and analysis to a system. Incorrect commissioning will mean that the system settings will be inaccurate, and the system operational performance will never achieve the designer's intent.

Even after commissioning is completed, changes may be made to systems and components (for example during defects liability period) which can negatively impact operating energy efficiency. Ongoing tuning is an appropriate energy efficiency tool to use in both refrigeration and commercial air conditioning sectors.

A meta-analysis of commissioning in 643 buildings in the USA found median whole-building energy savings of 16% for existing buildings and 13% for new construction[23] when commissioning was properly completed on the RAC systems.

The non-technical barriers to effective commissioning are numerous, and include insufficient time allowed in the building program, costs and lack of management understanding of the value of commissioning.

The industry has not agreed a clear single set of requirements or Australian Standards to define the scope and objectives of HVAC Building commissioning and the process for the testing adjusting and balancing of the air, water and refrigerant aspects of commercial air conditioning systems. In the absence industry-agreed requirements and minimum Standards to define the scope, objectives, and technical processes of RAC commissioning the prevalence of system control faults and installation errors due to poor commissioning is likely to remain high.

Lack of information on commissioning process and methods is not the problem. The AIRAH Application Manual DA27 Building Commissioning[58] and the Chartered Institution of Building Services Engineers (CIBSE) Australian/New Zealand version of Soft Landings[59] have documented Australian industry-endorsed building commissioning and tuning guidelines. Green Star tools and NABERS commitment agreements also encourage and recognise commissioning, handover and tuning initiatives that ensure all building services operate to their full potential and as designed. Australian Standards often include testing and validation requirements for particular systems. International Industry Guidelines from the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), CIBSE, National Environmental Balancing Bureau (NEBB), and Building Commissioning Association (BCA) provide a range of Standards and Guides that detail technical approaches to system and building commissioning.

Recommissioning, retro-commissioning, and building or system tuning methodologies are all potential cost-effective solutions to the energy penalties associated with non-commissioned or poorly and incompletely commissioned commercial air conditioning. Some jurisdictions in the USA have mandated periodic building tuning processes for large building HVAC.[39] In Hong Kong continued occupancy of commercial buildings require an annual inspection of the mechanical services during which performance criteria for the system and maintenance records are inspected.

5.3 *Maintenance*

All systems will suffer faults over their operating lifetime leading to performance degradation. Maintenance is intended to be applied to minimise the occurrence and impacts of these faults.

Faults that develop due to a lack of maintenance include incorrect refrigerant charge, dirty filters, fouled evaporators and condensers, and inappropriate changes to control settings. These faults tend to build up over time across the operational life of the system. Environment and operator behaviour play a significant role.

A maintenance program that addresses common faults would address compliance activities and include finding and fixing refrigerant leaks, ensuring the correct refrigerant charge, cleaning coils (condensers and evaporators), replacing filters and ensuring good airflow, and calibrating sensors or resetting controls.

All RAC system performance efficiency will degrade over time, although the rate of degradation can depend on a range of design, installation and environmental factors. This section outlines the role maintenance can play in 'maintaining' the energy efficiency of RAC equipment and preventing or minimising degradation in performance.

Systems that have had no maintenance, or minimal maintenance and are old, will tend to have the largest operating energy penalty and conversely the largest potential initial energy efficiency uplift from technical maintenance. Systems that are regularly maintained tend to have operating efficiencies near to, or in some cases, greater than the original design/installation.

5.4 *What can be addressed with maintenance*

Scheduled maintenance is recommended by every manufacturer, supplier, and by many of the best practice guides that were discovered as part of this review.

Maintenance procedures do not address single faults but require testing and inspections to cover all potential faults in a system. Maintenance should be targeted to eliminate refrigerant leakage and reduce energy consumption.

Several reports have estimated the percentage energy uplift (the percentage increase in the coefficient of performance) that can be achieved by the application of good or best practice maintenance. *Table 6* below provides a summary of some of these reports.

Table 6: Potential energy uplift from applying RAC maintenance.

Topic and source	Energy efficiency uplift (%)
Building maintenance[22, 73]	10% to 20% from best practice maintenance.
HVAC system maintenance[40]	Best practices in this area are shown to reduce energy use 10% to 20% Bad practices in this area can increase energy use by 30% to 60%.
Top performing industrial[73] (non RAC)	8% to 12% from predictive maintenance.
Australian HVAC[49]	The provision of regular maintenance inspections and rectification work dedicated to the energy efficiency of the plant has the potential to keep the plant running at its optimal performance, reducing current and avoiding future operational costs. Up to 20% HVAC energy consumption reduction.
Global RACHP[74]	15% to 30% potential for RACHP efficiency improvement due to servicing.
Global RACHP[75]	10% to 20% potential for RACHP efficiency improvement by monitoring performance and correcting faults.
Global cooling [5]	Effective optimisation, monitoring, and maintenance of cooling equipment could deliver substantial electricity savings of up to 20% leading to emissions savings of up to 0.5 Gt CO_2e per year (13% global emissions).
Australian HVACR[76]	Maintenance for energy efficiency is anecdotally reported to be able to generate energy savings in the range of 10% to 60% in the first intervention and then savings in the range of 10% to 20% for annual interventions thereafter.

5.5 *Characterising maintenance*

5.5.1 Maintenance strategies

Maintenance strategies can generally be characterised as reactive, preventative or predictive.

1. **Reactive maintenance:** Service is only applied when the system can no longer meet the load (component failure or significant reduction in capacity due to refrigerant leakage and severe fouling) also called ‘operate to fail’ or ‘breakdown maintenance’.
2. **Preventative maintenance:** Periodic maintenance of HVAC equipment, generally as prescribed by the manufacturers or industry guidelines such as AIRAH DA19[53]. Refrigerant leaks are manually inspected on a schedule and/or fixed leak detection is applied, coils are visibly inspected and/or tested and cleaned when necessary, refrigerant and oil is tested periodically.
3. **Predictive maintenance:** System is monitored and analysed to detect the signs of refrigerant leakage, evaporator fouling, fan failure, drop in filter pressure, etc. Digital systems can replace human inspection and human intervention is only required when a problem is detected, or a manual test is scheduled.

In reality, maintenance practices applied to refrigeration and air conditioning systems is a mix of all of the above. Critical systems will have the highest level of maintenance and non-critical systems will have the lowest.

5.5.2 Levels of maintenance

The industry guideline for HVAC&R maintenance AIRAH DA19[53] defines three levels of maintenance that incorporate a mix of the maintenance strategies discussed above. These are based on equipment and system maintenance task and frequency schedules:

Level A: Best Practice: Includes all of Level B and C maintenance tasks/frequencies and would typically include for some tasks to be scheduled more frequently to ensure greater knowledge and understanding of plant condition, or suggest where additional proactive information may be continuously gathered to increase vigilance or analyse trends, such as vibration analysis, thermograph, etc.

Level B: Good Practice: Includes all of Level C maintenance tasks/frequencies and the additional work required to achieve a good scheduled maintenance program. This level is a good industry-practice level and is particularly important for equipment that does not have compliance requirements as there is no legislation requiring this work to be performed.

Level C: Compliance: This is the minimum maintenance standard required to meet statutory compliance, incorporating the requirements from the regulations, plus obligations to environment, health and safety and general duty of care, based on the maintenance compliance standards *AS 1851*[88], *AS/NZS 3666.2*[63], *AS/NZS 3666.3*[89] and *AS/NZS 5149.4*[87]. Statutory requirements in individual jurisdictions vary.

The selection of a maintenance approach and the level of maintenance to be applied to a system is ultimately based on the maintenance outcomes required by the client or demand organisation and the maintenance budget.

Table 7: Characterising maintenance.

Maintenance Strategies	Scope of work	Application (DA19)	Characteristics	Uptake (%)	Energy impact
Compliance Maintenance	Inspection of specified elements	Compliance maintenance only	Check only what is legally required	N/A	N/A Safety focus
Reactive Maintenance	No Scope	No Maintenance	Fix/service only when broken	60% (most common)	Large increases in energy consumption
Preventative Maintenance	Scheduled inspection and testing	Good practice	Follow manufacturer instructions and industry good practice (DA19)	30% (to some level)	Managed energy efficiency, small increases in energy consumption
Predictive Maintenance	Monitored and modelled performance	Best practice	Preventative maintenance supported by advanced testing and digital monitoring and analysis	10% (in some form)	Optimum energy efficiency, reduced energy consumption

(Based on: AIRAH DA19 HVAC&R Maintenance)[53]

5.6 *Maintenance procurement*

Typically, owners, maintenance clients or demand organisations will want to minimise the operation and maintenance costs of their RAC assets.

The attitude of the owner or operator to maintenance costs may influence the maintenance strategy applied to the system. Owners that see maintenance as a cost may tend to adopt a reactive maintenance strategy. Owners that see maintenance as an investment or cost controlling activity may tend to adopt a preventative or predictive maintenance strategy.

The strategy adopted could also be influenced by a lack of market information available on the additional costs (electricity consumed) for running poorly maintained equipment. Owners rarely have visibility on their RAC electricity consumption. This prevents equipment owners from making informed decisions on the actual costs versus benefits associated with regular maintenance.

In some cases (for example building owner/partial tenant) the entity procuring the maintenance is not the entity that benefits from the reduced costs or improved performance, which can create a split-incentive in the procurement of maintenance for energy efficiency.

Several surveys have looked at the prevalence of the three main maintenance strategies within the refrigeration and air conditioning sectors.

Table 8: Maintenance strategy prevalence within the RAC sectors.

Survey focus/sector	Maintenance strategy applied		
	Reactive (%)	Preventative (%)	Predictive (%)
Building maintenance[22, 73]	55	31	12
Commercial HVAC maintenance[257]	66	18	16
Commercial refrigeration[78]	80	20	
Australian HVAC&R[76]	60	30	10
Australian commercial HVAC&R[79]	-	21	
Top performing industrial[73] (non RAC)	<10	25 to 35	45 to 55

Even when an owner is informed about a fault on the system there is no guarantee that the owner will take the recommended corrective actions.[15] Understanding and accounting for the complex relationship between the maintenance service provider and the owner is an important part of the RAC energy efficiency puzzle.

Comprehensive maintenance packages that typically bundle preventative and reactive maintenance costs together, may not specifically target energy efficiency and reducing energy costs. Maintenance procurement can be used to incentivise energy efficiency by including energy targets and key performance indicators in all maintenance contracts.

5.7 *What is energy efficiency maintenance?*

Maintenance to maximise energy efficiency is predictive maintenance combining condition monitoring techniques and fault detection and diagnosis.[81]

As AIRAH DA19[53] notes:

'Due to the mega-trends of population growth, urbanisation, and the information technology revolution, the Australian economy depends on reliable, effective and efficient HVAC&R like never before, which means it also depends on reliable, effective and efficient HVAC&R maintenance like never before. HVAC&R maintenance is also widely acknowledged as a fundamental step towards achieving a net-zero emissions future'.

Good maintenance practice can improve energy efficiency, increase the reliability of refrigeration systems and reduce refrigerant leakage. These processes have traditionally been based on visual and manual inspection and judgement but are increasingly becoming automated through digitalisation.

A properly functioning predictive maintenance program can provide a savings of 8% to 12% over a program utilising preventive maintenance alone.[73]

Many end users have a relatively poor understanding of how to diagnose energy wasting faults on refrigeration systems – they need to be encouraged to monitor performance and helped to identify the reasons for poor efficiency. Automated systems for energy use and fault detection and diagnosis can help end users achieve cost effective monitoring.

Examples of maintenance activities to target energy would include:

- Maintenance for leak minimisation – refrigerant leakage significantly affects energy efficiency;
- Assessing actual refrigerant charge against design/optimal refrigerant charge;
- Cleaning heat transfer surfaces;
- Following each component manufacturer maintenance instructions;
- Review of the installation for deficiencies;
- Sealing/repairing of the building envelope and system ductwork, where relevant;
- Review of design assumptions and calculations for continued validity;
- Examination of controls and settings, recalibration of sensors;
- Logging and ongoing analysis of monitoring information - flows, pressures, temperatures, energy use, refrigerant leakage rate, etc.
- Setting Key Performance Indicators for maintenance delivery.

Examples of maintenance activities to target refrigerant leakage would include:

- Instigation of a regular leak inspection program, with follow up rectifications;
- Set-up of an ongoing monitoring system (automatic and/or log-based leak detection);
- Set up of refrigerant detection and/or AFDD for refrigerant leakage;
- Setting Key Performance Indicators for refrigerant management; and,
- A system review and audit, with follow up rectifications.

5.8 *Smart maintenance*

Traditionally maintenance tasks have been as much about visual and physical inspection - gathering data, assessing information, recording results – as about manually repairing components. Advances in digital technologies now provide opportunities for digitalisation of many maintenance tasks, services and solutions. Equipment and system data can be automatically recorded on system controllers, relayed by wireless sensor networks, analysed by cloud-based machine learning algorithms and ultimately visualised on mobile computing devices, generating alarms and recommended actions, even providing specialist technical instructions to the maintenance service provider.

This digitalisation of maintenance is disrupting traditional practices and creating new value opportunities, and DA19 terms this technical development as smart maintenance.

Information technology in maintenance can help to facilitate both the management and delivery of maintenance. Some of the relevant systems that can be used in smart maintenance include:

- Computer maintenance management systems (CMMS);
- Building management and control systems (BMCS);
- Energy management systems (EMS);
- Digital monitoring and metering systems;
- Automatic Fault Detection and Diagnosis (AFDD);
- Internet of Things (IoT);
- Cloud-based Software as a Service (SaaS);
- Mobile and wireless devices:
- Smart Tags; and,
- Diagnostic and handheld tools.

As in any digital system, data needs to be stored and adequately protected and backed up, with appropriate cybersecurity protocols applied.

6 Conclusion

This study concludes that there is significant potential to reduce the electricity consumption and leaks of refrigerant from large stocks of RAC equipment if that equipment was subject to more frequent maintenance.

Some of the common maintenance practices that would deliver improvements in operating efficiency would also have the effect of avoiding or reducing emissions of refrigerant gas.

The research has shown minimising unnecessary faults and energy wastage in RACHP requires:

1. Good installation/commissioning practices;
2. Good maintenance practices; and,
3. Equipment monitoring and metering for fault detection including leak detection, energy meters, airflow sensors to initiate early alarm, and/or field diagnosis, and/or repair procedures.

The maintenance activities that deliver both improvements in energy efficiency and reductions in loss of refrigerant charge require skilled technicians with the appropriate licensing, knowledge and understanding that is common and accepted practice in the RAC community. Failure to properly and regularly maintain equipment is primarily an economic outcome, where equipment owners do not understand the value of routine maintenance in reducing operating costs and avoiding business disruptions (from break downs).

In some cases, and classes of equipment it may also simply be the case that equipment owners are insufficiently aware that equipment requires routine (at least annual) maintenance to continue effective operation over the design life of the equipment.

7 Appendix A1: Technology format: Opportunity table

	Installation	Leak minimisation	Maintenance	Emission benefit (direct and indirect)
Small AC (self contained)	No	None identified	No	Minimal
Small AC (non-ducted)	Yes	Some	Some	Yes
Ducted AC (split and package) and light commercial AC	Yes	Commercial only - manual every 6 to 12 (incl. ducted systems upwards)	Yes, mostly commercial only	Yes
Central plant (chillers)	Yes	Manual every 6 to 12 months with auto on larger systems	Yes	Yes
Transport refrigeration	Yes	Yes	Yes	Yes
Domestic refrigeration	No	None	No	No
Self-contained equipment	Some types	Mostly none - manual every 12 months on larger systems	Yes, some types (e.g. harsh applications only, etc.)	Minimal, some types can be identified
Remote condensing units	Yes	Manual every 6 to 12 months with auto on larger systems	Yes	Yes
Supermarket	Yes	Automatic leak detection	Yes	Yes, mostly independents
Central plant (cold storage and process)	Yes	Automatic leak detection	Yes	Yes, only regulated refrigerants are within scope
Small MAC	No	None identified	No	No
Large MAC	No	Manual every 6 to 12 months	Yes	Yes

8 Appendix A2: The basics

All vapour compression refrigeration systems, irrespective of the application or the format, employ a sealed refrigerant circuit that includes an evaporator, where a refrigerant gas expands to create the adiabatic cooling effect, and a compressor, where the refrigerant gas is compressed to go through the circuit again, and a condenser where the compressed refrigerant sheds the heat produced by being compressed, cooled by either air (typically atmosphere), water or possibly the earth.

Vapour compression refrigeration system

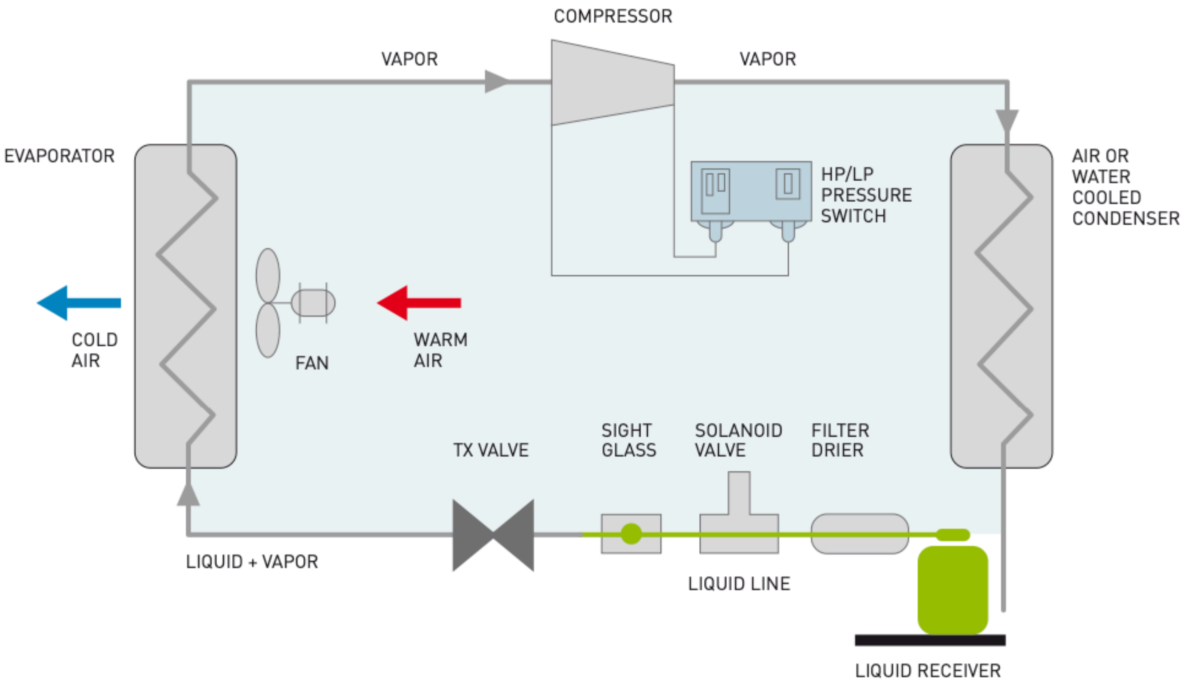


Figure 8: Typical single stage vapour compression refrigeration system.

The evaporator and the compressor/condenser are generally on opposite sides of a wall or insulated barrier. Incorporated in a vapour compression refrigeration system can be any number of components but almost always including at least an expansion device to control refrigerant flow, fans to both circulate chilled air into the space being cooled and to pass air over the condenser to dissipate heat, air filters, and possibly pumps where water chilling is involved.

The efficiency of the system reflects the overall efficiency of the electrical drives of the compressors, fans and pumps, the effectiveness of the insulation, and the efficiency with which the heat is exchanged across the surfaces of the evaporator and the condenser coils. In situations where air is being distributed via ductwork, or chilled water is being distributed in pipe work, the design and installation of the ducting and pipework also has an impact on total system efficiency.

When the efficiency of the heat exchange falls, the compressors, fans and pumps work harder to maintain the conditions (internal temperatures) that the control settings call for, consuming more and more electricity to deliver the required conditions.

While new equipment designs can deliver improved efficiency, and effective insulation and sealing is central to creating and maintaining refrigerated, or comfort conditions in a space or building, the major determinants of the efficiency of the vapour compression refrigeration system is the efficiency with which the heat is transported within the system and transferred at the evaporator and condenser heat exchangers.

System efficiency falls for several reasons including from sub-optimal refrigerant charge, physical and biological coatings building up on the surface of the evaporator and condenser, and poor air flow because of blocked filters or obstructions to air intakes. Almost all these common causes of poor system performance can be traced to either poor installation of the equipment in the first place or, more commonly, a lack of equipment maintenance.