Refrigerant Choices for Commercial Refrigeration

Finding the Right Balance

EMERSON
Climate Technologies

CONTENTS

1 Executive Summary

1.1. Introduction

Emerson Climate Technologies is committed to supporting solutions that safeguard food and protect the environment. Minimising the impact of climate change through responsible energy use and reducing carbon footprint are key environmental objectives.

This study is designed to help our customers meet these objectives by providing guidance to the complex decision-making process when specifying supermarket cabinet cooling systems, both for new build and major refurbishment projects. It focuses on the refrigerant but takes into account the refrigeration system architecture and technology which have an impact on energy consumption, environment and investment costs. Supermarkets were chosen in this study as they offer the greatest potential to integrate the latest refrigeration design principles in order to improve environmental performance.

Fourteen combinations of system technologies and refrigerants are investigated and referred to as "cases". The study sets out the refrigerant, compressor technology, and system type for each case, together with alternatives and the operating conditions associated with them.

We have started from a baseline with a reference supermarket containing a sales area of 1000-1200m^2, typical of the store formats found throughout Europe. This Case 1 supermarket establishes the base with which different refrigerant / technology combinations are compared.

The study includes five refrigerant / technology combinations for supermarket refrigeration systems - centralised Direct Expansion (DX), distributed Direct Expansion, cascade system, secondary system, and R744 booster transcritical system.

1.2. Glossary of terms

CO_2	Carbon Dioxide
COP	Coefficient Of Performance
DX	Direct Expansion
EVI	Enhanced Vapour Injection
GWP	Global Warming Potential
HFC	Hydro-Fluoro-Carbon
HFO	Hydrofluoro-Olefin
MT	Medium Temperature
LT	Low Temperature
ODP	Ozone Depletion Potential
Recip.	Semi-hermetic reciprocating compressor
TEWI	Total Equivalent Warming Impact

1.3. Summary

This study analyses the different refrigerant / technology combinations under three main angles that drive today's decisions: energy consumption, environmental impact and investment cost.

The main conclusions of the study are:

Energy consumption

- Latest technology like Copeland ZF scroll with Enhanced Vapor Injection (EVI) and ZB scroll compressors deliver the best efficiency with improvements of up to 12% compared to standard semi-hermetic reciprocating compressors.
- Energy consumption tends to be larger for non-DX systems because of the additional heat transfer barrier between low temperature (LT) and medium temperature (MT) circuits.
- Refrigerant R407A with a scroll compressor is an excellent solution in terms of energy efficiency.
- The best option when moving from R404A DX technology is R407A - better than R134a. Cascade R744/R407A is a good alternative.
- R744 has particularly good heat transfer properties which allow lower temperature differences across the heat exchangers, so improving system efficiency.
- In transcritical mode, coefficients of performance (COP) are lower than conventional vapour compression systems. In warmer climates like Southern Europe, this penalises R744.

Environmental impact

- In Europe, R404A is the most commonly used refrigerant. However, improving systems and moving to a refrigerant with a lower Global Warming Potential (GWP) can significantly reduce emissions.
- DX distributed systems can result in reduced direct emissions due to lower charge and lower leakage rates with factory-built units. Scrolls with brazed connections help contribute to these savings.
- DX distributed with R407A or R404A offers a very good alternative, particularly in Southern Europe.
- Secondary systems give the lowest Total Equivalent Warming Impact (TEWI) results as the refrigerant charge is lower.
- TEWI values can be improved by substituting R404A with R134a for the MT cooling duty. R134a is not suitable for LT.
- R744 booster is an excellent configuration to lower the TEWI in Northern Europe. Secondary systems with R744 and R410A can even provide slightly lower TEWI values.
- Cascade with R407A MT improves energy consumption, but as there are no direct emission savings from the LT, the TEWI is approximately 4% higher than the R134a alternative. However, the investment cost is significantly lower.
- A secondary system virtually eliminates the effect of direct emissions. A chiller with R410A can be employed for the MT and cascaded LT load, and the leakage rate from a factory-built unit is significantly reduced.
- By using R290 or HFO for the chiller, even this small direct emission can be eliminated, but with a cost penalty associated with extra safety precautions.
- A HFO (Hydrofluoro-Olefin) refrigerant in the secondary MT system application is a possible successor to R134a on the basis that it gives similar efficiency.

Investment cost

- Distributed systems are the lowest investment cost, but can only be applied to suitable building types e.g. allowing for roof top installations.
- Moving from DX to other systems will incur additional investment costs.
- R744 booster systems offering elimination of HFCs and flammable refrigerants will require the largest investment.
- Moving from R404A to R134a for the MT will improve TEWI but

there is an investment cost impact.

- An excellent alternative to R134a in MT systems is R407A in terms of investment cost and energy consumption.
- Using R290 or HFO for the chiller to drastically reduce direct emissions has a cost penalty associated with extra safety precautions.
- Since the volume of R744 required to achieve the same cooling effect is much lower than for HFCs, many components such as compressors and pipes can be smaller than in conventional installations.
- CO_2-transcritical refrigeration circuits operate at far higher pressures than conventional R404A systems. This requires the use of components and assembly techniques not common in the supermarket refrigeration sector today.
- Operation in a transcritical mode requires a different design versus conventional HFC systems and is not familiar to most technicians providing supermarket refrigeration maintenance thus causing a safety concern.
- R744 is not widely used in refrigeration systems. This limits the choice of components for designers and they tend to be higher in cost. The high pressures also require materials and designs of higher specification and cost.
- Moving to a R744 booster system would currently require a full store architecture change. Therefore, in many cases, this solution might remain limited to a few new builds, whereas major remodelling projects would still be HFC-based. During the evaluation phase alternatives should also be considered to address various constraints like capital investment, system maintenance and serviceability.

2 Refrigerant choices for commercial refrigeration - Finding the right balance

2.1. Introduction

The debate about what constitutes the 'right choice' of refrigerant for commercial refrigeration applications has intensified in recent years, especially as leakage studies have revealed the true effects of HFC emissions in centralised systems. Considerable reductions in emissions are certainly possible, but they do incur costs.

In Europe today, R404A is the most commonly used refrigerant. Although it is non-toxic and has zero Ozone Depletion Potential (ODP), it does have a high Global Warming Potential (GWP). Using alternative systems and moving to a refrigerant with a lower GWP can significantly reduce the impact of environmentally damaging emissions.

For example, alternatives to the direct expansion (DX) system with central plant room have been successfully employed. And natural refrigerants such as R744 offer the advantage of close to zero direct emissions, although they may have penalties in terms of energy consumption, indirect emissions and investment cost.

What is really needed is a clear focus on different refrigeration systems and the refrigerants they use together with an examination of the issues surrounding a move away from high-GWP R404A. That is what this study aims to achieve.

2.2. Scope of the study

Minimising the impact of climate change through responsible use of energy, helping to reduce the carbon footprint are key environmental objectives for Emerson Climate Technologies and his customers as corporate players.

This study is designed to help our customers meet these objectives. It focuses on the refrigerant and the refrigeration system architecture and technology which also have an impact on the environment, capital investment and operating costs.

When considering a move away from R404A, it is important to examine four refrigerant criteria in particular. Any alternative refrigerant / technology combination must:

1. Have proven safety properties and conform to the latest codes of practice;
2. Be environmentally friendly with zero ozone depletion and low GWP;
3. Offer long term availability at reasonable capital cost; and
4. Provide performance equal to or better than the best current R404A-based technology to keep energy consumption low.

For the sake of simplicity we have started from a baseline with a reference supermarket containing a sales area of 1000-1200m^2, representative of the type commonly found throughout Europe. Both the chilled cabinets and the freezer cabinets in this store use R404A refrigerant for their cooling. A plant room containing the central refrigeration system works in conjunction with remote cabinets cooled by direct expansion (DX) evaporators. The cooling capacity required to maintain the cabinet cold space temperature is termed “load”. Other loads such as those for food preparation areas, cold rooms or plug-in display cases are ignored.

Although we recognise that many users are considering integrating air conditioning, heating and heat recovery, these “total building” solutions are not considered in this study. Whilst such solutions may have an impact on a system's heat rejection and distribution arrangements, we would argue that cabinet cooling systems still play a major role in their own right, and it is these systems that are under focus in this study.

Fourteen refrigerant / technology combinations are investigated in detail in order to provide comparable information. These are referred to as Cases 1 to 14.

Case 1 supermarket establishes the base to compare refrigerant / technology combination options. Refrigerant, compressor technology, and system type for each case, together with alternatives and the operating conditions associated with them, are set out in this study.

System types

This study includes five refrigerant / technology combinations for supermarket refrigeration systems.

3.1. Centralised Direct Expansion

This is a direct expansion system using HFC for both the low temperature (LT) and medium temperature (MT) loads (i.e. frozen and chilled display cabinets respectively).

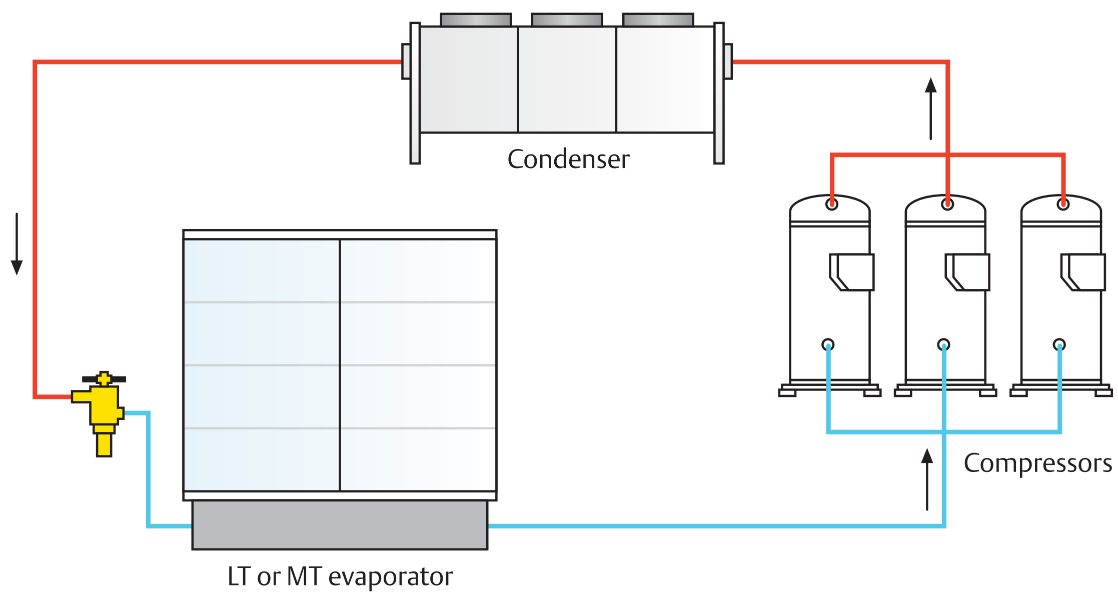
The centralised DX solution - comprising two completely separate systems (LT and MT) is typical of systems being installed in supermarkets throughout Europe today. Each system uses a central "multi-compressor pack" consisting of between three to eight semi-hermetic reciprocating or scroll compressors. The pack is located in a plant room and is connected to an external air-cooled condenser. High pressure refrigerant liquid is fed to the cabinets in the store, usually via a liquid receiver (not shown). The refrigerant vapour then returns to the compressor pack via the suction line. The condenser pressure is typically controlled by varying the air flow. This ensures that the condensing pressure is kept as low as possible, consistent with satisfactory expansion valve control when outdoor air temperatures are low. The minimum condensing condition is assumed to be 20°C for air-cooled vapour compression circuits.

The rate of refrigerant leakage from supermarket systems varies significantly between countries and depends on the type of installation. Even in good systems, there will always be slight refrigerant leakage (of around 2 to 3% of system charge per year). It is also inevitable that there will be a small number of catastrophic failures resulting in the total loss of the refrigerant charge.
For a new typical R404A DX refrigeration system across Europe, we have used an average annual refrigerant leakage of 15%. In some countries, leakage is likely to be lower than this, but in others it may be higher due to the different levels of technical skills.
The top common leakage points for refrigeration systems according to the REAL Zero Guide are:

- Shut-off/Ball/Schrader valves
- Flare and mechanical joints
- Pressure relief valves and fusible plugs
- Condensers
- Pressure switches
- Capillary tubes
- Return bends on evaporators and condensers

Additionally the overall leakage rate includes an allowance for "catastrophic" leaks. This is the term used to describe any major loss of refrigerant occurring in a single incident.

Centralised Direct Expansion



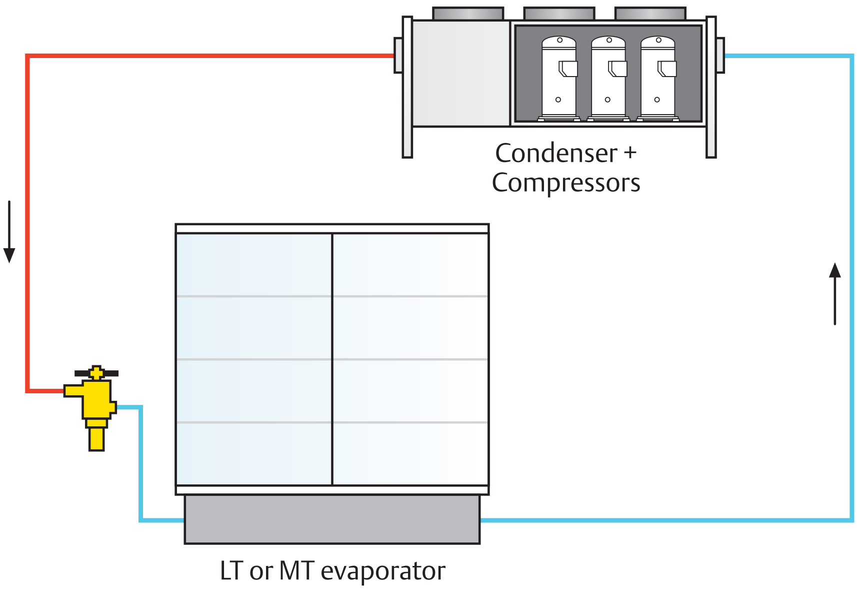
3.2. Distributed Direct Expansion

This system is the similar to the centralised DX except that the compressors are usually located adjacent to, or within the condenser housing.

Instead of a central plant room, a number of smaller compressors are mounted within each condenser unit. The condenser units are usually roof mounted, with each unit positioned directly above a group of cabinets so that long refrigerant lines are avoided. The condenser units can be factory-assembled, which enables their quality to be closely controlled and streamlines the construction process, making it faster, more efficient, safer and less costly. This approach also reduces the refrigerant charge and leakage rate due to smaller diameter pipe sizing. However, it is not always practical; whether or not it can be used depends on the location and structure of the building.

Compressors located within condenser housing

Distributed Direct Expansion



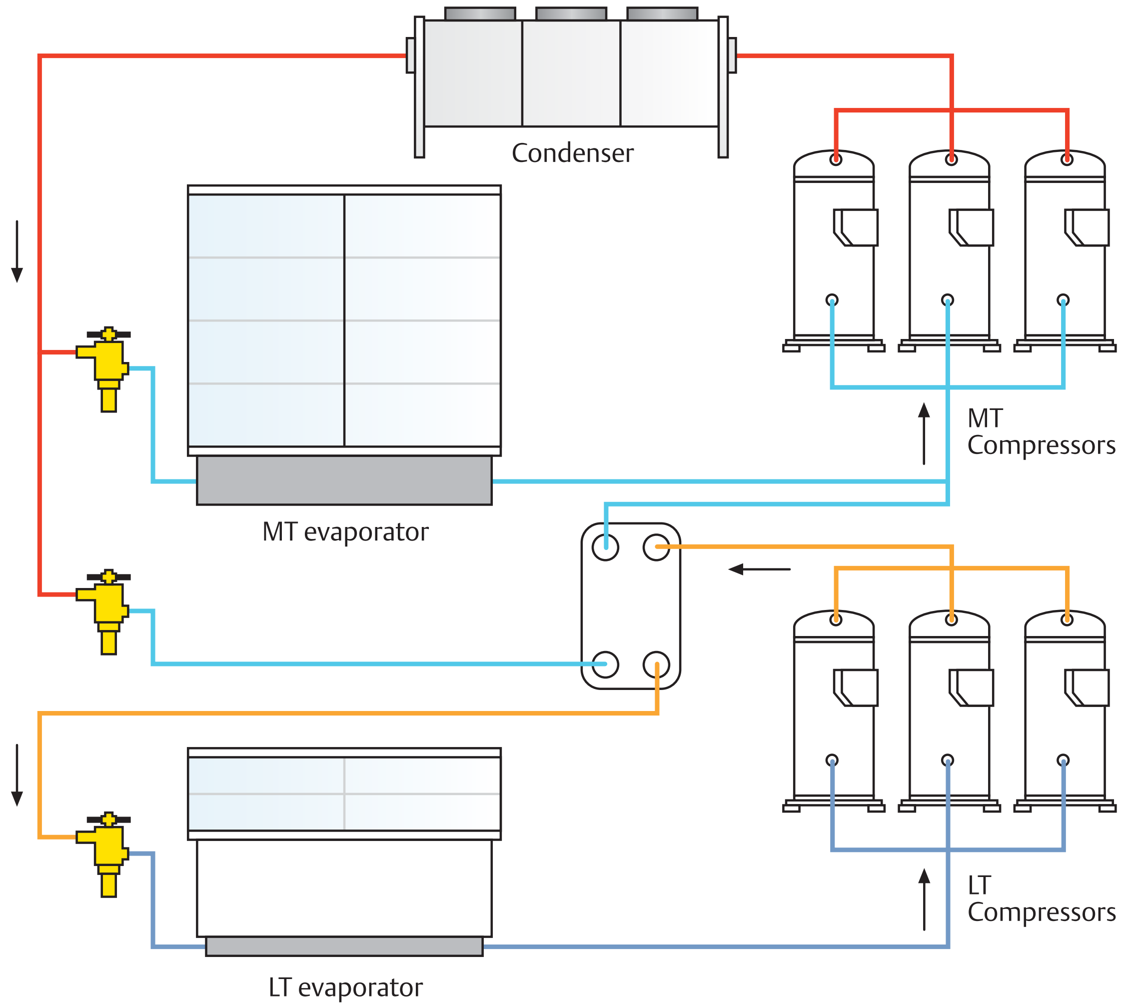
3.3. Cascade system

With this technology, an HFC centralised DX system is used for MT loads and the LT system has a separate circuit that discharges its heat into the suction stage of the MT system.

The LT circuit has a low condensation temperature so R744 (CO_2) can be applied in subcritical mode without excessive pressures. The challenges are not fundamentally different from systems with conventional refrigerants. The discharge pressure (at around 30 to 35 bar) is still within the normal design limits for refrigeration pipe work and components (typically 40 bar).

The temperature difference required to drive the heat transfer across this extra heat exchanger represents a slight loss in energy efficiency compared to a DX system.

Cascade system



3.4. Secondary system

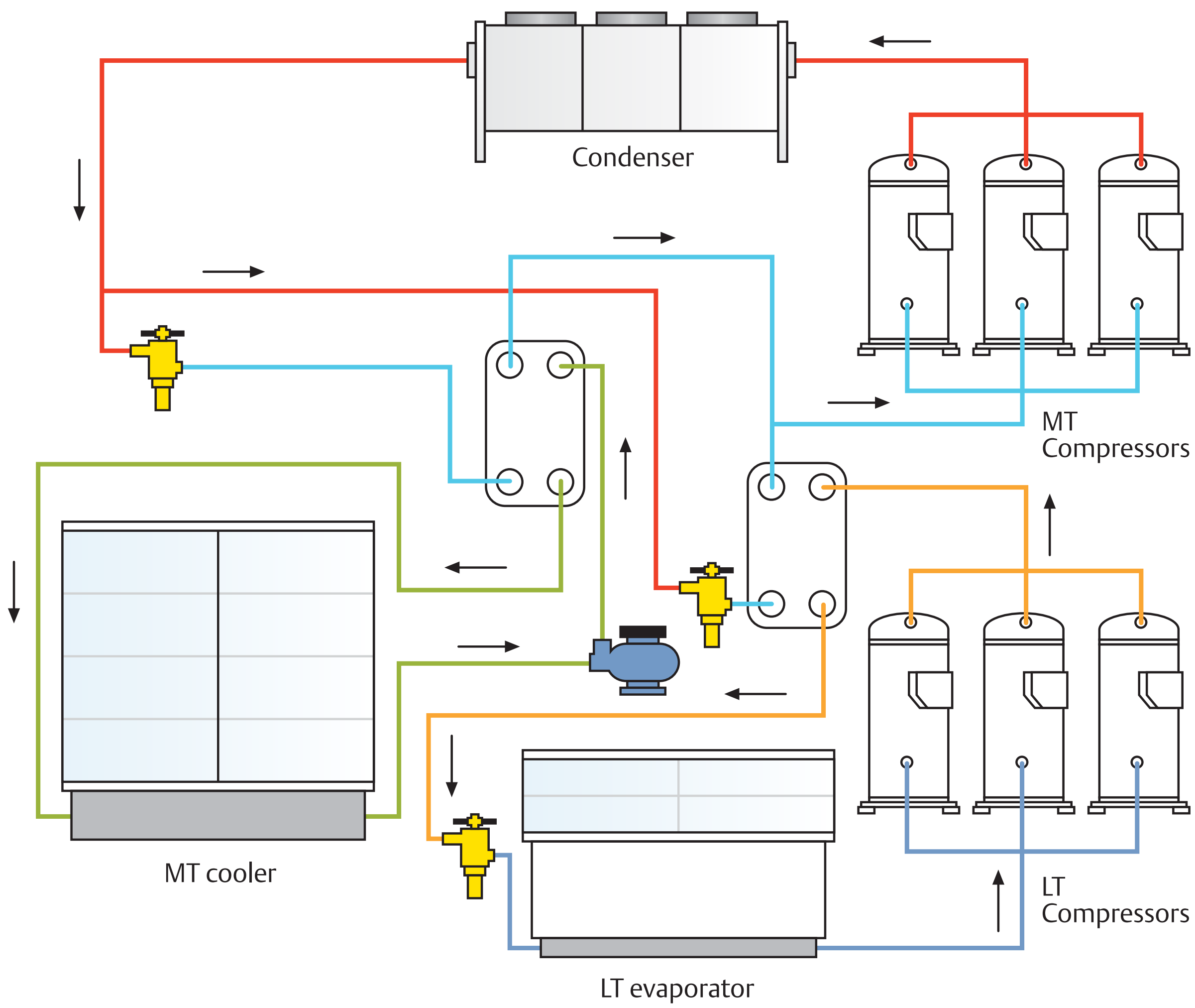
A secondary refrigerant distributes the MT cooling around the supermarket. The LT arrangements are identical to the cascade system described (3.3).

Heat from the chill cabinets is transferred to the MT evaporator/heat-exchanger by circulating a secondary fluid, typically glycol or some other heat transfer fluid. Heat exchangers can be located close to the compressors and when assembled with an air cooled condenser this package can be delivered as a factory-assembled unit similar to an air conditioning chiller. This results in a significantly reduced MT refrigerant charge and refrigerant leakage is reduced due to the factory manufacturing.

Secondary refrigerant systems require a pump to circulate the coolant around the supermarket and there is an extra heat exchanger temperature drop. The heat exchanger requires a temperature difference to drive the heat transfer and so the MT evaporating temperature must be lower than the secondary refrigerant temperature, leading to an increase in compressor energy consumption. In this study, we have assumed a temperature difference of 5K so that the MT evaporating temperature is -10°C.

Secondary systems require less refrigeration service effort than DX solutions.

Secondary system

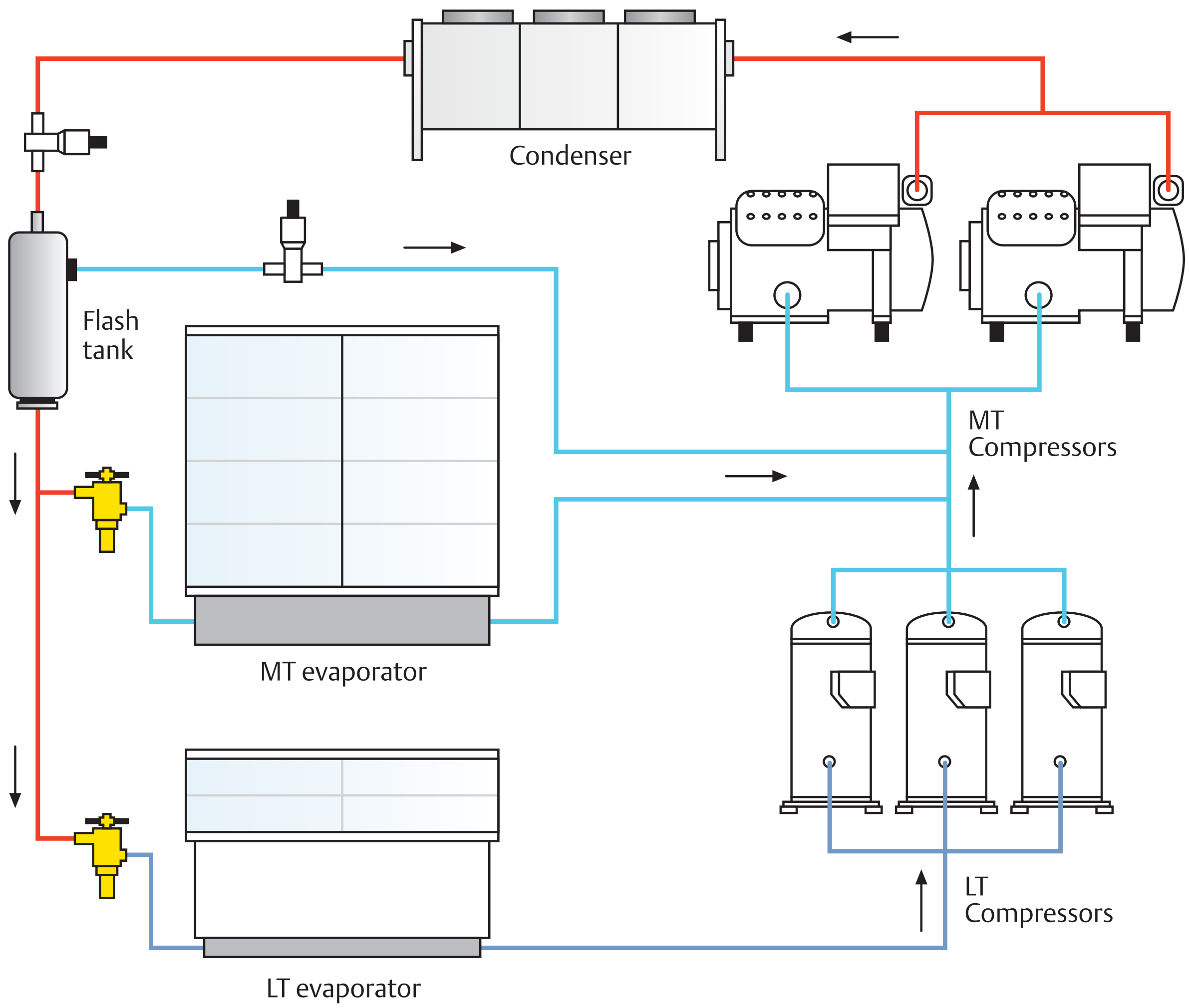


3.5. R744 booster transcritical system

This model uses R744 (CO_2) in both the MT and LT systems. The LT compressors act as boosters to raise the vapour pressure to the level of the MT evaporators.

At ambient temperatures above approximately 23°C the compressors discharge the gas above the critical pressure of R744 (74 bar). The condenser then acts as a gas cooler and reduces the temperature of the discharge gas without condensing it into liquid. Cooled fluid passes through a pressure reduction valve, at which point a portion condenses into liquid and the rest remains as gas. Liquid and gas are separated in a flash vessel controlled by the pressure relief valve at a pressure of around 35 to 40 bar. The liquid is then distributed to the MT and LT cabinets via the liquid line at this intermediate pressure. The flash gas is taken via an additional expansion device to the suction of the MT compressors. A separate flash gas compressor may be an adequate method to raise system efficiency in warmer regions.

R744 booster transcritical system



In this study, simplifications have been made to ensure that calculations of energy consumption and environmental impact are readily understandable. These simplifications may not represent actuality in a particular system, but this approach does allow a realistic comparison to be made because the same conditions are applicable to each case. Differences arising from the nature of the system, refrigerant and compressor type are varied according to the case.

4.1. Seasonal operating conditions

A condensing temperature of 25°C has been used to represent average operating conditions in Northern Europe, and 30°C for Southern Europe (see "Climate", below).

4.2. Loads

Loads are assumed to be constant throughout the year.

4.3. Parasitic loads

Suction line losses and pressure drops are ignored.

4.4. Efficiency and coefficient of performance (COP)

Compressor data is taken from Copeland Selection Software 7 and the software/catalogues of other compressor manufacturers. We have chosen typical semi-hermetic reciprocating and scroll compressors using the latest available technology. COP is defined as the compressor COP, i.e. the ratio of compressor published capacity and power at the evaporating and condensing conditions specified in the table in Section 4.12.

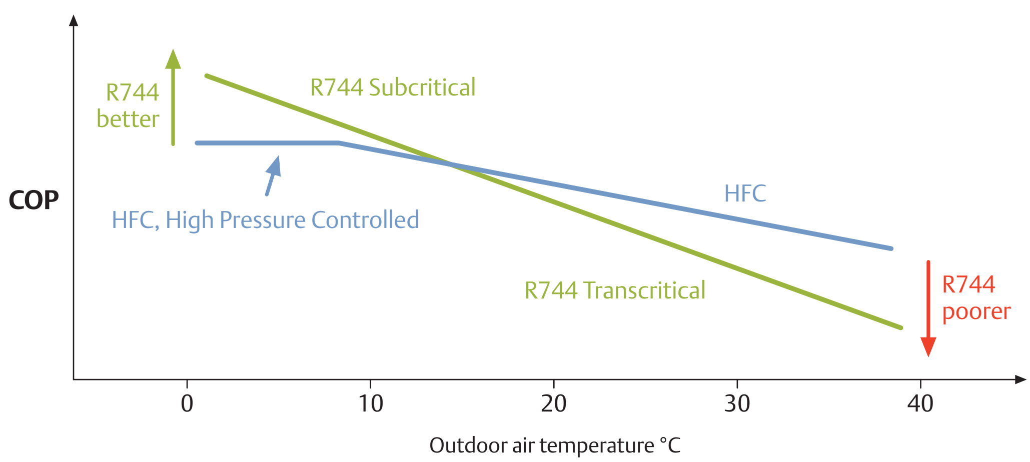
CO_2-transcritical technology is at an early stage of development and, whilst compressor data is available, the method of application and control can have a significant influence on system efficiency. Operation in the subcritical mode can offer better efficiencies than today's conventional systems. This better efficiency is needed to offset the low transcritical efficiency that comes with high ambient conditions. Location therefore plays an important role. The warmer the climate, the more the system will operate in transcritical mode.

For this study, we have taken a "best case" scenario for the CO_2-transcritical system. Studies have shown that optimised CO_2-transcritical systems serving both the LT and MT loads can operate at average COPs similar to semi-hermetic reciprocating R404A systems in the Northern European climate. This is the comparison normally made when assessing the merits of a totally natural refrigerant solution. For this to happen, advantage is taken of lower R744 pressure drops and better heat transfer properties, both of which have the effect of reducing the compressor "lift".

Subcooling is also beneficial with R744 and would normally be required for the optimised R744 system to reach the COP parity mentioned here.

For the R404A system we have assumed that the head pressure is set at minimum 20°C condensing at all ambient conditions below 10°C whereas the R744 head pressure is allowed to float down to a much lower temperature. The graph below illustrates the relative change in COP with outdoor temperature.

Reference Case 1 system with scroll technology shows an average MT COP improvement of approximately 10% when compared to typical reciprocating compressors. We have assumed that the R744 solution can reach the same average COP as a typical



reciprocating solution in the Northern European climate. For Southern Europe, the CO_2-transcritical system is assumed to operate at 10% lower average COP than the HFC MT system, and this is to account for more operating time at transcritical conditions.

4.5. Climate

The average HFC condensing temperature of 25°C representing Northern Europe conditions is based on an average outdoor temperature of 15°C with a condenser temperature difference of 10K. This is with condensing temperature controlled at 20°C minimum, and therefore with all ambient temperature hours below 10°C counting as 10°C. Consultation over temperature profiles for a number of Northern European cities has revealed that, on this basis, the average ambient temperature is between 14 and 16°C, and so 15°C is a good average. A seasonal BIN analysis is splitting the annual outdoor temperatures into segments (bins). The loads and energy consumptions for all segments are added together. The ratio of these totals is the Seasonal COP and it has proved to be almost identical to the selected value at 25°C condensing.

A typical city in Southern Europe would have an average ambient temperature of 18 to 20°C. In this study, 30°C average condensing temperature has been taken as the representative temperature of Southern Europe, based on the same approach than for Northern Europe.

4.6. Model supermarket

This study considers the refrigeration system of a typical European supermarket. The following equivalent continuous loads have been assumed for a 1000-1200m^2 supermarket: MT - 75kW and LT - 18kW.

4.7. Generation factor

The generation factor is the quantity of carbon dioxide (CO_2) emitted per kWh of electricity generated. It depends on the proportion of electricity generated from by fossil fuel, the type of fossil fuel and the efficiency of the generation. For example, where energy comes from a renewable source such as wind or hydro, the factor will be small. We have used an average factor of 0.4 kg CO_2/kWh for Europe and this is taken from European Commission Directorate-General for Transport and Energy (EU DG-TREN) 2003: European Energy and Transport Trends to 2030 (PRIMES), Brussels.

4.8. Lifetime

The TEWI analysis is for a system lifetime of 10 years. The data represents the CO_2 emissions and electrical energy input over a 10 year period. This is the period adopted in the example shown in the British Refrigeration Association/Institute of Refrigeration TEWI guidelines.

4.9. End of life recovery

It is assumed that 95% of the refrigerant charge is recovered after the 10 year period and not released to the environment.

4.10. Refrigerant charge per kW load

For a distributed DX system, the charge is 75% of the equivalent centralised system. For the cascade systems the medium temperature charge in kg per kW load is the same as for DX centralised. Secondary MT charge levels are based on those of a factory-built chiller.

Refrigerant charge, kg/kW Load	
DX Low Temperature Centralised	4
DX Low Temperature Distributed	3
DX Medium Temperature Centralised	2
DX Medium Temperature Distributed	1.5
Secondary Medium Temperature, R410A	0.5
Secondary Medium Temperature, R290	0.75
Secondary Medium Temperature, HFO	1

4.11. Refrigerant leakage rate

Distributed DX has a one-third lower leakage rate than a centralised system because it uses less pipe work and typically comprises a small factory-built system using hermetic scroll compressors. With this type of low-charge system, refrigerant loss can quickly be detected and stopped. Leakage rates for MT secondary cases are based on those for a factory-built chiller.

Refrigerant leakage rate, % charge per annum	
DX Low Temperature Centralised	15
DX Low Temperature Distributed	10
DX Medium Temperature Centralised	15
DX Medium Temperature Distributed	10
Secondary Medium Temperature	5

These hypotheses are based on current published data reflecting today's situation. However several regulations are already in application in order to reduce leaks in refrigeration installations and therefore reduce TEWI (direct emissions).

4.12. Loads, operating conditions and ancillary loads for calculations

	Low temperature				Medium temperature			
System type	DX Centralised and Distributed	Cascade	Secondary	R744 Booster	DX Centralised and Distributed	Cascade	Secondary	R744 transcritical
Load (kW)	18	18	18	18	75	97	97	97
Evaporating Temperature (°C)	-35	-32	-32	-32	-5	-10	-10	-5
Condensing Temperature (°C)	25 or 30	-5	-5	optimized	25 or 30	25 or 30	25 or 30	optimized
Superheat (K)	10	10	10	10	10	10	10	10
Subcooling (K)	0	0	0	0	0	0	0	optimized
Cascade HX Temperature Difference (K)						5	5	
Condenser Fan Power (kW)	1	0	0	0	3.5	4.5	4.5	4.5
Evaporator Fans, Lights, Defrost (kW)	4	4	4	4	10	10	10	10
Brine Pump (kW)							1	

Notes:
- R407A data is based on mid-point pressures as this gives closer average evaporating and condensing temperatures.

4.13. GWP values

The GWP values used in this study are from IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report: Climate Change 2007.

We have ignored carbon embodied in the materials used to manufacture the refrigeration plant, in the production of the major components and refrigerant and the energy used in manufacturing and distribution.

Refrigerant	GWP
R404A	3922
R407A	2107
R410A	2088
R134a	1430
HFO	4
R290	3
R744	1

4.14. Limits of applicability

The study refers to technology as used in current (2010) European supermarket installations. Findings should not be directly applied to other types of refrigeration or air conditioning. Actual installations vary considerably depending on many factors, including:

- Regional preferences - Different technologies are used in different countries across Europe because of different retail industry characteristics, regulatory conditions and for historical reasons. The skill levels of the maintenance technicians must also be taken into account.
- Climate - Typical Northern and Southern Europe conditions have been chosen, but there are wider ranges of typical annual temperature profiles across Europe.
- House/company preferences - Even within the same country, various retail chains can differ in their preferences for refrigeration plant. Some may prefer to install higher quality and higher cost systems than others. There may also be preferences that are not based on cost, but other factors such as uniformity or ease of maintenance.

Supermarket refrigeration technology is developing rapidly and there is considerable interest in alternative refrigeration systems and refrigerants. The intention of this study is to highlight differences in the key factors between today's good practice systems and possible future system alternatives with today's known technology.

5 Cases configuration

5.1. Introduction

Following fourteen cases have been analysed. Case 1 has the latest technology with low temperature Enhanced Vapour Injection (EVI) scroll and medium temperature ZB type scroll and is used as the reference. All other DX cases have various refrigerant and compressor types. Distributed systems normally incorporate scroll compressors which are lighter and more compact than semi-hermetic compressors.

Two refrigerant options have been chosen for distributed systems. Refrigerant R134a would reduce the advantages of distributed system technology as approximately 70% more displacement is required, resulting in much larger, heavier and more costly equipment. R134a is therefore not included as a distributed system option.

Cascade systems introduce an R744 LT circuit, with varying MT refrigerant alternatives.

Secondary systems, which have no MT refrigerant circulated in the store, can use flammable or even HFO refrigerants because the refrigerant is kept outside public areas and it is restricted to the confines of the chiller unit. A complete R744 system is examined in Case 14.

Cases 12 and 13 may be regarded as possible future solutions, and therefore have been included to show the likely environmental and cost implications. Availability of products for these cases needs to be investigated before planning a system with these refrigerants.

5.2. Cases

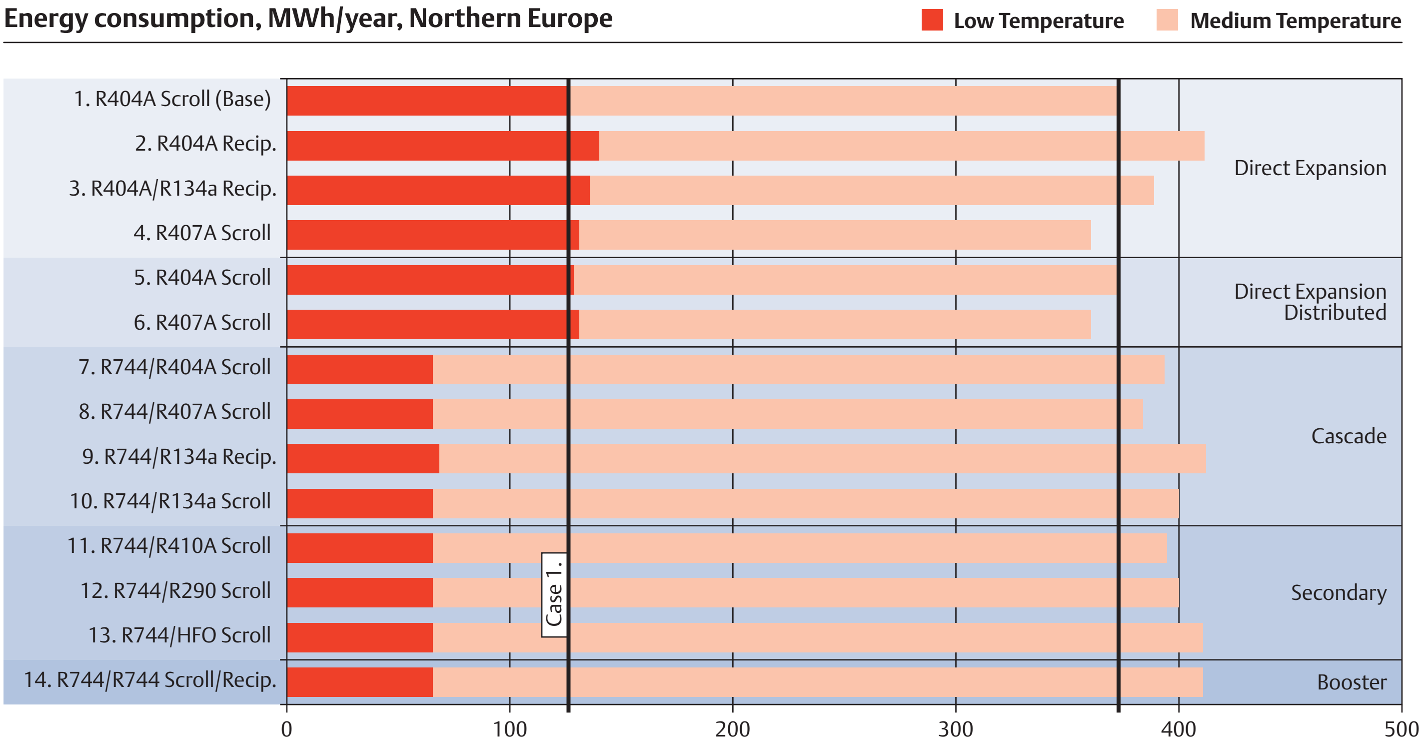
Case	Model	Refrigerant LT	Refrigerant MT	Technology LT	Technology MT
1	DX	R404A	R404A	Scroll EVI	Scroll
2	DX	R404A	R404A	Typical Reed semi-hermetic recip.	Typical Reed semi-hermetic recip.
3	DX	R404A	R134a	Discus semi-hermetic recip.	Discus semi-hermetic recip.
4	DX	R407A	R407A	Scroll EVI	Scroll
5	DX distributed	R404A	R404A	Scroll EVI	Scroll
6	DX distributed	R407A	R407A	Scroll EVI	Scroll
7	Cascade	R744	R404A	Scroll	Scroll
8	Cascade	R744	R407A	Scroll	Scroll
9	Cascade	R744	R134a	Semi-hermetic recip.	Discus semi-hermetic recip.
10	Cascade	R744	R134a	Scroll	Scroll
11	Secondary	R744	R410A Chiller	Scroll	Scroll
12	Secondary	R744	R290 Chiller	Scroll	Scroll
13	Secondary	R744	HFO Chiller	Scroll	Scroll
14	R744 booster	R744	R744	Semi-hermetic recip.	Semi-hermetic recip.

6 Cases comparison and results

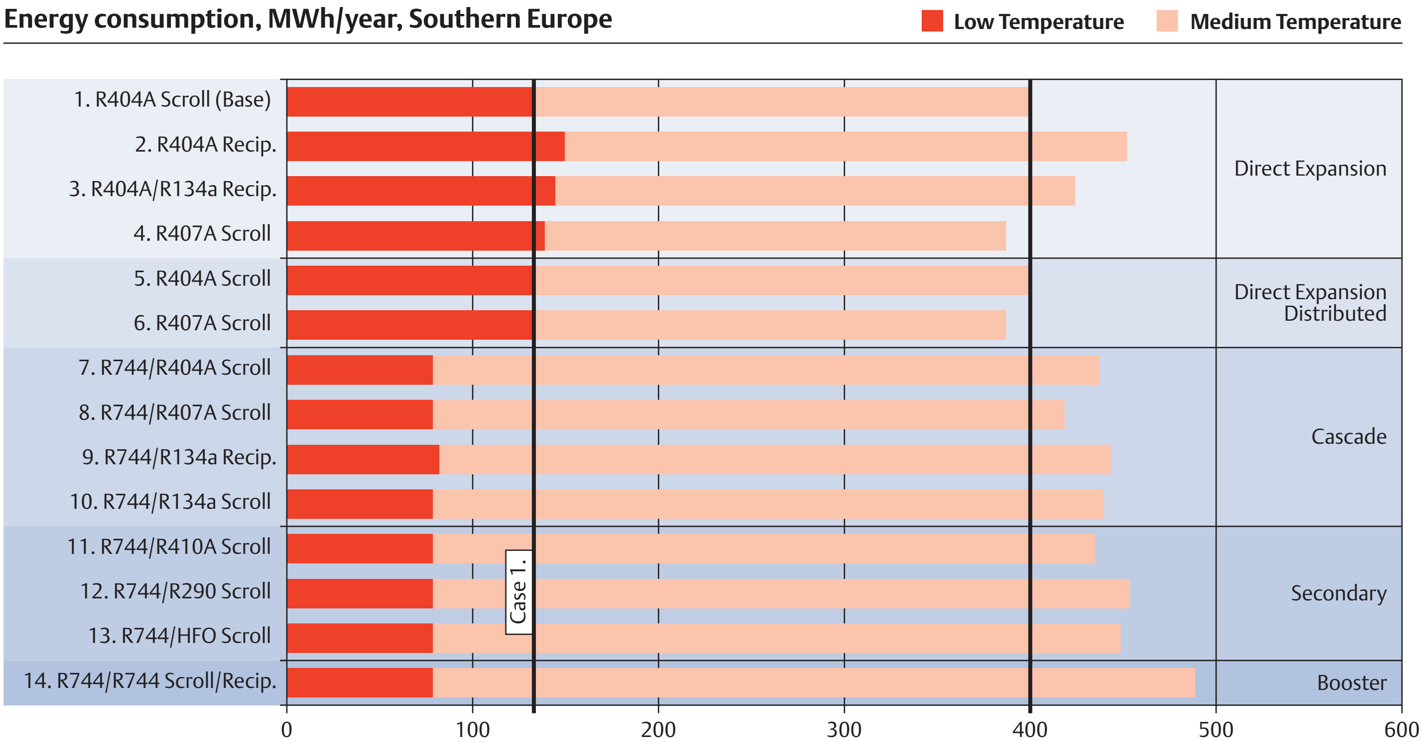
6.1. Energy consumption

Annual energy consumption including that of compressors, cabinets and secondary refrigerant pump for each of the cases is in accordance with the above definitions. Compressor power input is taken from Copeland Selection Software 7, other compressor manufacturer's software or, in the few cases where data is not readily available, by using typical efficiency data.

Energy consumption, MWh/year, Northern Europe



Energy consumption, MWh/year, Southern Europe



Observations

1. Data has been taken from representative compressor models. There is a variance of COP between models, but the trends remain clear.
2. Cases 1 and 4 feature scroll DX systems and Cases 2 and 3 use semi-hermetic reciprocating equivalents. The latest technology EVI and ZB scroll compressors deliver the best efficiency.
3. Energy consumption tends to be higher for non-DX systems because of the additional heat transfer barrier between the LT and MT circuits.
4. R407A with a scroll compressor (Cases 4 and 6) offers the best solution in terms of energy efficiency.
5. A cascade system with R744 scroll and R404A or R407A MT (Cases 7 and 8) shows slightly higher energy consumption is due to the lower MT evaporating pressure.
6. A Cascade semi-hermetic reciprocating system using R744 in LT and R134a in MT (Case 9) shows a distinct increase in energy requirement.
7. For the same system using scroll technology (Case 10), the LT energy consumption is reduced due to the lower power requirement of the R744 scroll bringing the total energy consumption closer to the R407A solution (Case 8).
8. Cases 11 to 13 are secondary systems with various MT chiller refrigerant options. The R410A scroll solution (Case 11) provides the lowest overall energy consumption in the range of secondary systems.
9. R290 (Case 12) has a slightly lower efficiency than R410A so energy consumption is a little higher.
10. An eventual transition to an HFO refrigerant could be possible for the MT chiller (Case 13). This is expected to perform in a similar way to R134a and require more energy consumption than the R410A optimum (Case 11).
11. The CO2-transcritical booster system (Case 14) has an equivalent average COP to an R404A DX reciprocating compressor system (Case 2) in Northern Europe and it therefore shows the same energy consumption.
12. In Southern Europe, the R744 booster requires 10% more energy. The total energy requirement difference is less than 10% because the ancillary requirement (for cabinets, fans, etc) is assumed to remain the same.

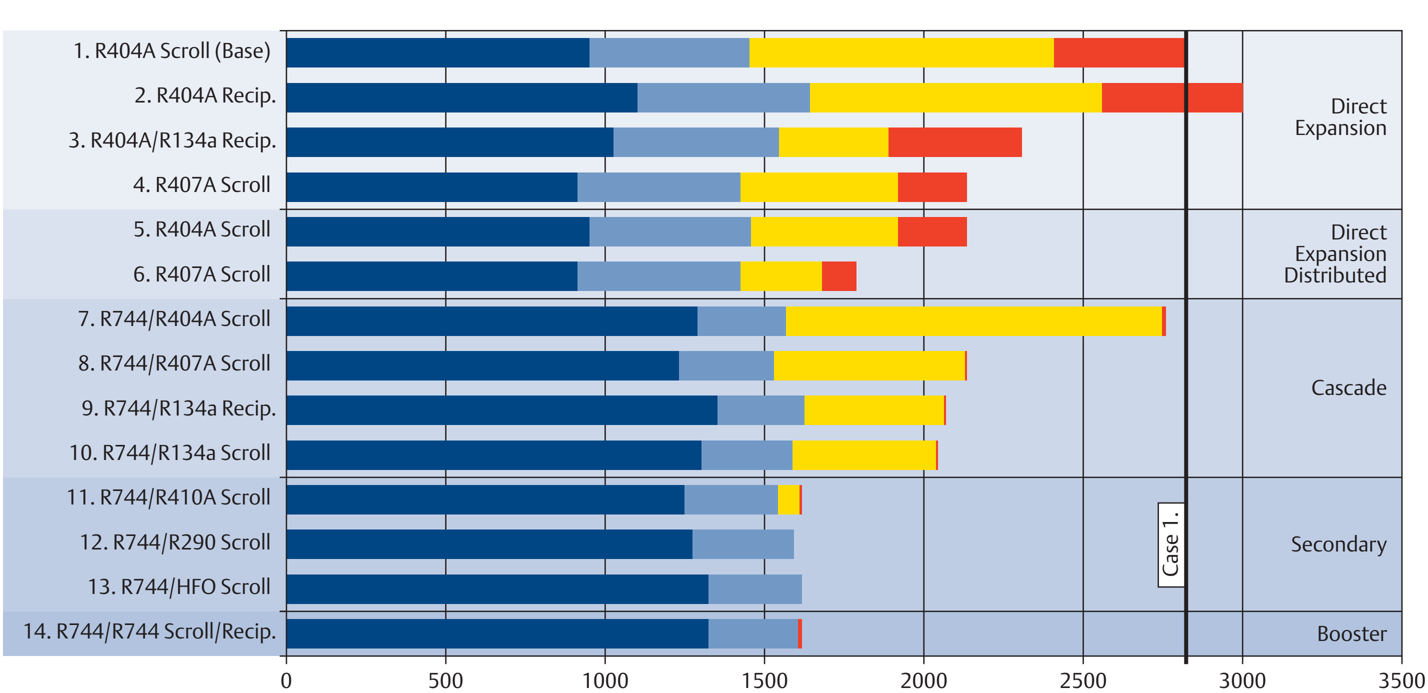
Main conclusion for energy consumption:

The best option when moving from R404A DX technology is R407A. In DX with both centralised and distributed systems, the overall energy consumption is slightly reduced when compared with the R404A reference. Cascade R744/R407A is also a very good alternative.

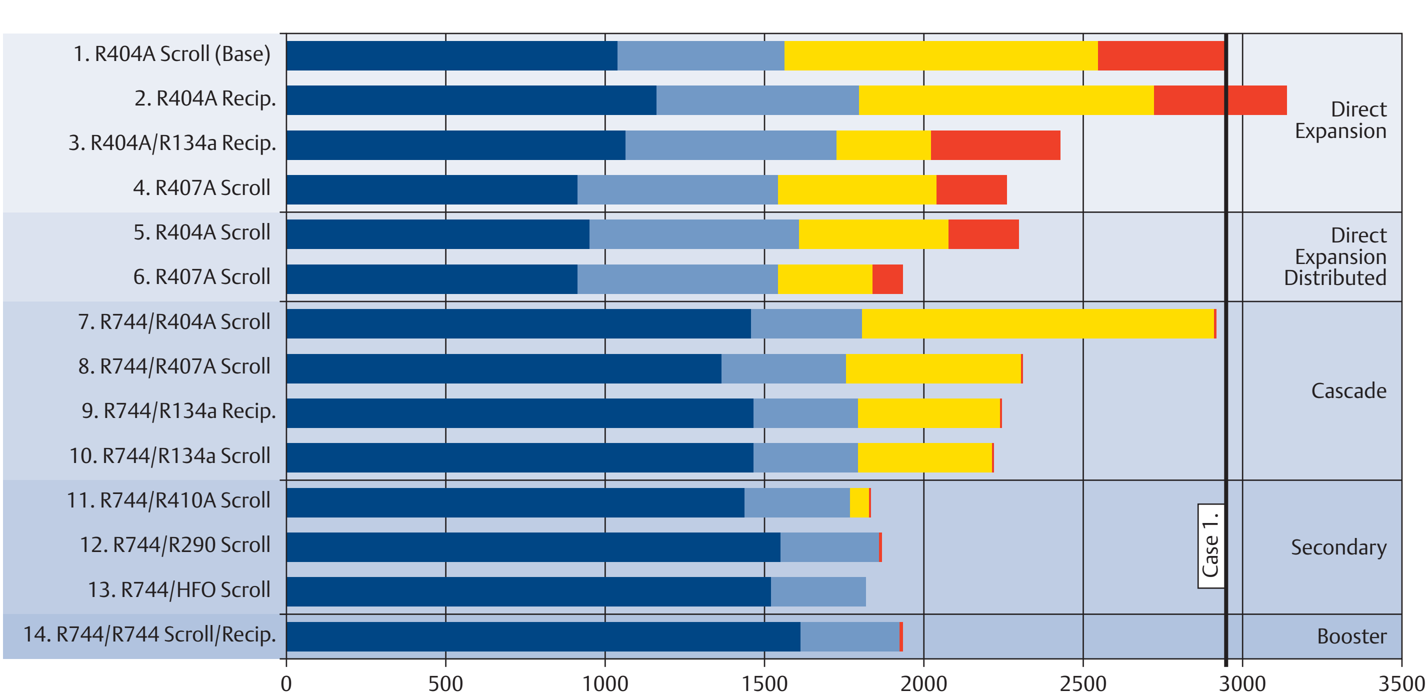
6.2. Environmental Impact / Carbon Footprint

Data in the definitions above provide the information needed to calculate Total Equivalent Warming Impact (TEWI) for each case. TEWI is a comparative tool; the precision of the lifetime CO_2 emissions depends on various assumptions so the relative values are important. The TEWI values shown in this study cannot be directly compared with other sources, studies or papers where different assumptions are used.

Lifetime CO_2 emissions, tonnes (TEWI), Northern Europe



Lifetime CO_2 emissions, tonnes (TEWI), Southern Europe



Observations

1. Changing refrigerant in DX systems from R404A to R134a (MT only) or R407A (Case 3 and 4 compared to 1 and 2) results in a large TEWI reduction, R407A being the best option.
2. A distributed system with R404A (Case 5) gives similar TEWI reduction to R407A in the centralised DX (Case 4).
3. A R407A scroll distributed system (Case 6) demonstrates a TEWI value close to the R744 booster solution (Case 14). In Southern Europe, the CO_2 emissions for Case 6 are as low as Case 14.
4. Cascade systems (Cases 7 to 10) are penalised by high leakage rates on the MT DX centralised system that now is also handling the LT heat rejection. The result is very little saving if R404A is employed (Case 7).
5. For low TEWI, it is necessary to choose a low-GWP refrigerant (i.e. not R404A) for cascade systems. With R404A (Case 7), the effect of leakage emissions dominates. Moving to a lower GWP refrigerant such as R134a or R407A (Cases 8,9,10) shows TEWI reductions, and the lower GWP of R134a plays an important part in securing the best cascade TEWI figures (Cases 9 and 10).
6. Secondary systems (Cases 11 to 13) give the best TEWI figures. Indirect emissions arising from power input are similar to cascade systems, but the direct emissions are small, even with R410A (Case 11).
7. With appropriate safety precautions, flammable refrigerants could be applied in these systems, but not in the DX and cascade systems. Systems with low GWP flammable refrigerants (Cases 12 and 13) give an indication of the TEWI reduction achievable with this approach.
8. The secondary system with a low charge R410A factory-built scroll chiller, assuming 5% leakage rate (Case 11), returns a better TEWI value than the R744 booster system.
9. In Southern Europe, all the secondary types (Case 11 to 13) - together with the R407A distributed DX type (Case 6)- perform better in TEWI terms than the R744 booster system (Case 14).
10. The R410A scroll (Case 11) draws less power than the equivalent R290 compressor (Case 12) in Southern Europe, and this effect more than outweighs the small direct emission effect on TEWI. There is no merit in choosing R290 from this perspective.
11. An HFO in the secondary application is a possible successor to R134a since it offers similar efficiency. It could be applied to resolve the issue of direct leakage, but the effect is small when compared with R410A on a TEWI basis (Case 11) and the chiller system will be considerably larger.

Main conclusion for TEWI:

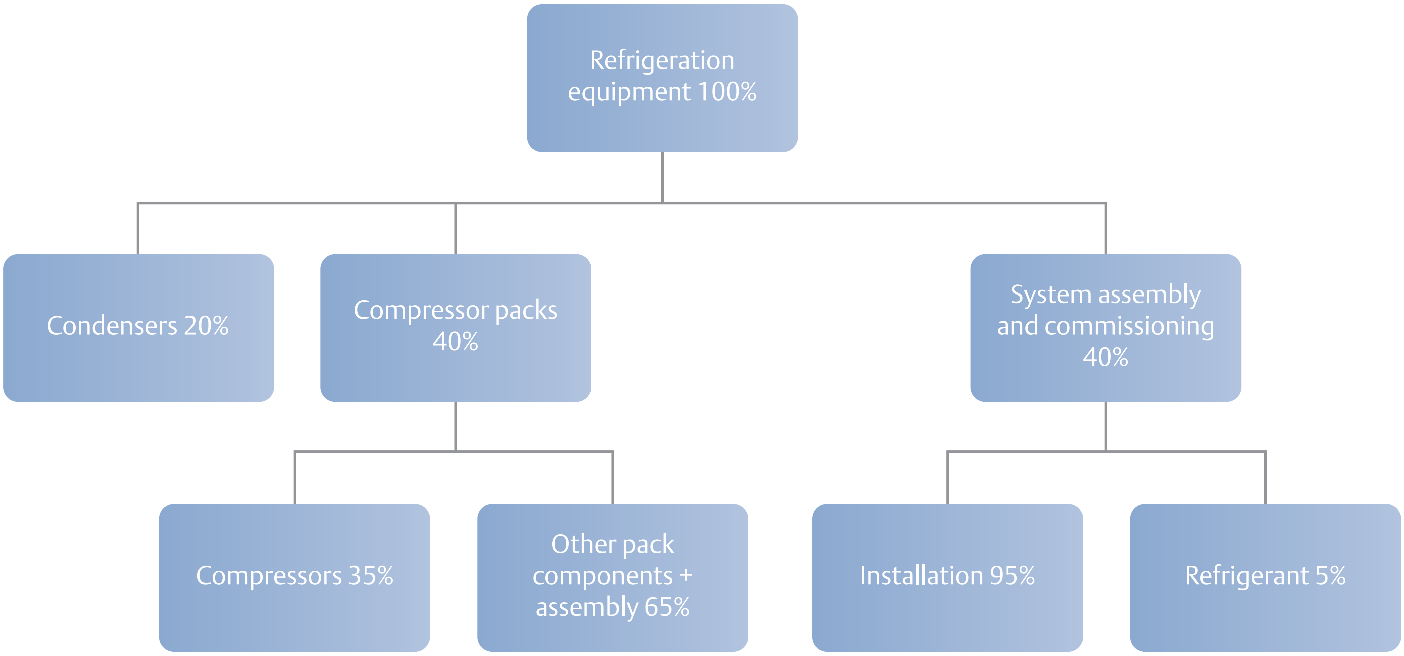
In Northern Europe, R744 booster is an excellent configuration for TEWI. Secondary systems with R744 and R410A can even provide slightly lower TEWI values.

In Southern Europe, all secondary systems will perform better. DX distributed systems with R407A offer an excellent alternative in all regions.

6.3. Investment cost

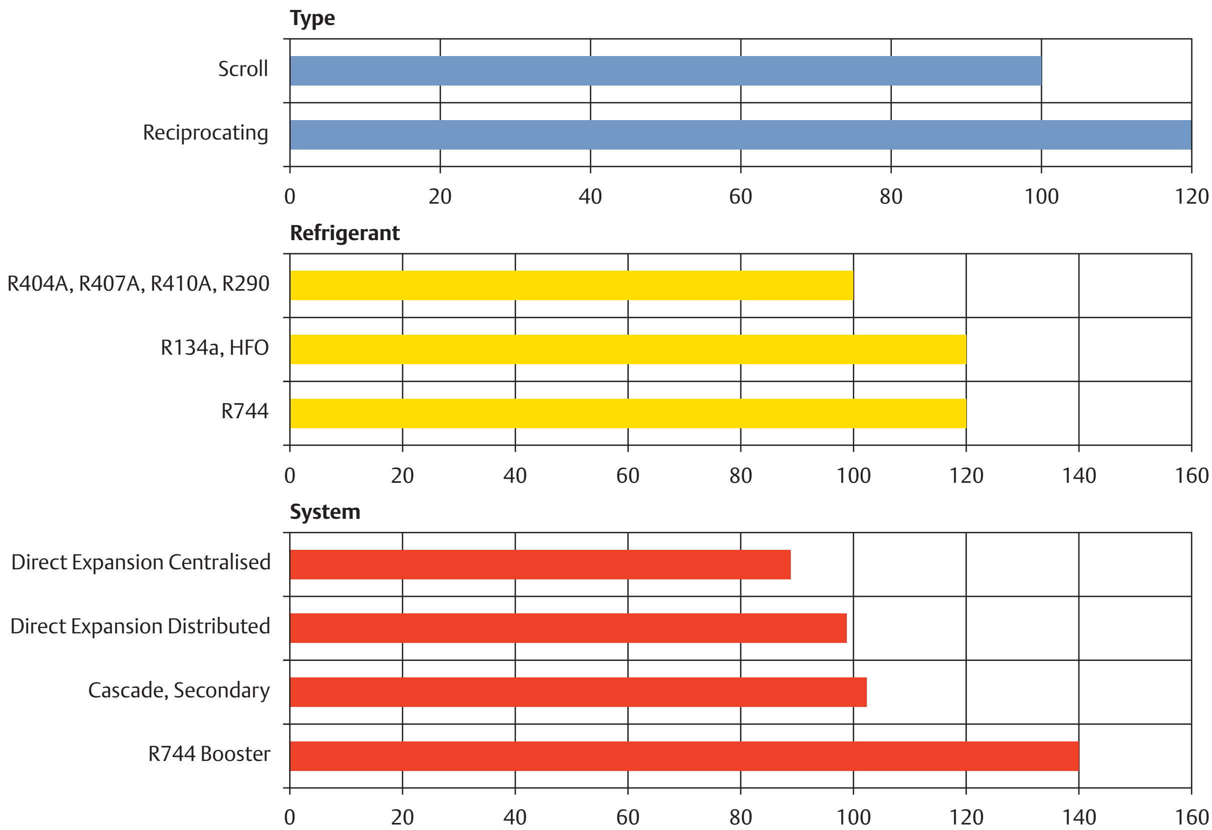
6.3.1. Investment cost structure and system component weightings

A simple relative investment cost structure for the refrigeration equipment, compressors, condensers and installation has been built up on the following basis:



Cooling cabinets are not included.
Within this framework, taking a scroll compressor with R404A in centralised systems as reference, the following weightings are made:

Compressors



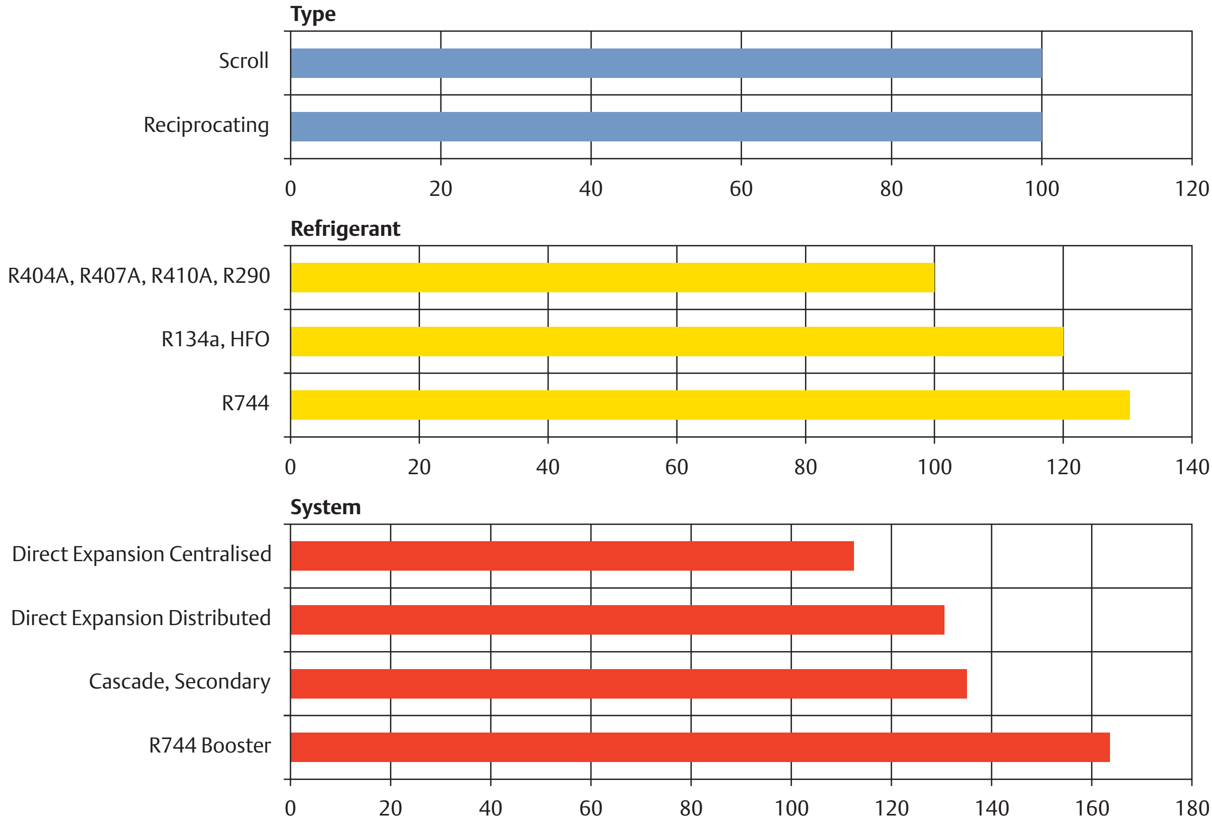
These charts show the "adders" applicable in each case. So, for example, under compressor type, we have a 20% applied cost adder for a semi-hermetic reciprocating compressor to be comparable with a scroll with the same refrigerant. There is no cost adder for most refrigerants although there is a penalty for R134a and HFO (70% more displacement required) and for R744 (high pressure technology).

System type also affects the compressor investment. More cooling capacity redundancy is needed for distributed systems and the cascade and booster systems require more displacement as the LT vapour is handled twice.

Example:

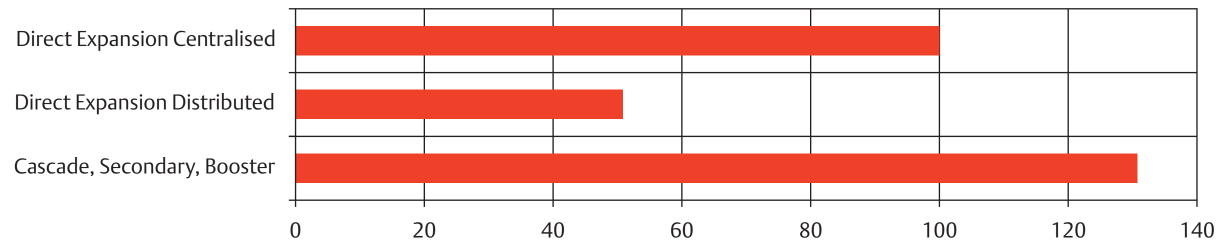
- A semi-hermetic reciprocating compressor with R134a will have an adder of 20% (type) plus 20% (refrigerant) giving a total adder of 40% to the baseline scroll R404A.
- A booster system using R744 will have a cost adder of 20% (type) plus 20% (refrigerant) plus 40% (system) giving a total adder of 80%. The assumption is made for CO_2-transcritical compressors out of large volume production. Today's cost/prices may still be significantly higher.

Other pack components

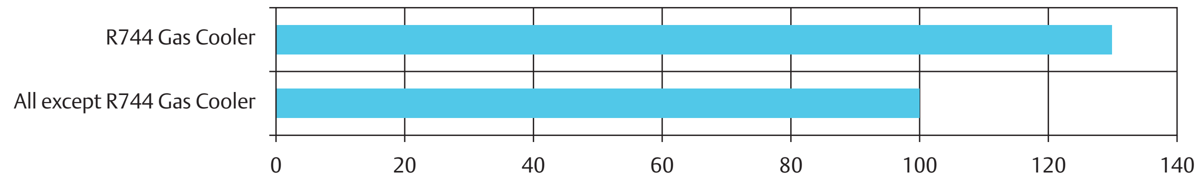


Additional volume flow rate of R134a and HFO is the reason for a 20% additional cost with a 20% adder also applied to R744 components. DX distributed systems have more cost built into the pack, but require less site assembly, and this is reflected below. Cascade and booster systems have additional circuits, controls and heat exchangers.

Installation

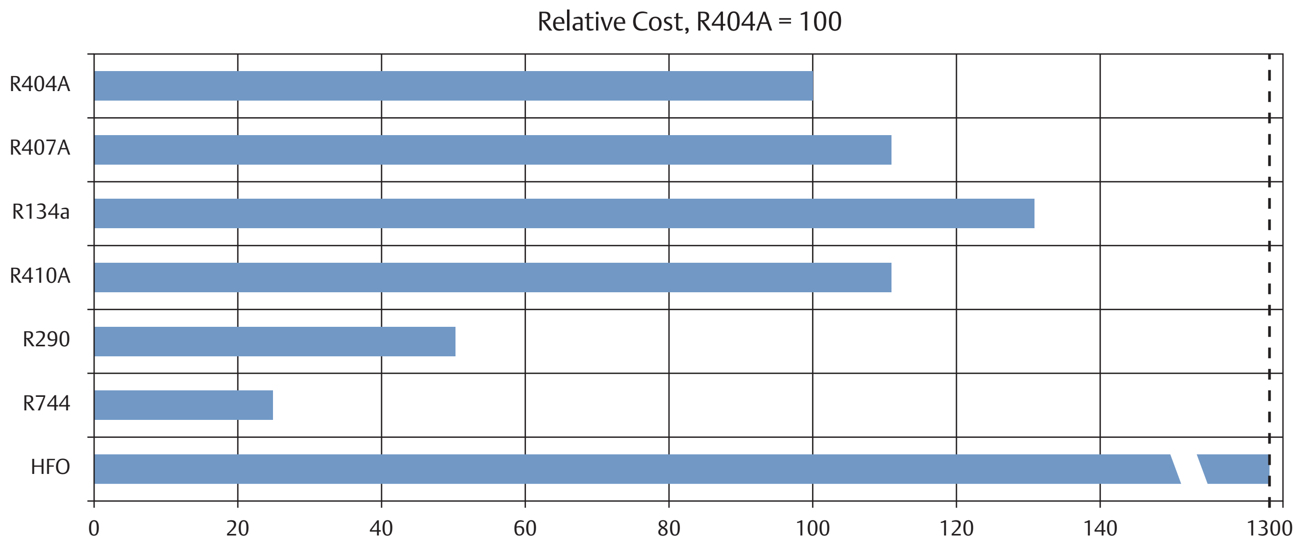


Condenser



A 30% cost adder has been included for the R744 gas cooler, receiver/separator and additional controls.

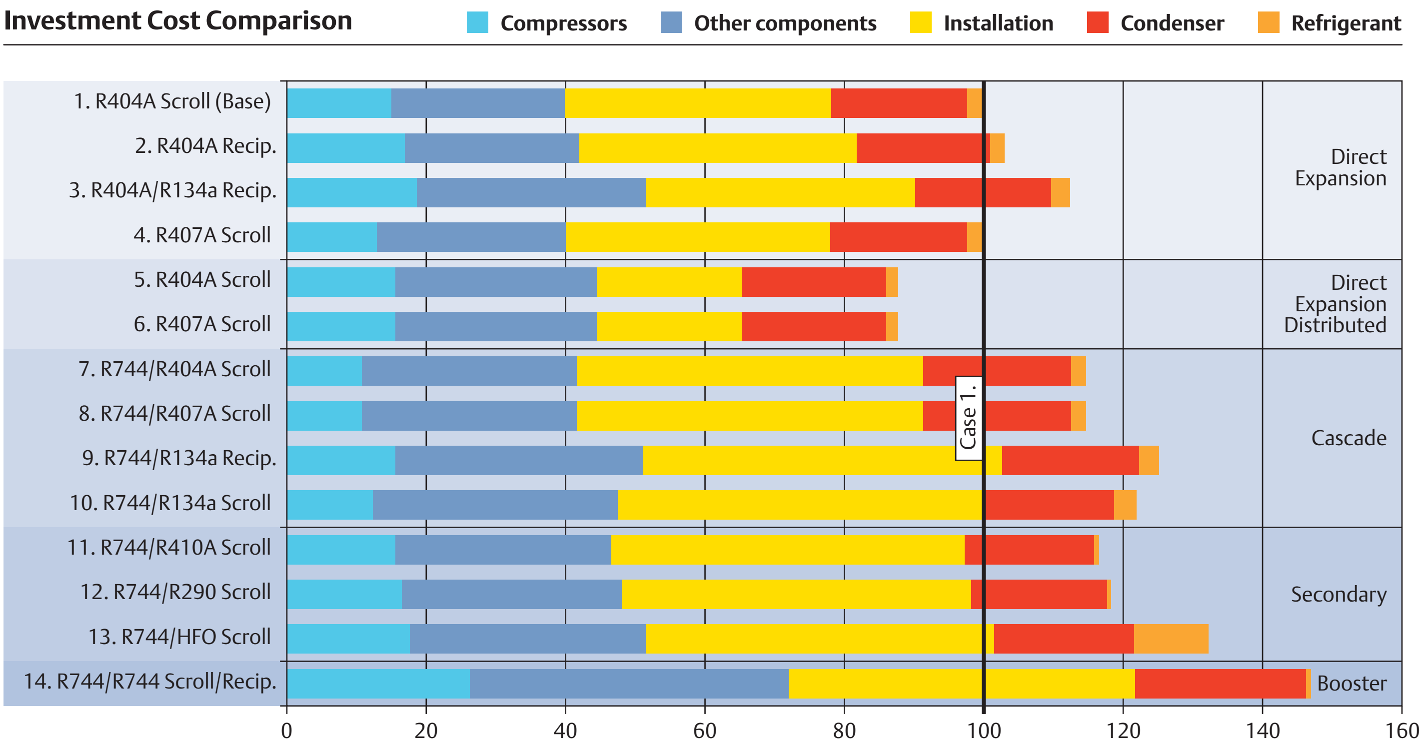
Refrigerant



The refrigerant element is only 5% of the total installation cost so the weightings have little effect except in the case of HFO where a very high cost is involved. There is a degree of uncertainty about the eventual HFO cost, and a factor of 10 times R134a has been applied in absence of specific information from refrigerant manufacturers.

6.3.2. Investment cost comparison

Data in the definitions above provide the information needed to calculate the total investment cost for the different cases. The graph below is a comparison tool where again R404A Scroll DX is used as base (100) and show the participation of the main costs into the total.



Observations

- Distributed systems are the lowest cost, but can only be applied with suitable building architecture/structure.
- Moving from DX systems to cascade, secondary or R744 systems will incur additional costs.
- Use of scroll technology in cascade and secondary systems offers the best alternative.
- Refrigerant cost plays a small part except in the projected cost of HFO.
- R744 booster systems eliminating HFCs and flammable refrigerants will require the largest investment.

7 Conclusions and findings

7.1. Conclusions

The tables and charts set out clearly the energy consumption, environmental impact and investment cost implications of various supermarket systems. Values for these key criteria follow directly from the recorded assumptions and compressor data. The results are not based on opinion or the need to be seen to be "green"; rather, they are based on quantified data. We can form a number of conclusions from these numbers:

For direct expansion systems:

- Reference Case 1 is a straight forward DX system based on the best performing compressors - scroll EVI and ZB. State-of-the-art compressor technology gives the lowest energy consumption at a competitive cost. The environmental impact of such systems can be considerably reduced by switching to R407A refrigerant.
- Semi-hermetic solutions on the same system show approximately 10% greater energy consumption and a correspondingly higher TEWI. Reports of R744 performance in supermarket systems usually make the efficiency comparison with a typical R404A semi-hermetic DX system, and this is Case 2 in our study.
- TEWI values can be improved by substituting R404A with R134a for the MT cooling duty. This is because there is a substantial reduction in leakage effect arising from lower GWP and lower pressures. However, there is a cost impact due to an extra 70% displacement requirement. Also R134a is unsuitable for LT systems.
- An alternative to R134a in MT systems is R407A allowing the design of a compact system, similar to R404A. The efficiency with R407A MT scroll tends to be better than R404A and this, combined with vapour injection technology on the LT units, results in better overall energy consumption and lower TEWI than the R134a DX solution. R407A in DX centralised DX, Case 4, is the most cost-effective solution where Distributed DX is impractical.

For direct expansion indirect system (sometimes termed close coupled):

- DX distributed systems can result in lower direct emissions because of the lower charge and lower leakage rates with factory-built units.
- Scroll compressors with brazed connections contribute to these savings.
- Normally, scrolls are used in this type of application where roof mounting is possible. The effect on TEWI can be seen when comparing Case 5 with Case 1. Energy consumption is recorded as the same as for baseline Case 1 although, in practice, some savings should be possible with shorter pipe lengths and smaller diameters (which will result in lower pressure drop and temperature rise).
- Case 6 shows the benefits of using R407A in this system configuration.

For cascade system:

- A cascade system enables R744 to be applied in the LT circuit using conventional vapour compression technology. In Case 7, R404A is used in DX for the MT load and introduces the relatively high direct emission effect because the total load on the MT system now includes the LT heat rejection. A larger DX system with proportionately greater charge and leakage effects is the result.
- Moving to R134a for the MT load significantly improves the TEWI for the cascade system, but there is a considerable cost impact.
- A cascade system with R407A MT, Case 8, improves energy consumption but the TEWI is approximately 4% higher than the R134a alternative (due to a higher GWP). However it is significantly lower in cost.

For secondary systems:

- A secondary system virtually eliminates the effect of direct emissions. A R410A chiller can be employed for the MT and cascaded LT load, and the leakage rate from a factory-built unit is small.
- By using R290 or HFO for the chiller, even this small direct emission can be eliminated, but with a cost penalty associated with extra safety precautions.

For R744 booster systems:

In considering the R744 booster type system we can make a number of observations. It is necessary to take advantage of the following benefits if the system is to attain the performance shown in the comparison charts:

- Better heat transfer - R744 has particularly good heat transfer properties, which allow lower temperature differences across the heat exchangers, thus improving system efficiency.

- High cooling effect - The volume of R744 required to achieve the same cooling effect is much lower than for HFCs. This allows many components (including compressors and pipes) to be smaller than in conventional installations.

However, it is also necessary to recognise:

- High pressure - CO_2-transcritical refrigeration circuits operate at much higher pressures (up to 110 bar) than conventional R404A systems (up to 25 bar). This requires the use of components and assembly techniques not common in the supermarket refrigeration sector.
- Serviceability - Operation in transcritical mode requires a different design from conventional HFC systems which is not familiar to most technicians providing supermarket refrigeration maintenance.
- High cost - R744 is not widely used in refrigeration systems. This limits the choice of components for designers which therefore tend to be higher in cost. The high pressures also require materials and designs of higher specification and, therefore, higher cost.
- Poor performance in high ambient conditions - In transcritical mode, COPs are lower than conventional vapour compression systems. This has to be compensated for by operation as a subcritical vapour compression cycle at lower outdoor temperatures. In Southern Europe, this penalises R744.

Moving to a R744 booster system would currently require a dramatic architecture change to the supermarket. This solution might therefore remain limited to new builds, whereas major retrofits/refurbishments would still be HFC-based. Without simpler, lower cost alternatives, 2020 carbon reduction targets are unlikely to be achievable.

7.2. Finally, aggregating the three criteria

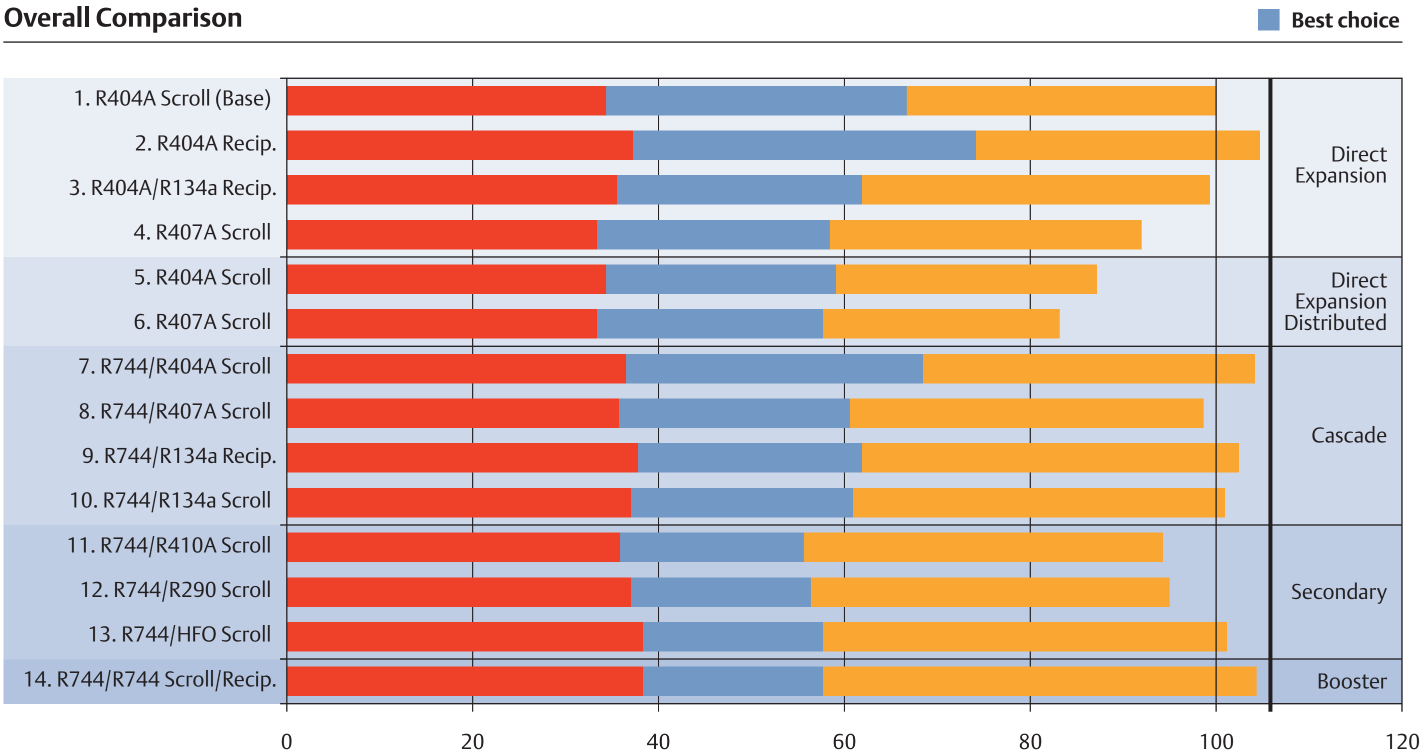
This is a straightforward aggregation of the relative values of the three parameters - energy consumption, environmental impact (TEWI) and investment cost. All numbers are now expressed as a percentage compared to the R404A scroll base (Case 1).

Case		1	2	3	4	5	6	7	8	9	10	11	12	13	14
System		Direct Expansion				Direct Expansion Distributed		Cascade				Secondary			Booster
Refrigerant Medium Temperature		R404A	R404A	R134a	R407A	R404A	R407A	R404A	R407A	R134a	R134a	R410A chiller	R290 chiller	HFO chiller	R744
Refrigerant Low Temperature		R404A	R404A	R404A	R407A	R404A	R407A	R744	R744	R744	R744	R744	R744	R744	R744
Compressor technology Medium & Low Temp.		Scroll	Recip.	Recip.	Scroll	Scroll	Scroll	Scroll	Scroll	Recip.	Scroll	Scroll	Scroll	Scroll	Scr/ Recip.
Normalised Score	Power	**Base**	12%	5%	**-3%**	0%	**-3%**	7%	4%	12%	9%	7%	9%	12%	12%
	TEWI	Base	6%	-18%	-24%	-24%	-36%	-2%	-23%	-27%	-28%	**-42%**	**-43%**	**-41%**	**-42%**
	Investment Cost	**Base**	3%	11%	0%	**-14%**	**-13%**	13%	13%	25%	21%	17%	18%	32%	48%

-3% Best Option 0% Second Best Option 4% Third Best Option

Results can also be compared on the graph below.

Overall Comparison



Assuming we can give equal importance to these 3 parameters, an average has been used to arrive to a ranking of these different refrigerant / technology combinations

Case	1	2	3	4	5	6	7	8	9	10	11	12	13	14
System	Direct Expansion				Direct Expansion Distributed		Cascade				Secondary			Booster
Refrigerant Medium Temperature	R404A	R404A	R134a	R407A	R404A	R407A	R404A	R407A	R134a	R134a	R410A chiller	R290 chiller	HFO chiller	R744
Refrigerant Low Temperature	R404A	R404A	R404A	R407A	R404A	R407A	R744	R744	R744	R744	R744	R744	R744	R744
Compressor technology Medium & Low Temp.	Scroll	Recip.	Recip.	Scroll	Scroll	Scroll	Scroll	Scroll	Recip.	Scroll	Scroll	Scroll	Scroll	Scr/ Recip.
Average	100	7%	0%	-9%	-12%	**-17%**	6%	-2%	3%	1%	-6%	-5%	1%	6%
Rank	7	14	8	3	2	**1**	12	6	11	9	4	5	10	13

We see that the distributed system with R407A scroll is the best choice (Rank 1) when combining all three criteria. R404A DX Systems are Rank 2 (Case 5).

However, where it is not possible to install a distributed system the user can turn to a DX R407A system with separate plant room (case 4, Rank 3).

For the customer looking for the lowest TEWI while keeping investment cost under control, secondary systems (cases 11 and 12) are excellent options (Rank 4 and 5).
In reality, the end user's weighting between these factors will further influence the comparison. Each customer will have to take a decision with strong emphasize on 'the most important' criteria for his business. While one customer has a strong preference for low investment cost, another customer might prefer a low environmental impact or the low energy consumption.

Emerson Climate Technologies offers a wide range of technology choices for all these cases. Scroll dominates the leading solutions and is especially applicable to distributed DX and secondary systems where it can be applied in a compact form using the best R410A technology available.

We know that your system will not precisely match any of the cases outlined in this study, but the analysis -using the same basic assumptions across the board - provides useful guidance for comparison.

There is no universal panacea; no solution will give you both a low cost and CO_2 emission free refrigeration system. However, this study should offer useful pointers to allow you to assess the relative values of the various claims made by proponents of individual systems.

Emerson Climate Technologies at a Glance

Emerson Climate Technologies is the world's leading provider of heating, ventilation, air conditioning, and refrigeration solutions for residential, industrial, and commercial applications. We combine technically superior products and services from our industry-leading divisions and brands with our global engineering, design and distribution capabilities to create reliable, energy efficient climate systems that improve human comfort, safeguard food, and protect the environment.

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