

**MONTREAL PROTOCOL
ON SUBSTANCES THAT DEplete
THE OZONE LAYER**



UNEP

**REPORT OF THE
TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL**

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VOLUME 5

**DECISION XXIX/10 TASK FORCE REPORT ON ISSUES
RELATED TO ENERGY EFFICIENCY WHILE PHASING DOWN
HYDROFLUOROCARBONS**

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The text of this report is composed in Times New Roman.

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Foreword

The 2018 TEAP Report

The 2018 TEAP Report consists of five volumes:

Volume 1: *Decision XXIX/9 Working Group Report on hydrochlorofluorocarbons and decision XXVII/5*

Volume 2: *Decision XXIX/4 TEAP Task Force Report on destruction technologies for controlled substances*

Volume 3: *TEAP 2018 Progress report*

Volume 4: *MBTOC interim CUN assessment report*

Volume 5: *Decision XXIX/10 Task Force Report on issues related to energy efficiency while phasing down hydrofluorocarbons*

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DECISION XXIX/10 TASK FORCE REPORT ON ISSUES RELATED TO ENERGY EFFICIENCY WHILE PHASING DOWN HYDROFLUOROCARBONS

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Executive Summary

At their 29th Meeting, parties requested the Technology and Economic Assessment Panel (TEAP) to report to the 40th Open-ended Working Group (OEWG-40) on issues related to energy efficiency (EE) while phasing down hydrofluorocarbons (HFCs), as outlined in Decision XXIX/10. Decision XXIX/10 requests, in relation to maintaining and/or enhancing energy efficiency in the refrigeration and air-conditioning and heat-pump (RACHP) sectors, an assessment of:

- Technology options and requirements including
 - Challenges for their uptake;
 - Their long-term sustainable performance and viability; and
 - Their environmental benefits in terms of CO₂eq;
 - Capacity-building and servicing sector requirements in the refrigeration and air-conditioning and heat-pump sectors;
- Related costs including capital and operating costs;

The decision also requested TEAP to provide an overview of the activities and funding provided by other relevant institutions addressing EE in the RACHP sectors in relation to maintaining and/or enhancing energy efficiency while phasing down HFCs under the Kigali Amendment.

Finally, Decision XXIX/10 requested the Secretariat to organise a workshop on EE opportunities while phasing-down HFCs at hydrofluorocarbons at OEWG-40, and, thereafter, for TEAP to prepare an updated final report for the 30th Meeting of the Parties to the Montreal Protocol, taking into consideration the outcome of the workshop.

In response to Decision XXIX/10, TEAP established the Decision XXIX/10 Task Force, which included TEAP and Technical Options Committees members as well as outside experts. EE is a broad topic of major importance for the environment, economics and health, and there is an enormous amount of published literature and reviews. In preparing its response to the decision, the Task Force referenced information provided in earlier TEAP reports (e.g., Decision XXVIII/3 Working Group Report – October 2017) and examined updated, available research and studies. Outside expert members of the Task Force provided relevant information from their own research and of work done by their colleagues and organisations for consideration in this report.

This report is organised, following the format requested in Decision XXIX/10, into an introduction and two main chapters. Chapter 2 deals with the technology opportunities related to maintaining or enhancing EE during the phasedown of HFCs. Various aspects of the EE opportunities in the RACHP sector were considered. Chapter 2 also considered the other topics requested from the decision including the long-term sustainability and viability of the technology opportunities, consideration of high ambient temperature conditions, climate benefits from adopting the RACHP EE measures, and consideration of related capital and operating costs. Chapter 3 examines other financial institutions where these may intersect with support for realizing EE goals in the RACHP sectors during the phasedown of HFCs. Contained in two annexes are information about the different challenges to the technology uptake in the RACHP sectors and examples of relevant projects funding or financing.

Below are summaries of the various sections of the report.

Technology opportunities and challenges to maintain and/or enhance energy efficiency of new RACHP equipment

By using a rigorous integrated approach to RACHP equipment design and selection, the opportunities to improve energy efficiency (EE) or reduce energy use can be maximised. This approach includes:

- 1) Ensuring minimisation of cooling/heating loads;

- 2) Selection of appropriate refrigerant;
- 3) Use of high efficiency components and system design;
- 4) Ensuring proper installation, optimised control and operation, under all common operating conditions;
- 5) Designing features that will support servicing and maintenance.

While the benefits of higher EE, such as savings in energy, operating cost to the consumer, peak load and GHG emissions are widely recognised, many barriers to the uptake of more efficient equipment continue to persist. There are a number of common challenges that apply to all types of RACHP equipment. There also are certain market and sector-specific issues that are presented in further detail. Broadly, these barriers can be classified into the following categories: financial, market, information, institutional and regulatory, technical, service competency and others.

Technologies resulting in efficiency improvement opportunities available for high-GWP refrigerants may be applicable to low-GWP refrigerants as well.

The largest potential for EE improvement comes from improvements in total system design and components, which can yield efficiency improvements (compared to a baseline design) that can range from 10% to 70% (for “best in class” unit). On the other hand, the impact of refrigerant choice on the EE of the units is usually relatively small – typically ranging from +/- 5 to 10%.

Long-term sustainable performance and viability

In assessing consideration of long-term sustainable performance and viability (of technology options and requirements in the context of maintaining or exceeding energy performance), it was necessary for the Task Force to define the terms and timeframes for this assessment. The Task Force interpreted the term “long-term” for RAHCP technologies to mean for a period of up to 15 years, which is consistent with previous assessments of this term used and reported by the TEAP.

For the phrase “sustainable performance and viability” (over the 15-year “long-term” timeframe), the Task Force looked to assess whether or not the options and requirements for technology that are commercially available today and being commercially developed for the nearer term (which include zero or low-GWP refrigerants - single chemicals and blends, and compatible equipment/hardware), would be anticipated to at least meet EE needs (i.e., would be viable) and whether or not they would remain viable over the next 15 years, including considerations for servicing.

Therefore, the relevant aspects that will impact the long-term sustainment of performance are expected to be as follows:

- Technological environment,
- Minimum Energy Performance Standards (MEPS).

While the challenge of researching and finding sound, technical solutions is important, in some cases it may be even more important to ensure engagement with the customer and the industry and consideration of issues of the whole supply chain in order to ensure that the process of putting those technologies to practical use is not jeopardized.

High ambient temperature (HAT) considerations

A HAT environment imposes an additional set of challenges on the selection of refrigerants, system design, and potential EE enhancement opportunities.

HAT conditions impose additional requirements such as ensuring the refrigerant can continue to deliver and sustain acceptable efficiency at elevated ambient temperatures, and that the refrigerant doesn't breakdown or react with system components at high temperature.

Environmental benefits in terms of CO₂eq

Over 80% of the global warming impact of RACHP systems is associated with the indirect emissions generated during the production of the electricity used to operate the equipment (indirect), with a lower proportion coming from the use/release (direct emissions) of GHG refrigerants where used. The environmental impact of improving system efficiency is a factor of the type of equipment, how many hours and when it is used (influenced by ambient temperature and humidity conditions), and the emissions associated with generating power, which vary by country.

Climate and development goals are driving governments to adopt policies to improve the EE of equipment. In the RACHP sector, a holistic approach is important for reducing equipment energy consumption.

Servicing sector requirements

The present concern in most Article 5 countries in the HCFC phase-out process is to train technicians on the use of new refrigerants. EE aspects require additional training and further awareness.

Some EE degradation over the life time of equipment is inevitable; however, there are ways to limit the degradation through improved design and improved servicing which include both installation and maintenance.

The impact of proper installation, maintenance, and servicing on the efficiency of equipment and systems is considerable over the life time of these systems while the impact on additional cost is minimal.

The benefits of proper maintenance are considerable. Appropriate maintenance and servicing practices can curtail up to 50% reduction in performance and maintain the rated performance over the lifetime.

Capacity-building requirements

There are enabling activities such as capacity building, institutional strengthening, demonstration projects, and national strategies and plans that help to bridge Montreal Protocol activities under the Kigali Amendment and EE. A number of enabling activities supported by the other funds such as, the Kigali Cooling Efficiency Programme and the Global Environment Facility, have advanced both ozone depletion and EE goals.

Additional enabling activities under the Kigali Amendment can bridge the current Montreal Protocol activities with those destined towards EE and serve as examples of potential synergy between HFC phasedown and EE opportunities.

Costs related to technology options for energy efficiency

A summary is presented of methods developed by various countries with established market transformation programs for promoting EE including MEPS programs and labelling programs.

It should be noted that the presented methodology offers a "snapshot" of the cost of efficiency improvement at any given time and will tend to provide a conservative (i.e. higher) estimate of the cost of efficiency improvement. In actual practice, the prices of higher efficiency equipment have been found to decline over time in various markets as higher efficiency equipment begins to be

produced at scale. This applies especially for small mass-produced equipment where manufacturers quickly absorb the initial development costs and try to get to certain “price points” that help them sell their equipment.

Retail price of products is not an adequate indicator for the costs of maintaining or enhancing EE in new equipment due to:

- bundling of various non-energy related features with higher efficiency equipment,
- variation of manufacturer’s skills and know-how,
- variation in manufacturer’s pricing, marketing and branding strategies, and
- the idea that efficiency can be marketed as a “premium” feature.

Rigorous cost analysis may be needed to fully understand the impact of EE improvements. These types of analyses are relevant when setting MEPS as several EE levels need to be evaluated compared with the baseline. These studies can take more than 1 year to conclude for a single product category. As such, in this report we would like to refer parties to the corresponding methodologies and present simplified examples based on products already introduced on the market.

Funding institutions

There are numerous financial resources for projects implementation in the field of EE. Besides funding institutions that provide resources in the form of directed grants, there are financing institutions that provide project funding support through mechanisms such as loans, green bonds or other instruments. Moreover, private capital is an additional source through companies who might be interested to finance project implementation against investment payback.

Broad consideration of the various potential interested stakeholders, opportunities for partnerships with shared goals, and options for co-financing would be important to planning for potential projects related to EE in the RACHP sector while phasing down HFCs.

1 Introduction

1.1 Decision XXIX/10

At their 29th Meeting, parties adopted Decision XXIX/10. The text of Decision XXIX/10 is as follows:

Recalling decision XXVIII/2, in which the Meeting of the Parties, inter alia, requested the Executive Committee to develop cost guidance associated with maintaining and/or enhancing the energy efficiency of low-global-warming-potential (GWP) or zero-GWP replacement technologies and equipment when phasing down hydrofluorocarbons, while taking note of the role of other institutions addressing energy efficiency, when appropriate,

Recognizing the importance of maintaining and/or enhancing energy efficiency while transitioning away from high-GWP hydrofluorocarbons to low-GWP alternatives in the refrigeration, air-conditioning and heat pump sectors,

Noting that the use of air-conditioning and refrigeration is growing in countries operating under paragraph 1 of Article 5,

Recognizing that maintaining and/or enhancing energy efficiency could have significant climate benefits

1. *To request the Technology and Economic Assessment Panel in relation to maintaining and/or enhancing energy efficiency in the refrigeration and air-conditioning and heat-pump (RACHP) sectors, including in high-ambient temperature conditions, while phasing down hydrofluorocarbons under the Kigali Amendment to the Montreal Protocol in parties operating under paragraph 1 of Article 5, to assess the following items:*
 - a. *Technology options and requirements including*
 - i. *Challenges for their uptake;*
 - ii. *Their long-term sustainable performance and viability; and*
 - iii. *Their environmental benefits in terms of CO₂e;*
 - iv. *Capacity-building and servicing sector requirements in the refrigeration and air-conditioning and heat-pump sectors;*
 - b. *Related costs including capital and operating costs;*
2. *Also to request the Technology and Economic Assessment Panel to provide an overview of the activities and funding provided by other relevant institutions, as well as definitions, criteria and methodologies used in addressing energy efficiency in the RACHP sectors in relation to maintaining and/or enhancing energy efficiency in the RACHP sectors while phasing down hydrofluorocarbons under the Kigali Amendment to the Montreal Protocol, as well as those related to low- and zero-GWP HFC alternatives including on different financing modalities;*
3. *To request the Technology and Economic Assessment Panel to prepare a final report for consideration by the Open-ended Working Group at its fortieth meeting, and thereafter an updated final report to be submitted to the Thirtieth Meeting of the Parties to the Protocol on Substances that Deplete the Ozone Layer taking into consideration the outcome of the workshop taking place as per paragraph 4 below;*
4. *To request the Secretariat to organise a workshop on energy efficiency opportunities while phasing-down hydrofluorocarbons at the fortieth meeting of the Open-ended Working Group.*

1.2 Approach and sources of information

1.2.1 Approach

In order to prepare its report responding to Decision XXIX/10, the TEAP established a task force. The composition of the Dec. XXIX/10 Task Force is as follows:

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Bella Maranion, Co-chair, TEAP	US
Fabio Polonara, Co-chair, RTOC	IT
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Omar Abdelaziz, Outside expert	EG
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Sukumar Devotta, Member, RTOC	IN
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Per Henrik-Pedersen, Member, RTOC	DK
Roberto Peixoto, Co-chair, RTOC	BRA
Alessandro Giuliano Peru, Outside expert	IT
Rajan Rajendran, Member, RTOC	US
Helene Rochat, Outside expert	CH
Nihar Shah, Outside expert	IN
Dan Verdonik, Co-chair, HTOC	US
Ashley Woodcock, Co-chair, TEAP	UK

Although not members of the Task Force, TEAP would like to extend its appreciation to RTOC members Holger Koenig and Carloandrea Malvicino for the specific information they provided on the automotive and transport sectors.

1.2.2 Sources of information

Energy efficiency (EE) is a broad topic of major importance for the environment, economics and health, and there is an enormous amount of published literature and reviews. In preparing its response to the decision, the Task Force referenced information provided in earlier TEAP reports (e.g., Decision XXVIII/3 Working Group Report – October 2017) and examined updated, available research and studies. While the methodology of calculating costs was adapted from the U.S and Europe, the practical examples were provided from India, China, and other countries. Outside expert members of the Task Force provided relevant information from their own research and of work done by their colleagues and organisations for consideration in this report.

1.3 Structure and procedure for the completion of the report

This report is organised, following the format requested in Decision XXIX/10, into an introduction and two main chapters. Chapter 2 deals with the technology opportunities related to maintaining or enhancing EE during the phasedown of HFCs. Various aspects of the EE opportunities in the RACHP sector were considered. Chapter 2 also considered the other topics requested from the decision including the long-term sustainability and viability of the technology opportunities, consideration of high ambient temperature (HAT) conditions, climate benefits from adopting the RACHP EE measures, and consideration of related capital and operating costs. Chapter 3 examines other financial institutions where these may intersect with support for realizing EE goals in the RACHP sectors during the phasedown of hydrofluorocarbons (HFCs).

Information about the different challenges to the technology uptake in the RACHP sectors and examples of relevant projects funding or financing can be found in Annexes A and B, respectively.

The report was drafted and reviewed by the Task Force, including at a meeting of the Task Force, 21-22 April 2018, in London. The draft was then reviewed by TEAP and a final report addressing all comments was submitted to UNEP's Ozone Secretariat.

2 Technology options and requirements for energy efficiency in the refrigeration, air conditioning, and heat pump (RACHP) sectors

Decision XXIX/10 requests the TEAP,

...in relation to maintaining and/or enhancing energy efficiency in the RACHP sectors, including in high-ambient temperature conditions, while phasing down hydrofluorocarbons under the Kigali Amendment to the Montreal Protocol in parties operating under paragraph 1 of Article 5, to assess the following items:

- a. Technology options and requirements including
 - i. Challenges for their uptake;
 - ii. Their long-term sustainable performance and viability; and
 - iii. Their environmental benefits in terms of CO₂eq;
 - iv. Capacity-building and servicing sector requirements in the refrigeration and air-conditioning and heat-pump sectors;
- b. Related costs including capital and operating costs.

Aligning with the information as requested in the decision, to the extent practicable, the structure of this chapter is as follows:

Section 2.1 summarizes the **technical opportunities** available to improve EE and then describes some of the **challenges** that must be overcome to achieve the uptake of the same or higher efficiency RACHP equipment.

Section 2.2 assesses the **long-term sustainability performance and viability** of the technologies aimed at maintaining and/or enhancing EE.

Section 2.3 explores the challenges of maintaining and enhancing EE under **HAT** conditions.

Section 2.4 assesses the **environmental benefits in terms of CO₂eq** that can be achieved while improving EE of RACHP.

Section 2.5 describes the requirements for the **servicing sector**.

Section 2.6 describes the **capacity-building** requirements.

Section 2.7 summarizes the current understanding with respect to the **capital and operating costs** to the consumer and manufacturer for maintaining and/or enhancing EE.

2.1 Opportunities and challenges to maintain and/or enhance energy efficiency of new RACHP equipment

Summary

- By using a rigorous integrated approach to RACHP equipment design and selection, the opportunities to improve EE or reduce energy use can be maximised.¹ This approach includes:
 - 1) Ensuring minimisation of cooling/heating loads;
 - 2) Selection of appropriate refrigerant;

¹ When EE improvements are referred to in this report we compare the energy used by an improved design to a baseline design. For example, if System A uses 10 units of energy and System B uses 8 units, there is a 20% efficiency improvement.

- 3) Use of high efficiency components and system design;
 - 4) Ensuring proper install, optimised control and operation, under all common operating conditions;
 - 5) Designing features that will support servicing and maintenance.
- While the benefits of higher EE, such as savings in energy, operating cost to the consumer, peak load and GHG emissions are widely recognised, many barriers to the uptake of more efficient equipment continue to persist. There are a number of common challenges that apply to all types of RACHP equipment. There are also certain market and sector-specific issues that are presented in further detail. Broadly, these barriers can be classified into the following categories: financial, market, information, institutional and regulatory, technical, service competency and others.
 - Technologies resulting in efficiency improvement opportunities available for high-GWP refrigerants may be applicable to low-GWP refrigerants as well.
 - The largest potential for EE improvement comes from improvements in total system design and components, which can yield efficiency improvements (compared to a baseline design) that can range from 10% to 70% (for a “best in class” unit). On the other hand, the impact of refrigerant choice on the EE of the units is usually relatively small – typically ranging from +/- 5 to 10%.

2.1.1 Background

To provide cooling or heating, RACHP equipment and systems consume energy, which is, in most cases, electricity. The amount of energy consumed by a unit, **the unit energy consumption**, is basically related to the quantity of cooling/heating load that needs to be provided (the amount of cooling or heating service) and to the energy needed to deliver that service. A more energy efficient unit or system will deliver the same amount of service for a lower level of energy consumed.² Reducing cooling/heating loads and increasing system and equipment EE are the main components of a strategy that aims to reduce or slow the growth of RACHP energy consumption.

EE and the efficient use of energy³ have been important factors for the development of new products in all RACHP sectors since well before the ozone issue affected the technology [Kuijpers et al., 2018]. For example, during the 1970s and the 1980s the focus on EE had been motivated by the need to make RACHP technologies accessible to larger markets. With the signing of the Montreal Protocol and implementation of the phase-out of ODS, EE continues to be a priority consideration in the development and choice of ODS alternatives and of paramount importance when assessing the potential climate impact of the RACHP sector.

RACHP equipment contributes two distinct types of greenhouse gas (GHG) emissions:

- a) **Direct emissions**, as a result of leakage of refrigerants. Chlorofluorocarbon (CFC) and many

² The International Energy Agency (IEA) defines EE as “a way of managing and restraining the growth in energy consumption. Something is more energy efficient if it delivers more services for the same energy input, or the same services for less energy input. For example, when a compact florescent light (CFL) bulb uses less energy (one-third to one-fifth) than an incandescent bulb to produce the same amount of light, the CFL is considered to be more energy efficient.” (<http://www.iea.org/topics/energyefficiency/>, accessed March 18, 2017)

³ EE can be a performance parameter specifically associated with a product or RACHP unit (e.g., domestic refrigerators, split air conditioners, refrigerated displays, chillers, etc.). It can also refer to RACHP system, for example in the case of a building chilled water air conditioning system, where the system efficiency includes the efficiency of the chiller itself, the air and water displacement efficiencies (pumps, fans, etc.), the cooling towers, etc. EE is sometimes used to indicate the **efficient use of energy** and it is related to the amount of energy that is used for an equipment or system to perform a task.

hydrochlorofluorocarbon (HCFC) and HFC refrigerants have very high GWPs, hence the importance of reducing direct emissions.

- b) **Indirect emissions**, linked to the energy consumption of the equipment [UNEP, 2017a]. The indirect energy-related emissions are dominant for most types of RACHP equipment.

Around 80% of annual global RACHP GHG emissions are indirect and only 20% are direct, coming from refrigerant leakage. It should be noted that the ratio between indirect and direct emissions varies in different sectors of the RACHP market. It also varies with when and for how long equipment is used over the year and is strongly influenced by the level of CO₂ emissions from the source of electricity. For some types of equipment such as large, field-installed commercial refrigeration systems, the direct emissions can be as high as 40% of the total emissions. In contrast, factory-sealed systems direct emissions can be lower than 1%. It is important to recognise that the indirect emissions from energy consumption are always substantial and steps should be taken to minimize the energy required to deliver the desired cooling/heating. The RACHP industry has provided the market with increasingly energy efficient products driven by market forces and by regulations, and this effort is likely to continue during the Kigali Amendment implementation.

2.1.2 Types of efficiency improvement, new RACHP equipment

Improvements⁴ to the EE of equipment are best addressed when new equipment is designed and manufactured. The designer can incorporate appropriate energy saving features that will deliver multiple benefits including:

- a) Reduced energy-related GHG emissions throughout the life of the equipment;
- b) Reduced energy costs, providing good financial benefits to the end user; and
- c) Reduced peak electricity demand, providing potential financial benefits by reducing the need for electricity generation and distribution capacity, which translates into lower investment, fuel and costs of operation for electricity generators.

By using a rigorous integrated approach to RACHP equipment design and selection, the opportunities to improve EE can be maximized. This approach includes:

- 1) Ensuring minimisation of cooling/heating loads;
- 2) Selection of appropriate refrigerant;
- 3) Use of high efficiency components and system design;
- 4) Ensuring optimised control and operation, under all common operating conditions; and
- 5) Designing features that will support servicing and maintenance.

Point 1) may be not directly related to more energy efficient equipment design and selection, but it should be taken into account in an integrated approach because of its importance in reducing energy consumption overall. Each of these five requirements is discussed in the following paragraphs.

⁴ When EE improvements are referred to in this report we compare the energy used by an improved design to a baseline design. For example, if System A uses 10 units of energy and System B uses 8 units, there is a 20% efficiency improvement.

2.1.3 Ensuring minimisation of cooling/heating loads

Eliminating or reducing loads can significantly reduce energy consumption while still delivering the desired level of heating or cooling capacity. An important first step in the design of a cooling system is to review the causes of excess need for heating or cooling and take steps to avoid them. Substantial energy savings are often seen. Some examples of load reducing actions include:

- 1) Building design features that reduce summer heat gains, e.g. shading, reflective roof materials, location of windows, insulation;
- 2) Putting doors on retail refrigerated display cabinets;
- 3) Pre-cooling of hot products prior to refrigeration (e.g. in a food factory using cooling tower water to pre-cool a cooked product);
- 4) Reducing heat created by electrical auxiliaries such as evaporator fans, chilled water pumps or lighting; and
- 5) Reducing cold storage heat load with improved insulation and prevention of warm air entering through open doors.

Reducing loads may require extra investment, e.g., added insulation, orientation of building shading or adding a door to a display cabinet case. However, the reduced cooling load may result in some capital cost savings due to, for example, smaller-sized refrigeration systems and reduced electric interconnection rating.

2.1.4 Selection of appropriate refrigerant

Refrigerant selection is a trade-off between environmental benefits, safety, thermodynamic cycle efficiency, system design and reliability, and cost. It is very important to recognise that the impact of refrigerant choice on the EE of the units is usually relatively small – typically ranging from +/- 5 to 10%. This has been discussed in the TEAP 2017 Working Group Report on Energy Efficiency [UNEP, 2017a] and recently confirmed in the literature [Kuijpers et al., 2018]. Designers should carefully select the best refrigerant from an efficiency perspective but should also address the wide range of other design issues discussed in this chapter. It is also important to note that technologies resulting in efficiency improvement opportunities available for high-GWP refrigerants may be applicable to low-GWP refrigerants as well.

Tables 2-3 and 2-4 of TEAP 2016 Decision XXVII/4 Task Force Report [UNEP, 2016] on “Further Information on Alternatives to Ozone-Depleting Substances” list several alternative refrigerants for different categories of equipment. The applicability of various new refrigerants has been the subject of a number of recent studies and assessments [Wang and Amrane, 2014; Abdelaziz et al., 2015; Abdelaziz et al., 2016; Wang and Amrane, 2016; PRAHA, 2016; Majurin et al., 2017].

Simplified thermodynamic analysis demonstrates the relative impact of different refrigerants on the EE of the unit, which can help designers create a “short-list” of options [McLinden et al., 2017]. For a given application there will be a limited number of refrigerants that are likely to be within $\pm 5\%$ in terms of energy performance. A thermodynamic analysis provides a useful starting point but it is essential to consider “real-world” performance, which is based on the way the refrigerant interacts with the various system components, in particular the compressor and heat exchangers. This can be illustrated with the comparison of HCFC-22 and R-410A for use in small room air-conditioners. A thermodynamic analysis shows efficiency advantages for HCFC-22, but the most efficient equipment currently available on the market uses R-410A. This reflects the fact that equipment manufacturers stopped research and development (R&D) to improve HCFC-22 equipment after the HCFC phase-out

began under the Montreal Protocol. Modern R-410A equipment has a number of efficiency innovations not available with HCFC-22, making the real-world efficiency of R-410A higher. A thermodynamic analysis of HFC-32 shows it has an advantage of about 5% over R-410A for small building air-conditioners [REFPROP, 2013; Mota-Babiloni et al., 2017].

In comparison with HCFC-22, a thermodynamic cycle analysis of propane (HC-290) shows coefficient of performance (COP)⁵ loss ranging from -2% to 0% dependent on the evaporating temperature. However, the volumetric capacity for HC-290 is consistently lower than HCFC-22 by ~14%. Drop-in testing of HC-290 in HCFC-22 equipment showed that COP improvement of 7% and capacity reduction of 8% compared with HCFC-22 at standard rating conditions [Abdelaziz et al. 2015]. This is primarily attributed to the improved transport properties of HC-290 versus HCFC-22. One major barrier for the use of HC-290 in room AC is the flammability rating which currently restricts its use. With engineering optimisation, HCFC-22 alternatives such as R-290, can match or exceed the performance of existing HCFC-22 units with efficiency increase of up to 10% [Shen et al, 2017].

2.1.5 Use of high efficiency components and system design

Vapour compression RACHP equipment consists of a number of primary components (e.g., evaporator, condenser, compressor, expansion valve, refrigerant) and secondary components (e.g., fans, pumps and cooling towers). To maximize EE, it is important to: a) select an appropriate “system design” that defines the overall system arrangement and operating temperature levels and b) select individual components that can contribute to the system efficiency.

There are many examples which illustrate EE improvements related to system and component design, and the examples given below illustrate some important points.

System design

Example 1: Compressor size. System designers consider the optimum number of compressors to suit a given load. For very small systems there is always one compressor. However, for larger systems it may be more efficient to select several small compressors rather than one large one, with a trade-off being made between the extra capital cost and the resulting energy savings. This is especially important to support high efficiency under part-load operating conditions.

Example 2: Cooling at appropriate temperature level. To maximize efficiency, RACHP systems should provide cooling at the maximum possible temperature level. Raising the evaporating temperature by just 1°C can improve efficiency by between 2% and 4%. A common design is to group several cooling loads onto one cooling system, even though the temperature requirement is different for each load. The evaporating temperature has to suit the coldest load – which means that the warmer loads are being cooled inefficiently. A system design that separates loads at different temperatures can be significantly more efficient, but this comes at the additional cost for multiple systems. Another example is the choice of chilled water temperature within a space cooling system – using a higher temperature provides better efficiency for the same cooling load.

Component design

Example 1: Heat exchanger selection. The designer should select heat exchangers with the lowest practical temperature difference to optimise evaporating temperature (which should be as **high** as possible) and condensing temperature (as **low** as possible). Heat exchangers with a tube-

⁵ The coefficient of performance or COP (sometimes CP or CoP) of a heat pump, refrigerator or air conditioning system is a ratio of useful heating or cooling provided to work required. Higher COPs equate to lower operating costs

and-fin design with smaller diameter tubes have been introduced. This is aimed at improving the heat transfer rate and the EE, although the designer must also consider the impact of higher pressure drops. This can reduce the internal volume of the heat exchanger, making it possible to reduce the required amount of refrigerant. Micro-channel heat exchangers (MCHX) have also been developed and provide another design option.

Example 2: Full load compressor efficiency. The EE of the compressor has a direct impact on energy use of RACHP equipment. The compressor used needs to be optimised for the refrigerant selected and the expected range of operating conditions (in terms of evaporating and condensing temperatures). There can be as much as a 20% difference in efficiency between two compressors of similar size and cost. Good selection can provide good efficiency improvement at little or no extra cost.

There are numerous ancillary components that the designer must consider, e.g., evaporator and condenser fans, chilled water, condenser water and oil pumps, crankcase heaters, and standby power. Similarly, there are numerous possibilities for improvement in the thermodynamic cycle, e.g., two-stage compression, tandem operation of compressors, compressors with economizers, vapor/liquid injection, expansion work recovery using either mechanical expanders, ejectors, or vortex tubes. Table 2.1 summarizes efficiency improvements for a range of component design improvements [Shah et al., 2014] from a “base case” represented by a European minimum energy performance standard (MEPS).

Table 2.1 Efficiency improvement options and the corresponding energy savings based on European conditions

Option	Description	% improvement from base case	
		Min	Max
Efficient Heat Exchanger	High efficiency microchannel heat exchangers, larger sized heat exchangers	9%	29%
Efficient Compressors	Two-stage rotary compressors, high efficiency scroll compressors with DC motors	6%	19%
Inverter/Variable Speed	AC, AC/DC or DC inverter driven compressors	20%	>25%
Expansion Valve	Thermostatic and electronic expansion valves	5%	9%
Crankcase Heating	Reduced crankcase heating power and duration	9%	11%
Standby load	Reduced standby loads	2%	2%

Note: the cumulative efficiency improvement of multiple measures from the above table will not be the sum of all the individual components.

2.1.6 Ensuring optimised control and operation

Controls can be treated as another component of a RACHP system, but it is helpful for the designer to consider the control and operation of the system as a separate issue. This has a significant impact on efficiency and often provides very good efficiency improvement at relatively low investment cost.

The introduction of modern sensors and electronic control systems provide numerous new control options that were not available just a few years ago. RACHP equipment usually operates under widely varying conditions, mainly in terms of: a) the required cooling load and b) the prevailing ambient temperature.

Equipment is designed to achieve a ***nominal design point***, which is the peak cooling load during the hottest expected ambient conditions. This design point can be considered as the “worst case” load condition. In reality, most systems spend very few hours per year close to this design point. Most of the time, the cooling load is lower and the weather is cooler.

In a well-controlled system, the EE should improve at conditions away from the design point. For example, in cool weather the condensing temperature should fall, giving a potentially significant increase in efficiency. In a poorly controlled system these improvements do not occur, and the efficiency might degrade more as compressors operate at part-load capacity.

There are many examples that can illustrate EE improvements related to optimised control. The examples given below illustrate some important issues. It must be noted that improvements are not for free and add to the cost of the unit: a thorough analysis of costs and benefits usually accompanies their introduction.

Example 1: Condenser pressure control. Many RACHP systems have “head pressure control” which stops the condenser pressure floating downwards in cold weather. The use of such controls can be eliminated or minimised through improved design. For example, by using an electronic expansion valve in place of a thermostatic expansion valve the head pressure control setting can be significantly reduced. Energy savings of ~20% are often possible.

Example 2: Compressor variable speed control. When a cooling load falls e.g. due to change in ambient conditions, the compressor needs to operate at part-load as the load is lower than the system’s nominal design point. On small systems this is done with on-off control and on large systems with compressor load adjusters such as cylinder unloading for reciprocating compressors or slide valves for screw compressors. These are very inefficient ways of providing part-load control. Recent advances in variable speed drives (VSDs, e.g., the inverter) allow for the use of variable speed compressors, which can often deliver over a 25% efficiency improvement.

Example 3: Control of auxiliary pumps and fans. Many systems use fans to circulate air being cooled or pumps to circulate chilled water. Traditionally, these were fixed speed devices that are designed to suit the nominal design load. Auxiliary loads on the cold side of a RAC system are “paid-for-twice” because as well as running the pump or fan, they create an extra heat load that must be removed by the refrigeration system. At part-load, these auxiliary loads can become a disproportionately large part of the total power consumption. By using VSDs, the fans and pumps can be slowed down at part-load.

There are many other examples of good controls including adjustable suction pressure control and defrost-on-demand control in refrigeration equipment. In terms of costs, as a general rule it can be said that effective control technologies offer a cost-effective EE strategy.

2.1.7 Design features that will support servicing and maintenance

Energy savings related to servicing and maintenance can easily make up to 20% of the overall system performance in India room AC sector [TERI, 2017]. When new equipment is being considered, the designer should consider the servicing and maintenance aspect and provide features that will help ensure good on-going EE throughout the life of the system. Proper servicing and maintenance begins with proper installation and commissioning of equipment. Poor installation and start-up practices can

reduce the EE of the equipment substantially and such losses cannot be recovered for the rest of the life of the equipment.

An important example in servicing and maintenance is the need for instrumentation such as energy meters or key temperature and pressure measurements. As discussed in Section 2.5, it is not uncommon to find existing system operating well below peak efficiency. Good monitoring and control systems can help the plant operator or maintenance technician check performance and correct any energy wasting faults. It is always better to include meters and sensors as part of a new system than to add them at a later date.

2.1.8 Challenges for the uptake of energy efficient technologies

While the benefits of higher EE, such as savings in energy, running cost, peak load and GHG emissions are widely recognised, many barriers to the uptake of more efficient equipment persist. There are a number of common challenges that apply to all types of RACHP equipment. There are also certain market, sector-specific issues that are presented in further detail for informational purposes in Annex A of this report.

Broadly, these barriers can be classified into the following categories:

- ***Financial:*** Higher efficiency equipment generally costs more to produce than less efficient equipment. Efficient components are also frequently bundled together with other features and sold at a premium. Therefore, prices for higher efficiency equipment tend to be higher at any point in time.⁶ The availability cost of finance also plays a significant role.
- ***Market:*** Often the purchasers of equipment are different than the users of the equipment, e.g. in rental housing. This can be a barrier to the purchase of the higher efficiency equipment as the incentive to do so is not directly available to the purchaser.
- ***Information:*** Information regarding the availability or benefits of higher efficiency equipment may not be available to the end user. EE metrics can also be too technical or hard to understand. This type of barrier can be partially addressed through various types of mandatory or voluntary labelling schemes, star ratings, MEPS or other types of education and awareness programs.
- ***Institutional and Regulatory:*** There may be a lack of legislation for EE, a non-existent or weak regulatory framework, weak or unenforceable standards or a lack of technical capacity to enforce EE related activities such as standards or labelling.
- ***Technical:*** Testing facilities to evaluate, measure and verify EE may not be available at all or lack sufficient resources or capacity to serve the demand. Local manufacturers may lack the technical capacity to manufacture high efficiency equipment. Intellectual property may also be a barrier to manufacturing high efficiency components.
- ***Other:*** There may be misperceptions about high efficiency products, i.e., that they may suffer in terms of quality and/or maintenance or other performance criteria etc.

⁶ Research has shown that over time, and with increasing scale of production the prices of more efficient equipment has come down in most markets. However, at any particular time, the most efficient equipment will still tend to be sold at a premium, even if the market as a whole tends toward higher efficiency.

- Service competency: High efficiency equipment may require the use of the latest technology that requires new technical skills. If there is skill gap between that required for the equipment selected and the competency of the service provider and their technicians, high efficiency equipment might not be used.

2.2 Long-term sustainable performance and viability

Summary

- In assessing consideration of long-term sustainable performance and viability (of technology options and requirements in the context of maintaining or exceeding energy performance), it was necessary for the Task Force to define the terms and timeframes for this assessment. The Task Force interpreted the term “long-term” for RAHCP technologies to mean for a period of up to 15 years, which is consistent with previous assessments of this term used and reported by the TEAP.
- For the phrase “sustainable performance and viability” (over the 15-year “long-term” timeframe), the Task Force looked to assess whether or not the options and requirements for technology that are commercially available today and being commercially developed for the nearer term (which include zero or low-GWP refrigerants - single chemicals and blends, and compatible equipment/hardware), would be anticipated to at least meet EE needs (i.e., would be viable) and whether or not they would remain viable over the next 15 years, including considerations for servicing.
- Therefore, the relevant aspects that will impact the long-term sustainment of performance are expected to be as follows:
 - Technological environment,
 - Minimum Energy Performance Standards (MEPS).
- While the challenge of researching and finding sound, technical solutions is important, in some cases it may be even more important to ensure engagement with the customer and the industry and consideration of issues of the whole supply chain in order to ensure that the process of putting those technologies to practical use is not jeopardized.

2.2.1 Technological environment

The technological development in building materials, energy sources, controls and communication expand the concept of sustainability beyond that of only the equipment. Equipment and systems are smarter and can interact with surrounding environment and changing application demands.

This approach is evident in buildings and the sustainable building concept. Sustainable building design can lead to great reductions in annualized energy use and, in some cases, can eliminate the annualized cost of energy (Net-Zero-Energy-Buildings). The sustainable building concept looks at the building location, materials, systems, equipment, occupants and controls as an integrated system designed for better environmental benefits. Measures considered to evaluate the sustainability of a building are as follows:

- lower CO₂ emissions (direct and indirect RACHP emissions),
- lower water consumption,

- lower waste, more recycling and reusing, and
- more environmental quality.

The implementation of a demand-based, or application-based concept in building design and development requires a proper framework of building energy models, regulations and codes to implement. A number of national, regional and international codes have been developed and are in use globally for new buildings and for retrofitting existing buildings as well. Additional work is ongoing to support the growing interest in this concept globally.

In the long term, the Internet-of-Things (IoT) and use of digital controls may result in high penetration of inverter compressor technology, electronic expansion valves, and smart thermostats. Furthermore, it is expected that increase market share of inverter compressor technology at the small capacity would continue to put market pressure and drive the cost of larger inverter compressors to a feasible cost premium. As for heat exchanger technologies, it is expected that small diameter tubes, flat tubes and micro-channel heat exchangers may become mainstream, primarily to minimise the refrigerant charge and improve the heat transfer performance. Permanent magnet and high efficiency motors are expected to become the norm.

Eventually, “big data” technologies can help the implementation of new strategies for on-site performance measurement and fault diagnosis that can be used both for improving design and improving service and maintenance procedures.

2.2.2 Strengthening the Minimum Energy Performance Standards (MEPS)

It is important for National Ozone Units (NOUs) to be aware of EE policies and targets that may affect RACHP equipment in their own countries and in key trading partners, especially those countries that manufacture equipment or components. Cooperation among Ozone Officers and the authorities responsible for EE might result in reduced costs to manufacturers and might offer coordinated policy direction to meet national targets, such as Nationally Determined Contributions. Over 75 countries, regions, or territories have adopted MEPS and/or labelling programs for RACHP since 1977, when the US State of California adopted the first MEPS for refrigerators and air conditioners. As of 2015, these programs include at least 67 MEPS, 84 comparative labels, and 25 endorsement labels for various types of refrigerators and air conditioners⁷. As discussed in Section 2.6 on capacity building, coordination among ozone and energy policy authorities in the development of national strategies can help identify opportunities to integrate EE into refrigerant phase-down planning and use additional policy mechanisms to advance national environmental and development targets. As an example, OzonAction is conducting voluntary trainings for National Ozone Officers and National Energy Policymakers as part of a two-year “twinning” project to exchange experiences, develop skills, and share knowledge and ideas on the energy efficient refrigerant transition in support of the Kigali Amendment⁸.

Key elements of designing and implementing successful MEPS and labelling programs are described below to enhance awareness among ozone stakeholders and help identify areas for potential coordination:

⁷ See CLASP.ngo, [Standards & Labeling Database](#) (last accessed 12 November 2017).

⁸ See OzonAction, <http://web.unep.org/ozonaction/partnership/k-cep> “Under this 2-year project (2018-2019), one national energy policymaker (NEP) per country will be identified and twinned with the NOO from the same country to exchange experiences, develop skills, and share knowledge and ideas on the energy efficient refrigerant transition in support of the Kigali Amendment. UN Environment and its partners will provide these officials with specialized training, capacity building tools, country assessments, and national pilot project opportunities. This interaction will catalyze enhanced cooperation at the national level between these two stakeholder groups, and enable individual governments to integrate energy efficiency more rapidly into the ongoing Montreal Protocol process. Participation in the project is voluntary and offered as a service to NOOs and NEPs.”

- MEPS can be powerful and cost-effective instruments for pushing the market towards higher-efficiency products by removing inefficient equipment from commerce (see Figure 2.1);
- MEPS can work together with labels and other incentive programs, such as rebates, to “pull” the market towards more efficient technologies;
- MEPS can encourage manufacturers to improve the efficiency of their products, especially their lower-priced (lower profit margin) products sooner than they would without performance standards⁹.

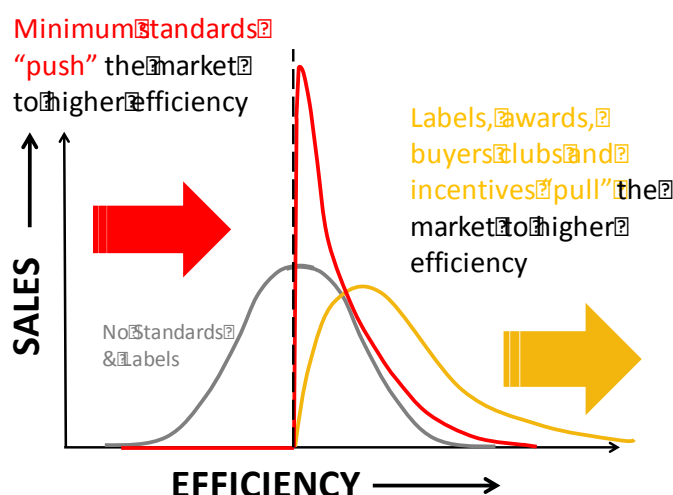


Figure 2.1: Representation of the combined “push-and-pull” effect of MEPS, labels and other incentive programs. (adapted from [Wiel and McMahon, 2005])

The energy saving potential from properly implemented MEPS is known to be substantial: in the European Union, for example, the combination of the MEPS (Ecodesign regulation) and the energy label is expected to save about 175 million tonnes of oil equivalent (Mtoe) by 2020, roughly the annual primary energy consumption of Italy. The measures also benefit consumer with an estimated saving of 456 € on their yearly household energy bill.¹⁰

In MEPS making processes, EE policymakers compare the increase in purchase price for higher efficiency equipment (see Section 2.7 related to capital and operating costs) against the energy savings to the consumer. They then set the MEPS level to “pay-back” the average consumer within a specified time period. In Europe, this approach calculates the least life cycle cost (LLCC) of the product, which represents a combination of all costs to the consumer (initial purchase price, installation, and operating expenses) throughout the life of the product to ensure that products fulfilling the MEPS are the most economical over the lifetime of the product. A crucial aspect in the calculation of the LLCC is the assumed lifetime of the equipment.

⁹ [Gallaher et al., 2017] (2-8 “For refrigerators, and appliances more generally, energy performance is not a key selling point for most consumers, who tend to be more interested in other features. Standards programs are therefore essential to influence companies to direct R&D toward energy performance. In contrast, manufacturers of heat pumps and central air conditioners do differentiate their product lines by energy performance, the highest-priced (highest profit margin) product lines being the most energy efficient. There, the effect of standards is to push manufacturers to incorporate the energy-efficient components and designs into lower-priced (lower profit margin), larger-market product lines sooner than they otherwise would.”).

¹⁰ <https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficient-products>

Different countries will have different climatic, economic and energy cost conditions that will affect the most economical MEPS level, or have other policy priorities that affect the choice of MEPS level. In a country where energy costs are low (for example, due to subsidies), the monetary savings on energy bills from energy efficient equipment alone is often not sufficient to promote their wide-spread adoption. In these cases, only standards and labels will achieve the “push” needed that will transform the market. Historically, MEPS solely focused on the reduction of energy consumption. However, MEPS can also include other design requirements that address other quality aspects of the regulated products.

It is typical that future levels of MEPS are strengthened over the years in accordance to the assessed rate of technological innovation for a given product. Knowledge of these future, strengthened MEPS can provide manufacturers with the security that there will be a return on their investments in R&D. MEPS that are technology neutral and apply similarly to all products in the same product category can achieve a level “playing field” for efficient equipment. Technology-specific MEPS or exemptions might favour inefficient technologies and increase the difficulty of new technologies to enter the market.

The measurement of energy performance of refrigeration equipment constitutes the base for the EE rating. Measurement methods need to be replicable, repeatable and reliable without being too costly for the verification and compliance authorities. They can be adapted to better reflect local climates and user behaviour. However, the downside of modifying test methods too significantly is that the comparability of the equipment amongst regions is limited. In countries that do not have the appropriate infrastructure for product testing to verify product compliance, they can make use of existing accredited regional testing facilities.

For the purposes of this report, efficiency improvements are characterized in terms of percentages to be independent of the metric used. Converting across different Seasonal Energy Efficiency Ratio (SEER) metrics is not straightforward because different metrics use different testing standards and different weightings for part-load performance (see Table A.1 in Annex A). Consider as an analogy different drive cycles for vehicle fuel efficiency ratings. Drive cycles with more highway driving will tend to give better fuel efficiency ratings than drive cycles with more city driving. The case is similar with SEER metrics: some give more weight to part-load operation, which is similar to more highway driving, and these will tend to result in a higher range for SEER ratings.

Harmonising MEPS among countries with similar usage and energy cost conditions across the same product categories can help with verification and compliance. For example, the ASEAN countries—including Indonesia, Malaysia, Philippines, Singapore, Thailand, and Vietnam—have agreed to use a test method based on ISO 5151: 2010 and the seasonal EE metric defined in ISO 16358-1: 2013 [ASEAN SHINE, 2017]. Harmonized measurement standards facilitate the work of market surveillance authorities because only one test is required and used across different markets, hence avoiding test duplication. Harmonization also relieves nations from the burden of developing new standards and allows them to leverage existing resources from other nations. Ultimately, it increases the comparability of products among regions and the transparency of the market.

2.2.3 Not-In-Kind and district cooling contribution to energy efficiency

Not-In-Kind (NIK) technologies are unlikely to provide a significant contribution to EE in the near future, as already discussed in the previous TEAP Decision XXVIII/5 Working Group Report [UNEP, 2017a]. Nevertheless, there is one technology that is gaining more attention related to reduced energy use, especially for air conditioning applications under HAT conditions. This technology is known as Separate Sensible and Latent Cooling (SSLC).

In SSLC devices, the hot air undergoes, in series, the following two processes: 1) dehumidification using appropriate desiccant technologies (liquid absorbent or solid adsorbent), and then 2) cooling by

mechanical refrigeration or even evaporative cooling. SSLC can have many impacts on energy consumption and refrigerant usage:

- if evaporative cooling can be used, no mechanical refrigeration is needed and therefore no refrigerant is used and, most of all, there isn't any compressor and no energy is consumed,
- if, evaporative cooling cannot be used, then vapour compression is used to only reduce the temperature. No dehumidification is needed and that means that smaller capacity and higher evaporating temperature are needed, resulting in higher system efficiency,
- re-generation of the desiccant material requires only low-grade heat that can usually be waste heat or renewable heat, resulting in additional energy savings.

In summary, the same amount of refrigeration can be obtained with a substantial reduction of energy input in comparison with vapor compression. The technology is consolidated for medium to large size applications, but yet its impact in the overall energy scenario remains quite marginal. On the other hand, it still has to be completely developed and industrialized for small size applications, where it may have the largest potential impact on energy use.

Recently, the Middle East has seen a significant increase in the use of district cooling which also has a significant potential for EE gains and reduced refrigerant charge for a given cooling capacity. Furthermore, these very large district cooling plants are usually water cooled with sea-water that would further contribute to EE. However, water consumption in a conventional water-cooled chilled water system remains a challenge in many HAT regions due to water shortage.

2.2.4 Importance of customer engagement to improving energy efficiency

In certain countries, air conditioning consumes up to 70% of the generated electric power due to the excessive use of cooling almost all year round and for long hours [Kuwait Times, 2018]. The public is aware of the burden that air conditioning adds to their financial situation and hence could be more willing to welcome regulatory and other measures to lessen that burden through the use of energy efficient systems which consume less power. This is unfortunately not true where utilities are subsidized, so that the cost of energy to the consumer is low, which removes any incentives for improving or installing new energy efficient systems.

Another challenge is the billing scheme that utilities use for their residential, commercial, and industrial clients. Some countries use one billing rate across the hours of the day but increase the rate according to the consumption bracket. While this scheme can work reasonably well for residential customers, it unfairly penalizes large commercial/industrial customers operating larger, more efficient plants like district cooling if these plants are not taken in consideration. A recent example is one country with large district cooling plants, which needed a strong industry lobby to create government awareness about the issue [Gulf News, 2011]. Hours-of-day differentiated billing that is used in many non-article 5 parties for residential customers creates a good incentive for consumers to control the timing and operation of their AC systems through simple or smart programming.

Energy labelling of units and energy programs are a step in the right direction. Most countries have energy labelling schemes for domestic air conditioning and refrigeration units. One of the challenges of energy labelling and meeting energy standards in general is the testing and verification process to ensure that the stated levels are true and have been verified.

2.3 High ambient temperature (HAT) considerations

Summary

- A HAT environment imposes an additional set of challenges on the selection of refrigerants, system design, and potential EE enhancement opportunities.
- In HAT conditions, any refrigerant must continue to sustain acceptable efficiency at elevated ambient temperatures, and must not break down or react with system components at high temperature.

2.3.1 Refrigerant selection considerations

It has already been mentioned that refrigerant selection is an act of trade-off between environmental benefits, safety, EE, system design and reliability, and cost. HAT conditions impose additional requirements such as ensuring the refrigerant can continue to deliver high capacity and sustain acceptable efficiency at elevated ambient temperatures, and that the refrigerant doesn't breakdown or react with system components (lubricant, seals, valves, etc.) at high temperatures – especially those associated with the compressor discharge temperature.

Critical temperature and molar heat capacity are the key thermodynamic parameters affecting refrigerant performance at HAT [Domanski and Yana Motta, 2000]. For HAT conditions, alternative refrigerants should have equal or higher critical temperature than the baseline-refrigerant. Furthermore, other thermodynamic and transport parameters are important to ensure lower compressor discharge temperature, higher efficiency, and equal or higher capacity. As such, the alternative refrigerants should be expected to operate at equivalent pressures to the baseline refrigerant(s) and adequate measures should be taken to account for refrigerant flammability when flammable refrigerants are used.

2.3.2 System design considerations

Design covers both the aspects of designing RACHP systems and that of the components that go in them. The challenges in the application of technology for the system design are not different under HAT conditions even if the technology itself can be different. On the other hand, there are additional challenges in the design of units to meet HAT conditions with the new alternative refrigerants.

In HAT conditions, the increased cooling load requires larger system capacity, which exacerbates the flammability risk with a larger flammable refrigerant charge. It is therefore important to use advanced technologies to minimise the refrigerant charge (e.g., smaller diameter tubes for evaporators and microchannel heat exchangers for condensers) as well as selecting the appropriate refrigerant for a specific application.

As described earlier, HAT conditions can result in degradation of thermodynamic performance especially in extreme conditions, and require larger refrigerant charge. Furthermore, larger condensers and compressors are used to mitigate the compressor discharge temperature rise and keep them within allowable limits. Another state-of-the-art technology is compressor injection technology, which requires additional system components and larger system charge. While previous generation refrigerants worked equally well in different climates, the expectation is that RACHP systems designed for HAT conditions will employ specific alternative refrigerants optimised for their conditions. However, smaller expected unit sales in some parts of the world could result in a disproportionate cost to the consumer in introducing new products.

The higher pressure will likely require either higher wall thickness (with reduced thermal performance or heat exchangers), or the adoption of novel heat exchangers such as MCHX and small diameter tubes (which could improve thermal performance). However, both thick-walled tubes and advanced heat exchanger concepts would result in additional cost. When flammable refrigerants are used, original equipment manufacturers (OEMs) would have to comply with different maximum charge requirement based on the safety controls provided. A trade-off between suboptimal refrigerant charge (and accordingly lower EE) and cost will have to be considered during the product development stages. New system designs and alternative configurations need to be investigated to:

- reduce the refrigerant charge,
- reduce the operating pressure, and
- minimise the compressor discharge temperature.

2.3.3 Manufacturing sustainability considerations

Under HAT conditions, some countries are experiencing a slow transition to energy efficient equipment. This is either because energy is inexpensive or because of low per capita income, both of which lead to persistence of old inefficient equipment. Consequently, it has not been a top priority for global manufacturers to design special energy-efficient units for HAT conditions. In addition, not all the design temperatures adopted by different countries are the same, even though the T3 conditions as specified by ISO [ISO, 2017] are mostly used. Also, MEPS differ between countries. The difference in design requirements in different markets means either designing special units or testing them at additional conditions for each specific model. This is an added burden on manufacturers for a relatively small number of units, which raises the cost.

For local OEMs, designing for local conditions is important. Some OEMs have design capability while others depend on imported technology. The OEMs who depend on imported technology for their designs face the problem as stated above. OEMs with their own design capabilities have been gaining strength in R&D and are committed to their markets. However, they could face Intellectual Property Rights (IPR) challenges related to the use of certain refrigerants, the application of those refrigerants in the units, or improved design configurations to accommodate new alternative refrigerants.

2.3.4 Installation, service and safety considerations

The challenges in the application of energy-efficient systems and units in the installation phase under HAT conditions are related to the increased charge amounts of the larger units and the effect of the application of safety codes for the new flammable alternatives. The higher pressure of the more efficient low-GWP alternatives, with the exception of HC-290, has been a challenge that has been addressed with previous refrigerant transitions.

Previous research has shown that at HAT conditions, the condensing temperature increase is associated with an increase in refrigerant discharge from compressors, resulting in a risk of system failure, and loss in efficiency [Li, 2014]. One particular challenge for the GCC countries is the fact that a lot of the service work is done by expatriate labour which is constantly changing and hence the need for continuous training and awareness.

Risk assessment for the alternative refrigerants is normally done on a country or regional basis since it depends on the installation and servicing practices as well as the number of units sold. Risk

assessment under HAT conditions is part of the PRAHA-II [PRAHA2, 2017] project where a model for local conditions done by local researchers is in process in 2018.

The biggest challenge for the service sector is that in a lot of cases the driver for owners to change to more efficient units is the advice they receive from a service technician providing personal expertise on the advantages and value of EE. For this, service technicians need to be trained on relevant new skills in order to have the competency to promote EE.

2.3.5 Summary of HAT considerations

One of the most effective means to improve EE under HAT conditions is to increase the condenser size. However, this results in increased refrigerant charge and system cost. The transition to lower GWP alternative refrigerants must not undermine product safety. There is a need to examine the transition impact on flammability, toxicity, and operating pressures. Standards and codes development bodies are working on improved adoption of the new generation of alternative lower GWP refrigerants. The recent Task Force report under Decision XXVIII/4 “Safety Standards for Flammable Low global warming potential (GWP) Refrigerants” [UNEP, 2017b] provides a detailed overview of available safety standards including scope and content as well as relationship with legislation. Table 2.3 below summarizes the various considerations on the effect that HAT has on EE.

Table 2.3 Various considerations on the effect that HAT has on energy efficiency

Consideration	Description	Effect of HAT	Special Measures
Refrigerant selection	Thermodynamic properties and flammability characteristics	<ul style="list-style-type: none"> • Closeness to critical temperature reduces efficiency • Limitation of large amount of refrigerant charge • 	Choice of refrigerant
System Design	Cooling loads, condensing temperatures and pressures	<ul style="list-style-type: none"> • Larger cooling loads lead to larger equipment, • Higher condensing temperatures and pressures 	Testing the system (burst pressure, tightness, functional) to account for higher operating pressure, while maintaining efficiency
Manufacturing	Design and construction need to account for higher pressure	<ul style="list-style-type: none"> • Need for a special design and special components to meet EE standards at HAT conditions 	Local manufacturers to continuously improve design and manufacturing capabilities
Service	Service practices at higher temperatures and pressures	<ul style="list-style-type: none"> • Risk of system failure and loss in efficiency 	Technician training
Safety	Codes	<ul style="list-style-type: none"> • Quantities of refrigerants per occupied space due to the higher heat loads • Limitation due to increased charge 	Risk assessment

2.4 Environmental benefits in terms of CO₂eq

Summary

- Over 80% of the global warming impact of RACHP systems is associated with the indirect emissions generated during the production of the electricity used to operate the equipment (indirect), with a lower proportion coming from the use/release (direct emissions) of GHG refrigerants where used.
- The environmental impact of improving system efficiency is a factor of the type of equipment, how many hours and when it is used (influenced by ambient temperature and humidity conditions), and the emissions associated with generating power, which vary by country.
- Climate and development goals are driving governments to adopt policies to improve the EE of equipment. In the RACHP sector, a holistic approach is important for reducing equipment energy consumption. Reducing cooling/heating loads present the best opportunity to reduce both indirect emission through lower consumption of electricity and direct emissions through the reduction of the refrigerant charge associated with the load.
- For the purposes of this report, the approach and examples presented below consider only the indirect CO₂eq environmental benefit from energy efficient technologies in the RACHP applications related to a single unit of equipment.

2.4.1 Background

Demand for comfort, refrigeration, and refrigerated transport is growing rapidly as a result of increasing urbanization and growing incomes. The International Energy Agency (IEA) finds that space cooling is one of the fastest-growing uses of energy in buildings, with global final energy use for air conditioning in residential and commercial buildings tripling between 1990 and 2016 to over 2,000 TWh of electricity every year [IEA, 2018]. Net reduction in CO₂eq emissions under growing demand is not expected for the RACHP sector. Given uncertainties in future demand projections, and building on previous sections, we describe here how environmental benefits in terms of CO₂eq can be calculated for technology options that enhance EE for a given product at the unit level. This allows a calculation of the environmental benefits against a business as usual baseline efficiency for new equipment purchases.

The environmental benefits of RACHP technologies in terms of the mitigation of global warming can be assessed by GHG emission reduction in terms of CO₂eq. GHG emission consists of direct and indirect contributions. The direct contribution is due to the emission of refrigerants into the atmosphere. The level of direct emissions is a function of a refrigerant's GWP, charge amount and leakage rates (annual, catastrophic, and during servicing and decommissioning) from the air-conditioning and refrigeration (RACHP) equipment. The relative importance of the direct and indirect contributions will depend on the type of system, the refrigerant used, the general leakage rate, and to RACHP equipment electricity consumption, which is a function of its efficiency, operating characteristics, and the “carbon intensity” of the electricity matrix or the emissions factor of the local electricity production (see Table C in [de la Rue du Can et al., 2015]).

Systems that are “more leaky”, e.g., automotive vehicle air conditioning, typically have larger relative contributions from direct impact than would “tighter systems”, e.g., hermetically sealed chiller systems, although this can be offset for systems that have much shorter operating periods or where power is supplied from a source with low carbon content.

2.4.2 Methodologies

There are several methodologies that estimate the total emissions from a system. Most common are Total Equivalent Warming Impact (TEWI) and Life Cycle Climate Performance (LCCP) which attempts to quantify the total global warming impact by evaluating the RACHP systems during their lifetime from “cradle to grave” [IIR, 2016]. Sometimes, a TEWI calculation may be simplified by neglecting broader effects including manufacture of the refrigerant and equipment, and disposal of the refrigerant and equipment after decommissioning. More in-depth analyses not usually performed also look at the emissions associated with the production and disposal of the equipment, e.g., including the mining and recycling of the metal used to manufacture compressors, heat exchangers, and other components.

As discussed in preceding sections, over 80% of the global warming impact of RACHP systems is associated with the indirect emissions generated during the production of the electricity used to operate the equipment (indirect), with a lower proportion coming from the use/release (direct emissions) of GHG refrigerants where used [TEAP, 2017a]. Also, as discussed in Section 2.1, the largest potential for EE improvement comes from improvements in design and components, which can yield efficiency improvements¹¹ of 10 to 70% compared with 5-10% for the refrigerant in most cases.

2.4.3 Calculating environmental benefits

For the purposes of this report, the approach and examples presented below consider only the indirect CO₂eq environmental benefit from energy efficient technologies in the RACHP applications. The results highlight the importance of local context, specifically hours of use and emissions factor for electricity generation, when converting a given EE enhancement into CO₂eq.

Calculating the environmental benefits of EE in RACHP equipment in CO₂eq terms involves three steps:

Step 1: Determine the type of equipment (e.g., ductless split air conditioner, 3.5 kW cooling capacity), identify the baseline model unit energy consumption as a function of the current market in the country or territory, or the units manufactured by a given facility. The examples shown are selected from country assessments (United 4 Efficiency) and product registries (TopTen, India’s Bureau of Energy Efficiency). In the case of TopTen, the units were tested to validate stated energy performance. Then determine the EE improvement to be evaluated. Examples below were informed by actual models available on the market in countries with characteristics of each case.

Step 2: Calculate the energy savings for the higher efficiency model as a function of baseline unit energy consumption and hours of use. Hours of use vary significantly by country and climate and application. In some cases, national standards define the hours of use as part of the EE metric (for example, the India Seasonal Energy Efficiency Ratio is defined using 1600 hours of use annually). It is important to note that actual energy performance of installed equipment may be lower than the designed efficiency due to poor installation or maintenance. Since the efficiency improvement is compared to a baseline unit, this approach assumes that performance degradation due to poor installation or maintenance or high temperatures would have a comparable effect on the baseline unit, so the relative energy savings are maintained. If hours of use increase in the case of the higher efficiency unit due to lower electricity bill

¹¹ When EE improvements are referred to in this report we compare the energy used by an improved design to a baseline design. For example, if System A uses 10 units of energy and system B uses 8 units, there is a 20% efficiency improvement.

costs, a form of rebound behaviour, the energy savings would be reduced (see [TEAP 2017a] for a discussion of rebound).

Step 3: Convert energy savings to CO₂eq by multiplying by the end-use emission factor for electricity generation. The examples shown here use the end-use emission factors calculated by [de la Rue du Can et al., 2015], which are based on default fuel emission factors from the IPCC inventory guidelines and generation mix and transmission and distribution loss data from the IEA. The emission factors used here are annual averages, which is appropriate for refrigerators, which generally run 24-hours. Air conditioners tend to run during the hottest times of day, and tend to coincide with peak electricity demand. For this reason, use of “marginal emission” factors, which represent the carbon intensity of the generators that produce power to meet peak demand, may be more accurate. Whether the carbon intensity of marginal generation is higher or lower than the annual emission factor depends on the grid composition of the country. However, as more renewable capacity is added, the trend is towards lower marginal emissions factors.

In addition to the CO₂ emitted by power plants, the power sector is a major source of other air pollution, including short-lived climate pollutants. According to the IEA, electricity generation linked to air conditioning was responsible for 9% of global emissions of SO₂ from the power sector and 8% of NO_x and PM_{2.5} [IEA, 2018]. By considering the share of fossil fuels in the electricity generation mix and their short-lived climate pollutant emissions per kWh generated, the environmental benefits in terms of CO₂eq related to EE improvements would be further enhanced than considered here. Reducing emissions of these air pollutants would also yield co-benefits related to health [Climate and Clean Air Coalition, 2017].

For each equipment type, three to five scenarios are presented, covering a range of hours of use (with highest hours of use generally associated with high ambient temperature conditions) and emission factors, and considering three levels of efficiency: baseline, higher EE (generally market average or better), and highest efficiency (best available on a representative market). The EE improvement is characterized in terms of percent improvement in unit energy consumption, where the percent improvement is derived from commercially available models in markets consistent with the scenarios presented.

In Table 2.4 the calculations for a room AC unit are reported for 5 scenarios (very low, low, high hours of use, high emissions factor, highest with high hours of use and high emission factor) representing most of the situations that can be found in the actual scenario of climate zones and emission factors throughout the world. We follow the three steps to present the ranges of CO₂eq benefits for two levels of efficiency improvement across the 5 cases to illustrate the effects of hours of use and electricity emission factors.

In the following, the same calculations are presented, in graphical form, for equipment unit in different sectors of RACHP.

Room Air Conditioning

In the case of room air conditioning, hours of use range in our cases from very low (350 hours per year) to high hours of use (2880 hours per year). Figure 2.2 shows the annual environmental benefits per unit across five scenarios for higher efficiency of 10-20% and highest efficiency of 40-50%.

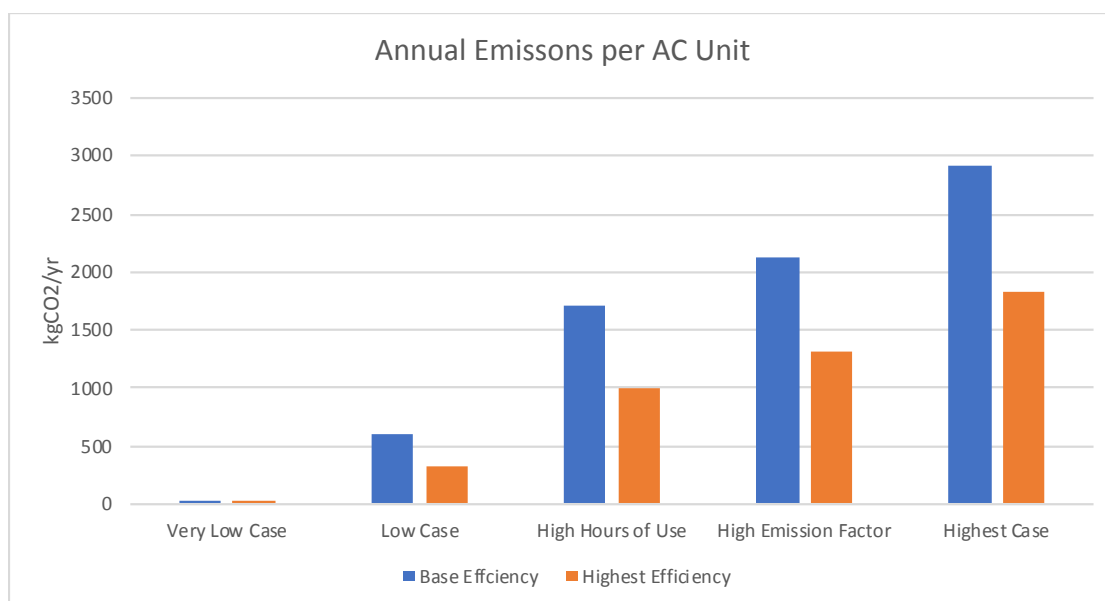


Figure 2.2: Annual emissions for a room AC unit in the 5 cases represented in Table 2.4

Domestic Refrigeration

In the domestic refrigeration sector, savings due to energy efficient appliances range from 55% to nearly 70% with technologies that are presently available (see Figure. 2.3). It is assumed in this case that refrigerators operate 24 hours per day and that HAT do not impact the performance of the devices, as they are placed indoor in environments with controlled temperature.

Table 2.4: Energy savings in term of CO₂eq reduction for a room AC unit in 5 cases representing the situations that can be found in the actual scenario of climate zones and emission factors throughout the world

	Step 1. Identify product-specific baseline unit energy consumption and efficiency improvement.					Step 2. Calculate per unit energy savings for efficient models.		Step 3. Convert energy savings to per unit reduction in CO ₂ eq		
	Hours of Use per year	Unit Type / Cooling Capacity (kW)	Base AC unit energy use (kWh/yr)	Higher EE	Highest EE	Higher EE (kWh/yr)	Highest EE (kWh/yr)	End-use Emissions Factor (kgCO ₂ /kWh)	Higher EE (kgCO ₂ /yr)	Highest EE (kgCO ₂ /yr)
Very Low Case^a (Very low hours, very low electricity emission factor)	350	Split unit / 3-4 kW	266	20%	50%	53	133	0.017	1	2
Low Case^b (Low hours, low electricity emission factor)	120	Split unit / 3.5 kW	1355	20%	50%	271	678	0.45	122	305
High Hours^c (High hours, middle electricity emission factor)	288	Split unit / 3.5 kW	2965	10%	40%	297	1186	0.58	172	688
High Emission Factor^d (Middle hours, high electricity emission factor)	160	Split unit / 5.275 kW	1300	10%	40%	130	520	1.3	169	676
Highest Case^e (High hours, high electricity emission factor)	288	Split unit / 5.275 kW	5759	25%	40%	1440	2304	0.97	1397	2234

^a Hours of use for cooling in Europe (Topten.eu); unit energy use from Topten.eu with inefficient (266 kWh/yr) and highest efficiency (122 kWh/yr), higher efficiency from ranges presented in Table 2.1; emission factor for Norway (de la Rue du Can et al., 2015).

^b Hours of use and base AC unit energy consumption from United for Efficiency Country Assessment for Argentina (December 2016); percent improvement based on Topten.eu and Table 2.1; emission factor similar to Argentina (0.44) and Chile (0.47) (de la Rue du Can et al., 2015).

^c Hours of use and base AC unit energy consumption from United for Efficiency Country Assessment for Thailand (December 2016); percent improvement based on India BEE 3-star and 5-star examples; emission factor for Thailand (de la Rue du Can et al., 2015).

^d Hours of use and base AC unit energy consumption from Indian ISEER standard and BEE 1-star level; percent improvement based on India BEE 3-star and 5-star examples; emission factor for India (de la Rue du Can et al., 2015).

^e Hours of use for 8 hours for 360 days; base unit 2.6 W/W EER converted to energy consumption by dividing capacity by EER times hours of use; mid = 3.5 EER and highest = 4.5 EER; emissions factor between Saudi Arabia (0.84) and Kuwait (1.1) (de la Rue du Can et al., 2015).

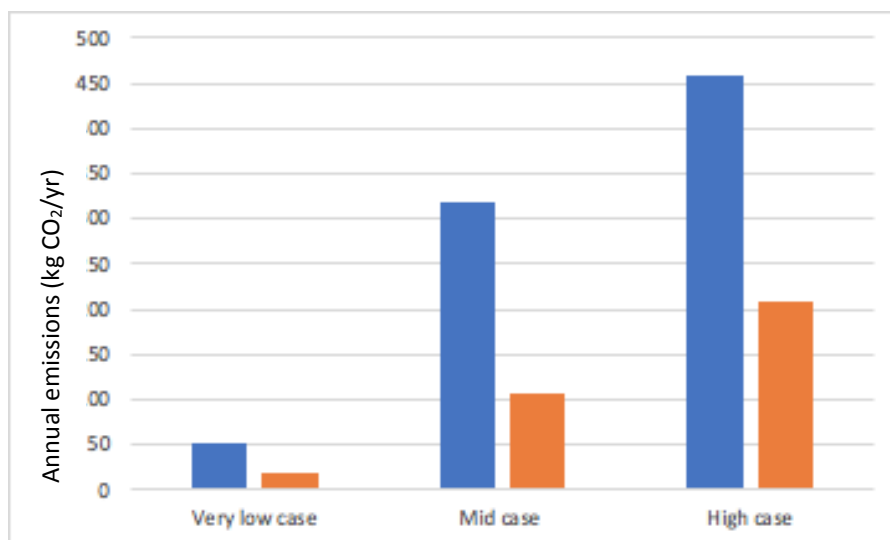


Figure 2.3: Annual emissions for a domestic refrigeration unit in 3 typical cases

Heat pumps

Insufficient data were available to calculate the CO₂eq saving potential for heat pumps. The comparison in between technologies is complicated by the difference between devices related to their heat source (air, water and ground) and the temperature at which the water is heated.

Commercial refrigeration

There is a very high energy and CO₂ saving potential in the commercial refrigeration space (see Figure 2.4). In some cases, as in open- versus closed-door freezers and coolers, savings can range from 70-80%. In the case of ice cream freezers, the energy consumption was measured at 25°C and 31°C. The energy consumption increased 13% at the higher ambient condition. However, the energy consumption was still much lower than an inefficient, vertical freezer. This shows that also in HAT conditions, the choice of the device is crucial to achieve a reduction of CO₂.

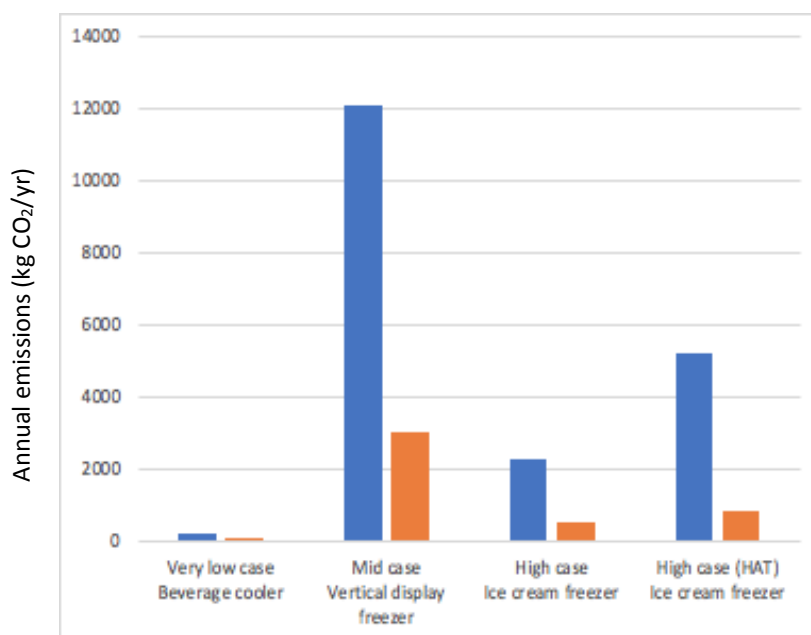


Figure 2.4: Annual emissions for some commercial refrigeration units in typical case

Mobile Air Conditioning

The steps for calculating the CO₂eq for EE enhancement in mobile air conditioning are similar but require estimates of the range of potential EE improvement, as well as conversion from energy saving to CO₂e as a function of the fuel and engine type, which were not readily available for this report. While this information was not readily available for this report, some passenger vehicle fuel economy standards include credits for high-efficiency air conditioning, which could be used as an indicator of the potential benefits and range from 0.9 g CO₂/km to 6.1 g CO₂/km [Yang and Bandivadekar, 2017].

2.5 Servicing sector requirements

Summary

- The present concern in most Article 5 countries in the HCFC phase-out process is to train technicians on the use of new refrigerants. EE aspects require additional training and further awareness.
- Some EE degradation over the life time of equipment is inevitable; however, there are ways to limit the degradation through improved design and improved servicing which include both installation and maintenance.
- The impact of proper installation, maintenance, and servicing on the efficiency of equipment and systems is considerable over the life time of these systems while the additional cost is minimal.
- The benefits of proper maintenance are considerable. Appropriate maintenance and servicing practices can curtail up to 50% reduction in performance and maintain the rated performance over the lifetime.

2.5.1 Servicing sector impact on EE

The reduction in EE and increase in the energy consumption during the lifetime of the units and systems in the RACHP sector is from several sources, some of which are almost totally controllable, while others are less so. The most difficult to control is the normal wear-and-tear that affects the operation of the units and by extension, the system. This wear-and-tear can be minimised through proper preventive maintenance, but it cannot be totally avoided.

It is widely recognised that residential and commercial RAC equipment can undergo significant loss of capacity and efficiency, depending on how the components are sized, assembled, installed, and subsequently field-maintained. However, sound installation and maintenance practices are hard to deliver in a marketplace which keeps first-cost pricing low, resulting in poorly performing equipment [Hourahan et al., 2011].

According to International Institute of Refrigeration, “better optimization, monitoring, and maintenance of cooling equipment has the potential to save 30 Gt of CO₂ emissions by 2050 – contributing a further 38% of savings on top of those delivered through the planned phase down of high GWP refrigerants agreed at Kigali” [K-CEP, 2016].

There are ways to decrease the degradation of EE during the lifetime of the equipment. Improved design can contribute to easier and efficient servicing, thereby impacting EE (e.g., reducing the number of connections, applying corrosion resistant coating, etc.).

Improving servicing, which is understood to include both installation and maintenance can be used to achieve EE as a result of better practices. Table 2.5 provides a compilation of data made by the

International Energy Agency (IEA) from several manufacturers that identified the most common faults resulting in EE degradation.

Table 2.5 Energy efficiency degradation for air-to-air heat pump due to poor installation and maintenance

	Fault	Occurrence as % of total faults
The most common faults	Fan	26%
	Control and electronics	25%
	Temperature sensors	16%
The costliest faults	Control and electronics	23%
	Refrigerant leakage	17%
	Fan	15%

Source: [Hourahan et al., 2015]

In addition to the faults mentioned above, EE degradation is affected by either lack of maintenance or from the wrong operating practices described below:

- Lack of proper coil cleaning, or the miss-calibration of controls and component settings result in refrigerant leaks or other operating problems and eventually leads to loss of efficiency. Commercial refrigeration systems installed in supermarkets are one of the highest leaking systems due to the nature and complexity of the systems;
- Wrong operating practices includes items such as over or under-charging of a system during servicing and using the wrong or defective components for replacement.

The examples below were summarized in the Kigali Cooling Efficiency Program publication on optimizing cooling through proper maintenance [K-CEP, 2016]:

- A study by the UK Department of Environment, Food, and Rural Affairs (DEFRA), show that cleaning a dirty condenser delivers 8% energy saving, and resetting the temperature set point to the design temperature yielded an additional 11% energy saving [Swain, 2009].
- The UK Institute of Refrigeration and the Carbon Trust identified a basket of monitoring, optimization and maintenance measures such as training, cleaning and maintenance, re-commissioning, set-point temperature, and room temperature setting that could improve EE. [CARBON TRUST, 2017]
- A study from a building in New York City showed that good maintenance and operating practices including coil cleaning significantly improved the EE of the RACHP systems by 10% to 15%. The trial also identified other optimization and maintenance processes that will improve EE for years to come [Montgomery, 2006].

The refrigerant issue

The use of refrigerants during servicing that are not compatible with the system, either to top-up the charge or to replace it completely, increases the energy consumption and reduces system efficiency. The proliferation of inappropriate drop-in refrigerants could reduce EE of old equipment even further. Illegal refrigerants that are not suitable for the operation of machines can also result in safety issues in addition to EE loss.

Another important aspect is the introduction of zeotropic refrigerants, i.e. with larger difference between the saturation vapor and liquid temperature. In this case, refrigerant leakage will result in refrigerant composition change, fractionation, and potential impact on the performance. Subsequently, systems running with refrigerants with high glide cannot be topped-up and the refrigerant charge must be completely recovered before it any service. The recovered refrigerant cannot be reused and would have to be either reprocessed or destroyed. The risk is that it would be vented or dumped.

Effect of servicing and controls on the efficiency of central and large air conditioning systems

While this report is limited in scope to four segments of the RACHP industry, it is worth mentioning that maintaining the proper performance and control in large central plants can contribute considerably to energy savings. While large central plants are normally better maintained due to the size of the plant and the impact of size of operation, certain measures that can contribute to further enhancement of performance are often neglected. Keeping logbooks for systems or plants above a certain kW capacity can show trends of operation and can predict problems before they occur. An example is by using the logbooks to reduce unnecessary over-charging of refrigerants, which leads to better efficiency and lower consumption.

Central Plant management contributes to maintaining or increasing EE. The industry is quickly approaching the theoretical limit of how much efficiency can be expected from individual components which over the past 25 years have contributed to as much as 40% improvement. Moving forward, engineers and building owners will have to look beyond the component level to reach increasingly aggressive EE goals. Central plant optimization is a process that involves measurement and verification, maintenance, optimization, automation of systems, and the selection and application of components. Once fully implemented, Central Plant Optimization can deliver central plant energy savings of up to 60% [Klee and Gigot, 2011].

2.5.2 Benefits achieved through better servicing

The benefits of proper maintenance are considerable. Appropriate maintenance and servicing practices can curtail up to 50% reduction in performance and maintain the rated performance over the lifetime [Usinger, 2016].

In the table below, the effect of not doing the proper maintenance and set point adjustments are shown as percentage of the rated efficiency. While the cost level of doing the work, translated into US\$ from the original Euros reported, reflect an industrialized country (non-Article 5) level, it demonstrates a relative cost and the consideration of that cost as compared to other service work done in that country.

Table 2.6 Effects of improper maintenance

Improvement	Measures to be taken	Effect on Rated Energy Efficiency	Maintenance Cost Level
Correct levels of refrigerant and oil	Check levels periodically and refill	Up to 50%	Less than USD 300 considered very low
Air recirculation into condenser	Reduce recirculation by cleaning filters and removing obstacles	Up to 25%	Less than USD 300 considered very low
Thermostatic expansion valve (TEV) settings	Check and make set point adjustments	Up to 10%	Up to USD 600 considered low
Condenser pressure control	Check and make set point adjustment	Up to 10%	Up to USD 600 considered low

Source: [Usinger, 2016]

2.5.3 Maintaining and/or increasing EE in the maintenance and installation sub-sector

In most instances the methods to maintain and/or increase EE are inseparable and indistinguishable from “best practices” for maintenance and installation. For example, ASHRAE’s “Refrigeration Commissioning Guide for Commercial and Industrial Systems” [ASHRAE, 2013] presents a number of best practices for design and commissioning of refrigeration systems.

Some of the ways to achieve better servicing practices to improve EE are described below:

- Training and education of service technicians, system operators, and refrigerant handlers can be complicated if there is the presence of an informal sector that operates outside the scope and reach of both the government and the industry associations. The present concern in most Article-5 countries in the HCFC phase-out process is to train technicians on the use of new refrigerants. EE aspects require additional training and further awareness. Both issues can be treated together, however, and EE needs to be incorporated in the curricula of new courses. Some topics within such a training module would be handling of flammable refrigerants and refrigerant blends and best practices with handling new zeotropic blends. In case of the former, the need of specialized equipment that are certified to operate with flammable refrigerants is important, while in the case of the zeotropic blends, technicians should be aware that they can’t practice top-up and that that recovered refrigerants is not useable in some cases.
- Certification of technicians and other entities on handling of refrigerants: The requirement is being introduced in many Article 5 parties as part of their HPMP; however, the degree and extent of application differ and the certification for handling the different types of refrigerants can also be different. Linking certification to the proper handling and operation of systems to maintain EE would require additional input and coordination between the different stakeholders. It would also require the certification of technicians to service those systems, which can be different than the certification for handling refrigerants.
- Policies can also be developed to encourage regular maintenance and servicing, i.e., maintenance contracts or warranties could be included as part of government procurement.

Sectoral Requirements

The requirements for capacity building in the refrigeration sector are not distinctively different than those in the air conditioning sector. The major difference is that the refrigeration sector is more defined with mostly established and experienced players. However, the systems and the machines involved are also more complex and use a variety of refrigerants that are not used in the AC and HP sectors.

In the refrigeration sector, and to an extent in the AC and HP sector, the requirements differ by the size of the plant as follows:

- 85% of large industrial refrigeration plants use ammonia [UNEP, 2014]. The plants are efficient and the maintenance is usually good since bad maintenance can lead to disastrous consequences due to the toxicity, and to a lesser extent, the flammability of the refrigerant. This is not to say that all plants are operating at maximum efficiency. However, the cases of inefficient operation due to inefficient servicing are less than in other sub-sectors.
- Commercial plants such as field-installed, large supermarket refrigeration systems are one of the highest leaking systems in the sector due to the nature and complexity of the plants. This contributes to a reduction in EE that can be controllable. Pricing of utilities that are disincentives to run plants inefficiently and the use of incentives for reducing power demand can be used to incentivise operators to running plants more efficiently.
- The Domestic sector has made big strides through the labelling system that makes EE information directly in front of consumers and end-users. Maintenance of the systems to ensure the continued efficient operation is less evident and more easily neglected by owners of domestic appliances. Hence, it is often lacking. This can also be exacerbated by self-employed informal sector technicians who are not aware, or potentially not interested in monitoring EE.

2.6 Capacity building requirements

Summary

- There are enabling activities such as capacity building, institutional strengthening, demonstration projects, and national strategies and plans that help to bridge Montreal Protocol activities under the Kigali Amendment and EE. A number of enabling activities supported by the other funds such as, the Kigali Cooling Efficiency Programme and the Global Environment Facility, have advanced both ozone depletion and EE goals
- Additional enabling activities under the Kigali Amendment can bridge the current Montreal Protocol activities with those destined towards EE and serve as examples of potential synergy between HFC phasedown and EE opportunities.

2.6.1 Bridging enabling activities

Several categories of enabling activities can potentially serve to bridge activities related to enhancing or maintaining EE with phasedown activities. Examples include capacity-building and training for the handling of HFC alternatives in the servicing, manufacturing and production sectors as well as Institutional strengthening; Article 4B licensing; Reporting; Demonstration projects; and

Development of national strategies (Decision XXVIII/2¹ paragraph 20). Within these, some components can be coordinated with complementary activities to advance both HFC phase-down and EE goals.

2.6.2 Capacity building and training

Technical capacity-building for manufacturing could include information exchange and data sharing, analysis on design options and their costs, efficient component sourcing for maintaining or enhancing equipment energy performance, particularly at HAT conditions and for selection of low-GWP alternatives with significant energy efficient benefits. Training activities could include the development of train-the-trainer manuals, syllabi for the relevant courses, case studies, and training sessions on integrating EE best practices into manufacturing. These activities are complementary to training for safety.

2.6.3 Institutional strengthening

It includes a range of bridging activities, such as:

- Training and networking for ozone officers and policymakers on key EE concepts to enable enhanced cooperation at the national level between energy and ozone stakeholder groups, and enable governments to integrate EE considerations more rapidly into the on-going Montreal Protocol process (e.g., it would be possible to include EE components in regional network meeting agendas);
- Awareness raising, for example through public communications campaigns directly to manufacturers and consumers or through retailers; and
- Customs training for Article 4B and reporting (i.e., a customs manual can be important for importing/exporting HFC-free, energy efficient items).

2.6.4 Demonstration projects

Projects can include development of national rebate and exchange programs, integrating environmentally sound management practices and new sources of finance; procurement or buyers' clubs for high-efficiency and low-GWP equipment; testing new technologies with low GWP alternative refrigerants and designs that enhance EE.

2.6.5 Development of national strategies and plans

Direct dialogues and meetings of relevant government, industry and other stakeholders could be made to assess opportunities to integrate EE into HCFC phase-out and HFC phase-down planning, identify

¹ Decision XXVIII/2: To request the Executive Committee to include the following enabling activities to be funded in relation to the hydrofluorocarbon phase-down under the Kigali Amendment:

- Capacity-building and training for the handling of hydrofluorocarbon alternatives in the servicing, manufacturing and production sectors;
- Institutional strengthening;
- Article 4B licensing;
- Reporting;
- Demonstration projects; and
- Development of national strategies;

mechanisms, inform prioritization of sectors and interventions, and develop strategies and roadmaps. This could include coordination on:

- Funding proposals informed by the national strategy within the Montreal Protocol context and outside sources;
- Program design and implementation, including for example, design of labels integrating efficiency and refrigerant information, and coordinated strategies for promoting efficient, clean cooling;
- Defining national testing and certification procedures, training inspectors, monitoring proper labelling, and coordination on enforcement;
- Program design considerations, including financial mechanisms for implementing replacement programs, including bulk procurement/ buyers' clubs;
- Consideration of implications to electricity grid, peak load;
- Input into Nationally Determined Contributions;
- Input for reporting into Sustainable Development Goals (SDGs) progress;
- Data collection and analysis complementing existing data collection efforts to include information needed to incorporate EE into planning, inform policies and programs, and support program evaluation and monitoring.

2.6.6 Cost estimates

Some projects supported by the Kigali Cooling Efficiency Programme (K-CEP) and the Global Environment Facility (GEF)² were reviewed and components were mapped to the framework to provide cost estimates for each type of enabling activity linked to EE. As mentioned before, several components can be complementary with marginal costs, for instance, current train-the-trainer sessions in HPMPs can be revised to add EE aspects. Costs are provided as ranges based on the information publicly available. The table presents only some examples for a very limited number of countries. It is important to note that by the end of 2015, the GEF had invested in 1,000 climate mitigation projects, including more than 200 EE projects.

Some of the activities in the table below for building institutional capacity include activities to support the design and implementation of MEPS and labels. While these programs are generally under the jurisdiction of energy ministries, the data collection, labelling, monitoring, and verification and enforcement activities that support successful implementation of these programs in many cases can have relevance to ozone stakeholders. Some initiatives can be done with coordination between the NOU and energy bodies if one is to integrate EE in future HFC phasedown management plans.

² For more information on specific projects, see <http://k-cep.org/wp-content/uploads/2018/03/Global-regional-and-country-profiles-of-K-CEP-projects.pdf>; www.thegef.org.

Table 2.7: Activities and associated cost examples

Bridging Enabling Activities	Country/Description	Source of Funding	Cost Example in USD (co-finance)
Capacity building and training	Lebanon, Nigeria / integration into servicing sector training manuals, syllabi, and courses of EE best practices; conduct trainings.	K-CEP	Average: 212,500
	Bangladesh, Thailand, Vietnam, Philippines, Mexico / technical assistance to industry on design options and their capital costs, efficient component sourcing.	K-CEP	156,000 – 430,000 per enterprise (475,000 – 1,500,000)
	Guatemala, Ecuador, Uganda, Lebanon, Jordan, Morocco, Tunisia / technical assistance to businesses to assess potential incremental capital and operating costs for improved EE in commercial refrigeration.	K-CEP	Average: 44,000 per enterprise
Institutional strengthening	147 A5 countries / UN Environment “Twinning” project / UN Environment’s OzonAction and United for Efficiency initiatives are organising voluntary capacity building events to jointly build the capacity of National Ozone Officers (NOOs) and national energy policymakers (NEPs) for linking EE with Montreal Protocol objectives in support of the Kigali Amendment.	K-CEP	Average: 12,000 per country
	Chile / Enhance Awareness among consumers and market players to understand, afford and purchase EE refrigerators and freezers	GEFTF	Chile: 446,341 (1,806,000)
	Ghana/ Awareness among importers and distributors, consumers and business byers	GEFTF	Ghana: 150,000 (500,000)
	Customs officials training	K-CEP	Average 55,000 per country
Demonstration projects	Chile / Voluntary implementation of the national framework for environmentally sound management of refrigerators/freezers.	GEFTF	Chile: 351,299 (1,283,000)
	Ghana / Pilot test for an accelerated market transformation through innovative economic incentives/pilot rebate turn in programmes for efficient refrigeration appliances demonstrated.	GEFTF	Ghana: 400,000 (600,000)
	12 countries / Demonstration projects including replacement programs,	K-CEP	Average: 208,000 per country

	procurement, buyers' clubs, and development of novel financial mechanisms.		
Development of national strategies	27 countries / Convene relevant government, industry and other stakeholders to assess opportunities to integrate efficiency into refrigerant transition, identify mechanism, inform prioritization of sectors and interventions; may provide basis for funding proposals.	K-CEP	Average: 139,000 per country
	12 countries / Design procurement, awareness, incentives or other market transformation programs.	K-CEP	Average: 226,750
	Ghana/Design of certification, labelling and enforcement mechanisms	GEFTF	Ghana: 100,000 (250,000)
	Chile / Monitoring, Verification and enforcement of EE labelling regulations, testing protocols and methodologies for residential refrigerator/freezers	GEFTF	Chile: 283,853 (823,000)
	4 countries and 2 regions / build testing, certification, and enforcement capacity.	K-CEP	Average: 319,000 per country/region
	13 countries / improve data collection and analysis.	K-CEP	Average: 93,000 per country
Activities related to MEPS [included for information only]	Chile/ Market transformation of the EE residential refrigerators/freezers via MEPs implementation and EE labelling in line with international best practices and provision of associated capacity building.	GEFTF	Chile: 106,334 (1,572,550)
	Ghana/ Strengthening of regulatory and institutional framework for S&L program / mechanisms for implementation of appliance EE standards and labels (S&L).	GEFTF	Ghana: 50,000 (250,000)
	21 countries / support for EE MEPS for refrigerators and/or air conditioners and supporting analysis and policies.	K-CEP	Average: 222,500

2.7 Costs related to technology options for energy efficiency

Summary

- A summary is presented of methods developed by various countries with established market transformation programs for promoting EE including MEPS programs and labelling programs.

- It should be noted that the presented methodology offers a “snapshot” of the cost of efficiency improvement at any given time and will tend to provide a conservative (i.e. higher) estimate of the cost of efficiency improvement. In actual practice, the prices of higher efficiency equipment have been found to decline over time in various markets as higher efficiency equipment begins to be produced at scale. This applies especially for small mass-produced equipment where manufacturers quickly absorb the initial development costs and try to get to certain “price points” that help them sell their equipment.
- Retail price of products is not an adequate indicator for the costs of maintaining or enhancing EE in new equipment due to:
 - bundling of various non-energy related features with higher efficiency equipment,
 - variation of manufacturer’s skills and know-how,
 - variation in manufacturer’s pricing, marketing and branding strategies, and
 - the idea that efficiency can be marketed as a “premium” feature.
- Rigorous cost analysis may be needed to fully understand the impact of EE improvements. These types of analyses are relevant when setting MEPS as several EE levels need to be evaluated compared with the baseline. These studies can take more than 1 year to conclude for a single product category. As such, in this report we would like to refer parties to the corresponding methodologies and present simplified examples based on products already introduced on the market.

2.7.1 Methodology to calculate capital and operating costs

Various parties have established market transformation programs for promoting EE including MEPS programs and labelling programs. For example, the United States Department of Energy (DOE)’s Appliance and Equipment Standards Program [DOE, 2016] and the preparatory studies for the EU Ecodesign Directive [EuP, 2009] both use “bottom-up” engineering analysis based on detailed data collection, testing and modelling of the more efficient equipment to identify the actual manufacturing cost (as opposed to the retail price) of efficiency improvement. Similar processes have also been used to a more limited degree to support EE standards processes in countries such as India and China (see [Shah et al., 2016; Lin and Rosenquist, 2008; Fridley et al., 2001]). While this methodology can be used generally to estimate the costs to the manufacturers of maintaining and/or enhancing EE for both A5 and non-A5 parties with manufacturing capacity, the costs to the consumer of maintaining and/or enhancing EE are likely to be similar for all Parties with the additional costs of shipping for importing Parties.

Figure 2.5 shows a simplified overview of the typical analytical approach followed by the US DOE and EU Ecodesign using this engineering analysis. This “bottom-up” approach usually uses industry standard equipment design software³ and test data of higher efficiency equipment to identify design options for higher efficiency equipment from a “base case” model representing low or average efficiency on the market in question. Subsequently, the costs of these higher efficiency design options are surveyed by interviewing industry experts, manufacturers and component suppliers to build up a picture of the costs of higher efficiency equipment.

³ For example, [Fridley et al 2001] used the Oak Ridge National Laboratory (ORNL) Heat Pump Design Model, Mark V, version 95d [ORNL, 1996; Fischer & Rice, 1983; Fischer et al. 1988].

It should be noted that this above methodology offers a “snapshot” of the cost of efficiency improvement at any given time and will tend to provide a conservative (i.e. higher) estimate of the cost of efficiency improvement. In actual practice, the prices of higher efficiency equipment have been found to decline over time in various markets as higher efficiency equipment begins to be produced at scale. This applies especially for small mass-produced equipment where manufacturers quickly absorb the initial development costs and try to get to certain “price points” that help them sell their equipment. Figure 2.5 below shows such a trend in the US residential AC market.

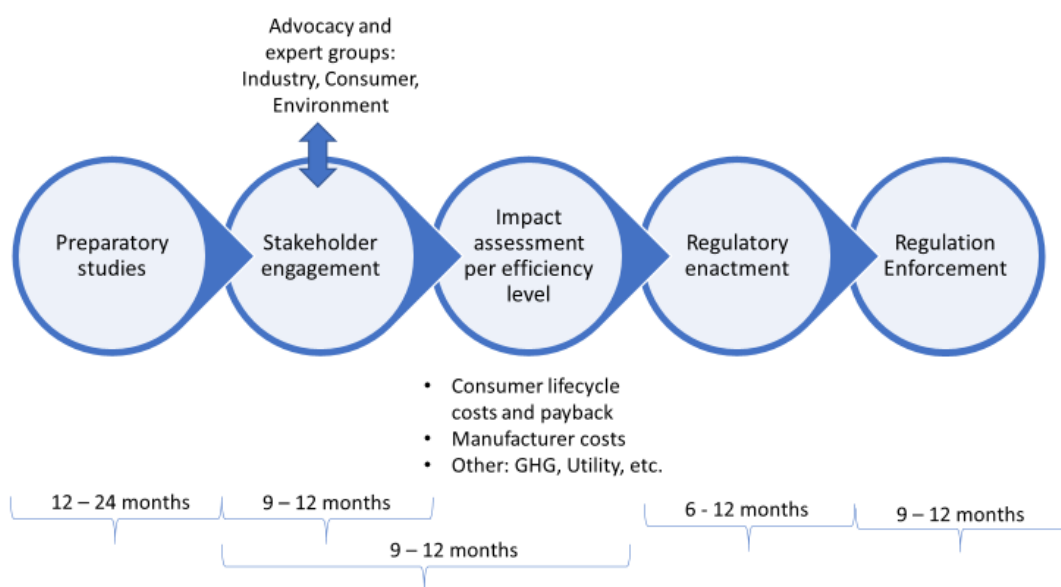


Figure 2.5 Overview of typical analytical approach used to evaluate capital and operating costs associated with MEPS program efforts to improve EE, simplified from the DOE Appliance and Equipment Standards Program and the EU Ecodesign Program.

Source: [DOE, 2016] and [EU, 2015]

Rigorous cost analysis as presented above (DOE and EU Ecodesign) may be needed to fully understand the impact of EE improvements. These types of analyses are relevant when setting MEPS as several EE levels need to be evaluated compared with the baseline. As shown in Figure 2.5, these studies can take more than 1 year to conclude for a single product category. As such, in this report we would like to refer parties to the corresponding methodologies and present simplified examples based on products already introduced on the market.

2.7.2 Data collection

Due to the proprietary nature of business operations, there is limited publicly available data on capital and operating costs to the manufacturer attributable to improvements in EE for air conditioning and refrigeration equipment. Furthermore, a glance at retail prices and efficiencies of equipment on the global market shows a wide variation in the prices of equipment at similar efficiency levels, as discussed earlier in the introduction to this section, indicating that retail prices alone are not a good indicator of the cost of maintaining and/or enhancing EE in new equipment.

Several examples of data collected in order to develop the methodology presented here follow.

Example 1: Retail prices are not sufficient to understand the cost of maintaining and/or enhancing EE

See Fig 2.6 for an example of the retail prices of small unitary variable speed ACs in China that have a cooling capacity of 3.5KW and EE level of about 4.5 W/W (measured according to the Annual Performance Factor (APF) metric) which varies from approximately US\$ 500 to 2000, i.e. a four-fold (400%) variation. This effect of wide price variation at a single efficiency level holds for multiple cooling capacities, multiple efficiency levels and across both fixed-speed and variable speed ACs.

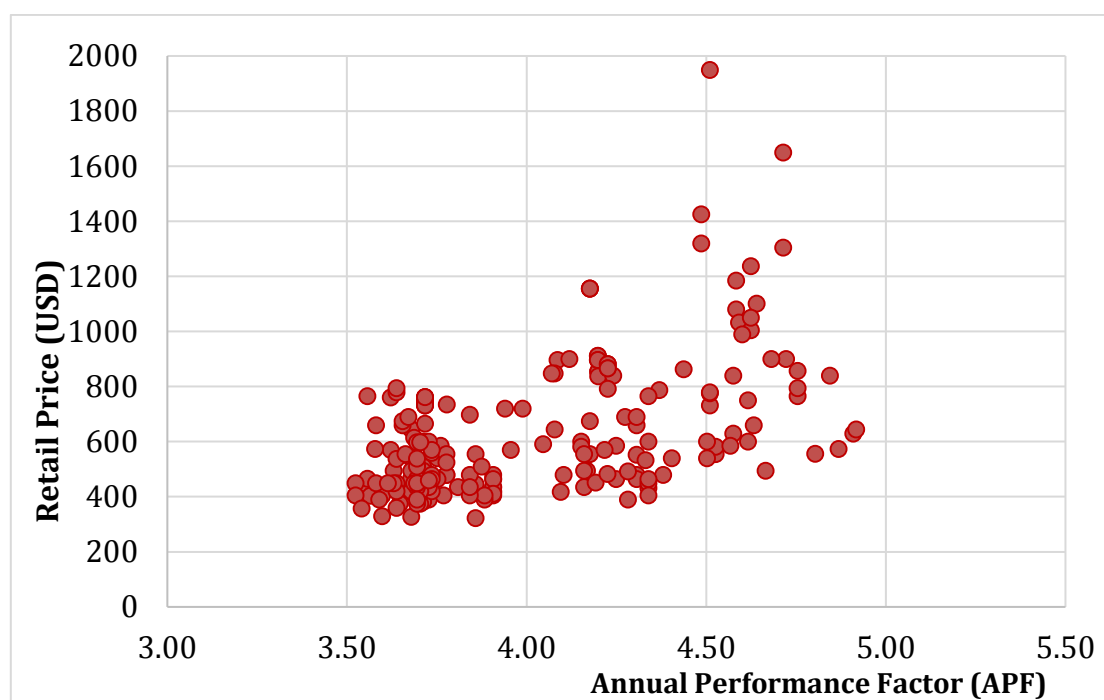


Figure 2.6 Retail price versus efficiency of 3.5kW mini-split ACs on the Chinese market [Shah, Park and Gerke, 2017])

Source: LBNL's IDEA database and the Chinese National Institute of Standardization database

A review of the Japanese AC market shows that ACs on the market have a higher range of EE. Whilst there is a strong underlying association between the EE and the unit price (Okada, 2018), there remains a wide variation in price at a particular efficiency level. Figure 2.7 depicts the correlation between price and EE for all 3.5 kW models operating with HFC-32 as the refrigerant. The rate of price increase is roughly \$603 per EE (APF) point.

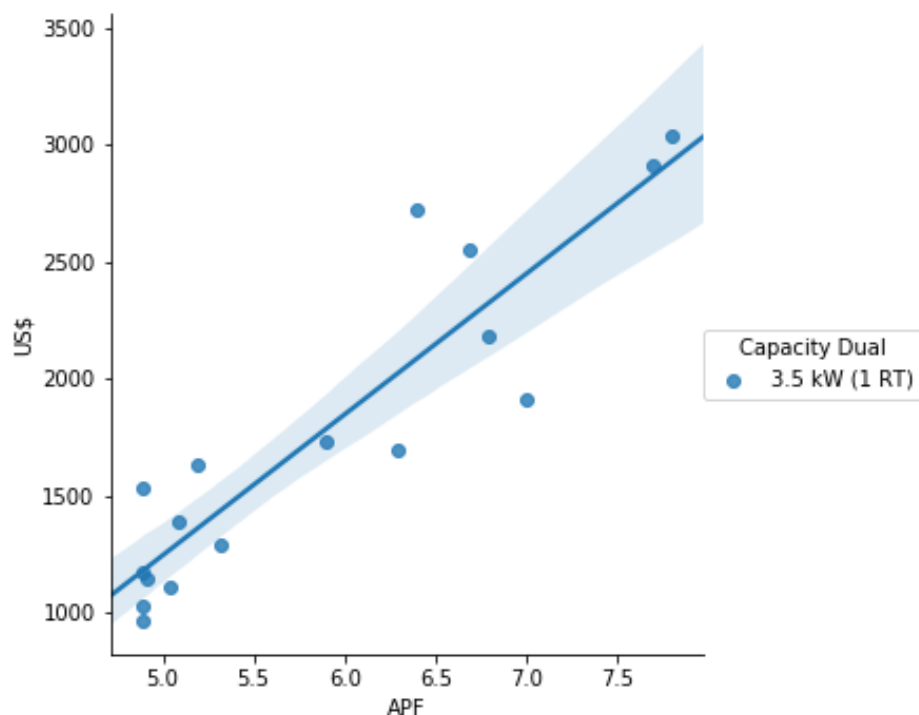


Figure 2.7 Survey of retail price vs EE in APF of mini-split AC in the Japanese market

The limited publicly available data on the cost of EE improvement is published in some larger markets during the process of setting of MEPS for RAC equipment. As part of this process, the DOE's Appliance and Equipment Standards Program [DOE, 2016] and the preparatory studies for the EU Ecodesign Directive [EuP, 2009] both use "bottom-up" engineering analyses to identify the actual manufacturing cost (as opposed to the retail price) of efficiency improvement. Similar processes have also been used to a more limited degree to support EE standards processes in countries such as India and China (see [Shah et al., 2016; Lin and Rosenquist, 2008; Fridley et al., 2001]).

Example 2: Costs and energy savings of various efficiency improvement options

Table 2.8 shows a recent example from India, of efficiency improvement options for various components for a 5.27 kW mini-split AC with the expected energy savings from the "base case" model and their corresponding costs per unit (in Indian rupees). Next, a manufacturing cost versus EE model is created based on the most feasible and least expensive design options available. Retail and wholesale mark-ups are estimated based on this estimated manufacturing cost and the available retail price data on the market to arrive at a retail price versus EE curve.

Table 2.8 Efficiency improvement options, energy savings and manufacturing cost for a 5.27 kW mini-split AC in India [Shah et al, 2016]

Technology	Energy Saving Compared with Baseline	Incremental Manufacturing cost (Rs)
Improved compressors	5.5% – 15%	100 – 860
Variable speed compressors	21% – 23%	1,800 – 8,100
Variable speed drives for fans and compressors	26%	3,150 – 9,450
Heat Exchanger improvement	7.5% – 24%	735 – 11,000
Expansion valve	3.5% – 6.5%	125 – 2250

Example 3: Price increase of efficiency with and without change in refrigerant

For one Chinese brand, the price increase for an approximately 13-15% efficiency improvement for a 3.5 kW variable-speed AC using R-410A is about 6%. However, when both the efficiency and refrigerant were updated (i.e. from 5-8% improvement and from R-410A to HFC-32), the price increase was about 11% (Li, 2018.).

Example 4: Declining price trends over time

The US unitary AC equipment evolution since the 1970s has shown steady efficiency improvement while at the same time achieving cost effectiveness as shown in Figure 2.8. U.S. manufacturers have reduced the inflation-adjusted price of unitary A/C equipment, as Figure 2.8 shows for residential central ducted A/C systems (equipment costs only). The dotted green line depicts the Producer Price Index (PPI) while the blue line depicts the inflation adjusted PPI. The inflation adjustment is calculated by dividing the PPI series by the gross domestic product chained price index for the same years and normalize them to the year 2015.

The trend of decreasing prices has been concurrent with the ODS phase-out, as well as periodically increased efficiency standards. The reasons for this trend are complex, including technological innovations and manufacturing efficiencies, as well as macroeconomic factors related to globalization of manufacturing and commodity price trends. It is important to note that the adjusted equipment price didn't increase following the introduction of the efficiency standards or the increase in the standards. It is also important to note that prices didn't react adversely with the ban of HCFC-22 in 2010. Please refer to section 2.2 for more information about the barriers to uptake in developing economies as well as in section 2.3 on long-term sustainable performance and viability.

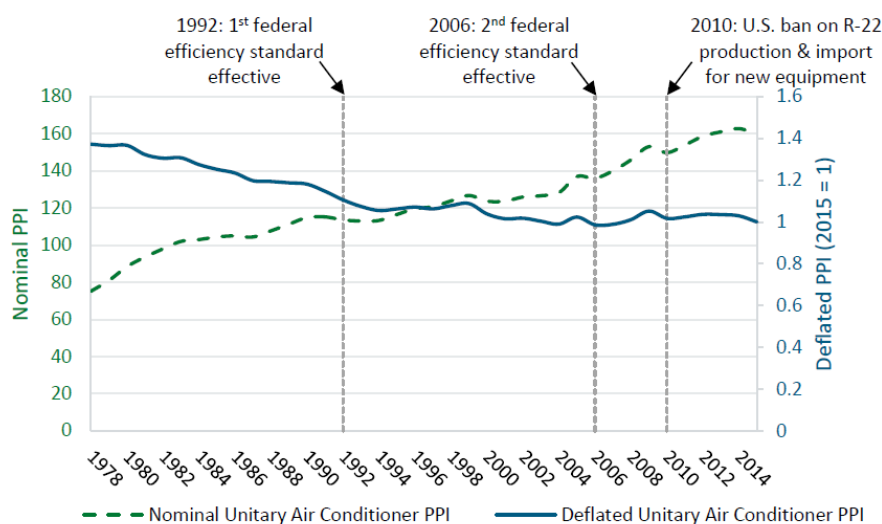


Figure 2.8 - Residential central AC equipment costs from 1978 to 2015 [Goetzler et al 2016]

Example 5: Significant potential for efficiency improvement without increased cost

A simple example that illustrates the enormous potential for efficiency improvement without extra capital cost is summarised in Figure 2.9. This shows a breakdown of the lifetime CO₂ emissions of a typical residential fridge-freezer in developed economies [IPCC, 2013]. The global best practice

refrigerator in 2015 has GHG emissions that are nine times lower than a typical 1980s refrigerator sold in developed countries (non-A5).

Some of the reduction comes from the switch away from CFC refrigerant and foam blowing agent. The EE improvement also makes a vital contribution – the 2015 best practice unit uses 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 lower in real terms than the 1980s model.

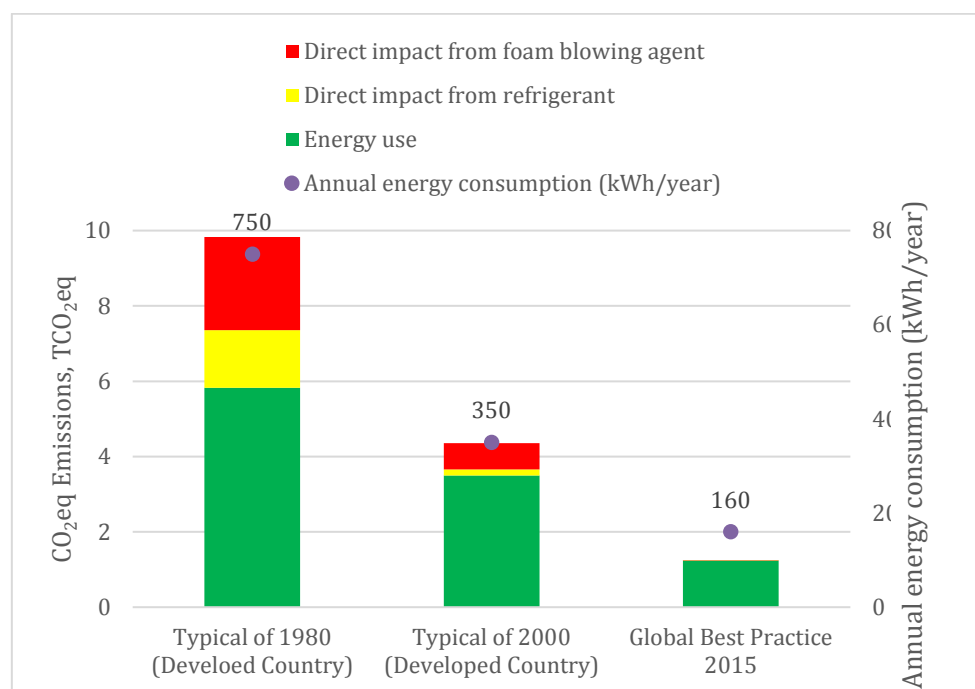


Figure 2.9 Reduced energy consumption and GHG emissions from domestic refrigerators-freezers

Further and consistent information on the same trend can be drawn from Figure 2.10.

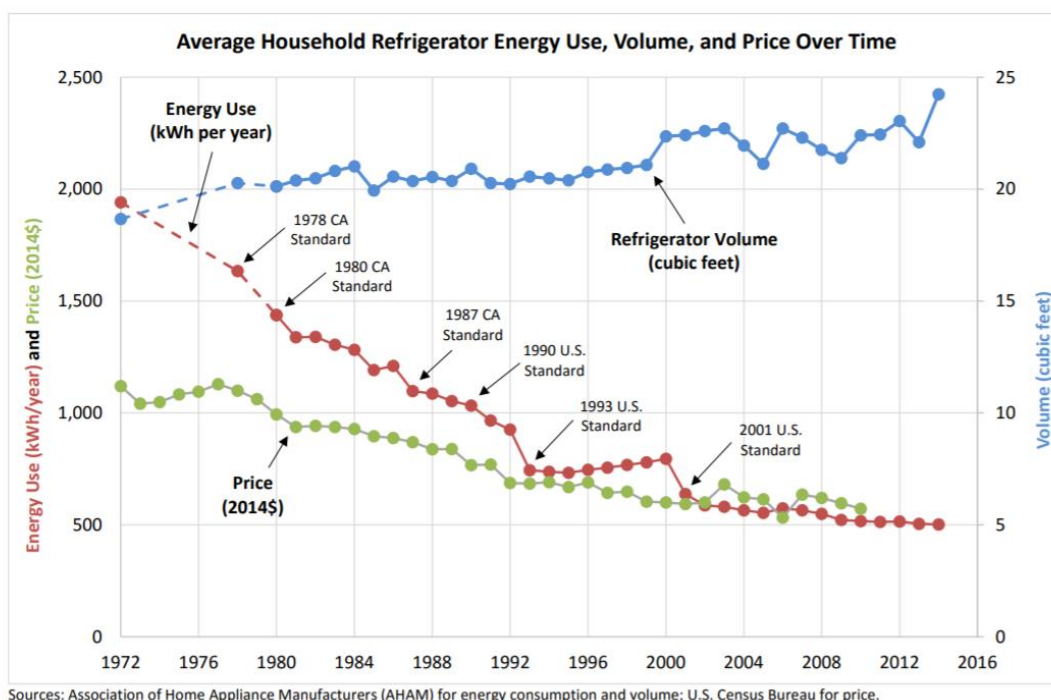


Figure 2.10 Average household refrigerator energy use, volume and price over time in US
(https://appliance-standards.org/sites/default/files/refrigerator_graph_Nov_2016.pdf)

Example 6: Cost and payback period to the consumer for different efficiency levels.

Table 2.9 below shows the lifecycle cost (retail price plus installation cost plus energy cost over the lifetime of the equipment) and payback period (period of time over which the energy savings exceed the higher installation cost) to the consumer calculated using the above outlined methodology from a recent US DOE⁴ rulemaking document for four efficiency levels above a base level considered for mini-split air conditioning. The higher efficiency levels have higher installed costs, but lower lifetime operating costs. The data imply that at the current technology development that there is a ceiling of efficiency at which point the energy savings will not pay back the higher installed cost within the lifetime of the equipment.

⁴ <https://www.regulations.gov/document?D=EERE-2014-BT-STD-0048-0098>

Table 2.9 Installed cost, lifecycle cost and simple payback period to the consumer for various efficiency levels for mini-split air conditioners in the US

	Average Costs 2015 (US\$)				
SEER W/W)	Installed Cost	Lifetime Operating cost	Lifecycle cost	Simple payback (years)	Average lifetime (years)
4.1 (Base)	\$3,714	\$4,758	\$8,472	N/A	15.3
4.3	+\$38	-\$93	-\$55	4.5	15.3
4.4	+\$105	-\$189	-\$84	4.8	15.3
4.7	+\$259	-\$295	-\$36	8.2	15.3
5.6	+\$1,105	-\$602	+\$503	16.6	15.3

Example 7: Lifecycle cost including refrigerant for different efficiency levels (Example from India)

Figure 2.11 shows the breakdown of the lifecycle costs of typical 5 kW AC units at 3 EE levels in India (2 Star, 3 Star, and 5 Star). These EE levels represent roughly 90% of the market in India. As can be seen, the refrigerant contribution to the lifecycle cost is minimal (less than 1%). The lifecycle cost for the 2, 3, and 5 Star units are 117.2, 119.5, and 108.0 thousand INR respectively. This indicates that while the system price increases from 2 Star to 5 Star, it results in a net lifecycle cost saving of 9,200 INR.

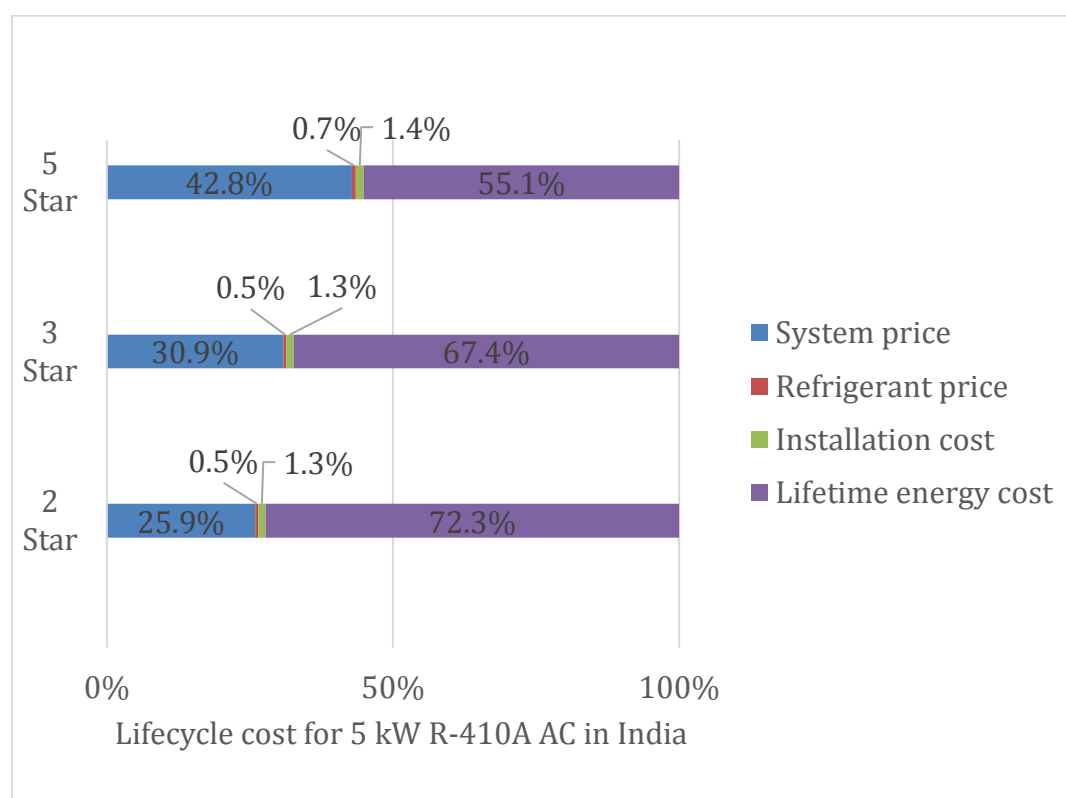


Figure 2.11 – Breakdown of the lifecycle cost for 5 kW R-410A AC in India at different efficiency levels [Bhambure, 2018]

2.7.3 Capital costs

Commercial refrigeration sector

Stand-alone equipment:

Transitioning from high GWP HCFC and HFC to low GWP options will require some investment in manufacturing and equipment. This is especially true when the transition is to flammable refrigerants such as A2L or A3 hydrocarbon refrigerants. In general, data from the field indicates that the cost to the consumer for an HC-290 stand-alone system can vary from 0% to 5% over conventional systems. The higher price, if any, can often be recovered, with the lower power consumed by these newer systems.

The cost to implement the other efficiency improvement ideas will vary from small, as in the case of LED lighting, to high for the variable speed or higher efficiency compressors. Payback will depend on the cost of electricity in the respective region but since most regions regulate these systems, the market would be expected to adopt the lowest cost method to achieve the minimum efficiency required.

Condensing units:

Similar to stand-alone equipment, transitioning from high GWP HCFC and HFC to low GWP options will require some investment in manufacturing and equipment. This is especially true when the transition is to flammable refrigerants such as A2L refrigerant blends or A3 hydrocarbon refrigerants. Thermal load reduction through better insulation, especially in walk-in coolers and freezers, use of LED lights, and some of the other efficiency improvement ideas are lower first capital cost and yield gains throughout the life of the equipment. Again, payback is a function of the local cost of electricity and can vary from region to region. Regulations play a key role in which efficiency improvement gets adopted.

Centralized and Distributed systems:

Market driven economics have justified many centralized and distributed systems to adopt many of the efficiency methods listed in the Annex. In the case of R-744 systems, for both cascade sub-critical and especially for transcritical systems, capital costs have prevented widespread adoption, particularly in warm climates. A recent study⁵, for a small store in Europe with ten refrigerated cases, compared a distributed HC-290 system to a transcritical CO₂ system. The efficiency of the HC-290 system was about 5% better on an annual basis and about 25% less capital cost than the transcritical CO₂ system. One can expect that this would be similar if the HC-290 system were replaced with a low GWP blend of HFC/HFO in the distributed system. In order to improve the performance of the CO₂ system, ejectors or parallel compressors could be added but the initial (purchase) cost will increase.

AC and HP sector

As discussed earlier there exist several EE improvement options with a different perspective for commercial and residential equipment. There are technologies that are shown to be cost neutral, such as advanced heat exchanger designs, rotary compressors, and variable capacity centrifugal compressors. There are others that result in a cost premium that can be reduced with time due to the economies of scale, such as the MCHX and the electronic expansion valves, or remain as a premium cost element such as the variable capacity compressors for room and packaged air conditioners.

Further data are collected from interviews with industry experts, manufacturers and component suppliers to quantify the costs of conversion to these higher efficiency levels. This is used to conduct

⁵ http://www.emersonclimate.com/europe/en-eu/About_Us/News/Documents/FFR196-Emerson-Fact-sheet-Integral-Display-Case-Technology-EN-1711.pdf

a “manufacturer impact analysis” to estimate the industry average capital and operating costs of conversion to these higher efficiency levels.

Table 2.10 below shows an example from a recent US DOE rulemaking document for capital costs of higher efficiency for four efficiency levels considered for mini-split air conditioning by the US industry as a whole.

Table 2.10 Industry-wide capital conversion costs for various efficiency levels⁶

SEER (W/W)	Capital Conversion Costs (2015 US\$ million)	2015 Shipments ⁷ (million units/year)
4.2	61	6.5
4.4	205.6	6.5
4.7	337.9	6.5
5.6	373	6.5

Source: DOE 2016

2.7.4 Operating costs

Commercial refrigeration sector

Stand-alone equipment:

Transitioning to low GWP refrigerant options will result in operating cost improvements from 0% up to 10% depending on the refrigerant chosen. Hydrocarbon HC-290 refrigerant could reduce electricity cost by 5 – 10 % compared to HCFC-22; R-290 is an example of an early adoption of a low GWP refrigerant in this application that has been successful from an EE point of view. Additional improvements with variable speed fans, compressors, LEDs and other efforts will further reduce the power consumption depending on the improvement that has been made.

Condensing units:

Similar to stand-alone equipment, transitioning from high GWP HCFC and HFC to low GWP options can be expected to reduce or keep flat the operating energy costs depending on the refrigerant choice made. Thermal load reduction through better insulation, especially in walk-in coolers and freezers and the use of LED lights are some examples of EE methods that yield reduced power consumption, leading to lower operating costs.

Centralized and Distributed systems:

Market driven economics have justified many centralized and distributed systems to adopt many of the efficiency methods that were listed in earlier sections. Operating costs for the new lower GWP HFCs and HFC/HFO blends are comparable to the systems that they replace, mainly due to the technology not being much different. In the case of R-744 systems, for both cascade sub-critical and especially for transcritical systems, operating costs are flat to slightly higher in the case of transcritical, compared to R-404A. Of course, as mentioned before, a store design with A2L Low

⁶ Trial standard levels 1,2,3 and 4 correspond to seasonal energy efficiency ratio (SEERs) of 14.5, 15.0, 16.0 and 19.0 BTU/hr/W respectively for 2 ton mini-split ACs. These “Trial standard levels” were defined differently for various product categories.

⁷ Total 2015 shipments included all types of central AC and heat pump systems shipped in the US.

GWP HFC/HFO blends could be expected to be close to the HC-290 store performance. While the HC-290 architecture mentioned in this study could work for a small store format, it will be difficult to justify this in a store where the refrigeration systems are much larger.

AC and HP sector

Previous studies have indicated that lower GWP HFC/HFO blends can be readily used to replace R-410A while maintaining or improving the system performance of the RACHP [Abdelaziz et al., 2015; Abdelaziz et al., 2016]. However, HCFC-22 alternative lower GWP refrigerants and refrigerant blends were not able to readily match the performance. A later study by Shen et al. 2017, showed that with engineering optimization, HCFC-22 alternatives can match or exceed the performance of existing HCFC-22 units with efficiency increase of up to 10%.

3 Funding institutions related to energy efficiency in the RACHP sector while phasing down HFCs

Summary

- There are numerous financial resources for projects implementation in the field of EE. Besides funding institutions that provide resources in the form of directed grants, there are financing institutions that provide project funding support through mechanisms such as loans, green bonds or other instruments. Moreover, private capital is an additional source through companies who might be interested to finance project implementation against investment payback.
- Broad consideration of the various potential interested stakeholders, opportunities for partnerships with shared goals, and options for co-financing would be important to planning for potential projects related to EE in the RACHP sector while phasing down HFCs.

3.1 Background

Decision XXIX/10 requests the TEAP “to provide an overview of the activities and funding provided by other relevant institutions, as well as definitions, criteria and methodologies used in addressing EE in the RACHP sectors in relation to maintaining and/or enhancing EE in the RACHP sectors while phasing down [HFCs] under the Kigali Amendment to the Montreal Protocol, as well as those related to low- and zero-GWP HFC alternatives including on different financing modalities.” In order to respond to this request, the Task Force interpreted the reference to “activities and funding provided by other relevant institutions” to exclude the Montreal Protocol Multilateral Fund (MLF) given the fact that funding guidelines to phase-down HFCs are still under discussion. In paragraph 10 and other parts of Decision XXVIII/2, parties outline the funding considerations for phasing down HFCs and request “the Executive Committee to develop, within two years of the adoption of the Amendment, guidelines for financing the phase-down of hydrofluorocarbon consumption and production, including cost-effectiveness thresholds, and to present those guidelines to the Meeting of the Parties for the parties’ views and inputs before their finalization by the Executive Committee.” Thus, the Task Force focused on institutions other than the MLF.

As noted in its earlier Decision XXVIII/3 Working Group Report on Energy Efficiency [UNEP, 2017a], enhancement of EE has already been a resulting side benefit of the Montreal Protocol. The parties to the Montreal Protocol have led three successful transitions of refrigerants over 30 years and are preparing a fourth transition to phase down the use of high GWP HFCs. These transitions to more environmentally friendly refrigerants had been implemented in a transparent manner, through successful implementation of the control measures mandated by the Montreal Protocol, and as technology has developed. Several project completion reports to the ExCom of the MLF have noted that the projects that led to the phase-out of the old refrigerants resulted in parallel EE improvements due to new regulations, new designs, new components, new factories, retooling of production lines, new equipment, etc. In part, these gains have occurred as the result of competitive factors that are a natural by-product of phasing in newer refrigerants, technologies and equipment.

Improved EE (and associated energy savings) has been achieved previously in the reduction of the inventory of old and inefficient ODS containing RACHP equipment, and controlled ODS in the servicing sector. This has been demonstrated in MLF assisted demonstration projects, such as CFC chillers and refrigerator replacement schemes, designed to scale-up financial assistance and incentive programmes. These projects were funded by domestic, private and non-domestic (multilateral and bilateral) institutions (such as governments, utilities, national banks, the Global Environment Facility (GEF), Inter-American Development Bank (IADB), World Bank (WB), Asian Development Bank (ADB), and Germany bilateral cooperation) and led to successful market transition to products with lower GWP than the refrigerant replaced, and with higher EE.

Multilateral development and financial organisations have been investing in EE projects addressing market and information barriers for several years (e.g. GEF, Green Climate Fund (GCF), United Nations Development Programme (UNDP), United Nations Environment Programme (UNEP), United Nations Industrial Development Organisation (UNIDO), United Nations Department of Economic and Social Affairs (UNDESA), The United Nations Foundation, WB, IADB, and ADB). Other financial institutions are based on philanthropic initiatives (e.g., Kigali Cooling Efficiency Programme, Climate Works Foundation).

The Task Force made a distinction between financing and funding institutions. Financing institutions were considered as those providing loans for projects under typical application requirements and terms. Funding institutions were considered as those providing direct monetary support to a project based on defined criteria and application process. In this chapter, the Task Force considered where these financing and funding institutions specifically intersect with the objective of providing support for, among other things in the decision, “addressing EE in the RACHP sectors while phasing down HFCs.”

This chapter provides a general overview of the activities and funding provided by some of these other relevant institutions in addressing EE in the RACHP sectors in relation to maintaining and/or enhancing EE while phasing down hydrofluorocarbons. It is not an exhaustive list.

3.2 Funding Institutions

This section provides information on two main funding institutions that intersect with the objective of providing direct support to address EE in the RACHP sector: the Kigali-Cooling Efficiency Programme and the Global Environmental Facility. Only the Kigali-Cooling Efficiency Programme also has a specific objective to support the phasedown of HFCs while enhancing EE.

3.2.1 Kigali-Cooling Efficiency Programme (K-CEP)

Overview

The Kigali Cooling Efficiency Program (K-CEP) is a US\$ 52 million philanthropic initiative launched in April 2017 with the aim of supporting Article 5 parties to integrate improved EE into the refrigerant transition. The initial commitment from philanthropic foundations and individuals was announced in September 2016 coupled with an additional contribution of US\$ 27 million to the MLF by non-Article 5 parties to support the early adoption of HFC phasedown activities.

Objectives of the program include:

- Increase the probability of achieving the overall mitigation potential of up to 50 GtCO₂eq for increased energy-efficient cooling (cumulative through 2050);
- Incentivize early and rapid additional action to replace inefficient, high-GWP cooling solutions;
- Successfully connect EE with the work of the Montreal Protocol;
- Build and enhance EE policy and program awareness and stringency;
- Develop and enhance institutional, civil society, and market capacity for work on efficient and low-GWP cooling solutions;

- Contribute to sustainable development by increasing access to efficient and low-GWP cooling;
- Reduce the operational cost of cooling without a material rise in capital costs, where a material rise in capital costs is defined as an increase in capital costs that would make a significant change in current and projected market demand and supply for cooling solutions; and
- Attract and leverage additional funding, and, at the same time, complement public and private funding.

More than US\$ 35 million has been committed to supporting activities including training and development of national cooling strategies (Window 1); policies, standards, and programs (Window 2); and access to cooling (Window 4). While the majority of K-CEP funding is being provided through grants to implementing partners working with participating Article 5 parties' governments, approximately US\$ 10 million has been allocated under the "Finance Window" (Window 3). K-CEP's Window 3 aims to help mobilize finance for efficient clean cooling and complements global, regional and country activities supported under other windows. It seeks to demonstrate how targeted grants can unlock the additional finance needed to integrate efficiency improvements with the F-gas transition. While not restricted to scaling up existing work supported by K-CEP, the finance window is open to proposals that build on activities supported in K-CEP's other "windows" which offer a potential funding pipeline that can serve as the basis to realise more and potentially greater emissions reduction opportunities, as well as to identify new opportunities that align with K-CEP objectives.

Additional information providing an overview of K-CEP is summarized below. More information about K-CEP, its structure, and funders can be found at k-cep.org.

Scope: K-CEP is supporting a wide range of projects to improve cooling efficiency together with the HCFC phaseout and HFC phasedown. The projects include activities to: strengthen efficiency by building capacity; improve policies, regulations, standards and labelling; develop cooling plans; unlock manufacturing capacity for efficient equipment; improve monitoring and analysis of cooling efforts; catalyse investment in efficient cooling; and better understand access to cooling. While the majority of activities focus on the residential and commercial refrigeration, air conditioning sectors, K-CEP is also supporting district cooling, and will consider other areas that will be identified in the access to cooling report being prepared for July 2018. This portfolio of activities is being delivered across developing countries in Africa, the Middle East, Asia, Latin America, the Pacific, and the Caribbean alongside various efforts at a global level to improve cooling efficiency awareness and action. K-CEP prioritizes support for the greatest possible reductions in greenhouse gas emissions, working in countries willing to move furthest and fastest, building on existing efforts, and ensuring geographical diversity.

Definitions - High Efficiency: An important concept when working in the EE sector is continuous improvement. For this reason, what counts as energy efficient is not a stationary value but should be defined with respect to the market average or best available technology. K-CEP is working with the International Energy Agency on a "Kigali Progress Tracker" that combines a database on policy and technology with data collection from partners and data dissemination via the IEA exchange platform: <http://www.iea.org/exchange/cooling/>.

Financing modalities and potential market mechanisms

K-CEP recognises that overcoming finance barriers is key to advancing EE in cooling solutions. The target market for K-CEP's Finance Window is cooling investment by the public or private sector. Based on discussions with stakeholders, there are two financing requirements needed to raise the environmental performance of cooling technology and to drive increased investment in higher efficiency cooling solutions:

- Finance for technical assistance (TA) for project preparation and securing interest and for project management: specialized assistance is required to devise the appropriate technical specifications and performance metrics and generate the demand for the financing mechanism. It is also important to make the case for cooling efficiency investment when suppliers and buyers have other options to maximize their utility. TA is also often needed for project management since EE projects can be complex (e.g., monitoring, reporting, and verification needs).
- Finance for capital costs – which could include some concessional funding to cover the incremental cost of the higher efficiency option.

K-CEP's Window 3 funding is intended to attract finance from financial institutions, governments and the private sector. Given the limited size of the resource envelope, it is intended to serve as a pilot, and is deliberately designed to allow for multiple approaches to addressing efficiency in the context of F-gas replacement. A call for proposals is ongoing through 27 July 2018.

Criteria and methodologies

K-CEP is making available a total of up to US\$ 10 million under [Window 3](#) to fund programs seeking US\$ 2 million to US\$ 5 million to support energy efficient, clean cooling finance in eligible developing countries. Window 3 is open to providing technical assistance (e.g. project identification, energy audits, detailed project preparation and awareness-raising) and finance for incremental cost support (e.g., fees associated with first loss or guarantee facilities, or interest rate subsidies on loans to end customers). Separate funding for the capital component of programs will need to be secured from governments, development banks, private sector banks, climate funds, or other financial institutions (in-principle commitments to provide such funding, or strong indication of financing availability, will be required).

K-CEP is open to supporting new initiatives or building on the momentum of existing EE finance schemes where doing so will lead to faster implementation of efficient clean cooling finance. Proposals will be evaluated using screening criteria that include a clear and compelling program concept, significant scale greenhouse gas emissions reductions, the mobilization of significant additional capital, a readiness to implement, transformational long-term impacts, a strong team with relevant experience, and a compelling financial story.

K-CEP has developed a monitoring, reporting, evaluation, and learning framework that aims to be simple and transparent and build off of existing methodologies where available, to be compatible with Multilateral Fund and International Energy Agency methodologies. This includes reporting projected and verified emissions reductions from EE in CO₂eq.

Table 3.1. Overview of K-CEP activities

Focused support	<p>Enabling technology projects</p> <p>Support to refrigerator and air conditioner manufacturers and supermarkets to enhance efficiency while phasing down F-gases.</p>	<p>National cooling plans</p> <p>Support to develop cooling plans that can inform HPMPs and Nationally Determined Contributions.</p> <p>Standards and labelling</p> <p>Minimum energy performance standards and labelling for commercial and residential refrigerators and air conditioners.</p> <p>Set of model energy performance standards for air conditioners</p> <p>Compliance</p> <p>Monitoring, verification, and import controls.</p>	<p>Identifying finance needs and incentives</p> <p>Bulk procurement, rebates and/or other financial mechanisms.</p> <p>Report on cooling market and investment landscape</p> <p>Window 3- Finance</p> <p>Launch planned in 2018; will include technical assistance for proposal preparation for funding from other financial institutions.</p>
Cross-cutting support	<p>Training and capacity building</p> <p>Support to ozone and energy policy makers, refrigerator and air conditioner small and medium-sized enterprises, service sector.</p>		
	<p>Cooling for all</p> <p>Identifying the best solutions to make clean cooling accessible to all.</p>		

3.2.2 Global Environmental Facility

Overview

The Global Environment Facility (GEF) was established on the 1992 Rio Earth Summit to help tackle the most pressing environmental problems in the planet. Since then, the GEF has provided over US\$17 billion in grants and mobilized an additional US\$88 billion in financing for more than 4000 projects in 170 countries.¹

The GEF is an international partnership of 183 countries, international institutions, civil society organisations and the private sector that addresses global environmental issues. In addition, The GEF partners with 18 agencies — including United Nations agencies, multilateral development banks, national entities and international NGOs. The GEF has a large network of civil society organisations, works closely with the private sector around the world, and receives continuous inputs from an evaluation office and a scientific panel.

¹ www.thegef.org

The GEF is a Financial Mechanism for five major international environmental conventions:

- The United Nations Framework Convention on Climate Change (UNFCCC);
- The United Nations Convention on Biological Diversity (UNCBD);
- The Stockholm Convention on Persistent Organic Pollutants (POPs);
- The United Nations Convention to Combat Desertification (UNCCD); and
- The Minamata Convention on Mercury.

The GEF, although not linked formally to the Montreal Protocol, supports implementation in Countries with Economies in Transition (CEIT). The GEF Secretariat and the Secretariats of the Montreal Protocol and the MLF defined areas of cooperation and coordination.

The GEF supports capacity development for successful implementation of the international conventions for which the GEF is serving as the financial mechanism. This is a primarily domestically-driven process that clearly defines the capacity needed in terms of people and infrastructure. Capacity development in the GEF adheres fully to the concerns and priorities expressed by the international community. For example, the enabling environment means capable individuals and effective infrastructure working together in a well-functioning political, economic and social system.

The GEF investments have been focused on the global environmental benefits in biodiversity, climate change mitigation, international waters, land degradation and forests, and chemicals and waste. However, the GEF is increasingly seeking to deliver multiple environmental benefits through integrated investments across the various dimensions of the global environment.

Within the Climate Change Mitigation area, the GEF includes the sustainable mitigation of the concentration of anthropogenic greenhouse gases (GHG) in the atmosphere. Specifically, it includes:

1. Mitigated GHG emissions;
2. Increased use of renewable energy and decreased use of fossil energy resources;
3. Improved EE;
4. Increased adoption of innovative technologies and management practices for GHG emission reduction and carbon sequestration; and
5. Conservation and enhanced carbon stocks in agriculture, forest, and other land use.

The GEF support a wide variety of mitigation strategies. As noted in the GEF-6 Climate Change Mitigation Strategy, the approach has three objectives:

1. Promote innovation, technology transfer, and supportive policies and strategies.
2. Demonstrate mitigation options with systemic impacts.
3. Foster enabling conditions to mainstream mitigation concerns into sustainable development strategies.

Financing modalities and potential market mechanisms

The GEF is established not only as an innovator, but also as a catalyst. By supporting multi-stakeholder alliances across a broad range of environmental issues, (e.g. to preserve threatened ecosystems, build greener cities, boost food security, promote clean energy etc.) it has leveraged US\$5.2 in additional financing for every US\$1 invested.

It has used blended finance (i.e. the synergy between development finance and private capital) to

reduce risks and increase the opportunities for private investors. It also helps rally partners from different sectors around an issue. Experience has shown that it incentivizes private investors to take action on climate change.

By the end of 2015, the GEF had invested in 1,000 climate mitigation projects, including more than 200 EE projects. The GEF had helped 46 countries to develop national plans to reduce their GHG emissions. The GEF pump-priming funding of US\$4.2 billion in the 1,000 climate mitigation investments generated almost 10-fold additional funding (\$38.3 billion) from other partners.

Co-financing is optional for GEF enabling activities but is required for all GEF full-size projects (FSPs), medium-side projects (MSPs), and GEF programmes. GEF financing is determined on the basis of the agreed incremental cost principle. Co-financing from the private sector or project beneficiaries during implementation, can be counted as confirmed co-financing, provided that the project document includes clear milestones and minimum matching funding levels.

A System for Transparent Allocation of Resources (STAR) is used. The GEF Secretariat allocates resources in an indicative way to its eligible countries in a replenishment period. In the fifth replenishment period of the GEF (GEF-5), the STAR covered three focal areas: biodiversity (BD), climate change (CC), and land degradation (LD). Future GEF replenishment periods may have STAR covering other focal areas and programs.

Examples of relevant GEF-funded projects

The methodologies used in addressing EE in RACHP are better understood through examples of GEF funded projects (such as for Chile and Ghana among others) that are described in Annex B and also available at the GEF database of approved projects [www.thegef.org].

3.3 Financing Institutions

This section provides information on other relevant financing institutions, those providing loans for projects under typical loan application requirements and terms. Specifically, the financing institutions discussed below, which potentially intersect with the objective of providing loans to support improved EE in the RACHP sectors are the Green Climate Fund, the World Bank Group and the regional development banks.

3.3.1 Green Climate Fund

Overview

The Green Climate Fund (GCF) is a global fund which support the efforts of developing countries, particularly the Least Developed Countries (LDCs), Small Island Developing States (SIDS), African States and nations that are particularly vulnerable, to respond to the challenge of climate change. The GCF is financed from a variety of sources, from the public (developed countries, but also from some developing countries, regions and cities) and private sectors. These resources address the mitigation and adaptation needs and priorities of developing countries through the principle of country ownership. The developing countries have a direct access modality so that national and sub-national organisations can receive funding directly beyond that of the multilateral institutions.

The GCF itself uses public investment to stimulate private finance multiplying the effect of its initial financing by opening markets to new investments. The GCF's investments can be in the form of grants, loans, equity or guarantees. The GCF portfolio has 76 projects and programmes approved,

amounting to US\$ 3,730.2 million to assist developing countries in their low emission and climate resilient development.

Financing modalities and potential market mechanisms

The GCF implement projects through partnerships with Accredited Entities (AEs) who submit a project proposal, in close consultation with national focal points. The AEs submit the project proposal for consideration to the GCF Board. Every project the GCF Board agrees to fund must be endorsed, via a no objection letter, by the national focal point.

If a project is approved, the AEs are responsible for overseeing, supervising, managing and monitoring the overall GCF-approved projects and programmes. Executing Entities can also do this on behalf of AEs by channelling funds and carrying out the funded activity. AEs can also respond to Requests for Proposals (RFPs) issued by GCF to fill current gaps and need in climate financing. In issuing some RFPs, the GCF may accept proposals from entities it has not yet accredited, but in this case, the non-accredited entities will have to team-up with AEs when formally submitting funding proposals to GCF.

Requests for Proposals (RFPs)

The GCF has established several supporting programmes to issue RFPs:

- Micro, Small and Medium-Sized Enterprises Pilot Programme: The programme aims to support micro, small, and medium-sized enterprises in addressing mitigation and adaptation challenges;
- Enhancing Direct Access: The GCF has allocated US\$ 200 million for 10 pilot funding proposals adopting Enhance Direct Access implementation modalities.
- Mobilising Funding at Scale Pilot Programme: The GCF has allocated US\$ 500 million for this programme to identify innovative, high-impact projects and programmes that mobilize private sector investment in climate change activity.

In addition, the GCF has established a Simplified Approval Process for some small-scale projects (Concept notes) that may also be submitted for consideration. Those projects may be presented as long as the project size is up to US\$10 million of the total project budget, the environmental and social risks and impacts are minimal and the small-scale project is ready for scaling up to low-emission and climate-resilient development. Funding proposals are submitted to the GCF Secretariat for the review process before the consideration of their approval by the GCF Board.

The Fund has identified 8 impact areas that deliver major mitigation and adaptation benefits (see GCF Decision [B.07/04](#)). In particular, the areas of “Energy efficient buildings, cities and industries” and “Low-emission transport” are relevant to the focus of this report. For the time being, projects are prepared and submitted to the GCF Board for approval. The component projects are approved if in line with the guidelines and procedures which are still under development.

With GCF Decision B.17/10: Establishing strategic programming priorities, the GCF Secretariat will develop a mapping document that identifies all elements related to project and programme eligibility and selection criteria included for funding proposals for the Board’s consideration at its eighteenth meeting. This also takes into account best practices from other multilateral funds and other approaches to address the following:

- (i) The development and application of an incremental cost calculation methodology and/or alternative methodologies, as appropriate;
- (ii) Guidance on the approach and scope for providing support to adaptation activities;
- (iii) A policy on co-financing; and

- (iv) Options for further guidance on concessionality², building on related work.

In terms of potential market mechanism, discussions of collaboration took place in 2016 between the Clean Development Mechanism (CDM) Executive Board and the GCF on how financing the CDM may work through international climate finance institutions, but no common understanding emerged on how to operationalize linkages between the two institutions.

Examples of relevant GCF -financed projects

Methodologies used in addressing EE in the RACHP are better understood through a GCF-financed project example contained in Annex B.

3.3.2 World Bank Group

The World Bank Group (WBG) is made up of five international organisations that make leveraged loans and provide assistance to developing and transition countries. Its five organisations are the International Bank for Reconstruction and Development (IBRD) and the International Development Association (IDA), collectively referred to as the World Bank; the International Finance Corporation (IFC), the Multilateral Investment Guarantee Agency (MIGA) and the International Centre for Settlement of Investment Disputes (ICSID).

The World Bank's (the IBRD's and IDA's) activities are focused on developing countries, in fields such as human development (e.g., education, health), agriculture and rural development (e.g., irrigation and rural services), environmental protection (e.g., pollution reduction, establishing and enforcing regulations), infrastructure (e.g., roads, urban regeneration, and electricity), large industrial construction projects, and governance (e.g., anti-corruption, legal institutions development). The IBRD and IDA provide loans at preferential rates to member countries, as well as grants to other countries. Loans or grants for specific projects are often linked to wider policy changes in the sector or the country's economy as a whole. For example, a loan to improve coastal environmental management may be linked to development of new environmental institutions at national and local levels and the implementation of new regulations to limit pollution.

In its 2016 Climate Change Action Plan,³ the World Bank Group (WBG) outlined its commitment to “deepen and scale up its actions in...high-impact areas” including EE: “The WBG will increase its share of energy efficiency operations and aim to invest US\$ 1 billion to promote energy efficiency and resilient buildings in urban areas.”

The WBG will invest in energy efficiency, especially in the built environment.

The WBG will increase the share of energy efficiency operations in the WBG portfolio, with an initial scale-up in the urban space, which offers large emission reduction potential and where the

² There is not a unique definition of concessionality but this term has traditionally been used in the context of lending to governments, particularly as part of the definition of external debt accounting. The International Monetary Fund (IMF) defines concessional lending as “loans that are extended on terms substantially more generous than market loans. The concessionality is achieved either through interest rates below those available on the market or by grace periods, or a combination of these. Concessional loans typically have long grace periods”. [IMF, 2003, External Debt Statistics: Guide for Compilers and Users – Appendix III, Glossary, IMF, Washington DC. GCF/B.19/12/R]

³ World Bank; IFC; MIGA. 2016. World Bank Group Climate Change Action Plan 2016-2020. World Bank, Washington, DC. <https://openknowledge.worldbank.org/handle/10986/24451>

clearest scale-up models exist. It will ensure that 50 percent of World Bank infrastructure operations in the urban space integrates energy efficiency measures (and reduces CO₂ and hydrofluorocarbon (HFC) emissions). By 2020, the WBG aims to support at least 10 operations, investing at least \$1 billion to promote energy efficiency and resilient building... The [International Finance Corporation (IFC)] will expand energy efficiency credit lines..., propose energy efficiency components in corporate loans and green bonds, and increase advisory services for sector-level interventions.

After the adoption of the Kigali Amendment to the Montreal Protocol in 2016, the WBG stated its “support of the amendment by helping countries phase down HFCs and improve EE in air conditioning and refrigeration, resulting in reduced emissions, decreased peak demand for electricity, and lower consumer electricity costs.”⁴ Further, the WBG indicated that as part of its Climate Change Action Plan, it had “developed a support plan that includes ramping up our lending for EE to accompany the HFC phase-down,” so that its expected [US] \$1 billion in lending by 2020 for EE in urban areas “could help support the development of high-efficiency cooling technologies that also use climate-friendly refrigerants.” This financing commitment directly intersects with the objectives of addressing EE in RACHP sectors during the phasedown of HFCs.

Beyond committing its own financing, the WBG promoted four other steps it would take to expand its work in this area:

- Undertake studies to identify where impacts could be the greatest – one study in Pakistan is cited where it is estimated that a transition to new refrigerants could cut power consumption from air conditioning by 40 percent and reduce greenhouse gas emissions by 8 million tons;
- Integrate technical assistance and policy work with concessional financing;
- Deploy new Montreal Protocol financing to help countries; and
- Share knowledge and practices across countries to accelerate action.

The US\$1 billion in lending by the WBG is expected to follow normal investment financing policies and procedures. At the time of the preparation of this report, updated information was not available to the Task Force on the status of current project financing and progress to date in meeting the WBG commitment for these funds.

3.3.3 Regional Development Banks

At the time of preparation of this report, updated information on the wide variety of activities and lending projects that the various Regional Development Banks promote and implement as part of their development and energy agendas was not available.

3.3.4 GIZ (The Deutsche Gesellschaft für Internationale Zusammenarbeit)

Overview

GIZ is an implementing agency, which has as main commissioning party, the German Federal Ministry for Economic Cooperation and Development (BMZ). It is focused in several areas of cooperation including the environment and climate change. Under this area, there are two programs:

⁴ <http://www.worldbank.org/en/news/feature/2016/10/17/staying-cool-without-heating-up>

Integrated Ozone and Climate Protection and Resource Efficient Economy, which support projects in EE. GIZ assists in the selection of environmental-friendly alternatives to ODS and the conversion of production lines to environmental-friendly technologies, including in specific applications in the refrigeration and air conditioning sector (i.e., domestic refrigeration, commercial refrigeration). In addition, GIZ has a Program for Energy Efficiency in Buildings (PEEB) that finances large-scale projects for increasing EE in buildings in selected partner countries.

Financing modalities and potential market mechanisms

GIZ has its own budget resources for project implementation coming from national financial resources. In addition, GIZ works with international programs and countries, including the private sector, to leverage additional resources, following the financial partnership approach.

Criteria and methodologies

GIZ finances specific work package or project component where it has expertise and knowledge.

Examples of relevant GIZ-financed projects

Below are GIZ project funding examples specifically for the RACHP sectors:

- **India:** The demonstration project helped the Indian manufacturer Godrej & Boyce to convert its production to systems using environmentally sound hydrocarbon refrigerants and introduce energy-efficient technology, thereby establishing a best-practice model. Since its launch in 2012, Godrej & Boyce sold up to 250,000 AC units and thus achieved a market share of over 11% in the 5-star AC segment making them the third largest supplier in this segment across India. [<https://www.giz.de/de/weltweit/16863.html>]
- **Swaziland:** The project produced refrigerators using alternative refrigerants such as isobutane (R600a) and propane (R290). Conducted from 2008-2011 at a cost of €1.4 million, the project included partners the Ministry of Tourism & Environmental Affairs and the Swaziland refrigerator manufacturer “The Fridge Factory”, formerly Palfridge Swaziland. The project is estimated to save 1.5 million t CO₂eq in 10 years (directly and indirectly); trained 500 more qualified employees and service technicians at “The Fridge Factory”; and resulted in cost reductions for the manufacturers as well as energy savings for the consumers from the use of more efficient refrigerators. [<https://www.giz.de/fachexpertise/downloads/giz2012-0103-en-proklima-keeping-cool.pdf>]

3.4 Others

The EU provides funding programmes to help finance European energy projects. Here are some general info in relation to the Global Energy Efficiency and Renewable Energy Fund and the Horizon 2020:

The Global Energy Efficiency and Renewable Energy Fund (GEEREF)

The GEREFF is an innovative Fund-of-Funds catalysing private sector capital into clean energy projects in developing countries and economies in transition. It was initiated by the European Commission in 2006 and launched in 2008 with funding from the European Union, Germany and Norway, totalling € 112 million.

More specifically, GEEREF invests public and private sector risk capital in specialist renewable energy and EE private equity funds developing small and medium-sized projects in emerging markets. GEEREF's funds focus on renewable energy and EE projects, which deploy proven technologies. There are currently 146 countries recognised as such and GEEREF's funds can target all of these

other than candidates for accession to the European Union. Priority is given to investment in countries with appropriate policies and regulatory frameworks on EE and renewable energy. The projects proposals have to be presented to the Funds according with their policies and procedures.

GEEREF has committed important volume of financial resources to several private equity funds who are focused on renewable and energy infrastructure investments such as: The Africa renewable Energy Fund (AREF), the Armstrong South East Asia Clean Energy Fund, the Catalyst MENA Clean Energy Fund, the Caucasus Clean Energy Fund, the Frontier Investment Fund, the Emerging Energy Latin America Fund II, the Evolution One fund, and other.

The Horizon 2020

Horizon 2020 is the biggest EU Research and Innovation programme ever with nearly €80 billion of funding available over 7 years (2014 to 2020). In addition to the private investment that this money will attract. It promises more breakthroughs, discoveries and world-firsts by taking great ideas from the laboratory to the market. The work programme for "Secure, Clean and Efficient Energy" include the focus area of EE. Within this area, research and demonstration activities are focusing on buildings, industry, heating and cooling, SMEs and energy-related products and services, integration of ICT and cooperation with the telecom sector. The Horizon 2020 is open to private and public entity from the EU and many developing countries. The Applicants have to submit their proposal electronically through the website and according with the guidelines on proposal submission and evaluation.

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5 Glossary⁵

APF: Annual Performance Factor (see Seasonal Energy Efficiency Ratio)

Coefficient of performance (COP, sometimes CP or CoP): For a heat pump, refrigerator or air conditioning system, this is a ratio of useful heating or cooling provided to work required. Higher COPs equate to lower operating costs.

Cooling capacity: A measure of a system's ability to remove heat. Measured in kW, Btu/h, or refrigeration ton (RT), where 1 RT = 3.5 kW = 12,000 Btu/h.

Cooling/heating load: The amount of energy needed to heat or cool to a desired level of service. Improving insulation in a building is a strategy for reducing heating and cooling load while providing the same level of comfort to the occupant.

Coefficient of Performance (COP): COP is defined as the ratio between the cooling capacity and the power consumed by the system. COP is also used for heat pumps and in this case it is defined as the ratio between the heating capacity and the power consumed by the system.

CSPF: Cooling season performance factor (see Seasonal Energy Efficiency Ratio).

Design efficiency: The energy performance of equipment as designed or as shipped, same as nameplate efficiency.

Energy Efficiency Ratio (EER): Ratio of the cooling output divided by the electrical energy input when measured at full load (i.e., at the maximum cooling capacity or the design point) and is measured in W/W or Btu/h/W (1 W = 3.412 Btu/h).

Energy performance: The amount of energy consumed for a piece of equipment or system to perform a specific level of service.

HSPF: Heating Seasonal Performance Factor (see Seasonal Energy Efficiency Ratio)

Installed efficiency: The energy performance of equipment as installed.

ISEER: Indian Seasonal Energy Efficiency Ratio.

Kilowatthour (kWh): A measure of electricity defined as a unit of work or energy, measured as 1 kilowatt (1,000 watts) of power expended for 1 hour. One kWh is equivalent to 3,412 British Thermal Units (Btu).

Manufacturing cost: cost to manufacture the equipment.

Million tonnes oil equivalent (Mtoe): 1 Mtoe = 11.63 billion kWh

Nominal design point: represents the set of conditions (e.g. indoor and outdoor temperatures) used to design the system

Operating cost: The cost to the equipment user to operate the equipment.

⁵ Sources:

https://www.nerc.com/files/Glossary_of_Terms.pdf, <https://www.eia.gov/tools/glossary/?id=electricity>,
<https://www.iea.org/statistics/resources/unitconverter/>, <http://www.iea.org/about/glossary/>

Part-load operation: condition that happens when the system has to face a load lower than nominal (nominal conditions are used for the design of the system). RACHP systems usually operate at part-load conditions for most part of their life cycle.

Peak Load: The highest electricity demand occurring within a given period on an electric grid.

Percent energy efficiency improvement: percent change in energy consumption of an efficient unit compared with a base unit.

Refrigeration Ton (RT): Measure of cooling capacity, where 1 ton refers to 12,000 Btu, equivalent to the energy required to freeze 2000 pounds of water in 24 hours.

Retail price: Price to purchase the equipment.

Seasonal Energy Efficiency Ratio (SEER): Ratio of cooling output divided by the electrical energy input, measured at full and part-load, and weighted to represent the overall performance of the device for the weather over a typical cooling season in each given country. An alternative name to SEER is the **Cooling Seasonal Performance Factor (CSPF)**. **Heating Seasonal Performance Factor (HSPF)** is used for heating mode. **Annual Performance Factor (APF)** is a metric used for reversible heat-pump room air conditioners that heat and cool.

Unit energy consumption: The amount of energy consumed by a unit of equipment, usually over one year.

Variable speed drives (VSD): A type of motor controller that drives an electric motor by varying the frequency and voltage supplied to the electric motor, also known as inverter.

ANNEX A

Sector-specific challenges to the uptake of technologies

A.1 Domestic refrigeration

State of the art

Domestic refrigeration includes appliances that are broadly used domestically, such as refrigerators, freezers and combined refrigerator/freezer products. Small beverage dispensing machines and similar products are commonly included in domestic refrigeration but represent a small fraction of total units. Approximately 170 million domestic refrigerators and freezers are produced annually [UNEP, 2014]. Long product life and large annual production volume combine for an estimated 2.0 to 2.3 billion units global installed inventory. [IIR, 2015] estimated that domestic refrigerators and freezers consume almost 4% of global electricity. The energy consumption of typical household refrigerators has dropped by around 65% in the last 15 years. Globally, energy efficiencies of refrigerators have been increasing constantly, as evident from the evolution of the energy labels in all many countries.

Opportunities

The conversion of new refrigerator production from ODS was completed worldwide by 2008. HC-600a (isobutane) or HFC-134a continues to be the refrigerant options for new production. No other new refrigerant has matured yet to become an energy-efficient and cost-competitive alternative. It was projected that by 2020, about 75% of new refrigerator production will use HC-600a (possibly with a small share by unsaturated HFC refrigerants) and the rest will use HFC-134a [UNEP, 2014]. Following the Kigali Amendment, refrigerant migration from HFC-134a to HC-600a is expected to accelerate, driven by local regulations on HFCs.

Energy labelling and minimum standards have been introduced in both developed and developing countries and are reviewed and upgraded on a regular basis, driving the product to reduced energy consumption levels. One example is the AHAM 7001-2012 Sustainability Standard for Household Refrigeration Appliances [AHAM, 2012], developed and endorsed by multiple stakeholders, including environmental, industry, government and consumers.

Significant technology options to improve product EE have been already demonstrated in mass production for robustness and long-term reliability. Both mandatory and voluntary EE regulation programs catalysed refrigerator efficiency development efforts. There are global standards and protocol developed for energy test (IEC 62552-1, 2 and 3, 2015) [UNEP, 2017b]. A number of improved EE design options are fully mature, and future improvements of these options are expected to be evolutionary. Examples of these options include:

- efficient compressors,
- high efficiency heat exchangers,
- improved low thermal loss cabinet structures and gaskets, and
- less variable manufacturing processes.

Extension of these to all global domestic refrigeration would yield significant benefit but is generally constrained by availability of capital funds and related product cost implications.

Design options with less economic justification are sometimes introduced in premium-cost models having incentive subsidies. Options that presently have limited or newly introduced application include:

- variable speed compressors,
- intelligent controls,
- system reconfigurations, such as dual evaporators,

- advanced insulation systems, and
- Demand Side Management (DSM) initiatives requiring interactive communication with energy providers in order to implement the Smart Grid concept.

The premium-cost of these options currently restrict their application to high-end models and constrain their proliferation for general use. A further constraint is the fact that not all energy saving measures result in a reduced energy value during tests according to the current test standards. The new universal test protocol mentioned earlier attempts to improve this situation.

Challenges

The investment cost for a manufacturing facility for domestic refrigerators using HC-600a is marginally higher than that of HFC-134a [Schwarz et al., 2013]. This is mainly due to the requirements for safety systems in relation to flammability. The annual running costs and lifetime cost of HC-600a equipment are also lower, resulting in an overall negative life cycle cost differential in the case of HC-600a.

HC-600a is the main energy-efficient and cost-competitive alternative. Concerns with the high flammability, which existed at the introduction of the refrigerant in 1994 in Europe, have been addressed with design features and safety standards, particularly as the charges required for domestic refrigeration are much smaller than HFC-134a. When the safety requirements are met (e.g. IEC 60335-2-24, [UNEP, 2017b]) and adequate risk assessment to address the flammable nature of the refrigerant, HC-600a is the ideal refrigerant for domestic refrigeration products, giving approximately 5 % greater efficiency than HFC-134a while at the same time reducing noise level of the unit.

HC-600a is right now the standard refrigerant for European domestic refrigerators and freezers originally and is proliferating into other regions, including Article 5 countries. Worldwide over 50 million appliances were produced annually with HC-600a in 2010. Increased EE and the low GWP of the HC-600a refrigerant reduce the climate impact of household refrigerators, due to mitigation of direct (refrigerant) and indirect (CO₂ associated with electricity consumption) GHG emissions, compared to HFC-134a.

In general, there are no significant technical barriers to the use of HC-600a, which are being used by an estimated 800 million domestic refrigerators in the field to date. In the USA, the use of HC-600a is limited by safety concerns, however significant progress is being made to convert from HFC-134a to HC-600a with the market introduction of freezers and small refrigerators. The service infrastructure is being developed even if US products using HC-600a tend to be non-serviceable systems as these include a second barrier to refrigerant leakage such as plastic liner.

A.2 Commercial refrigeration

State of the art

Commercial refrigeration is characterized by storing and displaying food and beverages at different levels of temperature within retail stores with sales areas varying in size from approximately 10 m² to 20,000 m². The refrigerating capacities of equipment vary from hundreds of Watts to as high as 1.5 MW. Two main levels of temperatures are generated by refrigeration systems from around 0°C to 8°C for the conservation of fresh food and beverages, and around -18°C for frozen food and ice cream.

In many non-Article 5 countries R-404A is widely used in commercial refrigeration. It has a very high GWP (3922) and is not the best efficiency refrigerant. HCFC-22 is widely used in Article 5 countries, although it is beginning to be replaced with R-404A.

Opportunities and challenges

In general, lower GWP options for this sector include HFO and HFC blends, lower GWP HFCs, hydrocarbons, ammonia (R-717) and carbon dioxide (R-744). The type of equipment, their location, the ambient conditions for heat rejection, availability of trained personnel for installation and maintenance, and the refrigerant choice affect the efficiency, first cost and operating costs of the equipment. In order to improve energy performance, several options are available for all types of commercial refrigeration equipment, and these can be applied to all of the lower GWP replacement refrigerants as well. Some of these are:

- use of glass doors or improved doors to reduce thermal load;
- door heaters and electronically controlled door “smart” door heaters to prevent or reduce the effect of condensation on the glass doors;
- higher efficiency fan motors, compressors;
- variable speed for part load performance improvement of fans and compressors;
- low energy, high performance LED lighting (has dual effect of consuming less energy and reducing parasitic heat load in the cooled space);
- larger and/or more efficient heat exchangers for evaporators and more importantly for condensing.

Some opportunities and challenges specific to the type of equipment in this sector are discussed below.

Stand-alone equipment are self-contained refrigeration systems and comprise a wide variety of appliances: ice-cream freezers, ice machines, beverage vending machines, and display cases. While HCFC-22, HFC-134a and R-404A refrigerants dominate this application, in Europe, and lately in other markets, the use of HC-290 and R-744 is steadily growing. New lower GWP HFCs, HFOs and their blends are also becoming commercially available and will find increased use in the near future. Some of these alternatives, especially R-290, have better efficiency characteristics than refrigerants such as R-404A. State-of-the-art stand-alone units are often considerably more efficient than older units, although the choice of refrigerant only has a small impact – other design improvements as listed earlier deliver most of the efficiency gains.

Stand-alone equipment efficiency is regulated by regional (such as the EU Ecodesign) and national performance standards (like the Department of Energy in the U.S.). In some countries, prescriptive requirements for components such as fan motors are also used to regulate efficiency of the system. Well established test procedures and laboratories exist that can test and certify this equipment in Article 2 countries; developing this capability in Article 5 countries will be important for increasing the use of efficient stand-alone equipment.

Condensing units exhibit refrigerating capacities ranging typically from 1 kW to 20 kW. They are composed of one (or two) compressor(s), one condenser, and one receiver assembled into a so-called “condensing unit”, which is typically located external to the sales area. Lower GWP HFCs, HFOs and their blends are the majority of the substitutes for the incumbent refrigerants. The use of hydrocarbon HC-290 can be expected to grow in this application and as in the case of the stand-alone equipment, the higher thermodynamic performance of HC-290 can lead to better overall system efficiency. However, high flammability restricts R-290 refrigerant charge, so it can only be used in very small condensing units. R-744 is also being promoted in some areas for this application and the challenge for this refrigerant is the transcritical cycle efficiency of the basic system. Mass-produced R-744 condensing units with good seasonal efficiency have recently been commercialized by some manufacturers.

In the case of condensing units, in addition to the opportunities listed earlier, some of the additional efficiency improvement methods available for all refrigerants are:

- reducing thermal load by better insulation etc.;

- designing for annual versus peak load energy performance;
- the use of mechanical subcooling or vapor injection subcooling of liquid to the evaporator;
- increased use of electronic valves and controls;
- “floating” the condenser temperature down with the ambient especially when electronics controls and valves are used.

Efficiency is often regulated by regional and national performance standards which include not just the refrigeration system but also the insulation panels, lighting and doors. In some countries, prescriptive requirements for components such as fan motors are also used to regulate efficiency of the system. Established test procedures and laboratories exist that can test and certify this equipment in Article 2 countries; developing this capability in Article 5 countries will be important for increasing the use of efficient condensing units. In addition, since the installation and commissioning of these systems is done in the field, trained installers and technicians is important for optimum performance to design. Too often, failure to install and commission correctly leads to higher energy consumption. When flammable refrigerants are used, safe handling by trained personnel is another important factor.

Centralized and Distributed systems are the preferred options in larger supermarkets. They operate with racks of compressors installed in a machinery room (as in the case of a centralized system) or on the rooftop while cooling coils are in the display cabinets or cold rooms. Distributed systems may be thought of as multiple smaller centralized systems which lead to lower charge levels. Two main design options are used: direct and indirect systems.

Direct systems are the most widespread. The refrigerant circulates from the machinery room to the sales area or cold rooms, where it evaporates in display-case heat exchangers, and then returns in vapour phase to the suction headers of the compressor racks.

Basic transcritical R-744 systems perform every well in colder ambient air conditions and perform poorly in high ambient regions where the system is operating predominantly in the transcritical mode. Subcritical R-744 systems are often cascaded with a lower GWP HFC, HFC/HFO blend or an HFO and can have higher efficiency than existing R-404A systems.

As far as *centralized and distributed systems* are concerned, with the exception of transcritical R-744 in high ambient conditions, system efficiencies are comparable to the HCFC-22 and R-404A systems that are being replaced. Since these systems are typically custom designed and installed, very few regulations exist for EE. However, market forces drive these systems to implement various efficiency improvement methods that are applicable for all refrigerants:

- reducing thermal load;
- designing for annual versus peak load energy performance;
- the use of mechanical subcooling of liquid to the evaporator;
- the use of vapor injection subcooling of liquid to the evaporator;
- the use of “parallel compression” especially in the case of transcritical R-744 systems;
- higher efficiency fan motors and compressors;
- variable speed drives for fans and compressors;
- compressor intercooling with vapor or liquid injection
- variable capacity compressors;
- increased use of electronic expansion valves and controls;
- larger condensers;
- “adiabatic condensers” where the dry inlet air to the condenser is “cooled” by adding moisture;
- “floating” the condenser temperature down with the ambient especially when electronics controls and valves are used.

In the case of transcritical R-744 systems, the use of ejectors as a method to improve EE is growing. But in all these instances, higher efficiency is traded off for greater equipment cost and complexity, which leads to better and increased training needs for installers and maintenance technicians.

A.3 Residential and commercial AC

State of the art

The International Energy Agency projects that the global stock for air conditioners (residential and commercial) will grow from 1.6 billion today to 5.6 billion by 2050, with more than half of the growth in residential AC ownership taking place in China and India, and significant growth in Africa and the Middle East (IEA, 2018). Under such circumstances, especially in A5 countries, the air conditioner of HFC-22 refrigerant is still mainstream, and improvement of EE along with phase-out of HCFC refrigerant is an urgent issue.

Metrics such as Energy Efficiency Ratio (EER) or Seasonal Energy Efficiency Ratio (SEER) have been mainly used for evaluating EE so far. In many countries, Minimum Energy Performance Standards (MEPS, see Section 2.2.2) have been introduced to improve the EE of air conditioners, and these markets have been transformed toward higher EE. However, significant additional technical potential still remains since the best ACs on the market are much more efficient than the average AC.

Opportunities and challenges

The technology of choice greatly depends on the equipment type, application, and load. This is largely due to the larger cost associated with energy efficient improvement measures. For example, an inverter compressor technology is less likely to be adopted in packaged or rooftop units, however it is already widely accepted in the large-scale chiller installations. Another example is the MCHX which shows high potential for EE when used as a condenser for both packaged units and air-cooled chillers. Finally, an important technology for the commercial AC sector is the high efficiency motors and blowers. Baseline AC motors are significantly less efficient than permanent magnet and electronically commutated motors that have the potential for being used along with a variable frequency drive to further increase the energy savings associated with air movement (through ducted systems) and with chilled water pumping (through chilled water pipe systems).

It is also important to understand the thermodynamic challenges and limitations as well as the possible opportunities that alternative low GWP refrigerants provide. The thermodynamic efficiency of all alternative low GWP refrigerants are lower than that of HCFC-22; except for ammonia (which is classified as B2L, toxic mildly flammable refrigerant). Propane and R-450 have thermodynamic efficiency within 2.5% of HCFC-22 by at the cost of 15% and 45% reduction in thermodynamic capacity respectively. Other alternative refrigerants show a trade-off between thermodynamic capacity and efficiency. In contrast to the thermodynamic cycle limitation, system manufacturers were able to match or exceed the performance of HCFC-22 with alternative refrigerants.

For example, in non-A5 countries, while the manufacturers transitioned from HCFC-22 to R-410A (lower thermodynamic efficiency) they were able to continually improve the efficiency and maintain the adjusted cost over time while the MEPS continued to drive the market towards higher efficiency units [Goetzler et al., 2016; Abdelaziz et al., 2015; and Abdelaziz et al., 2016] showed that there are several viable alternative lower-GWP refrigerants for HCFC-22 and R-410A in mini-split and packaged rooftop air conditioning respectively. Furthermore, the AHRI AREP phases I and II summary reports provided by [Wang and Amrane, 2014; and Wang and Amrane, 2016] show other refrigerants that meet or exceed the performance of the baseline refrigerants.

There is much potential for EE improvement of the average AC on the global market given that the average efficiency for room ACs is roughly 3 W/W while the best room ACs on the global market have SEERs of over 10 W/W. However, further improvement beyond the current best available technology gets more challenging as thermodynamic limits are approached.

As mentioned in Section 2.2.2 the EE rating is the basis for establishing MEPS. Different metrics are used in different countries for EE rating (as shown in table A.1) and harmonising MEPS among

nations with similar usage and energy cost conditions across the same product categories can help with verification and compliance.

Table A.1: Overview of unitary air conditioning energy-efficiency standards and metrics used around the globe⁶

Country/Economy	National Testing Standard	Reference Test Standard	Metric Used
Australia	AS/NZS: 3823-2013	ISO 5151	AEER
China	Fixed Speed: GB/T 7725-2004	ISO 5151	EER
	Variable Speed: GB/T 7725-2004, GB/T 17758-2010,	ISO 5151	SEER
EU	EN 14825	ISO 5151	EU SEER
India	Fixed Speed: IS 1391-1992 with all amendments	ISO 5151	EER
	Variable Speed: 16358-1:2013	ISO 5151	ISEER
Japan	JIS B 8616:2015 for commercial ACs JIS C 9612: 2013 for Room ACs	ISO 5151, ISO 16358	APF
Republic of Korea	KS C 9306: 2011	ISO 5151, ISO 16358	CSPF
USA	10 CFR 430, Subpart B, Appendix F	ASHRAE Standard 16/69	US SEER
Vietnam	TCVN 7830: 2015	ISO 5151, ISO 16358	CSPF

These performance standards are mostly adopted from international standards (ISO 5151 [ISO, 2017] and ISO 16358 [ISO, 2013] with a few countries following ANSI/ASHRAE 90.1 [ASHRAE, 2016]. Most standards are reviewed periodically. ASHRAE 90.1, for example, is reviewed every three years. For the latest version launched in 2016, a study by the US Department of Energy [DOE, 2016] found that by using the 2016 edition, the aggregated percentage energy savings for buildings at a national level over the 2013 edition can reach up to 25% for certain types of applications.

A.4 Mobile air conditioning and transport refrigeration

Mobile Air Conditioning (MAC)

State of the art

MAC is the system that ensures on road transport vehicles ventilation, heating and cooling to guarantee proper visibility and thermal comfort. Energy for MAC operation is provided by the on-board powertrain system being responsible of an additional fuel consumption in case of thermal engine, e.g. +10%, or electric range reduction up to -40% for battery electric vehicles.

⁶ [U4E, 2017]

Opportunities and challenges

For more than 20 years the global car industry has used HFC-134a (with a GWP of 1430) for all new MACs in cars and other small road vehicles. During the last 5 years a switch to HFO-1234yf (GWP 4) has begun in some geographic regions. The European Union MAC Directive has banned refrigerants with a GWP above 150 – this has applied to MACs in all new cars since January 2017. There is also significant uptake of low-GWP MAC refrigerants in the US where incentives are in force.

R-744 is being considered by a small proportion of car manufacturers in Europe, where some concerns exist about the environmental impact of HFOs in the long term. While R-744 may have some drawbacks in terms of EE with respect to HFOs when used in a MAC system for sole cooling, it becomes much more interesting if it is used as a heat pump both for cooling and heating: this is the case of pure electrical vehicles where there is no heat rejected by the engine to provide for the winter heating of car interior.

There are several options to improve MAC efficiency focusing on the vapor compression and on the whole system:

- Thermal load reduction through reflective glazing and paints – this is granted of CO₂ credit in US and other areas
- Higher efficiency fan motors and compressors
- Improved heat exchangers including liquid cooling
- Controlled compressor: variable displacement for part load performance improvement of fans and compressors;
- Internal Heat Exchangers to recuperate part of the residual cooling power

Transport refrigeration

Transport refrigeration includes refrigeration systems in trucks, trailers and reefer containers, refrigeration and air conditioning systems aboard ships, and air conditioning systems in railway cars. Transport applications have specific challenges such as resistance to shocks and vibrations, corrosion, flammability or availability concerns which make the design choices different from the other segments. Efficiency issues are very much significant for these transport applications as they are subject to very different ambient air conditions and often, space being limited, are challenged in terms of adequate air flow, size of heat exchangers, parasitic heat gain from other heat generating components and equipment etc. The main difference from commercial refrigeration is the variation in ambient temperature in which the transport system is operated, in some cases ranging from arctic to tropic conditions.

In general, lower GWP options for this sector include HFOs, HFO and HFC blends, lower GWP HFCs, hydrocarbons, and CO₂ (R-744). The type of equipment, their location, the ambient conditions for heat rejection, availability of trained personnel and network for maintenance, requirements for safety and the refrigerant choice affect the efficiency, first cost and operating costs of the equipment. These and their effect on the uptake of lower GWP technology in this sector are discussed below.

Truck and Trailer Refrigeration

State of the art

These are self-contained refrigeration systems, often with their own power generation equipment like an engine or an engine-alternator combination. These self-contained refrigeration systems have to control the insulated truck or trailer “box” to temperatures ranging from near +10°C to -25°C and operate in ambient air conditions that are varied from cold to very hot. Ambient air design temperatures can vary from +65°C (in cargo holds) to -20°C and therefore become a very important

factor. R-404A refrigerant dominates this application, with some HCFC-22, HFC-134a and R-410A as well.

Opportunities and challenges

In Europe, and lately in other markets, R-452A is an A1 (non-flammable) refrigerant that is becoming state of the art as a lower GWP alternate for these systems, especially as a retrofit candidate. New lower GWP HFCs, HFOs and their blends, such as R-448A and R-449A are also becoming commercially available and may find increased use in the near future because they are drop-in fluids with comparable efficiency with R-404A and only few adjustments are needed to operate.

Hydrocarbons such as HC-290 are thermodynamically more efficient than R-404A but their use is a challenge in this application due to their flammability. To meet this challenge, systems are being designed to be shock and vibration resistant and tightness in operation is part of the specification by customers. The flammability concerns remain in service and maintenance.

Since the equipment operate in highly varied outdoor ambient conditions year-round, equipment with basic cycle R-744 will operate in the transcritical mode. Nevertheless, R-744 systems may have lower TEWI or LCCP than other options, as recently reported in the literature [Finckh et al., 2016].

Container Refrigeration

State of the art

Container refrigeration is similar to trailer refrigeration, except all containers are electric and require power from an external source to operate. While R-404A systems continue to be in production, HFC-134a dominates this application and R-513A seems to be the only feasible alternative for the time being.

Opportunities and challenges

In order to improve performance, several options are available, and these can be applied to all of the lower GWP replacement refrigerants. Some of these are:

- Thermal load reduction through better insulation and minimizing parasitic heat gain;
- Higher efficiency fan motors, compressors;
- Control optimization, also through the use of variable speed for part load performance improvement of fans and compressors;
- The use of vapor injection sub-cooling of liquid to the evaporator;
- “floating” the condenser temperature down with the ambient especially when used with electronic controls and valves;
- Larger and/or more efficient heat exchangers (flow arrangements, fluid path, fin designs, etc.) for evaporators and more importantly for condensers.

These efficiency improvement methods are also available for the all transport applications such as truck, trailer, container and ship refrigeration as well as rail air conditioning.

In the case of transcritical R-744 systems, the use of ejectors as a method to improve EE is growing. But in all these instances, higher efficiency is traded off for greater equipment cost and complexity, which leads to better and increased training needs for installers and maintenance technicians.

A.5 HAT considerations

In addition to the overall refrigerant and system challenges there are more specific challenges for the different subsectors as shown below:

Commercial refrigeration technologies vary from self-contained single vending machine to central refrigeration system. In developing countries, small self-contained units are more common. However, rising standard of living and globalization led to larger supermarket facilities with large central refrigeration systems. Such systems have significant refrigerant charge (in the order of 1000 kg of refrigerant per supermarket). As such, energy efficient solutions will have to be tailored to the specific end-use with additional restriction on the refrigerant of choice. For example, propane or isobutane can be used to design higher efficiency self-contained units while a non-flammable higher efficiency refrigerant such as R-448A and R-449A would be required for central refrigeration plants. Finally, while transcritical CO₂ is gaining popularity in more temperate climates as a refrigerant of choice due to the potential energy savings, its use in warm and hot climate is still under investigation. One of the major challenges with operating a CO₂ refrigeration system in HAT condition is the supercritical operation. In order to ensure high efficiency, appropriate expansion work recovery technology should be used such as ejector or expander technology. A new demonstration facility just opened in Amman, Jordan to test the validity of CO₂ in HAT climates [Jordan Times, 2018].

For the **residential and commercial AC**, the main technical challenge of EE in HAT climates is the charge limitations to achieve higher EE levels, disseminating the knowledge regarding the safe use of alternative low-GWP, flammable refrigerants along with demonstrating the feasibility of most relevant EE upgrades such as variable capacity compressors, MCHX, and electronic expansion valves.

The **MAC** subsector imposes additional challenges due to the expected higher condensing temperatures, additional integration concern with respect to cabin comfort and power-train, and safety concerns. On the other hand, transport refrigeration has the additional challenge of using a belt-driven compressor run by the on-board dedicated diesel engine [Brecht et al., 2016]. These compressors require significant development cycle and are largely optimised for the larger market sector – not the smaller HAT conditions.

ANNEX B

Examples of projects

B.1 GEF Project/Programme Title: De-risking and scaling-up investment in energy efficient building retrofits in Armenia

Accredited entity: UNDP

Executing entity: Ministry of Nature Protection

Beneficiary: Direct beneficiaries include -30,000 people living in single-family individual buildings and 52,200 in multi-family apartment buildings, including at least 6,000 members of women-headed households; and - 23,000 users of large public buildings and 105,000 users of small public buildings, including at least 90,000 women

Project size category (Total investment, million USD): 29.820 USD Small ($10 < x \leq 50$) - The expected volume of finance to be leveraged by the proposed project as a result of the Fund's financing is US\$ 102.82 million. Of this, US\$ 86 million will be from the EIB loan and private sector (from residents, once loans are repaid), and US\$ 20 million will be public investment (from national and city governments, once loans are repaid) in EE retrofits, representing a total leveraging ratio of 1:5.

Estimated implementation timing: 01/09/2016 - 31/08/2022

Improving EE in buildings has been assigned the highest priority in Armenia's housing, energy and climate strategies, including the country's Intended Nationally Determined Contribution (INDC), its Third National Communication to the UNFCCC and its UNFCCC Technology Needs Assessment. The project aims at creating a favourable market environment and scalable business model for investment in EE building retrofits in Armenia, leading to sizeable energy savings and GHG emission reductions (up to 5.8 million tCO₂ of direct and indirect emission savings over the 20-year equipment lifetimes), green job creation and energy poverty reduction. It will directly benefit over 200,000 people and catalyse private and public-sector investment of approximately US\$ 100 million. The following components involve the RACHP sectors as a consequences of project implementation:

Component 1 – Policy de-risking: The policy de-risking component will support national, sub-national and local authorities to adopt and implement an enabling policy framework for EE retrofits. This Component will support on-going legal reform in the field of EE. It will also support the gradual introduction of binding legislation on energy auditing, energy passports / certificates and labelling for existing buildings.

Component 2 – Financial de-risking: A financial de-risking component will work in partnership with EIB, the Renewable Resources and Energy Efficiency Fund of Armenia (the R2E2 Fund), local commercial (private sector) banks and other relevant national and international financial institutions to provide access to affordable capital for EE retrofits. These financial de-risking instruments will take several forms, including credit lines from financial institutions and/or loan guarantees to stimulate local private sector commercial banks to lend to private ESCOs and/or building owners.

B.2 GEF Project/Programme Title: Promoting of appliance energy efficiency and transformation of the refrigerating appliances market in Ghana

The project aims to promote the EE of appliances manufactured, marked and used in Ghana, through the introduction of a combination of regulatory tool such as minimum energy performance standards and information labels, and innovative economic tools. Domestic refrigeration appliances will be the first end-use to be tackled, with a specific focus to address ozone depleting substances contained in the current stock of equipment. The focus area is: climate change (mitigation)

Project size and timeline:

- received by GEF 03/Feb 2009;
- preparation grant approved 24/Apr 2009;
- concept approved 01/Jun/2009;
- project approved for implementation 06/May 2011;
- project Closed (ended) 31 Dec 2014.

The following components have been implemented:

1. Strengthening of regulatory and institutional framework;
2. Design of certification, labelling and enforcement mechanisms;
3. Training and public outreach activities;
4. Establishment of refrigerator test facilities;
5. Development of CFC and used appliance collection and disposal facilities;
6. Development of efficiency programme evaluation and monitoring capacity;
7. Pilot test for an accelerated market transformation through innovative economic incentives;
8. Financial design of follow -up national market transformation programs.

The project has been co-financed by different stakeholders: Government Contribution (Ministry of Energy, Ministry of Environment with 2,200,000 US\$ in Grant and 800,000 US\$ in Kind), the Multilateral Fund for the Implementation of the Montreal Protocol (with 700,000 US\$ grant) and the GEF Agency UNDP-Ghana (with 200,000 US\$) with a total value co-finance project of US\$ 3,900,000.

B.3 GEF Project/programme Title: Leapfrogging Chilean's markets to more efficient refrigerator and freezers

The project aims to accelerate transformation of Chile's markets to more energy efficient residential refrigerators/freezers thereby achieving reduction of GHG emissions and contributing to improved energy access and energy security. The focus area is climate change (mitigation). The project target is 750 million tons of CO₂eq mitigated (include both direct and indirect).

Accredited entity: UN Environment

Executing entity: Fundación Chile, Ministry of Energy

Estimated implementation timing: 36 months from 15/11/2017

The following components involve the RACHP sectors as a consequences of project implementation:

Component 1 – Revising regulatory mechanisms, including minimum energy performance standards (MEPS): Accelerate transformation of the market for energy efficient residential refrigerators/freezers via implementation of advanced MEPS and EE labels in line with international best practices and provision of associated capacity building.

Component 2 – Enhancing monitoring, verification, and enforcement (MVE): Actors comply with improved MVE label

ling regulations, testing protocols and measurements methodologies to ensure residential refrigerators/freezers meet improved efficiency levels.

Component 3 - Developing supporting policies: Enhanced awareness among consumers (by gender) and market players in Chile to understand, afford, and purchase EE refrigerators/freezers.

Component 4 - Enhancing environmentally sound management: Voluntary implementation of the national framework for environmentally sound management of refrigerators/freezers started.

The project has been co-financed by different stakeholders: government contribution (Ministry of Energy, Ministry of Environment, Superintendence of Electricity and Fuels with US\$ 2,807,000 In-Kind), NGO contribution (Fundación Chile with US\$ 250,000 In-Kind), private sector contributions (US\$ 3,539,551 In-Kind), and the GEF Agency-UNE (US\$ 1,473,762 in Grants and US\$ 50,000 in In-Kind) with a total value co-finance project of US\$ 7,411,551.