Ammonia in Traditional HFC Territory.

Stefan S. Jensen, F.AIRAH
(B.Sc.Eng. FIEAust, CPEng, M.IIAR)

Scantec Refrigeration Technologies Pty Ltd
225 Queensport Road
Murarrie, Brisbane QLD 4172
ssjensen@scantec.com.au

ABSTRACT

During the lead-up to the historic passing of the Carbon Tax Bill in the Australian Senate in November 2011, refrigeration plant users explored ways of minimizing the impact of this new legislation. Not only does the legislation assign a price on carbon pollution thereby increasing electricity costs. It also includes a special levy on hydrofluorocarbon (HFC) refrigerants. The latter has increased the retail price of HFC's by 300 to 500% as of July 2012.

There are several pathways available to refrigeration and air conditioning plant users of avoiding the impact of the levy on HFC refrigerants. It has been a common misconception that these pathways are generally characterized by a capital cost penalty and lack of acceptable benefit(s) in terms of return on additional investment.

By way of practical, real life comparisons, this paper details the end-user business benefits associated with considering ammonia in those medium size applications, which prior to the advent of the Carbon Tax Bill were reserved for HFC refrigerants.

These real life comparisons are based on four dual stage ammonia refrigeration systems in different geographical locations in Australia ranging from temperate to subtropical environments. The plant designs are characterized by the application of a range of relatively innovative design concepts including automatic ambient air defrost in frozen storage facilities, automatic oil return and oil distribution to the compressors, office air conditioning by means of ammonia refrigerant, variable speed drive semi-industrial and industrial reciprocating compressors, employment of secondary refrigerant in chilled storage rooms, automatic venting of ammonia vapours from frozen storage rooms in the event of leaks, floating evaporating and condensing pressures and so on.

The facilities described would traditionally have been reserved for HFC based refrigeration systems. This is commercial reality based on plant capital costs, plant simplicity, the cost of electrical energy and the cost of maintenance. The paper describes the decision process on the part of the four end users that led to a departure from traditional thinking and what the practical and commercial consequences have been of a decision in favour of natural refrigerants and high energy efficiency plant design.

In the case of one particular end user, the paper will compare the annual energy consumption of two facilities that are almost identical in terms of floor area and refrigerated volume, but where the two facilities are serviced by two different types of refrigeration systems. One plant is serviced by a traditional HFC based refrigeration system, the other by a new generation ammonia based refrigeration system.

1. INTRODUCTION

The Australian Governments Clean Energy Future (CEF) Plan was first released 10 July 2011 and came into effect 1 July 2012. The objectives of the plan are to reduce pollution and to drive investment in lower polluting industries. Part of the plan is a carbon equivalent levy applicable to the six Kyoto Protocol gases carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride. This carbon equivalent levy is a direct function of the Global Warming Potential (GWP) of the fluid. For the calculation of the magnitude of levy, the Australian Government uses the GWP values of Assessment Report 2 (AR2) of the International Panel of Climate Change (IPCC). For the year 1 July 2012 to 30 June 2013, the levy applicable is \$23.00/ton of CO_2e. The term CO_2e refers to the equivalent warming impact of a chemical with CO_2 as the base of one (1). Using HFC404A with a GWP of 3,260 as an example, the levy payable upon importation is therefore 23*3.260=\$74.98 per kg. This does not include the non-carbon price import levy of \$165/ton. The non-carbon price import levy was introduced by the Australian Government prior to the introduction of the carbon equivalent levy. It does also not include the cost of the refrigerant itself, supply chain margins, labour to charge systems etc. To assist all stakeholders in calculating the levy, the Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC) has published a "Calculator for the Import Levy and Equivalent Carbon Price for SGG's and SGG/HCFC blends".

The levy has been fixed for the first three years from 2012 to 2015 at the values shown in Table 1.

Period	Carbon Price/metric ton
1 July 2012 – 30 June 2013	\$23.00
1 July 2013 – 30 June 2014	\$24.15
1 July 2014 – 30 June 2015	\$25.40

Table 1. Carbon equivalent levy applicable to HFC refrigerants

From 2015 onwards the carbon price will be market based except for synthetic greenhouse gases (SGG's). The Government has introduced funding programs to assist industry in the transition towards lower GWP technologies. One such program is the Clean Technology Investment Program (CTIP), which delivers grants of 50% of the cost of projects up to \$1,000,000. Another program is

Low Carbon Australia, which provides loans at favourable conditions for transition projects. The carbon equivalent levy applies to all imports and manufacture of the gases mentioned above. It also applies to those same gases imported in equipment. There are exemptions for veterinary, medical or Work Health and Safety reasons, but these are rare. Examples are inhalers for asthma patients and some foam products where the gas content cannot be assessed without destroying the product. The legislation provides for levy refunds if the fluid is exported. Effective July 2013 an incentive will be introduced for destruction of waste SGG's. In effect this will be a refrigerant buy-back program where the Government will return part of the levy following verification of the destruction of the gas.

2. THE FOUR REFRIGERATION PLANTS

This chapter summarizes the fundamental design details of the ammonia refrigeration systems and the equivalent, traditional HFC based systems that are being compared theoretically and practically. The technical data of the four ammonia refrigeration plants are summarized in Table 2.

Segment	**1**		**2**	
Geographic location	Brisbane	Mackay	Tweed Heads	Sydney
Design refrigeration capacities, low/high temperature, [kW]	133/140	110/164	70.0/72.0	83.3/78.5
Operating conditions, ET/IT/CT, [°C]	-33/-10/35	-33/-9/35	-30/-10/33	-32/-11/33
Compressor shaft power, P_L/P_H, [kW]	24.3/79.4	20.6/78.7	12.2/46.0	14.2/50.1
Condenser type	Evaporative	Evaporative	Evaporative	Evaporative
Refrigerant feed LT/HT (LR=liquid overfeed; F=Flooded)	LR/LR	LR/LR	F/F	LR/F
Secondary refrigerant (MT=medium temperature)	-	MT	MT	MT
Defrost for freezer segment	Hot Gas	Ambient Air	Ambient Air	Ambient Air
Freezer evaporator type	IDC	Alcove	Alcove	Alcove

Table 2. Technical Data of the Four Ammonia Refrigeration Systems

The four plants are grouped into two segments each comprising two systems. The segmentation is based on similarities with respect to compressor types, compressor swept volumes, plant capacities and so on. The two larger plants in the first segment employ industrial reciprocating compressors; the two smaller plants in the second segment are based around semi-industrial compressors and the use of a secondary refrigerant for all medium temperature services. All plants service refrigerated distribution facilities.

Plan layouts of the distribution facilities are reproduced in Figures 1, 2, 3, 4 and 5. The Brisbane, Mackay and Sydney facilities are new developments. The Tweed Heads facility was an existing cold store, which prior to the upgrade was serviced by an HFC based refrigeration system. The Tweed Heads extension coincided with the replacement of the existing HFC plant with the new, dual stage ammonia plant. Prior to the Tweed Heads upgrade, the chiller/freezer volumes were approximately 1400/1400 m³ respectively. Following the upgrade, these chiller/freezer volumes increased to 1750/4180 m³ respectively.

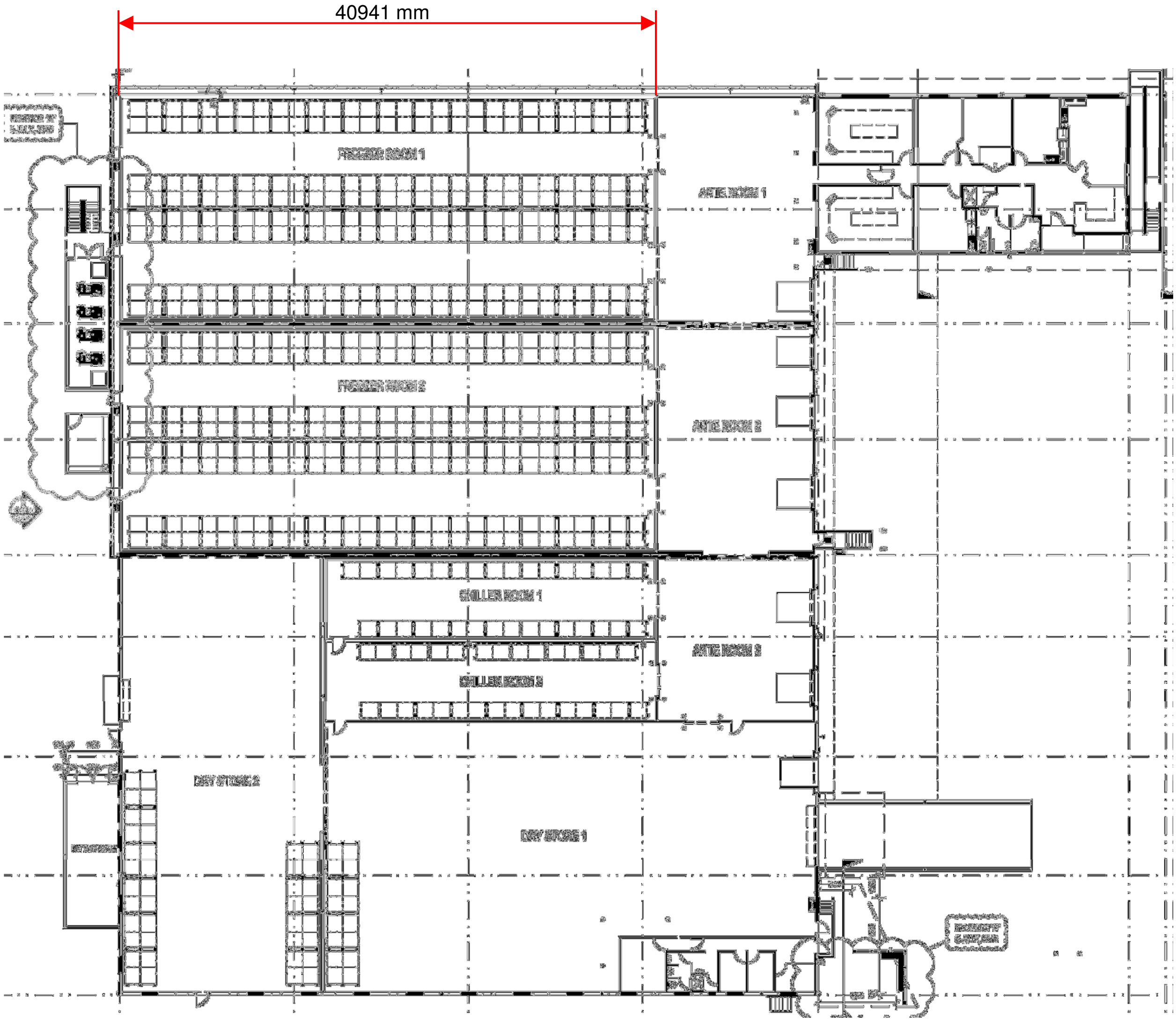

Figure 1. Plan View of Brisbane Distribution Facility

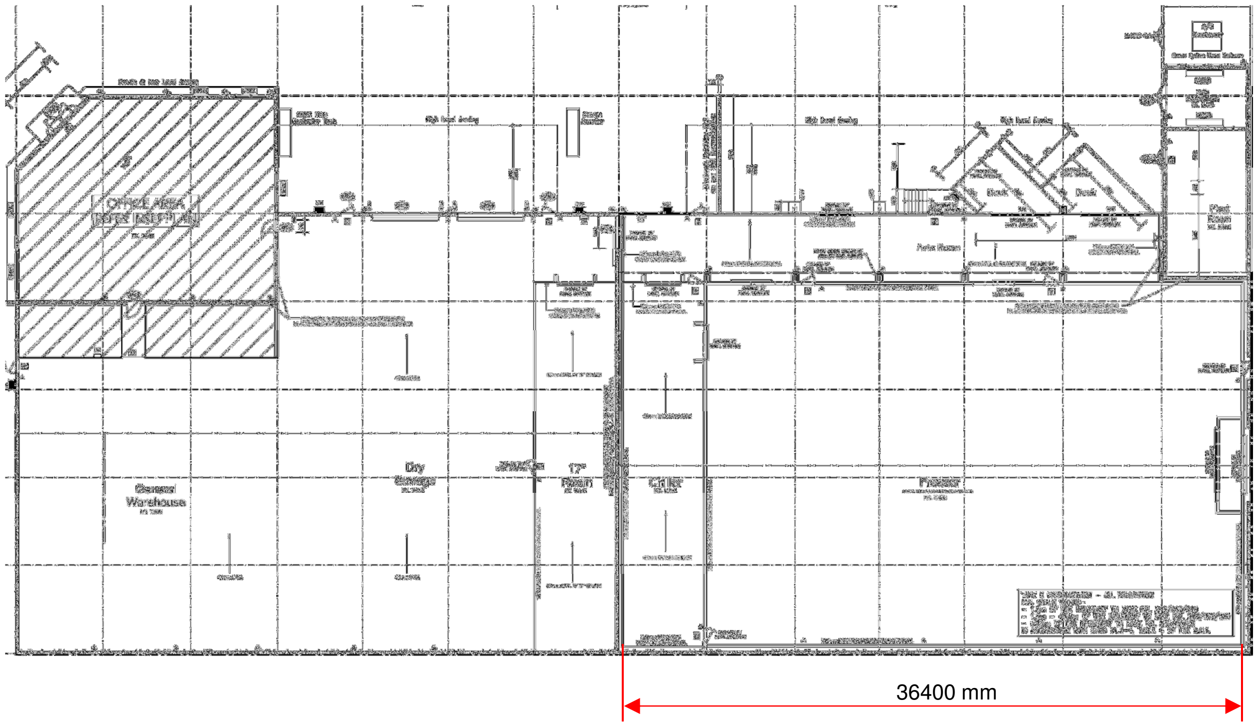

Figure 2. Plan View of Mackay Distribution Facility

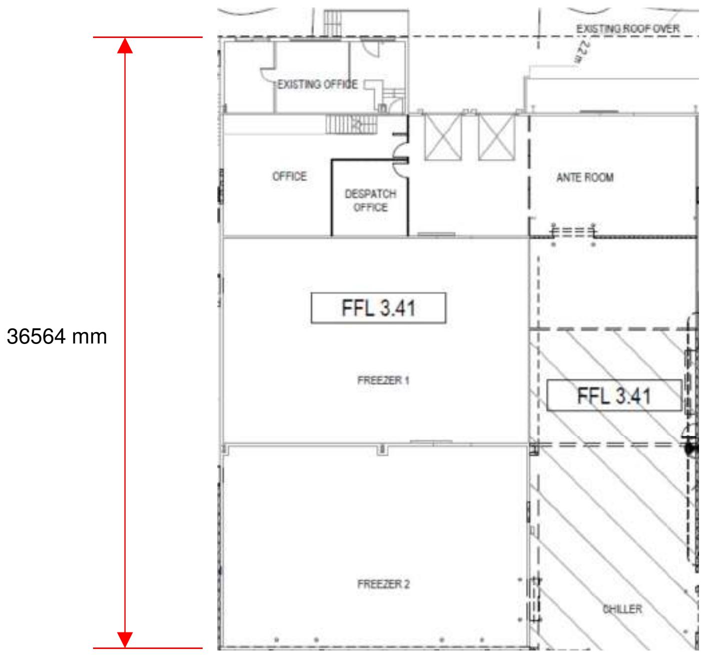

Figure 3. Plan View of Tweed Heads Distribution Facility prior to the Extension

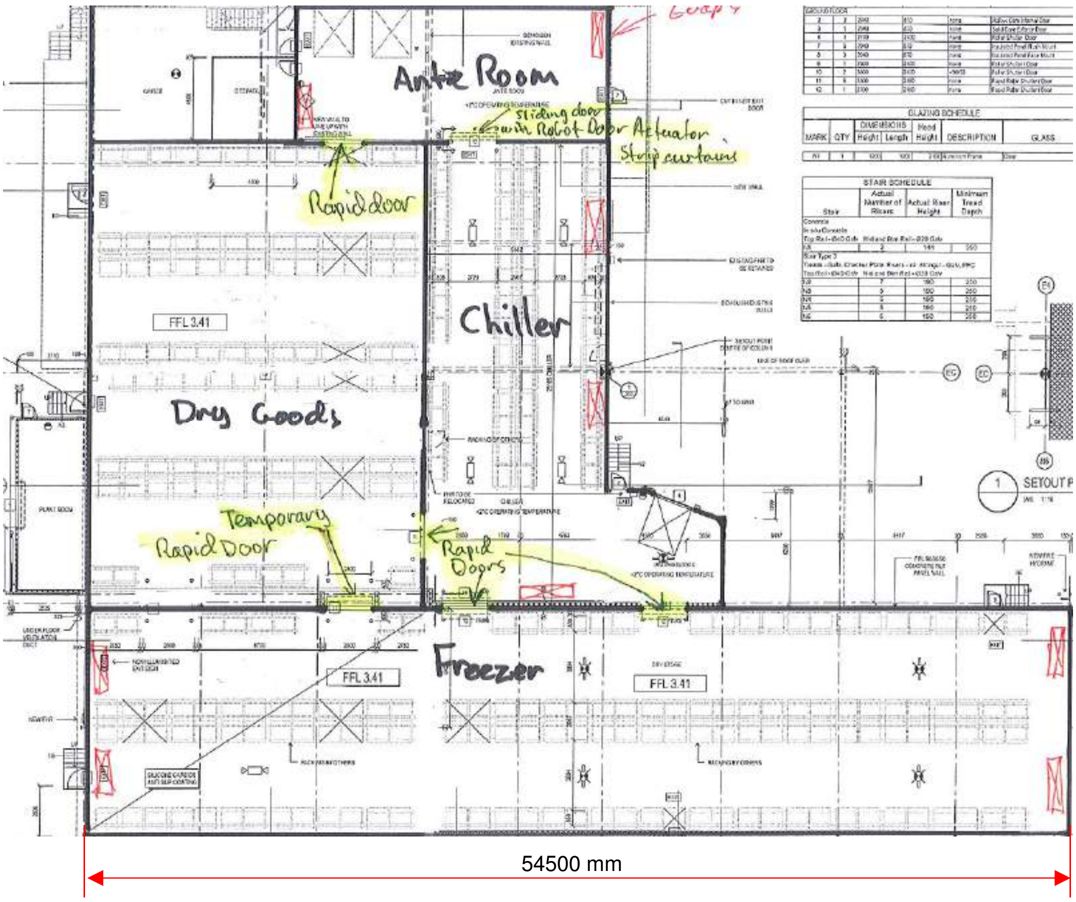

Figure 4. Plan View of Tweed Heads Distribution Facility after the Extension

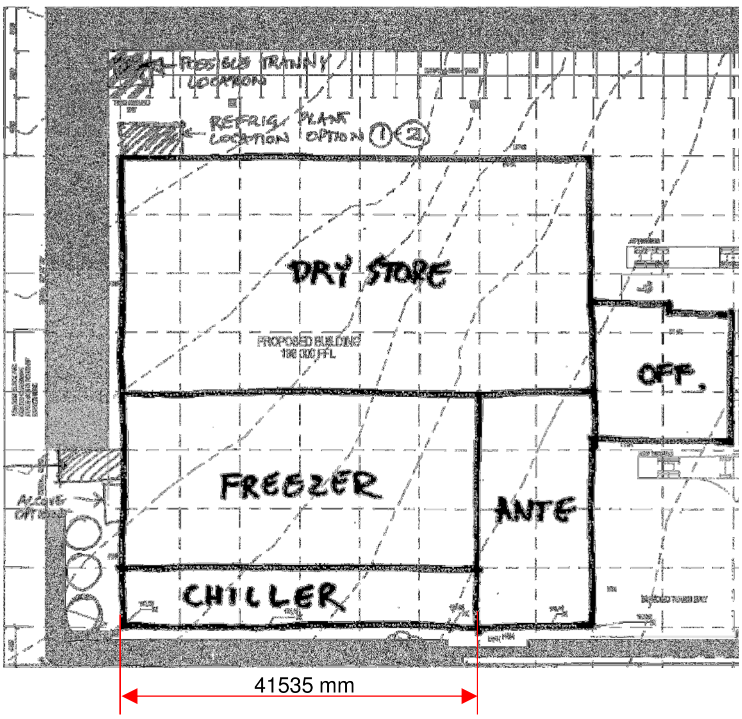

Figure 5. Plan View of Sydney Distribution Facility

The term IDC in Table 2 refers to an Induced Draught Cooler. An example of an alcove evaporator is shown in Figure 6.

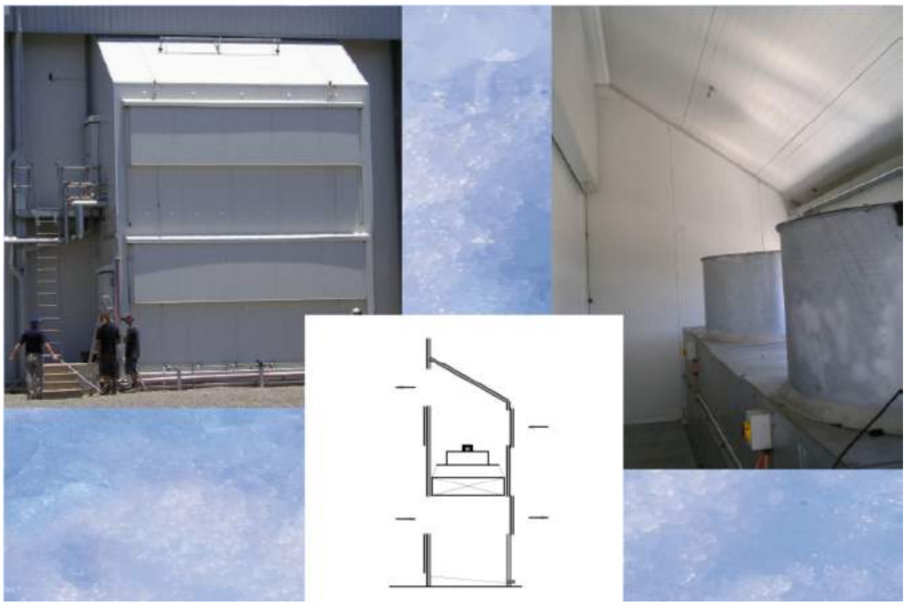

Figure 6. Single Coil Alcove Unit

The four HFC 404A plants that were being contemplated for the same applications are summarized in Table 3.

Segment	**1**		**2**	
Geographic location	Brisbane	Mackay	Tweed Heads	Sydney
Design refrigeration capacities, low/high temperature, [kW]	133.6/168.0	142.2/185.6	93.2/54.8	87.6/85.2
Operating conditions, ET/MT/CT, [°C]	-33.5/-8.5/46.0	-34.0/-7.0/48.0	-31.0/-7.0/46.0	-32.5/-7.0/48.0
Compressor shaft power, P_L/P_H, [kW]	127.4/74.6	154.2/104.4	81.8/27.8	81.0/44.2
Condenser type	Air cooled	Air cooled	Air cooled	Air cooled
Refrigerant feed LT/HT	Dry expansion	Dry expansion	Dry expansion	Dry expansion
Defrost for freezer segment	Electric	Electric	Electric	Electric
Freezer evaporator type	IDC	IDC	IDC	IDC

Table 3. Technical Data of the Four HFC 404A based Refrigeration Systems

Note that the minor variations in refrigeration capacities between Table 2 and Table 3 are a result of minor building changes between the initial HFC design and the final ammonia design. Some discrepancies are also a result of capacity steps between compressor capacities and the need for redundancy.

The connected electric power for the refrigeration plant is in many jurisdictions also important because it affects the structure of the energy charges. Secondly, the cost of the dedicated transformer for a new facility is often the responsibility of the facility owner. Table 4 provides a comparison of connected total electric power for the HFC and NH_3 systems that are the topic of this paper. The connected power includes all auxiliary equipment such as fans, pumps and electric defrost heaters.

Segment	**1**		**2**	
Geographic location→	Brisbane	Mackay	Tweed Heads	Sydney
HFC, [kW]	482	417	247	294
NH_3, [kW]	273	248	157	153
Difference, [kW]	209	169	90	141

Table 4. Connected Electric System Power.

3. THEORETICAL ENERGY PERFORMANCE COMPARISONS

Ammonia refrigeration systems are in most cases more capital cost intensive than HFC based refrigeration systems of equivalent refrigeration capacity. In most cases there are also a number of benefits associated with ammonia compared with HFC based systems. Quantification of these benefits to the user/owner of the refrigeration plant is what drives the investment decision in favour of ammonia.

In jurisdictions where unit energy costs are comparatively high, the energy consumption over the life of the plant should be one of the most important investment decisions. In this context the emphasis is on the expression “should be” because there are examples where the energy costs are either not considered at all, are considered to be constant whatever the plant type or are viewed as being relatively unimportant compared with system capital costs. It is, of course, also not in the commercial interest of proponents of low capital cost systems featuring high energy consumption to disclose lifecycle cost details to the investor. In view of the fact that the energy consumption cost over the life of a refrigeration system is often several times the initial capital outlay, ignoring energy performance comparisons between plant alternatives can be an expensive error.

Evaluation of annual energy performances for systems is often associated with complicated computer models taking into account a large number of variables. For relative energy performance comparisons between system concepts (investment proposals), simpler methodologies can be useful and can exhibit sufficient accuracy for the investment decision. An example in relation to the Brisbane based plant in Table 2 demonstrates this; for details refer to Appendix 1 showing the detailed calculation for plant "A". A summary of the results of this relatively simple manual calculation using a spread sheet is provided in Table 5.

Plant concept	A	B	C
Energy consumption, [MWh/a]	635	942	1248
Energy consumption, [kWh/m³a]	25.3	37.5	49.6
Annual energy cost	$132,000	$196,000	$259,000

Table 5. Relative Energy Performance Comparison for the Brisbane Plant of Table 2.

These are based on a unit electrical energy cost of $150/MWh, a power factor of 0.85 and an overall electric motor efficiency of 0.85. The plant concepts A, B and C are described below.

A) Dual stage ammonia (NH_3) refrigeration system with reciprocating compressors (rotational speed ≤ 970 rpm), liquid overfeed at both temperature levels, alcove evaporators with automatic ambient air defrost for the freezers, ceiling mounted induced draught air coolers for the high temperature areas, six pole fan motors for all air coolers, stainless steel/fiberglass evaporative condenser oversized by a factor of 1.23 and variable frequency fan drives throughout except in the Ante Rooms.

B) Ammonia refrigeration system with two single stage economized screw compressors for the freezer rooms, gravity flooded refrigerant feed for the low temperature segment, alcove evaporators with automatic ambient air defrost for the freezers, ceiling mounted induced draught air coolers for the high temperature areas, two reciprocating compressors for the high temperature areas, glycol reticulation for the high temperature areas, six pole fan motors for all air coolers, adiabatically assisted air cooled condensers at both temperature levels and variable frequency fan drives throughout except in the Ante Rooms.

C) HFC refrigeration system (R404A) comprising four single stage economized screw compressors (three duty and one standby) two of which service the freezer rooms and one which services the high temperature areas, dry expansion refrigerant feed throughout, ceiling mounted induced draught air coolers, electric defrost for freezers and chiller, common air cooled dual circuit condenser, air cooled oil cooler for the freezer compressors, six pole fan motors for all air coolers and condensers and variable frequency fan drives throughout except in the ante rooms.

The methodologies behind the calculations in Appendix 1 are in summary:

- Peak hours represent ~250 operating days/annum of 8 hours each; these hours are taken as being those from 8 a.m. to 4 p.m.
- Shoulder hours represent week days after hours; these hours are taken as being those from 4 p.m. to 8 a.m.
- Minimum hours represent non-peak and non-shoulder hours; these hours are therefore predominantly week-end hours and public holidays
- Heat loads are calculated at the average conditions matching the hours,
- Compressor speeds and shaft power are calculated to match loads,
- Condenser fan speed is varied linearly with heat rejection,
- Condenser spray pump operates at full capacity constantly,
- Ammonia pumps operate at full load constantly,
- Fan power is reduced by speed reduction cubed,
- Subfloor ventilation fan operates at full capacity constantly,
- Engine room ventilation fan power is varied with ambient temperature

The energy bill reproduced in Figure 7 verifies that the simplified energy performance modeling is sufficiently accurate for the purposes of arriving at an appropriate investment decision. The energy consumed over 56 billing days is 106.5 MWh for the entire site. This value includes light and power for the offices and some office air conditioning. Empirically for facilities such as this, light and power accounts for around 20-25% of the total electrical energy consumed. The billing period is also for the cooler autumn/winter months so a 15-20% increase can be anticipated for the summer period from December to end of February.

Account period:			07 Apr 2011 to 02 Jun 2011 - Bill Days 56			
Next anticipated reading:			02 Sep 2011 (± 2 business days)			

Electricity Tariff - Tariff 20 - General Supply

	Meter Number	Previous Reading	Current Reading	Usage kWh	@Rate c/kWh	Amount $
Peak Use						
Peak	1326765	0	306.2 [1]			
	1326765	0	34.6 [2]			
	1326765	0	324.7 [3]			
				106480	21.7500	23,159.40

[1] Your base usage of 306.2 is multiplied by 160 to calculate Total usage
[2] Your base usage of 34.6 is multiplied by 160 to calculate Total usage
[3] Your base usage of 324.7 is multiplied by 160 to calculate Total usage

Other Charges	
Service to Property	24.94

Figure 7. Energy Bill for the Brisbane Plant

Based on these assumptions, the energy consumption for the refrigeration plant based on meter readings may be estimated:

$$(106.5/56*182+106.5/56*183*1.2)*0.8=611 \text{ MWh}$$

where the factor 0.8 represents the 80% of the total consumed by the ammonia plant and the factor 1.2 represents the approximate increase in plant energy consumption between summer and winter. The corrected annual meter reading of 611 MWh is close to the estimate of 635 MWh in Table 5, which was actually the estimate that the client based the investment decision on. An interesting detail in Figure 7 is that the unit cost of electricity is significantly higher than the value used in Table 5. Applying a unit electricity cost of $0.2175/kWh in Table 5 would increase the annual electricity cost difference between “A” and “C” from $127,000 to around $184,000.

4. QUANTIFIABLE BENEFITS OF NH_3 OTHER THAN ENERGY

Compared with a single stage HFC 404A system, the example in Table 5 indicates a substantial energy consumption cost advantage associated with a dual stage ammonia plant. The energy consumption cost advantage will of course escalate with increasing unit electricity costs as demonstrated in the preceding chapter. Other quantifiable benefits are a) Immunity to any environmental legislation and synthetic refrigerant levies, b) Low refrigerant leakage rates and c) Longer technical plant life.

The immunity to environmental levies has recently become highly relevant in Australia following the introduction of the carbon equivalent levy on those synthetic refrigerants with high global warming potential. Mounting scientific evidence that continued unabated release of HFC refrigerant may be responsible for 28-45% of projected global CO_2 emissions (CO_2e basis) by 2050 [1] will most likely lead to further restrictions of their use world-wide. Based on a recent verbal survey among industrial refrigeration practitioners within AIRAH, leakage rates in modern ammonia refrigeration systems have been reduced to <1% of the system charge per annum. Compared with HFC systems, this is exceptional. In Australia, the working bank of HFC/HCFC/CFC refrigerants is officially estimated at 40,100 metric tons; the annual service consumption rate is estimated at 9% [2]. Applying this annual service consumption rate to plant "C" of Table 5 would give rise to an annual R404A replenishment cost of $8,000-$10,000. The low ammonia system leakage rates are a result of the high safety standards that are applicable, the materials of construction and the skill levels of designers, installers and maintenance staff [2]. The longer technical life of ammonia refrigeration plants compared with equivalent HFC systems is a reflection of the traditionally more industrial approach to component and system design displayed by ammonia practitioners. This in part explains the usually higher cost of ammonia plant, but "you get what you pay for" as this paper attempts to show.

5. QUANTIFIABLE PENALTIES ASSOCIATED WITH NH_3

It is a common generalization that ammonia plants are more maintenance intensive than HFC systems. These generalizations often originate from proponents of synthetic refrigerants in their attempts to disadvantage ammonia and other natural refrigerants. Traditionally ammonia has not been used extensively in small systems similar to those described here. In addition, ammonia plants are often also subjected to strict maintenance regimes due to the properties of the fluid. Thirdly, there is of course a return associated with spending money on good maintenance – this in part explains the much lower refrigerant leakage rates of NH_3 plants compared with HFC systems. It is therefore relatively difficult to verify such generalizations in relation to maintenance costs on the basis of practical experience. Most competent ammonia practitioners will most likely be sufficiently commercially courageous to offer five years warranty on the refrigerant charge provided the prescribed maintenance regime is complied with. Although this is far from common practice, it is proposed as a relatively low risk way (for the contractor) of providing an additional competitive advantage over proponents of less capital cost intensive HFC systems. It is unlikely that providers of HFC systems are in a position to match this.

The lack of miscibility between traditional refrigeration machine oils and ammonia is, however, an issue if ammonia is to compete with HFC's in small to medium size systems such as those described here. Owners and operators of such systems do generally not have full-time maintenance staff employed and regular oil drainage is therefore a significant operational cost. Figure 8 shows an automatic oil drainage and distribution system for the small dual stage ammonia refrigeration plant with five compressors servicing the facility shown in plan view in Figure 4.

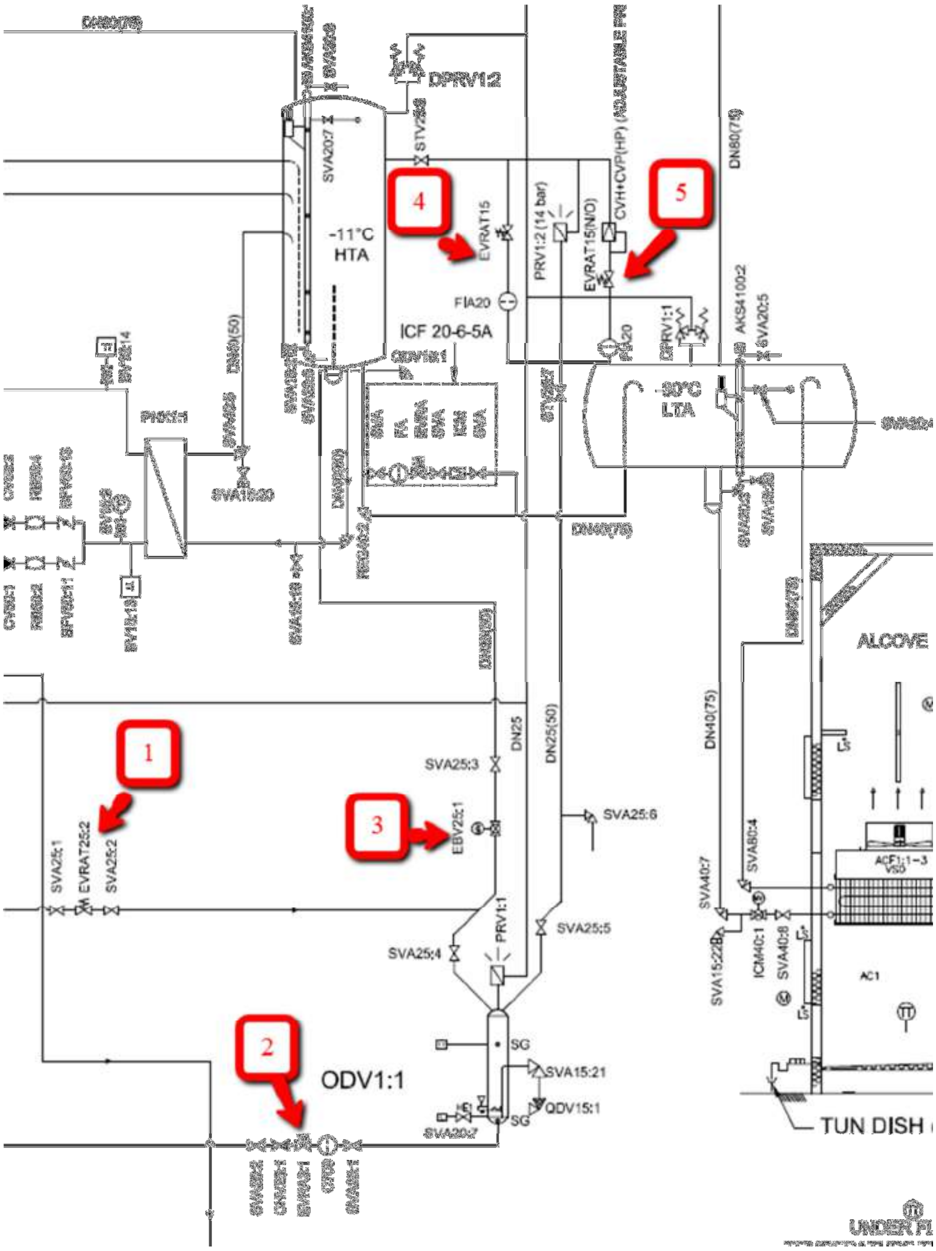

Figure 8. Automatic Oil Return System

Based on experience to date, this system can extend the time intervals between service visits to three months. During normal operation solenoid valve #1 that supplies hot gas to the oil transfer vessel ODV 1:1 is closed. The same applies to solenoid valve #2, which transfers oil from the oil transfer vessel back to the second stage compressor oil separator. The ball valve #3 and the solenoid valve #4 are both open during normal operation. This permits refrigerant circulation through the oil drain vessel by means of the thermosyphon effect. The automatic oil transfer is initiated by means of a temperature sensor in the top of the oil transfer vessel. Oil transfer occurs by closing ball valve #3, initiating and maintaining oil transfer vessel electric heater operation until all refrigerant is vaporized and returned to the intercooler (timer controlled), closing solenoid valve #4, closing solenoid valve #5, opening solenoid valve #1 and opening solenoid valve #2. During oil transfer from the oil transfer vessel to the second stage compressor oil separator, a differential pressure regulator in the second stage compressor discharge line (not shown) establishes a small differential pressure between the oil drain vessel and the second stage oil separator. Transfer of oil from the second stage compressor oil separator to the booster oil separator is initiated by means of a level sensor in the booster oil separator.

To minimize refrigeration system energy consumption in most Australian jurisdictions, it is necessary to substitute air cooled condensers with either water cooled condensers, evaporative condensers or air cooled condensers with adiabatic assistance. The water consumption associated with the application of any of these evaporative devices represents an additional operating cost, which partly offsets the energy cost savings. Following the 10 year drought between 2000 and 2010 and the resulting escalations in water costs, it has become common practice to collect rainwater from the roof of refrigerated distribution facilities. In the bottom left hand corner of Figure 5 and in Figure 9, examples of these collection and storage systems are shown. Usually a rain water storage capacity of four to six weeks evaporative condenser water consumption delivers a reasonable return of tank capital costs. The supply of rain water to the evaporative condenser has priority over the supply of mains water. This is controlled very simply with two automatic ball float valves fitted within the condenser sump. If the top rain water float fails to supply sufficient water because the rain water tank is empty, then the bottom float valve supplying mains water will start to make up water as soon as the condenser water level has dropped to the level where this second ball float is fitted.

Figure 9. Rain Water Storage Tank for Evaporative Condenser Make-Up Water

6. PRACTICAL ENERGY PERFORMANCE COMPARISONS

The main focus of any plant owner is verification that the refrigeration system energy consumption that was evaluated theoretically at project commencement is delivered at project conclusion. For the four systems that are the topic of this paper, two plants enable a "before" and "after" comparison based on electricity meter readings. Both of these systems are described in segment 2 of Table 2.

In the case of the Tweed Heads facility, the plant was, prior to the expansion, serviced by an HFC system. Electricity consumption records exist for the relevant periods immediately prior to the plant expansion and conversion from an HFC to an NH_3 based refrigeration plant. These electricity records are reproduced in Figure 10. The Tweed Heads plant expansion increased the refrigerated volume by a factor of around 2.1 with the freezer store volume being tripled and the medium temperature volume being increased by a factor of ~1.25.

Wednesday, 1 June 2011 - Thursday, 1 September 2011

15 mins Usage Summary for MeterNMI NFFF00KE0801

Channel	Key	Exception	Total	Average	Minimum	Maximum
KWH (e)			133787.775	15.315	3.615 07 Jul 2011 09:30	26.760 29 Jul 2011 05:00
KW (e)			NA	61.258	14.460 07 Jul 2011 09:30	107.040 29 Jul 2011 05:00
KVA (e)			NA	82.068	21.492 07 Jul 2011 09:30	129.985 10 Aug 2011 04:15
PF (e)			NA	0.748	0.634 12 Jun 2011 06:30	0.984 12 Jul 2011 01:45

Friday, 1 June 2012 - Saturday, 1 September 2012

15 mins Usage Summary for MeterNMI NFFF00KE0801

Channel	Key	Exception	Total	Average	Minimum	Maximum
KWH (e)			179453.940	20.770	0.000 06 Jul 2012 12:30	36.285 24 Aug 2012 16:00
KW (e)			NA	83.081	0.000 06 Jul 2012 12:30	145.140 24 Aug 2012 16:00
KVA (e)			NA	89.610	0.000 06 Jul 2012 12:00	154.923 24 Aug 2012 16:00
PF (e)			NA	0.927	0.867 24 Jun 2012 03:00	1.000 01 Aug 2012 09:00

Figure 10. Electrical Energy Consumption Records for Tweed Heads.

The Sydney facility owner has another very similar facility elsewhere that is serviced by an HFC based system of conventional design generally in line with concept "C" in Table 5. This HFC based cold store is shown in plan view in Figure 11.

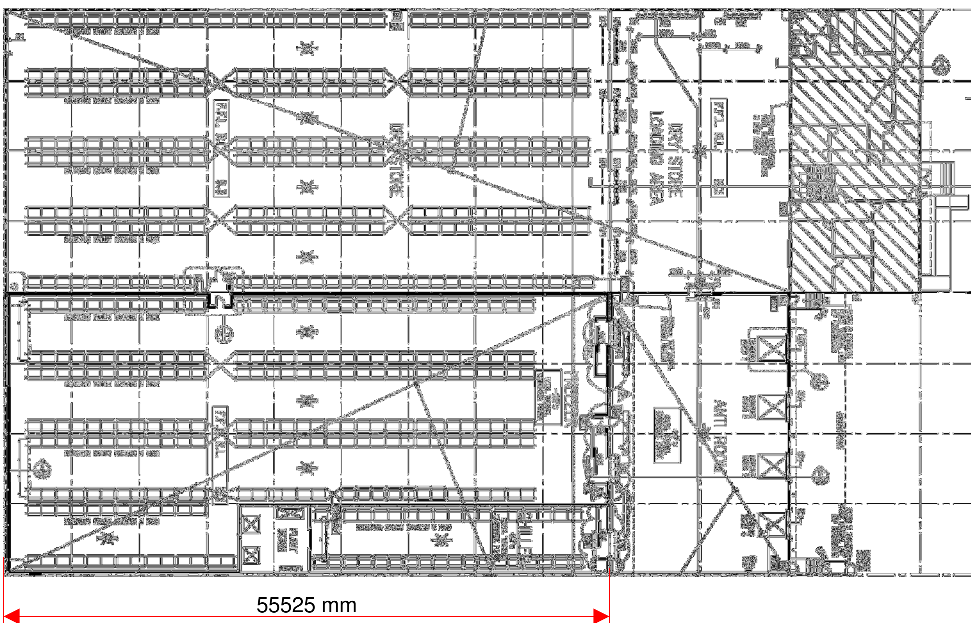

Figure 11. Cold Store Identical to the Sydney Facility, but Serviced by an HFC Plant

A comparison between Figure 5 and Figure 11 demonstrates the similarities between the two layouts. The freezer area in Figure 11 is around 1208 m² and the chiller area 177 m² or a total of 1,385 m². The combined chiller and freezer area for the cold store shown in Figure 5 is around 1130 m².

Table 6 summarizes the energy performance comparisons for the four refrigeration systems.

Segment	**1**		**2**	
Geographic location→	Brisbane	Mackay	Tweed Heads	Sydney
HFC, annual estimated energy consumption, [MWh]	1248	1200	N/A	881
NH_3, annual estimated energy consumption, [MWh]	635	700	N/A	546
HFC, annual measured energy consumption, [MWh]	N/A	N/A	1197	1265
NH_3, annual measured energy consumption, [MWh]	611	735	718	579

Table 6. Energy Performance Comparisons for Four Plants

For the Tweed Heads facility, the measured annual electricity consumption is calculated on the basis of the electricity consumption records prior to the plant expansion and conversion to NH_3. These records were for a freezer design heat load of around 32 kW and medium temperature rooms with combined design loads of 42 kW. The quarterly electricity consumption of 135 MWh (Figure 10) is simply allocated to freezer and medium temperature duties on the basis of loads and system coefficients of performance, which are 0.90 and 1.45 for the freezer and the medium temperature segments respectively. The refrigerated volumes prior to the extension were approximately 1400/1400 m³ for freezer/medium temperature segments respectively. The annual electrical energy allocations for the freezer and medium temperature segments hence become:

$$135*4/(32/0.90+42/1.45)*32/0.90 = 298 \text{ MWh (freezer duty)}$$

$$135*4/(32/0.90+42/1.45)*42/1.45 = 242 \text{ MWh (medium temperature duty)}$$

Increasing the medium temperature volume by a factor of 1.25 and tripling the freezer volume would therefore, if the existing HFC systems had been simply added to, have given rise to an approximate annual electricity consumption of:

$$242*1.25 + 298*3 = 1197 \text{ MWh,}$$

which is the value inserted in Table 6 under the heading measured annual HFC system energy consumption. The annual measured NH_3 system energy consumption for comparison is derived from Figure 10 by multiplying the quarterly record of 179.5 MWh by four.

The annual measured HFC system energy consumption for the Sydney facility is based on the electricity consumption records for the cold store shown in Figure 11 corrected for the difference in floor area. For the period June 1, 2011 to June 30, 2011, the electrical energy consumption was 115.2 MWh; for July 1, 2011 to July 31, 2011, the consumption was 116.1 MWh and for August 1, 2011 to August 31, 2011, the consumption was 121.8 MWh – the total consumption for that quarter was therefore 353 MWh. Annualizing these results and allowing a 5% per month increase for September to November 2011 (spring approaching summer) yields:

$$(115.2+116.1+121.8+127+133+139*4+133+127+122)/1385*1130 = 1265 \text{ MWh}.$$

The measured annual NH_3 system energy consumption for the Sydney system is based on electricity consumption records for about two weeks. The plant was commissioned end of August 2012.

7. FINANCIAL CONSIDERATIONS

For medium to large refrigeration plants it is, to a great extent, superfluous to attempt to convince any user to favour ammonia refrigerant – in most cases one would be preaching to the converted. In that area of application, ammonia has a proven track record of being able to deliver safe, efficient, reliable and long lasting service. In the small to medium capacity plant categories that are the topic of this paper, the use of ammonia needs to be "sold" to a much greater extent. This is because this area has up until now to a very great extent been reserved for HFC based plants. The most prominent argument to be presented to users that may be novices to the introduction of ammonia within their facility is financial. An example of a financial argument is presented in Table 7, which applies to the Sydney installation. The table reflects year 2010 price levels.

Refrigerant	NH_3	HFC
Total engine room shaft power	114.2	264.2
Comparison of annual energy consumption:		
Annual engine room energy consumption, [MWh/a]	546	881
Power factor	0.85	0.85
Electric motor efficiency	0.85	0.85
Unit electrical energy costs, [$/MWh]	150	150
Annual electricity costs, [$/a]	113,314	182,953

Refrigerant	NH_3	HFC
Comparison of annual electrical emission costs:		
CO_2 emission per kWh, [kg/kWh]	1.1	1.1
Annual CO_2 emission, [metric tons/a]	706	1140
Carbon Tax charge, [$/t of CO_2e] (1.7.2012-30.6.2013)	23	23
Annual emission penalty post 1.7.2012, [$]	16,245	26,229
Annual energy costs including emission penalties post July 1, 2012, [$]	129,560	209,182
Refrigerant loss comparison:		
Approximate system charge(s), [kg]	500	500
Annual average loss, [%/a]	1	16
Annual loss, [kg/a]	5	80
Global Warming Potential of refrigerant (GWP)	0	3300
Unit refrigerant costs post July 1, 2012 (CO_2e cost $23/t), [$/kg]	7	101
Annual refrigerant loss costs, [$/a]	35	8,072
Annual water treatment costs, [$]	3,000	0
Total annual operating costs excluding maintenance and water costs, [$]	132,595	217,254

Table 7. Financial Comparison between HFC and NH_3 for Sydney Installation

The difference in annual operating costs of approximately $85,000 is the annual income change that must provide the return on the differential investment between the HFC and the NH_3 based system. In 2010 price levels that differential investment is $323,300; this delivers a simple pay-back period for the differential investment of 323,300/85,000 = 3.8 years.

The financial viability of all four systems based on the value of the electrical energy savings associated with switching to ammonia refrigerant is summarized in Table 8. These simple pay-back periods are to be considered in conjunction with the simultaneous mitigation of the commercial risks associated with HFC losses that an ammonia alternative offers the plant owner. Following the introduction of the carbon equivalent HFC levy such commercial risks are significant and in some cases bordering on extreme depending on the HFC refrigerant in question. For the plant sizes discussed in this paper, the HFC charges would have ranged from ~400 to ~600 kg. At the current unit list price for HFC 404A in Australia of $373/kg, a catastrophic loss of charge could cost the plant owner $149,000 to $224,000. Considering contractor discounting and common supply chain margins, the cost of a catastrophic loss of charge could reduce to $80,000 to $120,000, but this remains a very considerable commercial risk. A decision in favour of an ammonia alternative builds in an insurance against this commercial risk and this has a tendency to encourage decision makers to accept longer pay-back times than would otherwise have been the case.

Segment	1		2	
Geographic location→	Brisbane	Mackay	Tweed Heads	Sydney
Differential capital cost between the NH_3 and the HFC system (+ represents a more expensive NH_3 system), [$/1000]	+499	+454	+264	+311
Approximate value of the measured energy consumption cost reduction associated with NH_3 (- represents energy saving associated with NH_3), [$/1000]	-92	-70	-72	-50
Simple pay-back period for the differential capital cost of the NH_3 system based on energy consumption cost reductions only, [Years]	5.4	6.5	3.7	6.2

Table 8. Simple Pay-Back Period for the Additional NH_3 System Capital Cost based on Energy Consumption Cost Reductions.

The unit electricity cost used is $150/MWh. The additional cost of a dual stage ammonia plant over and above the equivalent single stage, economized HFC based refrigeration system is in 1000's of Dollars. All cost comparisons have been brought forward to the month of September in the 2012 calendar year by applying a CPI (Consumer Price Index) of 3.5% per annum from the time of the cost estimate to September 2012. In those cases where measured energy consumption cost reductions are not available, the simple pay-back period calculation has been based on estimated energy consumption cost reductions using the methodology described in Appendix 1.

8. DISCUSSION

In a society of rising energy costs, ammonia solutions in the small to medium refrigeration capacity range from around 140 kW to 300 kW present themselves as economically very viable. This statement is based on a unit electricity cost of $150/MWh, actual system capital costs and actual energy consumption costs for small to medium size commercial cold storage applications. For various reasons, ammonia refrigeration systems have not been very common in this capacity/plant size range. Some of these reasons are relative insignificance of energy costs to date; prominence of synthetic refrigerant proponents in this market segment, proliferation of standard HFC based solutions, natural refrigerant skills shortages, lack of unbiased information for users, Government red tape and psychological barriers. The energy performances of ammonia solutions, however, speak for themselves.

It is, of course, a business reality that higher capital cost solutions are not always affordable. However, if Governments in many jurisdictions are under pressure to address global warming issues and the conservation of energy is part of addressing this problem, then the next logical step for legislators is to do what is necessary to simplify the implementation of natural refrigerant solutions.

Synthetic HFC refrigerants are powerful contributors to future climate forcing [1]. Owners and operators of refrigerated facilities may not agree that man-made global warming is an issue and may indeed adopt the stance that it is not an issue for them or for the role of their business in society. The introduction of a carbon equivalent levy on HFC refrigerants in Australia is, however, a prime example of how political reality can force the hands of owner/operators and drive change. Carbon taxes, which are or will be a prominent feature in many economies world-wide, will impact upon electricity prices. The carbon tax, which is now a reality increases the unit electricity cost by around $0.025 per kWh. Ammonia solutions have the capacity to address both the issue of fugitive emissions (refrigerant leaks) from refrigeration systems and indirect emissions that are a result of the consumption of electrical energy by refrigeration systems. Ammonia is not subject to any environmental levies. Ammonia has a superior vapour compression cycle efficiency to synthetic refrigerants. Ammonia is therefore part of the solution to the problems faced by many legislators in many jurisdictions.

References

[1] Guus Velders, David W. Fahey, John S. Daniel, Mack McFarland and Stephen O. Andersen. 2009. The Large Contribution of projected HFC Emissions to Future Climate Forcing, *PNAS Early Edition. www.pnas.org/cgi/doi/10.1073/pnas.0902817106*

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Appendix 1

					Energy consumption						
Heat load type →					Peak		Shoulder		Minimum		
Hours at prevailing load →					1920		3840		3000		
Temperature level (LT=Low Temperature; HT=High Temperature)					LT	HT	LT	HT	LT	HT	
Heat loads [kW] →					121.7	160.1	67.4	59.6	50	40	
Heat loads [TR] →					34.7	45.6	19.2	17.0	14.2	11.4	
Location	No. of drives	Drive motors	Drives installed	Nominal power consump-tion							
		[kW]	[kW]	[kW]							
Booster #1	1	18.5	18.5	13.0	13.0		0		0		
Booster #2 (dual duty)	1	75.0	75.0	10.5	8.5		12.0		9.0		
Compressor #1 (dual duty)	1	90.0	90.0	51.3		42.8		34.7		23.7	
Compressor #2	1	45.0	45.0	39.2		38.2		0		0	
Evaporative condenser:											
Fan	1	5.5	5.5	5.5		5.5		2.29		1.62	
Spray Pump (duty)	1	1.5	1.5	1.5		1.5		1.5		1.5	
Ammonia pumps (LT)	2	2.2	4.4	2.2		2.2		2.2		2.2	
Ammonia pumps (HT)	2	4.0	8.0	4.0		4.0		4.0		4.0	
Freezer evaporator fans	4	3.0	12.0	11.0		8.28		1.40		0.57	
Chiller air cooler fan	1	1.4	1.4	1.4		1.15		0.30		0.05	
Banana Room air cooler fan	1	1.4	1.4	1.4		1.15		0.06		0.02	
Ante Room 1 fan	1	0.9	0.9	0.9		0.82		0.65		0.46	
Ante Room 2 fan	1	1.4	1.4	1.4		1.31		0.59		0.43	
Subfloor ventilation fan	1	4.0	4.0	4.0		2.0		2.0		2.0	
Engine room exhaust fans	2	2.2	4.4	4.4		2.2		1.1		0.88	
TOTAL	21		273.4	151.7	21.5	111.1	12	50.8	9	37.4	
Electric power drawn, [kW]					132.6		62.8		46.4		
Electrical energy consumption (power drawn x hours), [kWh]					254606		241073		139287		634966
Specific electrical energy consumption [kWh/m³a]											25.3
Annual electricity cost assuming power factor 0.85, electric motor efficiency 0.85 and $0.15/kWh											$131,827