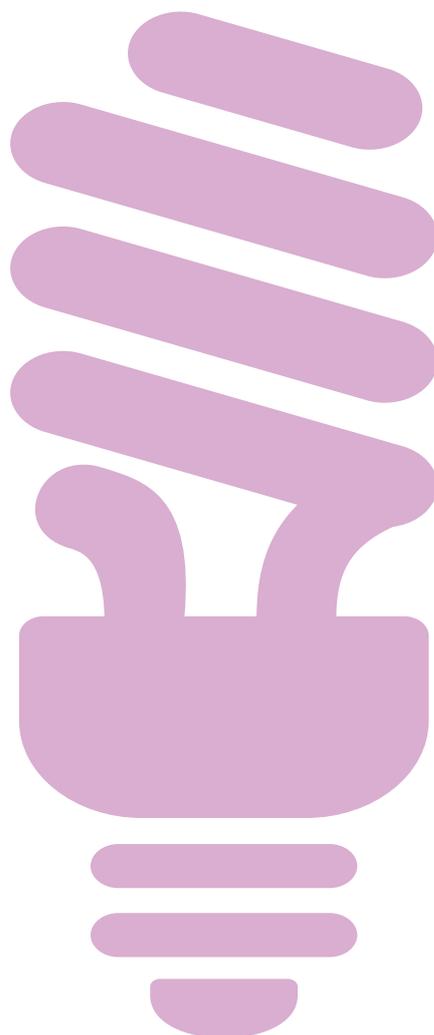


The Potential to Improve the Energy Efficiency of Refrigeration, Air-conditioning and Heat Pumps



Scope of the briefing note

The Ozone Secretariat has prepared three briefing notes to support parts A, B and C of the 9–10 July 2018 Vienna workshop on energy efficiency opportunities in the context of phasing-down hydrofluorocarbons (HFCs).

This briefing note, intended for part B, provides an overview of the technical potential to improve the efficiency of refrigeration, air-conditioning and heat pump (RACHP) equipment, looking in particular at:

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- the types of approach that can be adopted to improve the efficiency of RACHP systems;
 - examples of technical measures that can be applied to improve efficiency during the design and selection of new RACHP equipment;
 - examples of technical and management measures that can be applied to improve the efficiency of existing RACHP equipment.
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The purpose of this information note is to provide a background for the parties. It is not meant to be exhaustive or in any way prescriptive.

Factors influencing RACHP equipment energy efficiency

As discussed in Briefing Note A, there is significant potential to improve the efficiency of RACHP equipment, with good opportunities available when new equipment is being designed and purchased and through better use of existing equipment.

There are several important factors that influence the energy efficiency of RACHP equipment. The designer of the equipment needs to consider a wide range of different issues to ensure that efficiency is as good as possible. An integrated approach is needed, taking into account the different types of efficiency opportunity. Efficiency considerations should not be constrained to the RACHP equipment itself – they should include things like the type and variability of the cooling load as this can have a big influence on energy use. The most important issues to be considered are to:

i. Minimise the cooling load

Don't waste energy cooling something that does not need to be cooled! For example, put doors on retail display cabinets, ensure the space being cooled is properly insulated, or create shading on the sunny side of a building. It is surprising how often the cooling load is significantly higher than it needs to be.

ii. Minimise the "temperature lift" (see box 1).

This means providing cooling at the highest possible temperature and rejecting heat at the lowest possible temperature.

BOX 1: THE IMPACT OF TEMPERATURE LIFT ON RACHP EFFICIENCY

A refrigeration system collects unwanted heat at a low temperature and transfers that heat into the ambient surroundings at a higher temperature. Energy consumption depends on the temperature lift between the product being cooled and the ambient – with a bigger temperature lift, more energy must be used. What many cooling plant owners do not realise is that temperature lift has a dramatic impact on energy efficiency:

- **1-degree C** extra temperature lift will add 2% to 4% to the energy used by a plant.

Through poor design or poor plant operation it is easy to accidentally add an extra 10 or 15 degrees C to the temperature lift – that could add 20% to 40% to the total energy consumption. To minimise the temperature lift of an RACHP system it is important that:

- The "cold end" (the evaporator) should be at the highest possible temperature;
The "hot end" (the condenser) should be at the lowest possible temperature.

Energy consumption for systems running in high ambient temperature (HAT) conditions

Refrigeration and air-conditioning systems used in very hot countries generally use more energy than equivalent systems in cooler countries, because:

- The cooling load is higher for a given size of building, especially in high humidity.
- The temperature lift is bigger, because the "hot end" of the plant is rejecting heat at a much higher ambient temperature.

These two impacts lead to considerably higher energy consumption for refrigerant and air-conditioning systems in HAT countries.

iii. Take account of variable operating conditions.

Very few RACHP systems operate at their peak load "design point" (i.e. maximum cooling load under hottest possible ambient temperature) for many hours of the year. RACHP equipment usually spends the majority of time operating at part load and at ambient temperatures well below the peak. RACHP equipment needs to be efficient under a wide range of operating conditions. This is often ignored by the designer who creates maximum efficiency for the peak load design point instead of the more common part load conditions.

iv. Select the most efficient refrigeration cycle and components (see box 2).

There have been many recent advances in the efficiency of individual components such as compressors and heat exchangers and in the efficiency of advanced refrigeration cycles.

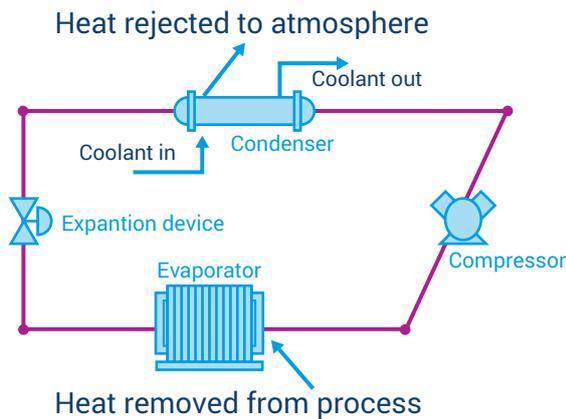
v. Design effective control systems

Modern sensors and control systems create many opportunities for improving efficiency through better control of the operation of a RACHP system. For example, many inefficient systems use a crude form of “on-off” control to achieve the required temperature. Use of a variable speed compressor improves the accuracy of temperature control and makes a significant efficiency improvement.

vi. Check operating performance and correct any faults of existing RACHP systems

Many RACHP systems develop faults that reduce efficiency – these can go unnoticed for months or even years! It is important to monitor performance and to recognise when a fault has developed – this is especially important on medium and large sized cooling systems. Refrigerant leakage leads to undercharging of a system and is one example of many different operating faults that can create a significant loss of efficiency.

BOX 2: A SIMPLE REFRIGERATION CYCLE



To understand some of the energy efficiency opportunities it is helpful to consider how a refrigeration or air-conditioning system operates. The configuration that is widely used in many RACHP systems is the simple “4 component cycle” illustrated in figure 1.

Heat is absorbed at a low temperature in a heat exchanger, the evaporator. The refrigerant is boiled in the evaporator and the vapour is compressed. The refrigerant rejects heat to the atmosphere by condensing into a liquid inside a heat exchanger, the condenser. The refrigerant then goes through an expansion device (usually a valve) and is returned to the evaporator to start the cycle again. Many systems employ more sophisticated cycles, but the basic principles apply.

Whilst the compressor motor is usually the biggest user of energy, it is important to remember that to move the fluids (e.g. air, water etc.) flowing through the evaporator and condenser there is a need for fans and/or pumps. These auxiliary devices can use a significant proportion of the total energy and can have a big impact on efficiency.

Figure 1: 4 component cycle

Coefficient of Performance (COP)

The efficiency of RACHP equipment is often expressed as the COP. This is the ratio of the heat absorbed in the evaporator to the energy used to power the compressor and related auxiliaries. The COP is usually in the range of 1 to 5 (although it can be lower or higher).

Refrigerant selection

The refrigerant should be considered as one of many “components” in a RACHP system. As with all components, it must be selected with energy efficiency in mind. Various other characteristics will also influence refrigerant choice, such as GWP, safety, commercial availability and cost. RACHP systems operate over a very wide range of different conditions. For example, a food freezing system might cool a product to -20°C whilst a room air-conditioning system is cooling

the room to +20°C. These different temperature requirements lead to the choice of a different “best efficiency” refrigerant for these applications. The choice of refrigerant is also affected by several other important parameters such as system size and ambient temperature.

Whilst the selection of refrigerant has an impact on energy efficiency, it is usually a much smaller effect than the other efficiency factors as described above. In a transition away from high-GWP HFCs, it will be important to have low-GWP refrigerants available for each type of RACHP application. However, if designers only focus on the refrigerant choice and do not incorporate the wide range of other technical and operational opportunities, it is unlikely that the most efficient systems will be placed on the market.



Mass-produced bottle coolers

Illustration of energy efficiency improvement potential

Mass-produced bottle coolers

Bottle coolers are used for selling cold drinks. An old inefficient design of bottle cooler can use six times more energy than a state-of-the-art model. Many existing bottle coolers were designed without giving attention to energy efficiency – the priority was low capital cost. A widely used bottler cooler is an open vertical display unit, using poor efficiency components.

A state-of-the-art model uses doors, high efficiency components and sophisticated controls. Figure 2¹ shows the dramatic improvements that are possible. Two levels of savings are illustrated:

- i. Between the “base case” (an old design without doors) and a state-of-the art bottle cooler with doors – there is an **85% saving**. Open cases are the least efficient especially in an outdoor location.
- ii. Between an old design with doors and a state-of-the art unit with doors – there is a **60% saving**. This illustrates that component design and control are also crucial to create state-of-the-art high efficiency.

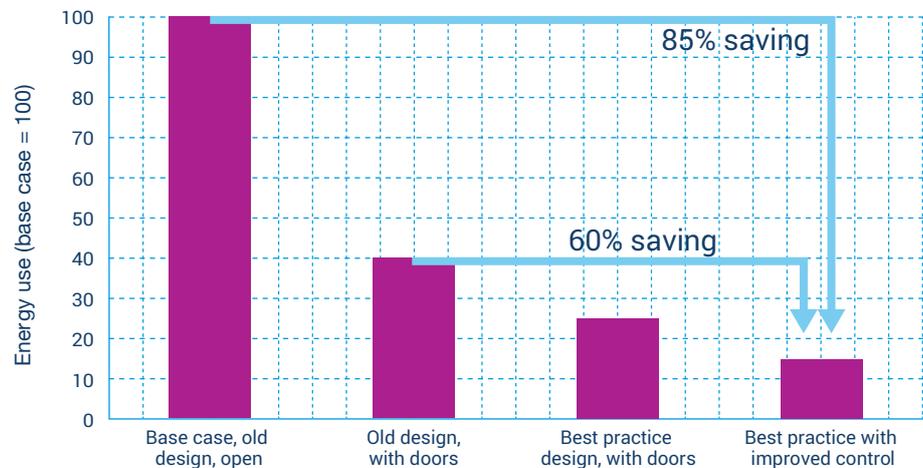


Figure 2: Bottle cooler energy savings

1 Defra, 2015: Use of Refrigeration in UK Soft Drinks Supply Chain.

Energy efficiency examples – new equipment design and purchase

There are many ways that designers and operators can improve the efficiency of new equipment. The examples below illustrate each of the factors that influence energy efficiency, introduced in section 2 of this briefing note.

Efficiency factor 1: Minimise the cooling load

There are many examples of RACHP equipment cooling an unnecessary load. The first step in a system design should be a review of the cooling loads, to try to identify loads that can be eliminated or reduced. Various strategies can be used to reduce the cooling load. A common opportunity is to use “free-cooling” to pre-cool a hot product prior to using refrigeration. For example, a cooked product in a food factory at close to 100°C is often cooled with refrigeration. The cooling load can sometimes be reduced by over 50% by pre-cooling the product with ambient air or water cooled in a cooling tower. **Efficiency example 1a illustrates a 50% energy saving that can be made without any extra capital investment by minimising the cooling load through use of doors on retail displays.**

EFFICIENCY EXAMPLE 1A: DOORS ON RETAIL DISPLAYS

It would be strange to use a domestic refrigerator without a door. However, retail displays (e.g. in supermarkets) are often built without doors. This is very inefficient, and it can also make areas of a food retail store uncomfortably cold. Using doors can reduce energy consumption by over 50%. The extra cost of the door is offset by being able to use a smaller refrigeration unit. Another benefit is that product quality is often improved (as the control of temperature can be more precise). This seems an obvious measure but display cases without doors are widely used both in small shops and large supermarkets.

Impact of refrigerant choice

The choice of refrigerant has no direct impact on this efficiency example. The same savings are achieved with any refrigerant.

Good insulation is important to minimise unwanted heat gains into buildings or process equipment. **Efficiency example 1b illustrates a 50% energy saving that can be made by insulating and properly maintaining a duct system in a house².**

EFFICIENCY EXAMPLE 1B: INSULATION IN AIR-CONDITIONED HOMES

A family bought a hundred year old house and planned to paint it and re-model the kitchen, but they were surprised by their very large energy bills. Instead of replacing the kitchen, they spent their money on making their home more energy efficient and reduced their energy bills by 50%. The family did three key things: (a) they sealed cracks in the building, (b) they replaced the old, dirty, and wet insulation with new insulation in the attic and (c) they sealed the older ductwork. Within a year, the family’s heating and cooling bills were reduced by half, and they’ve gone down every year since as they have continued to work on the house.

Impact of refrigerant choice:

The choice of refrigerant has no direct impact on this efficiency example. The same savings are achieved with any refrigerant.

Efficiency factor 2: Minimise the “temperature lift”

RACHP system efficiency is very sensitive to the temperature lift. The designer should try to provide cooling at the highest temperature possible – even a few degrees C can make a big difference. A common opportunity relates to the selection of chilled water temperature for a building air conditioning system. For example, by raising the chilled water temperature from 6°C to 9°C a chiller will provide cooling with 10% to 15% better efficiency. The designer should also try to ensure that heat is rejected at the lowest possible temperature. Good design of the condenser can allow the condensing temperature to be as low as possible under both full load and part load operating conditions. **Efficiency example 2 shows how a 35% saving was made by designing the refrigeration system in a brewery to provide cooling at the appropriate temperature level.**

EFFICIENCY EXAMPLE 2: NEW REFRIGERATION FOR A BREWERY

A brewery had 30-year-old chillers producing glycol at -6°C. A “like-for-like” replacement with a modern plant was proposed. An analysis of the cooling loads identified a much more efficient solution. By splitting the cooling loads into 2 groups, 60% of the load could be cooled with chilled water at +6°C, with only 40% requiring glycol at -6°C. Cooling with +6°C water uses 35% less energy than cooling with -6°C glycol.

Impact of refrigerant choice:

The choice of refrigerant has no direct impact on this efficiency example. The same savings are achieved with any refrigerant.

Efficiency factor 3: Take account of variable operating conditions

Many RACHP systems are designed and optimised for operation at the “design point”, which is the peak cooling load during the hottest ambient weather conditions. Cooling systems operate most of the year at “off design” conditions, either with a lower cooling load or in cooler ambient weather conditions (or both). Under these conditions the equipment operates at part load. Operation can be very inefficient if these off-design conditions were not considered when the plant was designed. **Efficiency example 3 shows how the selection of the size of a system can have a significant impact on efficiency when the plant is not operating at peak load.**

EFFICIENCY EXAMPLE 3: CHILLER FOR LARGE BUILDING

A university required a water chilling system to provide air-conditioning. The lowest capital cost option was a single large chiller with a cooling capacity of 1,000 kW. However, an energy review showed that this high level of cooling was only required in the hottest weather conditions and when the building was fully occupied. Most of the year the load was considerably lower. A single large chiller operating at part load is very inefficient. By selecting four smaller chillers the overall operating efficiency was improved by over 25% and the extra investment for buying the smaller chillers had a payback period³ of less than 2 years.

Impact of refrigerant choice:

The choice of refrigerant has no direct impact on this efficiency example. The same savings are achieved with any refrigerant. Large chillers are becoming available with a range of different ultra-low GWP refrigerants, including R-514A, HFO-1234ze and HFO 1233zd. The latest chillers using these refrigerants will be of equal or better efficiency to chillers using higher GWP HFCs such as HFC-134a.

3 Payback period is a simple way of expressing the financial return on an investment. For example, if an energy efficiency project costs \$100 and saves \$50 per year, the payback period is 2 years (100 divided by 50). The payback period for a refrigeration efficiency project is strongly affected by the price of electricity.

Efficiency factor 4: Select the most efficient refrigeration cycle and components

Cooling equipment is complex, consisting of numerous components, such as compressors, heat exchangers, controls etc. Each component needs to be optimised for maximum energy efficiency for the intended application. The designer should consider the likely variation in operating conditions to ensure that the cycle and individual components have a good efficiency across the whole range of possible conditions. **Efficiency example 4 illustrates how important it is to carefully select major components such as compressors.**

EFFICIENCY EXAMPLE 4: COMPRESSOR SELECTION

The main electricity using component of any RACHP system is the compressor. Compressors operate under many different conditions and with many different refrigerants. Selecting a compressor with the best efficiency for the range of conditions in a specific application needs to be prioritized. Two almost identical compressors, with the same capital cost, could have energy efficiencies that differ by more than 20%. A saving of over 20% can be made with no extra capital cost simply by selecting the best compressor for the expected operating conditions.

Impact of refrigerant choice:

Compressor selection must be made with data for the specific refrigerant to be used. There are numerous new refrigerants being introduced as a response to HFC phase-down. Compressor manufacturers are testing their compressors and optimising their designs to maximise the efficiency for these new refrigerants. It is important to check with the manufacturer that they have done this design optimisation before selecting a compressor for use with a particular refrigerant.

Efficiency factor 5: Design effective control systems

One of the biggest opportunities to improve RACHP energy efficiency relates to control. Many older systems have very poor control systems that do not optimise control to ensure maximum energy efficiency. A good opportunity relates to the use of variable speed drives (VSDs or inverters). These can be used to improve part load performance of compressors and auxiliary components such as pumps and fans, creating excellent savings. **Efficiency example 5a illustrates how temperature lift can be reduced through the avoidance of an unnecessary control of the condensing temperature of a RACHP system.**

EFFICIENCY EXAMPLE 5A: AVOID HEAD PRESSURE CONTROL

Many refrigeration plants are fitted with a head pressure control (HPC) system. An HPC can be very wasteful if it is set at an incorrect pressure level. To maximise efficiency a plant should be controlled to allow the condensing temperature to fall to the lowest practical level in cool weather. An incorrect HPC setting prevents this. Annual savings can be more than 25%. In some cases, these savings are achieved with no capital investment, by simply adjusting HPC settings. Sometimes a small extra investment is required, e.g. to use an electronic expansion valve in place of a thermostatic expansion valve.

Impact of refrigerant choice:

The choice of refrigerant has no direct impact on this efficiency example. The same savings are achieved with any refrigerant. If an electronic expansion valve is to be used it is important to check that the manufacturer has optimised the valve design for the refrigerant selected.

In many situations better control provides big energy savings with little investment cost. Many plants use fixed control settings that are suited to the worst expected operating conditions. For example, the defrosting of evaporators in large cold stores is done using timers, set to the same defrost frequency all year round. But, in summer time, the rate of frost build-up might be 4 times higher than that in winter. As each defrost cycle uses energy, it makes sense to have a control system that reduces the frequency of defrost outside the summer peak. **Efficiency example 5b illustrates how much energy can be wasted on RACHP systems operating at part-load.**

EFFICIENCY EXAMPLE 5B: OPTIMISE PART LOAD OPERATION

ManWater chiller systems are often very inefficient when operating at part load. If a system consists of, say, 3 chillers, the designer needs to consider how the chiller operation should be modified under part load conditions. If the water pipework is designed incorrectly, it can be difficult to control the chillers efficiently. For example, a badly designed plant running at 30% load might need to use all 3 chillers, each running at a 30% load setting. This can be very inefficient and could require **twice** the energy input of one chiller running at full load.

Impact of refrigerant choice:

The choice of refrigerant has no direct impact on this efficiency example. The same savings are achieved with any refrigerant.

4.

Energy efficiency examples – existing RACHP equipment

Most RACHP equipment has an operating life in the range of 10 to 20 years. For large water chillers and industrial refrigeration systems, the operating life can exceed 30 years. It is important that efforts are made to improve the efficiency of the large estate of existing RACHP equipment. Each of the efficiency factors demonstrated through the examples in section 3 can be applied to existing systems, although the design related opportunities are often more costly to implement on existing systems than for new systems. Some examples that are cost-effective on existing equipment include:

- Efficiency example 1, doors on retail displays: it is cost-effective to fit doors to existing retail displays.
- Efficiency example 5a, avoiding head pressure control: this can be done with existing RACHP equipment.
- Efficiency example 5b: avoiding part load operation: the control strategy for an existing plant can be improved.

The cost-effectiveness of making design-related improvements to RACHP equipment depends on the size of equipment. It may not be worth considering design improvements to small mass-produced equipment, but it is worth considering all six efficiency factors on large systems including improving energy efficiency by design changes to buildings (e.g. improved insulation).

Efficiency factor 6: Check operating performance and correct any faults of existing RACHP systems

This efficiency factor is the only one that specifically applies to existing equipment. Many RACHP systems operate for years with control or maintenance related problems that go undetected. Performance should be regularly measured. If energy use is creeping up there could be a maintenance issue that can quickly be resolved. It is common to find that savings of 10% to 20% can be achieved by monitoring the performance of an existing system and correcting any faults identified. Many end users have a relatively poor understanding of how to diagnose energy wasting faults on refrigeration systems – they need to be encouraged to monitor performance and helped to identify the reasons for poor efficiency.

It is only possible to identify energy wasting faults if relevant parameters are measured on a regular basis and compared against the values that would be expected if the plant was operating at full efficiency. Key parameters to be measured include:

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- Electricity kWh consumption of compressors and large auxiliaries.
 - Evaporating and condensing pressures.
 - Various temperatures (e.g. temperature of product being cooled and the ambient temperature)
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Another opportunity to ensure proper operating conditions for large systems is to install leak detection equipment that continuously monitors a space for refrigerant leakage. This equipment can allow equipment owners to identify leaks sooner, reducing both refrigerant leakage and energy use.

EFFICIENCY EXAMPLE 6A: REMOVE AIR FROM CONDENSERS

In some low temperature refrigeration systems (e.g. for freezing a product in a food factory) it is common for air to accumulate inside the condenser. Without monitoring, this can go unnoticed and continue for months or years. Regular monitoring of the condensing pressure will identify when this problem occurs. It can be cured via simple maintenance actions. Left unresolved, air inside the condenser can quickly begin to add 10% to 20% to the energy consumption of the plant.

Impact of refrigerant choice:

The choice of refrigerant has no direct impact on this efficiency example. The same savings are achieved with any refrigerant. To carry out effective fault diagnosis it is important to have data for the temperature – pressure relationship of the refrigerant being used. If a new refrigerant is being used, it is important to use the appropriate data.

EFFICIENCY EXAMPLE 6B: MINIMISE REFRIGERANT LEAKAGE

If refrigerant leaks from a RACHP system, it will lead to a decrease in energy efficiency. The level of efficiency loss gets greater as a larger proportion of the refrigerant leaks. If RACHP system performance is not being monitored, the loss in efficiency will not be noticed until the leak is so bad that the plant fails to operate – possibly leading to a consequential loss (e.g. product being stored in a frozen food warehouse could be lost). With a good performance measurement regime such as energy monitoring or use of leak detection equipment, the leak will be recognised much sooner. Through an early leak repair and refrigerant top-up less energy will be wasted, and the plant failure completely avoided.

Impact of refrigerant choice:

The choice of refrigerant has no direct impact on this efficiency example. However, it is important that the correct refrigerant is used to refill the plant after the leak has been fixed as efficiency will be reduced and there are potential safety risks if the wrong refrigerant is used in an existing system. In particular, it is important not to use a flammable refrigerant in a plant that was designed for a non-flammable refrigerant.

5.

Does better efficiency imply higher capital cost?

Improved RACHP equipment efficiency means lower running costs as less energy needs to be purchased. There is often a requirement for extra investment in order to purchase better quality components or a more complex control system. Despite the possible need for extra investment, most cooling efficiency projects have a very good rate of financial return on the extra investment. Many efficiency improvements are achieved with payback periods of between 1 and 3 years. However, there are numerous examples of better efficiency being delivered at equal or even lower capital cost.

An example that illustrates the enormous potential for efficiency improvements without extra capital cost is summarised in figure 3. This shows a breakdown of the lifetime CO₂ emissions of a typical residential fridge-freezer in developed economies⁴. The global best practice refrigerator in 2015 had GHG emissions that were **nine times lower** than a typical 1980s refrigerator sold in developed countries (non-Article 5). Some of the reduction comes from the switch away from CFC refrigerant and foam blowing agent (these CFCs had very high GWPs). The energy efficiency improvement also makes a vital contribution – the 2015 best practice unit used **five times less** energy than the 1980s model. What is important to note is that the domestic refrigerator market is highly cost-competitive and benefits from enormous economies of scale via mass production. The cost of the high efficiency 2015 refrigerator is not higher in real terms than the 1980s model. Data from the US⁵ (see figure 7 in Briefing Note A) indicates a 75% improvement of energy efficiency over 40 years, whilst the capital cost for buying a fridge has fallen in real terms by 50%.

⁴ IPCC, 2013: The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

⁵ US Association of Home Appliance Manufacturers, 2016: Appliance Standards Awareness Project.

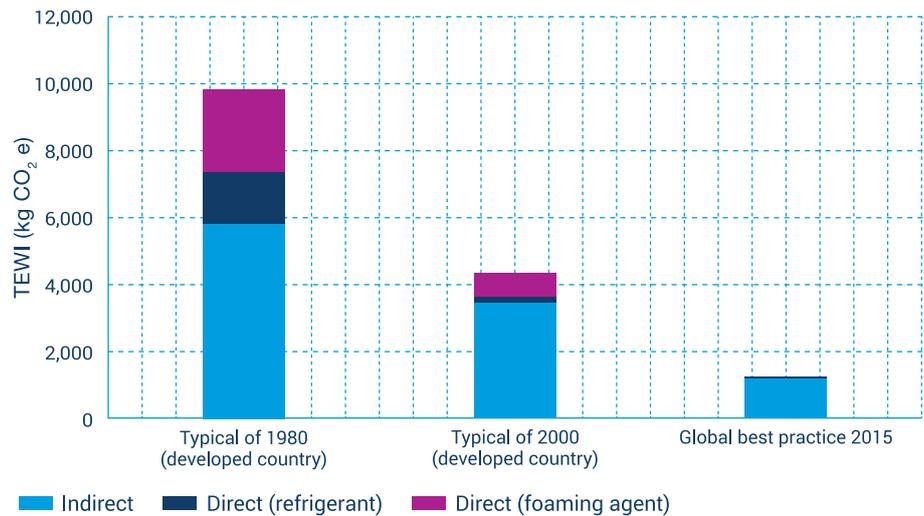


Figure 3: Reducing GHG emissions from domestic fridge-freezers

6.

Concluding comments

There are a wide range of technical measures that can be adopted to improve the energy efficiency of RACHP equipment. Use of a step-by-step integrated approach can help to ensure that efficiency is maximised when new equipment is designed or purchased and when existing equipment is operated. These steps include:

- i.** Minimising the cooling load.
- ii.** Minimising the temperature lift.
- iii.** Accounting for variable operating conditions.
- iv.** Selecting the most efficient refrigeration cycle and components.
- v.** Design of effective control systems.
- vi.** Checking operating performance and correcting any faults of existing RACHP systems.

The refrigerant used should be treated as one of the many components in the system. It must be selected with care, but refrigerant choice should be recognised as only having a relatively small impact on efficiency. Other design issues listed above have a much greater impact on efficiency than refrigerant choice.