MONTREAL PROTOCOL ON SUBSTANCES THAT DEPLETE THE OZONE LAYER

REPORT OF THE TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL

MAY 2022

VOLUME 3: DECISION XXXIII/5 - CONTINUED PROVISION OF INFORMATION ON ENERGY-EFFICIENT AND LOW-GLOBAL-WARMING-POTENTIAL TECHNOLOGIES

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Montreal Protocol on Substances that Deplete the Ozone Layer

United Nations Environment Programme (UNEP)

Report of the Technology and Economic Assessment Panel

May 2022

Volume 3: Decision XXXIII/5 - Continued provision of information on energy-efficient and low-global-warming-potential technologies

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Foreword

The 2022 TEAP report consists of 3 volumes:

Volume 1: Technology and Economic Assessment Panel 2022 progress report

Volume 2: Evaluation of 2022 critical-use nominations for methyl bromide – interim report

Volume 3: Decision XXXIII/5 task force report on energy-efficient and low-global-warming-potential technologies

This is Volume 3

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Executive Summary

Under **Decision XXXIII/5 on "Continued provision of information on energy efficient and low-global-warming-potential technologies",** parties requested the Technology and Economic Assessment Panel to prepare a report on energy efficient and lower- global- warming- potential technologies and on measures to enhance and maintain energy efficiency during hydrofluorocarbon transition in equipment for consideration by the Open-ended- Working Group at its forty-fourth meeting. Parties requested TEAP in the report to:

(a) Update information in the decision XXXI/7 report where relevant, and address additional subsectors not previously covered such as the heat-pump, large commercial refrigeration and larger air-conditioning system sub-sectors;
(b) Assess potential cost savings associated with adoption of lower global warming potential energy efficient technologies in each sector, including for manufacturers and consumers;
(c) Identify sectors where actions could be taken in the short term to adopt energy efficient technologies while phasing down hydrofluorocarbons;
(d) Identify options to enhance and maintain energy efficiency in equipment through deploying best practices during installation, servicing, maintenance, refurbishment or repair;
(e) Provide detailed information on how the benefits of integrating energy efficiency enhancements with the hydrofluorocarbon phase-down measures can be assessed.

<u>Key Messages from each Chapter</u>

Chapter 1: Introduction: Context of the Report

- The urgency of the need to mitigate global warming has been emphasised in 2021 and 2022 by both The Intergovernmental Panel on Climate Change (IPCC) and the COP-26 meeting. IPCC Working Group II highlighted vulnerability and limits to adaptation, while Working Groups I III showed the need to make strong and sustained emissions reductions immediately to limit global warming.
- The phaseout of ozone depleting substances through the Montreal Protocol has already avoided 1.1 degrees of warming over the Arctic by 2021, and projected to be 3-4 degrees by 2050, equivalent to ~25% of the mitigation of global warming
- Future HFC Phasedown through implementation of the Kigali Amendment can further mitigate global warming by 0.3 to 0.5 degrees. Synchronous improvements in energy efficiency of Refrigeration Air Conditioning and Heat Pump (RACHP) equipment could double this climate benefit.
- The major HFC use worldwide is in the RACHP sector. Most of this HFC use is for comfort cooling and heating and the remainder is for refrigeration, although the proportion varies by country and region. A large proportion of RACHP GHG emissions are related to the energy used. The ratio of "indirect" energy-related emissions to "direct" refrigerant emissions varies between countries depending on factors such as the carbon intensity of power generation, the leakage rate from different RACHP applications, and the GWP of the refrigerants used.
- Continued use of high GWP HFCs will result in an accumulation of a large stock of high GWP HFCs in RACHP equipment in A5 parties. This increasing stock of equipment containing high GWP HFCs has the potential to delay by 20-30 years (the lifetime of RACHP equipment in developing countries) the climate benefits through reduced direct emissions. In addition, if the high GWP HFCs were contained within inefficient RACHP equipment, this would create excess energy demand (indirect emissions) over the same period.
- In all sectors it is now possible to significantly enhance energy efficiency. The overall energy benefits from HFC phasedown depend on the RACHP application, sector and the HFC alternatives used. Incentives would encourage and support transition in the RACHP sector and enhanced energy efficiency benefits would be realised. There is excellent potential to synchronise the reduction in energy-related emissions with the phasing down the use and emissions of HFCs, for example by integrating with energy efficiency standards and labelling policy.

Chapter 2 "Availability of Low and Medium GWP Technologies and Equipment that Maintain or Enhance Energy Efficiency"

- RACHP equipment using low and medium GWP refrigerants with enhanced energy efficiency, is now available in all the sectors defined in this report, but not necessarily accessible in all countries. Technology developments are proceeding at pace. Early action through the Kigali Implementation Plans can enable their transition to this new generation of RACHP equipment.
- Country-specific incremental improvements in energy efficiency are being driven by MEPS, developed with the consideration of seasonal, full, and part load performances. Such MEPS are either being adopted or progressively enhanced. Technologies including variable speed drives (for compressors and fans), brushless DC motors, and electronic expansion valves are used to achieve seasonal performance requirements.
- Heat pumps are available with low and medium GWP refrigerants with energy efficiency measures implemented for the refrigeration cycle, the selection of ancillary components, and the integration of heat pumps with the building controls.
- Large commercial refrigeration equipment operates throughout the year which compels the need for higher efficiency to reduce energy costs. This is measured by the annual power consumption, which can be reduced by considering component selection and evaporative condensers.
- In larger AC systems, safety considerations limit the application of flammable refrigerants. However, large AC systems of all capacity ranges are available with low and medium GWP refrigerants with comparable efficiencies to the baseline high GWP refrigerants which can be further optimised for higher efficiency. Compressors designed to work with a range of refrigerants including baseline refrigerants as well as low and medium GWP refrigerants are now available.
- Not-In-Kind (NIK) technologies that do not utilise mechanical vapour compression can offer lower operational lifetime costs (OLC) than in-kind systems, in some circumstances. Some examples of NIK technologies include solar energy driven absorption systems, hybrid evaporative cooling and deep-sea cooling are some examples of these NIK technologies.

Chapter 3 "Cost of Equipment Using Low and Medium GWP Refrigerants whilst Maintaining or Enhancing Energy Efficiency"

- There is a wide range of RACHP equipment and a diversity of refrigerant options (low and medium GWP), which makes it necessary to evaluate material cost impact on a case-by-case basis.
- Refrigerant characteristics play an important role in the design of RACHP equipment in specific relation to maintaining or enhancing energy efficiency. The two main factors which influence the material cost of equipment are refrigerant thermodynamic characteristics (pressure, density, cycle COP etc.) and refrigerant safety characteristics (e.g., flammability/toxicity/pressure). Other factors may also play a role such as material compatibility.
- Flammability and/or toxicity characteristics may limit the acceptable amount of refrigerant for safety reasons and thus limit the cooling or heating capacity and/or energy efficiency that can be achieved. Reducing the refrigerant charge may be possible using different technologies such as microchannel heat exchangers but these can also bring technical and application challenges.

Chapter 4 "Cost Benefit Analysis of Low GWP Technologies and Equipment that maintain or enhance energy efficiency"

- The Parties to the Montreal Protocol have agreed to maintain or enhance energy efficiency while phasing down HFCs under the Kigali Amendment to the Montreal Protocol. However, in practice, it is difficult to decide what level of energy efficiency is optimal in any specific case, both at a project level and at an economy wide level, for example when setting minimum energy performance standards for equipment.

- Parties may choose to conduct economy-wide or project-specific cost-benefit analyses to maximize benefits to consumers and society from energy efficiency improvement as has been done historically in many economies.
- The US Department of Energy and EU Ecodesign typically conduct in-depth cost-benefit analyses to optimise the level of energy efficiency of equipment.
- Such studies vary in their depth, analytical rigor, and cost from multi-year studies with detailed engineering analysis to short market studies. However, such studies are crucial for understanding the value of energy efficiency particularly in the context of considering investments that may have varying benefits to consumers and manufacturers as well as varying environmental benefits.
- Regardless of the level of energy efficiency invested in, it is very likely that co-ordinated investment in energy efficiency and refrigerant transition will cost manufacturers and consumers less than if such investments are made separately.
- In order to conduct an in-depth cost-benefit analysis of concurrent refrigerant transition and energy efficiency improvement, detailed data is necessary including incremental capital and operational costs.
- General lessons from previous case studies suggest that:
    - Energy Efficiency is more valuable under cases with high hours of use and high electricity prices
    - Lifecycle CO_{2eq} savings are higher in cases with high hours of use and high grid CO_{2eq} intensity
    - Lifecycle cost savings can far outweigh higher first cost of more efficient equipment
    - In the case of large investments an in-depth analysis is essential.
    - Manufacturers may find higher cash flow and revenue through efficiency improvement

Chapter 5 "Short Term Roadmap for Adoption of Energy-Efficient Technologies While Phasing Down HFCs

- Roadmaps for adopting energy-efficient technologies while phasing down HFCs will vary based on national circumstances. These approaches can benefit from a common set of policies that would support these technology transitions. These include sector-specific and cross-cutting policies like integrated energy and refrigerant performance standards and labelling, best practice performance metrics and test procedures, enabling building energy and safety standards, support for ongoing service sector training, and monitoring, compliance, and enforcement. Several country specific case studies are provided in Annex 9.5
- The technology transition would be supported by coordination between National Ozone Units and national energy and climate authorities especially through the integration of lower GWP HFC standards into energy efficiency standards and labelling policies
- Raising awareness across government institutions and community-based consumer programmes can speed adoption of energy-efficient and low-GWP equipment, and increase access to additional financing mechanisms, such as through electricity utility efficiency programs and bulk procurement programs.
- Where A5 parties do not have the capacity to prescribe and enforce laws to prohibit shipping of obsolete products, the local and global harms inflicted as a result of increased environmental dumping in these most-vulnerable jurisdictions necessitate that non-A5 exporting parties share responsibility with A5 recipient countries to prevent the environmental dumping of obsolete products.

Chapter 6 "Options to Maintain and Enhance Energy Efficiency through Best Practices in installation, servicing, maintenance, refurbishment and repair".

- Design upgrades to meet energy efficiency levels require a higher level of knowledge and training for safe and effective installation and servicing. These new topics include units with variable speed drives, controls with self-diagnostics, and remote-control features which all require improved skills including knowledge of electronics.

- Energy efficiency degradation is affected by the severity of use and operating conditions, as well as corrosive environments. Improper installation and maintenance accentuate the loss of EE, and high quality and frequent planned maintenance minimise the loss of EE.
- Refrigerant leakage impacts EE. Reducing leakage continues to be a service priority for optimised systems using low-GWP refrigerants with reduced refrigerant charge.
- End-user environmental awareness is driving them to demand lower $CO_{2\text{-eq}}$ emissions from the operation of their systems. Preventive and eventually predictive maintenance are becoming a priority for both operators and service providers.
- Rigorous service requirements drive higher training, certification, and specialisation with improved rewards. This will tend to lower technician turnover and consolidate/spread good practices.

Chapter 7 "How to Assess the Benefits of Integrating Energy Efficiency Enhancements with the HFC phase-down"

Modelling tools can support the analysis of the potential to reduce energy related indirect GHG emissions from RACHP at the same time as phasing down use of HFCs and reducing direct HFC emissions.

Some important insights from modelling are discussed – these include:

- The relative importance of direct and indirect GHG emissions can vary considerably in different countries. This has an impact on the choice of policy to support an integrated approach. For countries with high electricity generation carbon factors, reducing energy use is the key priority. For countries with low carbon factors, a greater focus on reducing HFC emissions is beneficial.
- The relative importance of direct and indirect GHG emissions can also vary considerably across the wide range of different RACHP technologies and applications.
- There are many different pathways available to achieve the Kigali Amendment targets. Combining early action for HFC mitigation actions with simultaneous energy efficiency actions can lead to significant reductions in cumulative GHG emissions between now and 2050 and at the lowest cost. Grid decarbonisation also makes a vital contribution to reduced emissions.
- Using heat pumps in place of fossil-fuels for space, water and process heating will be essential for heating decarbonisation. The avoided fossil fuel emissions from the use of heat pumps will massively outweigh any direct and indirect emissions from the heat pumps.
- Ensuring that new RACHP equipment is as efficient as possible, and that existing equipment is operated and maintained for high efficiency makes a very cost-effective contribution to the path to net zero GHG emissions.
- There is a significant lack of reliable data on refrigerant banks and equipment stocks by sector which is needed optimise the outputs of modelling. Better data would improve modelling at national and regional levels.

Decision XXXIII/5: Continued provision of information on energy efficient and low-global-warming-potential technologies

Recalling decisions XXVIII/2, XXVIII/3, XXIX/10, XXX/5 and XXXI/7 relating to energy efficiency and the phase-down of hydrofluorocarbons,

Taking note of the reports of the Technology and Economic Assessment Panel in response to decisions XXVIII/3, XXIX/10, XXX/5 and XXXI/7, inter alia, covering issues related to energy efficiency while phasing down hydrofluorocarbons and the cost and availability of low global- warming- potential- technologies and equipment that maintain or enhance energy efficiency,

To request the Technology and Economic Assessment Panel to prepare a report on energy efficient and lower- global- warming- potential technologies and on measures to enhance and maintain energy efficiency during hydrofluorocarbon transition in equipment for consideration by the Open-ended- Working Group at its forty-fourth meeting, and in the report to:

(a) Update information in the decision XXXI/7 report where relevant, and address additional subsectors not previously covered such as the heat-pump, large commercial refrigeration and larger air-conditioning system sub-sectors;

(b) Assess potential cost savings associated with adoption of lower global warming potential energy efficient technologies in each sector, including for manufacturers and consumers;

(c) Identify sectors where actions could be taken in the short term to adopt energy efficient technologies while phasing down hydrofluorocarbons;

(d) Identify options to enhance and maintain energy efficiency in equipment through deploying best practices during installation, servicing, maintenance, refurbishment or repair;

(e) Provide detailed information on how the benefits of integrating energy efficiency enhancements with the hydrofluorocarbon phase-down measures can be assessed.

Approach and Scope of Decision XXXIII/5 Report

In order to prepare its report, TEAP established a new 2022 Energy Efficiency Task Force (EETF). Previous Task Forces had mainly restricted their scope to the domestic air conditioning (AC) and self-contained commercial refrigeration (SCCRE) sectors. When establishing the new expertise required to respond to Decision XXXIII/5, TEAP took into account the request to cover additional sectors (heat-pump, large commercial refrigeration, larger air-conditioning systems), installation and servicing, and the assessment of the integration of energy enhancements with HFC phasedown. The EETF Report was assembled in chapters, updating previous information, and addressing the additional subsectors not previously covered. The composition of the Decision XXXIII/5 Energy Efficiency Task Force (EETF) is in the following table. The 2022 Task Force has 24 members (5 female, 19 male) and two consulting experts. There are 13 members from A5 Parties and 11 members from non-A5 parties.

Membership

Omar Abdelaziz, co-chair	EGY	Herlin Herlianika	ID
Suely Carvalho, co-chair	BRA	Steven Kujak	USA
Ashley Woodcock, co-chair	UK	Saurabh Kumar	IN
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Paulo Altoé	BRA	Richard Lord	USA
Jitendra Bhambure	IN	Petter Neksa	NO
Daniel Colbourne	UK	Tetsuji Okada	JP
Hilde Dhont, chapter 3 lead author	BE	Mohamed Alaa Olama	EGY
Gabrielle Dreyfus, chapter 5 lead author	USA	Roberto Peixoto	BRA
Bassam Elassaad, chapter 2 and 6 lead author	LB	Nihar Shah, chapter 4 lead author	IN
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Disclosure of Interest

TEAP Task Force members were requested to provide their disclosure of interest forms relating specifically to their level of national, regional or enterprise involvement for the 2022 EETF process. The Disclosure of Interest declarations for the participation in the EETF in 2022 can be found on the Ozone Secretariat website at https://ozone.unep.org/science/teap/task-force-decision-xxxi7-energy-efficiency.

Main Findings of Previous Task Force Reports

Following the adoption of the Kigali Amendment, parties adopted a series of Decisions on Energy Efficiency (EE) at Meetings of the Parties:

- 2016 - Decision XXVIII/3;
- 2017 - Decision XXIX/10;
- 2018 - Decision XXX/5;
- 2019 – Decision XXX1/7

In response, TEAP has provided reports for the Open-Ended Working Group Meetings in each subsequent year. The first scoping report was provided by an internal TEAP Working Group which reported in 2017. This was followed by three Energy Efficiency Task Forces which reported in 2018 and 2019 and 2020/21. This fourth EETF 2022 report in response to Decision XXXIII/5 is intended as an update on previous reports with new information in additional RACHP market sectors. For a complete picture (and especially for domestic AC and SCCRE) please refer back to previous reports. Below are some consistent key messages that run through previous reports.

2018/2019 Reports

1. Evidence for Climate Change and its impact on the planet is increasing.
2. In Decision XXVIII/3, the Parties to the Montreal Protocol agreed to minimise the climate impact by harnessing the synergies with Energy Efficiency (EE) during the HFC phase-down

in a timely manner. This could double the climate benefit from timely implementation of the Kigali Amendment[1].

3. Access to cooling is essential to meet many UN Sustainable Development Goals. As temperature rises and as wealth in developing countries is growing, the demand for RACHP equipment is increasing rapidly - in 2018, it consumed 20% of the world's electricity production (IIR, 2019). This is creating a feedback loop between demand for cooling, direct emissions and electricity-related CO_2 emissions, and global warming.
4. Many energy-efficient technical innovations in RACHP using lower GWP refrigerants are widely available and increasingly accessible.
5. Lower GWP refrigerants to replace HCFCs and high-GWP HFCs are widely available in higher EE equipment and are becoming increasingly accessible.
6. In some regions and sectors, it is possible and beneficial for the Party to leapfrog from HCFCs directly to lower GWP refrigerants and higher EE.
7. MEPS are being introduced in some developing countries without including the transition to lower GWP refrigerants, which is leading to a continued use of high GWP refrigerants.
8. Some A5 parties with no or low MEPS, especially those without manufacturing capacity, only have access to low EE/ high GWP imported RACHP equipment. The excess power demand will place them at a substantial long-term economic disadvantage.
9. Combined finance from multilateral organisations could drive best practice in delivering EE gains during HFC phase-down in A5 parties.

2021 Report

1. Improved availability and accessibility to high EE/lower GWP products in A5 parties could be achieved sooner by:
    a. faster ratification of the Kigali Amendment,
    b. progress in operationalising the Kigali Amendment,
    c. enabling individual Parties for fast action,
    d. supporting policies designed to improve accessibility, e.g., tackling market barriers affecting the end consumer,
    e. adopting ambitious and progressive energy performance standards across regions that are integrated with HFC phase-down strategies (e.g., U4E model regulations),
    f. coordinating multi-agency funding for A5 enterprise conversions for both high EE and lower GWP refrigerants.
2. A5 parties creating a large installed base of low EE equipment, will be economically disadvantaged, as valuable electricity capacity is lost from other uses and because of the need to build more generating capacity. The economic disadvantage could last for decades due to the long product lifetimes of cooling equipment. Support for the development and enforcement of policies and regulations to avoid the market penetration of low efficiency RACHP equipment could stop environmentally harmful dumping and limit these economic impacts.

[1] Decision XXVIII/3 recognizes the opportunities and appreciates co-benefits: "*Recognizing* that a phase-down of hydrofluorocarbons under the Montreal Protocol would present additional opportunities to catalyse and secure improvements in the energy efficiency of appliances and equipment, *Noting* that the air-conditioning and refrigeration sectors represent a substantial and increasing percentage of global electricity demand, *Appreciating* the fact that improvements in energy efficiency could deliver a variety of co-benefits for sustainable development, including for energy security, public health and climate mitigation, *Highlighting* the large returns on investment that have resulted from modest expenditures on energy efficiency, and the substantial savings available for both consumers and Governments".

3. Individual parties could consider adopting a fast mover status, with ambitious synergistic regulation for the HCFC phase out and HFC phase-down with progressive EE improvement.
4. One facet of governmental cooperation that has proven absolutely essential is the coordination between senior energy efficiency officials and ozone officers. This expedites the further transition to lower GWP and higher EE equipment by the coordinated adoption of refrigerant policies with broad energy efficiency policies including the revision of minimum energy performance standards (MEPS) and labels. In contrast, the implementation of ambitious MEPS alone can undermine the HFC phase-down by encouraging improved EE of cooling equipment, but with the use of high GWP refrigerants, especially in countries that are primarily equipment receivers.
5. Integrated modelling of the direct (refrigerant-related) GHG emissions and indirect (energy-related) GHG emissions from refrigeration, air-conditioning, and heat pump (RACHP) markets provides valuable insights into the importance of linking improvements in energy efficiency with the HFC phase-down. A number of modelling tools are available and in development. Early outputs from the “HFC + Energy Outlook Model” suggest:
    a. indirect energy related GHG emissions represent around 70% of total GHG emissions from the RACHP sector,
    b. there are substantial benefits from earlier action to prevent the increase in high GWP HFC use in reducing the total cumulative emissions,
    c. combining faster phase-down of high GWP HFCs and improving efficiency provides substantial additional benefits in reducing the total cumulative emissions,
    d. there is a large potential to reduce both direct (>90%) and indirect emissions (>98%) by 2050, compared to a business-as-usual scenario,
    e. how to identify the measures that yield the greatest benefits through addressing both the refrigerant-related and the energy-related GHG emissions,
    f. transitioning to the use of heat pumps is important in terms of the abatement of fossil fuel emissions from heating.
6. An overarching conclusion of the (2021) EETF is that during the last five years, industry has responded, and technology has developed rapidly. There is now availability of high EE/lower-GWP equipment for most market sectors. These technologies are increasingly accessible worldwide. Market examples suggest that it is possible in the right regulatory and financial environment to consider an accelerated timeline for the HFC phasedown and the integration of energy efficiency, at least for domestic AC and commercial refrigeration.

1 Introduction: Context of the Report

1.1 Context related to climate change

Human induced Climate Change is a threat to our wellbeing and all other species. Since the last EETF report, the urgency of action to mitigate climate change has become the most important environmental issue worldwide. This has been emphasised in many publications, meetings, and initiatives over the last 12 months.

The IPCC Working Group 2 Summary for Policy Makers states: "Human Induced Climate Change including more frequent and intense extreme events, has caused widespread adverse impacts and related losses and damages to nature and people, beyond natural climate variability. Some development and adaptation of efforts have reduced vulnerability. Across sectors and regions, the most vulnerable people and systems are observed to be disproportionately affected. The rise in weather and climate extremes has led to some irreversible impacts as natural and human systems are pushed beyond their ability to adapt."

COP-26 was held in Glasgow UK in October 2022. This meeting emphasised the need for integrated action on a global scale to combat the climate emergency.

The Super-Efficient Appliance Deployment Initiative (SEAD) was launched at COP-26. Multiple partner governments joined together to recognise the critical importance of energy efficiency by supporting the SEAD initiative, which aims to double the efficiency four key products (two of which are refrigeration and air conditioning) which account for 40% of worldwide energy use.

The IPCC Working Group 3, 6th Assessment Report (April 2022) states "We are at a crossroads. This is the time for action. We have the tools and know-how required to limit warming and secure a liveable future. The critically important Working Group III contribution assesses progress made in mitigation and options available for the future. …. *Any further delay in concerted global climate action will miss a rapidly closing window."* "This is the report that gives us options. It offers strategies to tackle the critical questions of our time. How can we reduce greenhouse gas emissions? How can we sequester carbon? How can the buildings, transport, cities, agriculture, livestock, and energy sectors be more sustainable?"

1.2 Science of Cooling, HFCs, and Energy Efficiency

The critical importance of an effective Montreal Protocol for climate change is clear. ODS phaseout through the MP has already avoided 1.1 degrees of warming over the Arctic by 2021, and projected to be 3-4 degrees by 2050, equivalent to ~25% of mitigation of global warming (Goyal 2021).[2]

Solomon et al. (2020) emphasised this climate benefit, describing the need to reduce as quickly as possible all ODS and their substitutes that contribute to global warming, and suggested a "Kigali-plus" HFC amendment to the protocol. Early action and accelerated/enhanced HFC phasedown to 95% of baseline by 2050, could provide cumulative climate benefits of 69 Gt CO_2eq from HFCs alone. (Purohit et al., 2022)[3]

Cooling with high GWP refrigerants in inefficient equipment that consumes excessive energy would contribute to drive us past the 1.5°C warming limit as soon as 2030. The widespread adoption of the best currently available technologies could reduce the climate emissions from stationary AC and refrigeration by 130-260 GtCO_2-eq over 2030–2050. (25% from phasing down HFCs, 75% from improved energy efficiency) (Dreyfus et al., 2020). If energy efficiency improvements in cooling were fully implemented, then resulting electricity savings could exceed a fifth of future global electricity consumption with a side benefit of reduced air pollutants in the range of 9-16% (Purohit et al., 2020).

[2] https://iopscience.iop.org/article/10.1088/1748-9326/ab4874/pdf
[3] https://www.nature.com/articles/s41558-022-01310-y

The global COVID-19 pandemic and economic slow-down reduced CO_2 emissions by 8% in 2020/21 compared with 2019 levels (IEA, 2020b), but then rebounded. The Montreal Protocol could take the opportunity to support a "green" economic recovery, by supporting policies to drive towards more efficient RACHP equipment with low GWP refrigerants during the HFC phase-down. ("The Cooling Imperative" (2019) Economist Intelligence Unit)

1.3 Progress with Ratification of the Kigali Amendment

The Kigali Amendment to phasedown HFCs was signed in 2016 and came into force in 2019.

132 of 198 countries have so far have ratified as shown in Figure 1.1 (May 1, 2022).

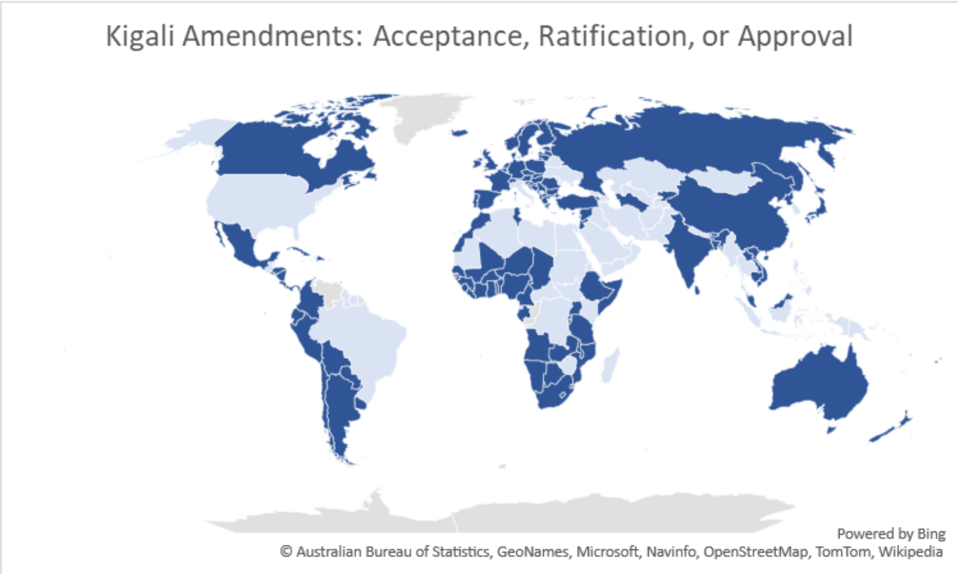

Figure 1.1. World map highlighting the current status of the Kigali amendment acceptance, approval, or ratification.

1.4 Regional developments with F-gas regulations

Some non-A5 Parties and Regions are making proposals to strengthen internal regulations for HFC phasedown and the use of alternatives. At this point, some are advisory, and some are prescriptive with varying levels of ambition.[4]

In April 2022, the European Commission has made some significant proposals for accelerated HFC Phasedown within the EU. These are under negotiation, could change, and will not be agreed until 2023.[5]

The American Innovation and Manufacturing (AIM) Act was enacted by the U.S. Congress on 27 December 2020. The AIM Act provides new authority for the U.S. Environmental Protection Agency (EPA) to address HFCs in three ways: (1) phasing down production and consumption, (2) maximizing reclamation and minimizing releases from equipment, and (3) facilitating the transition to next-generation technologies through sector-based restrictions. The AIM Act directs EPA to phase down production and consumption of 18 listed HFCs by 85% below baseline levels by 2036 through an allowance allocation and trading program. EPA has established U.S. production and consumption baselines using a formula provided by the AIM Act that considers past HFC, hydrochlorofluorocarbon (HCFC), and chlorofluorocarbon (CFC) amounts.

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[4] https://www.carel.com/-refrigerant-scenario-white-paper, https://www.hfcbans.com/bans-by-region.html, https://www.epa.gov/climate-hfcs-reduction/final-rule-phasedown-hydrofluorocarbons-establishing-allowance-allocation

[5] https://ec.europa.eu/clima/eu-action/fluorinated-greenhouse-gases/eu-legislation-control-f-gases_en

1.5 HFC Phasedown and Energy Use – some basic principles

The major HFC use worldwide is in the RACHP sector. The majority is used for comfort cooling and heating and the remainder is for refrigeration, although the proportion varies by country and region. A large proportion of RACHP GHG emissions are related to the energy used. The ratio of “indirect” energy-related emissions to “direct” refrigerant emissions varies between countries depending on factors such as the carbon intensity of power generation, the leakage rate from equipment of different RACHP technologies, and the GWP of the refrigerants used.

There is excellent potential to reduce energy related emissions at the same time as phasing down use and emissions of HFCs. The integration of energy efficiency and HFC phasedown activities will create maximum environmental benefit at lowest cost.

Energy benefits from HFC phasedown depend on the RACHP technology sector and the HFC alternatives used. In all sectors it is now possible significantly enhance energy efficiency. Some of the energy saving potential relates to the efficiency level of new equipment. Policies such as MEPs can drive up new product efficiency levels.

Two other efficiency opportunities are also very important. First, the demand for cooling should be minimised before selecting new equipment (e.g., reducing air-conditioning loads through building design measures and reducing food retail loads by using doors on all display cases). Second, good operation and maintenance of equipment can stop the performance of new equipment failing to meet its design efficiency

Small sealed systems have low leak rates (e.g., residential refrigerators, Self-contained Commercial Refrigeration (SCCRE)). Direct emissions from sealed systems during normal operation are low and end of life management of refrigerant is important. The energy efficiency of new equipment is getting progressively better so that the introduction of low GWP alternatives in new equipment reduces energy use. Improved efficiency also reduces peak electricity loads which can lead to significant savings related to power station investments.

Large customised RACHP systems usually have much higher leak rates, but proper containment measures, certification of technicians in combination with an HFC phase down are enablers to drastically reduce such leak rates. Moving to lower GWP refrigerants quickly will prevent the installation of equipment containing high GWP refrigerants. This will reduce immediately the large direct emissions, and the long term high GWP HFC servicing requirement. Servicing and training are critical.

The market for small room AC continues to increase especially in high ambient temperature developing countries. Low and medium GWP HFC alternatives are available in increasingly efficient equipment. Parties should consider integrating energy regulations (MEPS and labelling) with refrigerant GWP standards.

1.6 Expanded Scope

Previous EE Task Force reports only addressed small room-air conditioning and small retail systems (SSCRE). In this report, the energy efficiency task force was tasked to expand its scope and include additional RACHP equipment including heat pumps (HP), large air conditioning systems, and large commercial refrigeration systems. Room AC, SCCRE, large AC systems and large commercial refrigeration contribute to more than 60% of the refrigerant volume as shown in Figure 1.2. Furthermore, in many A5 countries the RACHP sector is considered as the most significant sector in the growth of the electricity demand from 2018 to 2050 as shown in Figure 1.3.

The HP market is a fast-growing sector that offers significant decarbonization potential. However, it is important that this environmental benefit is not offset by a growing bank of high GWP refrigerants, and potential for leakage. In this report we highlight the current status of the heat pump sector and offer insights on alternative medium and low GWP technologies to double the environmental benefit.

Large refrigeration systems are classified as remote condensing units, central systems, and distributed systems. They are used in a wide range of applications such as large food retail, bulk cold storage, and industrial processes. Some of these systems are prone to significant refrigerant leakage. In addition, large refrigeration systems tend to operate continuously and consume significant amounts of electricity. As such, the impact of indirect emissions varies between 50 to 100%[6] of total GHG emissions depending on the electrical carbon intensity factor and the refrigerant used. As such, energy efficiency and refrigerant selection are both key to a low carbon future.

Large AC systems include different types of systems and technologies. The EETF classified medium and large AC systems into 8 applications as described in section 2.6. These systems may be used in a variety of applications including residential, commercial, government buildings, etc. As such it is important to consider the equipment-building integration as an important factor in evaluating the energy efficiency potential. Building insulation materials and methods of construction play a significant role in minimizing the thermal load of the building and reducing the size and capacity of the AC equipment.

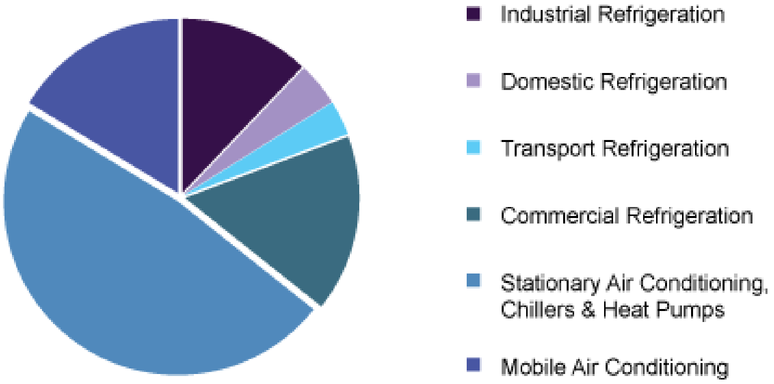

Figure 1.2. The global refrigerant market volume by application, 2016.[7]

[6] Peteren, M.,Pottker, G., Fricke, B.A., "Influence of commercial refrigeration system design and refrigerant options on life cycle climate performance.", Proceedings of the 25th IIR International Congress of Refrigeration: Montréal , Canada, August 24-30, 2019. n. 1597. http://dx.doi.org/10.18462/iir.icr.2019.1597; also available at: https://www.osti.gov/servlets/purl/1560429

[7] https://www.grandviewresearch.com/industry-analysis/refrigerant-market

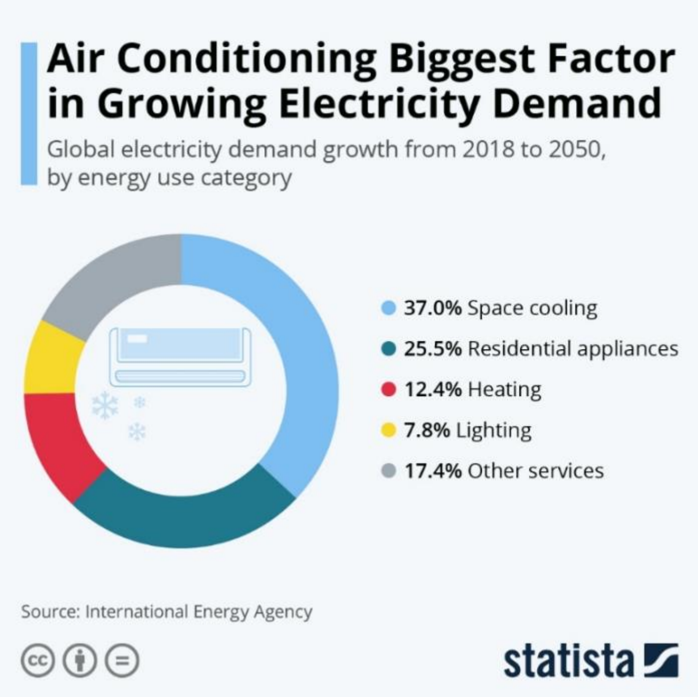

Figure 1.3. Global electricity demand growth from 2018 to 2050 showing RACHP significant contribution.[8]

1.7 Life Cycle, Carbon Emissions and Cost Effectiveness of Energy Measures

When considering heating and cooling, the energy efficiency of equipment in the context of building construction is key to reducing a nations energy use. Estimation of life-cycle energy savings, carbon emission reduction and cost effectiveness of energy efficiency measures has become critical for decision making processes of policy makers, manufacturers, and consumers.

For a specific country to succeed in transforming its market towards more sustainable products through their life cycle, including more energy efficient and low carbon equipment, governments should establish an integrated refrigerant policy and regulatory energy efficiency framework. For example, product energy efficiency standards and labelling programmes, should be linked to lower GWP refrigerant targets, by coordination between the country's Paris Agreement and the implementation of the Phasedown of HFCs under the Montreal Protocol. In addition, energy conservation laws are required to sustain any mandatory process requiring the implementation of progressive targets of maximum energy consumption and minimum performance standards of commercialised products.

If an individual country is to maximise the socio-economic benefits from the regulatory process, a road map needs to be established country-wide, starting with a study to determine the feasibility, timing, and impact of proposed MEPS (Minimum Energy Performance Standards) and Labelling regulations, and/or the frequency of updates of existing ones. A study should provide a detailed analysis of the national situation regarding the sectors/subsectors to be covered, the market and projected growth. These studies assist governments and their institutions in making informed decisions on the viability, timing and implementation of new standards and labelling for products, the environmental benefits, and the costs impact to manufacturers and consumers. The methodology for testing the energy performance of equipment should be assessed. It is then possible to estimate the

[8] https://www.statista.com/chart/14401/growing-demand-for-air-conditioning-and-energy/

possible future consequences in economic, social, and environmental terms, by conducting an analysis of several factors associated with a proposed new MEPS. including:

- the percentage of equipment which will be removed from the market
- the relative importance of the different equipment/appliances energy consumption as compared with the total energy demand in the country;
- the expected growth/penetration of those equipment/appliances in the market.

This type of analysis shows the impact of the introduction of a MEPS on the country's overall electricity needs and enables those sectors with the highest electricity demand and future growth to be prioritised.

The improvement in EE standards and labelling can make a major impact in reducing the pressure on a national electricity system, mitigating the peaks in electrical load[9] and avoiding the costs of installing new generating capacity. The energy gains resulting from stringent energy efficiency indicators standards are calculated based on market data and taken into consideration for future implementation schedules and the resulting long-term energy savings.

The economic impacts associated with energy conservation benefits resulting from the greater restriction of commercialization of less efficient products, including air conditioners are very significant, and tend to benefit both individual consumers as well as society as a whole.

The saving in indirect emissions from efficient equipment is of direct economic benefit to both the consumer and the country and fewer coal fired power stations also means better air quality. This makes MEPS relatively acceptable. In contrast, the saving in direct emissions (i.e., through using lower GWP refrigerants) is less tangible to the consumer, even if it does contribute to a country's commitment to the Montreal Protocol and to global climate change.

From a consumer perspective, it is therefore critical if parties are going to be successful in phasing down high GWP HFCs, that they "piggy-back" on to MEPS regulations. So far, many parties have failed to take the opportunity offered though the introduction of new MEPs to introduce controls on high GWP refrigerants. Integrated regulations would lead to market transformation to products which would reduce both indirect emissions (i.e., energy use), and direct carbon emissions (by using low GWP refrigerants and avoiding high GWP legacy servicing needs)

A renewed look at consumer behaviour is very important. For instance, AC use is seasonal and higher in summer, and this should be taken into consideration when considering the current patterns of use and projected growth. It is necessary to educate consumers as well as the people responsible for procurement of products, through awareness campaigns. Civil society organizations, in both developed and developing countries, can be important advocates and can help to increase consumer awareness and encourage faster introduction of energy efficient and low-GWP products in the market

Government organization(s) in charge of setting standards and labelling need strong monitoring and evaluation programmes to ensure that laws and regulations are fully operationalized. Finance for such monitoring and verification programmes is critical.

[9] For instance, the building sector (residential, public, and commercial) represents 51% of the electricity demand in Brazil (EPE 2019) and the cooling requirements are growing since 2000. (EPE estimates that more than 80% of the homes in Brazil will have at least one air conditioner till 2035, resulting in an increase in consumption from the current 18,7 TWh to 48.5 TWH, with 3.6% growth in energy demand per year (EPE, 2018, EPE, 2019) being the air conditioned the main item for the energy consumption in a Brazilian home.

2 Availability of Low and Medium GWP Technologies and Equipment that Maintain or Enhance Energy Efficiency

Key messages:

- RACHP equipment using low and medium GWP refrigerants with enhanced energy efficiency, is now available in all sectors but not necessarily accessible in all countries. Technology developments are proceeding at pace. Early action through the Kigali Implementation Plans can enable their transition to this new generation of RACHP equipment.
- Country-specific incremental improvements in energy efficiency are being driven by MEPS, developed with the consideration of seasonal, full, and part load performances. Such MEPS are either being adopted or progressively enhanced. Technologies including variable speed drives (for compressors and fans), brushless DC motors, and electronic expansion valves are used to achieve seasonal performance requirements.
- Heat pumps are available with low and medium GWP refrigerants with energy efficiency measures implemented for the refrigeration cycle, the selection of ancillary components, and the integration of heat pumps with the building controls.
- Large commercial refrigeration equipment operates throughout the year which compels the need for higher efficiency to reduce energy costs. This is measured by the annual power consumption, which can be reduced by considering component selection and evaporative condensers.
- In larger AC systems, safety considerations limit the application of flammable refrigerants. However, large AC systems of all capacity ranges are available with low and medium GWP refrigerants with comparable efficiencies to the baseline high GWP refrigerants, and they can be further optimised for higher efficiency. Compressors designed to work with a range of refrigerants including baseline refrigerants as well as low and medium GWP refrigerants are now available.
- Not-In-Kind (NIK) technologies that do not utilise mechanical vapour compression can offer lower operational lifetime costs (OLC) than in-kind systems, in some circumstances. Some examples of NIK technologies include solar energy driven absorption systems, hybrid evaporative cooling and deep-sea cooling are some examples of these NIK technologies.

2.1 Introduction

This chapter provides an update on the availability of Low GWP technologies and equipment that maintain or enhance energy efficiency for:

a) residential air conditioners (< 7 kW) and self-contained commercial refrigeration which were covered under previous decisions and EETF reports;
b) three new sectors i.e., heat pumps, larger commercial refrigeration, and larger air conditioning units (> 7 kW).

The chapter concludes with a summary on not-in-kind technologies and district cooling.

The discussion on the three new applications covers the availability of technologies for these applications in general before discussing the energy efficiency implications.

For more detailed description of the applications, please refer to Annex 9.2 9.2 at the end of this report.

2.2 Residential split AC: update

The range of residential AC is from 1.7 kW to 7 kW in both split systems and window-type or plug in/portable factory sealed systems, depending on the climate conditions and the size of the room. They are used both for cooling and heating, and together are responsible for very large consumption of energy and refrigerants.

There has been incremental development since the last TEAP report on Decision XXX/7 driven by MEPS programs being either adopted or enhanced in many countries. Most of those countries have adopted seasonal energy efficiency (SEER) as basis for evaluating the performance. Standard ISO 16358:2013 is the reference standard and takes into consideration the climatic conditions of each country. Energy labelling programs have motivated manufacturers to invest in the technology and training across the business chain.

Air-conditioning cooling and heating loads vary significantly on both daily and seasonal timescales. The use of variable speed drives to vary the system capacity have been steadily increasing. Variable speed systems have an advantage in achieving high SEER performance ratings. Some of the current SEER labels can be only achieved using variable speed systems and not by fixed speed systems.

There are increasing signs of the supply chain getting established in the manufacturing countries to meet the demand for components; however, the transition period to EE products can vary by country and region.

The majority of the market share in the Chinese, Japanese, and the EU markets for room air conditioners are reversible, which means the same unit can provide cooling in hot weather or heating in cold weather. The market driver in moderate climates requiring heating and cooling is convenience and affordability. In countries where the climate does not necessitate heating, the uptake of reversible systems has been slower. In India, for example, around 25% of the VRF market is reversible while the share in room ACs is less than 1%.

Until recently R-410A (GWP 2088) was the most used refrigerant for residential AC. Medium GWP HFC-32 adoption has increased. The conversion of production facilities to HC-290 (GWP 3) has been facilitated by funds provided by the multilateral fund and products will become increasingly available with the adoption of standards allowing for higher refrigerant charges. A new revision of standard 603325-2-40 will in future allow a larger charge, up to 998 grams, of A3 refrigerants like HC-290 in domestic air conditioners, heat pumps, and dehumidifiers for new equipment designed according to certain additional safety requirements to ensure the same high level of safety as equipment using non-flammable refrigerants.[10]

2.3 Self-Contained Commercial Refrigeration Systems

Self-contained commercial refrigeration equipment (SCCRE) (also “stand-alone” or “plug-in”) is widely used in food retail and food service alongside, or instead of, the larger equipment discussed later in this chapter. SCCRE is factory-built and comprises of a wide variety of appliances: e.g., ice-cream freezers, ice machines, vending machines, and display cases. SSCRE uses higher efficiency compressors, evaporators, condensers and suction-line heat exchange (discussed later in this chapter) for lower power consumption, and also relies on more efficient ancillary components (e.g., LEDs and high efficiency fans for circulating the air to improve performance. Many regions have MEPS for this equipment as well as voluntary higher standards for adding value to the consumer.

The use of hermetically sealed reciprocating compressors has increased by 15% year-on-year[11]. This growth in hermetically sealed compressors is expected as SCCRE volumes grow due to the latest safety standards allowing increase in charges of both A3 and A2L flammable refrigerants. This trend will continue and could have an unintended consequence on energy efficiency if energy standards are not harmoniously updated.

When comparing SCCRE to larger commercial systems, in general the larger systems have more efficiency options and perform better on annual basis. Larger systems have outdoor condensers which can take advantage of the varying outdoor ambient conditions. Larger compressors can have higher

[10] https://www.coolingpost.com/world-news/standard-revision-a-milestone-for-propane-ac/

[11] Reported by eJARN March 2022

efficiency than SCCRE compressors. Also, typical SCCRE purchases are generally more cost sensitive. The energy efficiency options that are available for larger commercial refrigeration equipment are described in section 2.5.

2.4 Heat Pumps

A heat pump (HP) is a system that is used primarily for the purpose of producing heat at a useful temperature. A HP extracts heat from a low temperature heat source (e.g., from ambient air) and delivers heat at a higher useful temperature (e.g., to heat a room). Reversible residential air-to-air heat pumps used for space cooling and heating were discussed in past EETF reports with an update under section 2.2. This section discusses heat pumps that are typically used for space heating and heating water but may also be used for a variety of other applications. There are three categories of HP:

- Domestic (hot water)
- Integrated HP (space heating and cooling and water heating) for domestic and commercial
- Industrial process

HPs for industrial process are categorised as “industrial refrigeration” system (e.g., RTOC, 2018) and often use low GWP natural refrigerants (such as R-744, R-717, etc.). Due to their application characteristics which can differ significantly from the domestic and commercial applications, the reader is referred to the industrial refrigeration chapter of RTOC Assessment Report 2018. The 2022 version of the report will be available end 2022/early 2023.

2.4.1 Sub-categories

Table 2.1 provides an overview for the various arrangements of HP systems and provides a general categorisation.

The heat source is the origin of the thermal energy, and the heat sink is where the thermal energy is supplied to. Note that a significant portion of products are dual purpose, i.e., providing thermal energy for both space heating and hot water (for washing, etc.).

The refrigerant circuit may be a factory sealed single package unit (all parts within a single housing and factory charged and sealed) or split, where the system is supplied in two or more parts, one to be located in the conditioned space and the other in another location (usually outdoors) and requiring a technician to connect and sometimes charge with refrigerant on site. Some types of factory-sealed HP are also referred to as “monobloc.”

HPs may use one or two intermediate water circuits to transfer thermal energy from the heat source to the refrigerant circuit or from the refrigerant circuit to the heat sink. Note that depending upon the local climate, a glycol or brine may be used in the first intermediate water circuit to reduce the chance of freezing.

Typical split AC systems may also be designed to provide a refrigerant flow reversal thereby allowing both for air cooling and heating. These are typically called reversable HPs where heat is directly extracted and rejected from and to the air. Further information on these related to lower GWP and energy efficiency is similar to the information discussed in the split AC section, section 2.2. HPs are an attractive option because they can use power from renewable sources, and low GWP refrigerants.

For discussion on refrigerants for air-to-air systems, refer to RTOC Assessment Report chapter 7.

*Table 2.1. Arrangements and general categorisation of space and domestic water heating HPs**

Heat source	1st intermediate	Refrigerant circuit	2nd intermediate	Heat sink	Category
Outside air	[none]	Integral/ Split	[none]	Indoor air	Air-to-air
Exhaust air	[none]	Integral	[none]	Indoor air	Air-to-air
Outside air	[none]	Integral/ Split	Water circuit	Hot water and /or space heating	Air-to-water
	[none]	Integral/ Split	[none]		
	[none]	Split	Water circuit	Space heating	
Ground	Water circuit	Integral/ Split	Water circuit	Hot water and/or space heating	Water-to-water
Outside water	Water circuit	Integral/ Split	Water circuit	Hot water and/or space heating	
	[none]	Integral/ Split	[none]		
	[none]	Split	Water circuit	Space heating	
	Water circuit	Integral/ Split	[none]	Indoor air	Water-to-air

** Please note that there are other HP applications such as tumble dryers and process heaters.*

2.4.2 Availability with Low and Medium GWP Refrigerants

HPs are available worldwide using a variety of high, medium, and low GWP refrigerants. includes those identified as available. Some high GWP and medium GWP options are available globally, whereas low GWP options are typically limited to Japan (hot water heaters) and Europe.

The IEA Heat Pump Programme Annex 54 project reports on the variety of alternative refrigerants within air to water HP systems in the European BAFA and Keymark programmes (Oltersdorf et al., 2021). This shows a fairly diverse selection of alternative refrigerants in use. Of about 2000 different models in both the BAFA and Keymark programmes, the majority (two-thirds) use conventional high GWP refrigerants, mainly R-410A, but also R-407C, R-404A and R-417A. The medium GWP alternatives used are HFC-32, R-452B, R-454B, R-454C and R-513A of which HFC-32 was dominant.

HC-290 was used in the remaining 5% of the models (about 20% of all the medium and low GWP models in BAFA and a few percent under Keymark). In BAFA, HC-290 models exhibited the highest overall efficiency (COP) to EN 14511 of all models and highest at two of the conditions (higher source temperatures), whereas HFC-32 models provided higher values at the other two conditions (lower source temperatures), although all within ±3%. Under Keymark, HC-290 had highest efficiency at medium leaving water temperatures), whereas HFC-32 models provided higher values at low leaving water temperatures. Under BAFA, these were all higher efficiencies than the most efficient HPs using high GWP refrigerants, R-410A, R-404A and R-407C.

For flammable refrigerants with nominal heating capacities of a few kW, systems are usually monobloc systems installed outside or split systems with the indoor part having a so-called ventilated enclosure, where any leak will be exhausted to the outside.

Table 2.2. Alternative refrigerants currently available in various categories of heat pumps

<table>
<tr><th rowspan="2">Category</th><th rowspan="2">Heat sink</th><th rowspan="2">Heating capacity</th><th>High* GWP</th><th colspan="2">Medium GWP</th><th colspan="2">Low GWP</th></tr>
<tr><th>Options</th><th>Options</th><th>Regions**</th><th>Options</th><th>Regions</th></tr>
<tr><td>Exhaust air</td><td>Space heating</td><td>< 8 kW</td><td rowspan="5">R-410A</td><td rowspan="5">HFC-32
R-452B
R-454B
R-454C</td><td rowspan="5">E, EA, A</td><td>HC-290</td><td>E</td></tr>
<tr><td rowspan="2">Air-to-water</td><td>Hot water</td><td>< 3 kW</td><td>HC-290
R-744</td><td>E, EA</td></tr>
<tr><td>Space heating</td><td>3 – 80 kW</td><td>HC-290
(HC-1270)
(HC600)
R-717***</td><td>E</td></tr>
<tr><td rowspan="2">Water-to-water</td><td>Hot water</td><td>< 3 kW</td><td>HC-290
R-744
HC-600</td><td>E, EA</td></tr>
<tr><td>Space heating</td><td>3 - >100 kW</td><td>HC-290
(HC-1270)
(HC-600)
R-717***</td><td>E</td></tr>
</table>

** Definition of High, medium, and low GWP is based on RTOC.*
*** A = Australia, E = Europe, EA = East Asia*
****Used with sorption systems, please refer to section 2.7 of this chapter for more details.*

2.4.3 Energy Efficiency Measures

There are numerous energy efficiency measures that are used with HPs. These can be divided into the following three aspects:

- vapor compression cycle – where the measure is directly part of the vapor compression cycle, such as improved heat exchangers, compressors, etc.
- Ancillaries – where the measure is not directly part of the vapor compression cycle, such as improved fans, pumps, etc.
- Integration – where the measure is related to the integration of the application, such as controllers linked to other services, solar collectors, etc.

In general, the ancillary and integration energy efficiency measures are not related to the refrigerant selection. All of the technologies detailed below are available globally.

2.4.3.1 Vapor compression cycles

Measures involved with the vapor compression cycles are broadly the same as with most other applications. These are:

- Cycle architecture and system balancing, to suit load and capacity at applicable temperature levels
- Higher efficiency compressors, including variable speed drives
- Heat exchanger design, including circuitry, micro-channels, internal turbulators, fins/extended surfaces, surface treatments
- Expansion device, primarily electronic expansion valves

All of these measures are available for all alternative refrigerants identified in Table 2.2.

2.4.3.2 Ancillaries

Ancillary measures are similarly also used with other applications, including:

- Optimised flan blades
- EC type fan motors
- Variable speed pumps

2.4.3.3 Integration

Measures associated with the integration of the HP with the building include:

- Correct sizing and balancing of the HP with the internal heat load and heat emitters including supply water temperature
- Integrated building controllers for capacity/load matching and broader energy management
- Use of thermal solar panels to provide a higher-grade thermal source
- For heat pumps simultaneous heating and cooling can be possible

2.4.3.4 Compliance with Safety Standards

As with all other refrigeration and air conditioning equipment, it is appropriate for HPs to comply with safety standards. Applicable safety standards include ISO 5149 and IEC 60335-2-40 in addition to any national standards.

In most countries, regulations are mandatory whereas safety standards are not. Ultimately, it is the regulatory requirements that manufacturers and installers must adhere to.

Safety standards address a wide variety of hazards, including electrical, equipment under high pressure and other mechanical aspects (such as sharp edges and trapping of parts, impacts to persons and animals, toxicity of materials, fire and flammability hazards, noise levels, confined spaces, etc.) Thus, HP products should be designed and approved such that the risk posed by all such hazards are maintained to an acceptably low level.

In addition to safety during the use phase of the products addressed by product standards such as IEC60335-2-40, manufacturers also need to consider the safety during manufacturing, transport, installation, servicing, decommissioning, and end-of-life treatment of the products, where several other national and international legislations need to be taken into account (examples: ATEX, building safety regulations, UNECE[12])

With a shift to medium and low GWP refrigerants, further consideration is usually required for two specific hazards: high pressure and flammability. The above-mentioned standards detail how these hazards should be addressed. Pressure safety requires additional strength of piping and components. Flammability safety requires avoidance of potential sources of ignition (which could ignite a refrigerant leak), ensuring releasable quantities of refrigerant are not large enough to result in unacceptably large flammable mixtures and that adequate airflow or ventilation is present to dilute and exhaust potential leaks. All HPs referred to in Table 2.2 comply to the listed or equivalent safety standards.

2.5 Large Commercial Refrigeration Systems

2.5.1 Overview

Large commercial refrigeration systems are usually found in food retail and food storage facilities and are characterized by refrigerating capacities of equipment varying from 2 kW to around 1.5 MW. These systems are usually custom designed to fit the site. As a result of not being factory finished as sealed units, the leak rates are much higher than SCCRE, especially if not expertly designed and installed. Two main levels of temperatures are generated by these commercial refrigeration systems:

- medium temperature operating between 0°C and 8°C, for the conservation of fresh food and beverages
- low temperature operating between -18°C and -25°C, for frozen food and ice cream

Large commercial refrigeration equipment operates year-long; hence energy efficiency becomes an important consideration. For moderate and cold climate regions recovering heat from the refrigeration system for heating purposes in the cold season can increase the overall system efficiency. Large commercial refrigeration systems can be broadly classified as Remote Condensing Units and Centralized or Distributed Systems. Remote condensing units are small split systems (typically in capacity range 2 to 20 kW) serving one or two display cases with a single compressor and condenser located outside the retail sales area. Centralized systems (typically in capacity range 50 to 500 kW) operate with racks of compressors installed in a machinery room and outdoor condensers. Distributed systems (typically in capacity range 20 to 50 kW) have compressors on rooftops, while cooling coils are in the display cabinets or cold rooms. Centralized and Distributed Systems can also be classified as “direct,” where the refrigerant enters the sales area or occupied space and “indirect” where the refrigerant is limited to a machinery room and only a secondary fluid like glycol enters the occupied space. By the nature of the two systems, direct systems are more energy efficient and are therefore preferred and the dominant architecture.

As is common practice, the term “energy efficiency” is used, but what is more relevant for any refrigeration system is the electrical energy consumed. Reductions in electrical energy consumption can come from reduction in cooling load, improvements in component and refrigeration system design, as well as optimum control, operation, and maintenance of the system.

2.5.2 Remote Condensing Units

Selecting the highest rated efficiency condensing unit may seem like the most obvious first step; while that can be true, it is more important to select the unit that can provide the highest efficiency or lowest electrical energy consumption, during those conditions at which the unit is most likely to operate.

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[12] UN model regulation for the transportation of dangerous goods. https://unece.org/transport/dangerous-goods/un-model-regulations-rev-22.

Since commercial refrigeration equipment operate all year, an annual electrical energy consumed by the unit based on the weather profile in the location is the best approach. Of course, it is assumed that the unit has been selected to provide the required cooling on the hottest day and that the maximum power draw is also acceptable.

In addition to the above, there are other considerations that can help improve the efficiency of the unit. Some of those are:

- *Electronic expansion devices* (instead of thermostatic expansion valves or capillary tubes etc.) which can help the unit lower the condensing temperature (which in turn lowers the compressor power while also increasing capacity) as the outdoor ambient temperature decreases (often called "floating condensing temperature" or "floating head pressure");
- *Mechanical or Vapor Injected subcooling* that decreases the liquid temperature leaving the condenser coil, which increases the capacity of the system and enables the expansion device to operate more efficiently, all serving to decrease power anywhere from 10% to 30% depending on conditions;
- *Suction line heat exchange* which is a low-cost method for some refrigerants to achieve some of the benefits of the mechanical or vapor injected subcooling discussed above. In this approach, the copper tube leaving the evaporator coil and the tube bringing the liquid to the expansion device of the coil are allowed to make close contact with each other, with insulation wrapped around them for better effect. The cool vapor leaving the evaporator is used to sub-cool the liquid entering the expansion device without the aid of an external sub-cooler;
- *Variable capacity compressors* in the unit allow for better matching of the refrigeration load to the capacity and reduce the number of on-off cycles of the compressor, thus resulting in less thermal and electric cycling losses;
- *Variable speed and high efficiency* condenser fans improve energy efficiency;
- *Evaporative condensing.* Typically, outdoor air-cooled condensers use the dry bulb air temperature to reject the heat that has been picked up in the system. A more efficient method is to use the wet-bulb temperature in a method called evaporative condensing. In its most simple form, it consists of adding a mist of water to the air that is being drawn over the condensing coils. The additional cost of the water, water treatment, and the effect on the coil should be factored-in before deciding to implement this measure. Evaporative condensers have become popular with the growth of trans-critical CO_2 technology.
- *Condenser cleaning.* Fouling of condensing coils through dust, foreign particles, etc. leads to reduced performance of the condenser. This may result in higher electrical energy consumption, longer run-time, loss of temperature and loss of food or products being refrigerated.

2.5.3 Central and Distributed Systems

Centralized and Distributed systems also employ the same energy efficiency methods discussed above for remote condensing units. Since these types of systems use more than two compressors, variable capacity is often achievable just by staging the compressors on or off. Short line lengths, insulating lines that are below ambient temperature etc. are all good practices to follow. One serious issue with larger systems is the presence of the many mechanical joints that can lead to refrigerant leaks. Loss of refrigerant, while harmful to the environment, also has the effect of reducing the energy efficiency of the refrigeration system. Frequent and automated checks on the system for operating conditions, leak sensors and diagnostics to alert for the presence of leaks are all good practices to keep the systems running at peak efficiency. In addition, periodic recommissioning of a refrigeration system is also recommended (see also chapter 6).

Trans-critical CO_2 (R-744) refrigeration systems are growing in use in non-A5 countries and to a lesser extent in A5 countries. These types of systems use several efficiency improvement techniques that are often not used elsewhere, some of which are discussed below.

- *Parallel compression:* Parallel compression is a method to reduce the power consumed in taking the vapor from the flash tank in a trans-critical CO_2 refrigeration system and compressing this to the higher pressure in the condenser.
- *Ejector:* A thermal ejector can recover some of the energy released during expansion by compressing the gas (and liquid) exiting from the evaporator. Hence, evaporators can be operated in flooded mode, without superheat. This increases the evaporation temperature. Furthermore, the compressor suction pressure is increased by the ejector, thereby reducing the compression power due to lower pressure lift. System efficiency may often be increased by as much as 20% (Reference: Hafner, 2014).
- *Adiabatic condensing/Evaporative condensing:* This was discussed earlier under remote condensing units and is listed here because it is most used with large trans-critical R-744 refrigeration systems. This technology is quite effective in dry warm climates for improving the efficiency of R-744 centralized systems, though this method of efficiency improvement is applicable to all refrigerants. Availability and treatment of water may however be a challenge in some areas.
- *Heat recovery and system integration:* This has always been one of the more popular forms of system efficiency improvement and has found an increasing number of applications with the growth of R-744 as a refrigerant. The heat from the condenser or gas-cooler of the refrigeration system – especially in a centralized system – can be recovered and used to heat or preheat water, indoor air heating in the winter, and even snow melting systems buried in sidewalks at the entrance to buildings. Utilisation of heat recovery can contribute to improve the overall efficiency of the entire refrigeration system beyond what is found by the traditional method of calculating performance.

2.5.4 Refrigerated Cases and Cold Rooms

In the discussion below, while reference is made to refrigerated cases or cold rooms, many of the ideas for one will apply to the other as well. The simplest way to reduce power and increase efficiency of operation is to reduce the refrigeration load. The addition of doors to retail display cabinets can reduce cooling load by as much as two-thirds, thus leading to significant energy consumption reduction. When doors are specified for new equipment the size and cost of the whole refrigeration installation is considerably reduced.

An Australian field study13 in 2015 of doors being retrofitted to existing display cases concluded that energy consumption was reduced by 42% providing a simple payback for the doors of 3.5 years and a return on investment (ROI) of 29% (annual energy savings equivalent of approximately US$23,000). Where it is not possible to install glass doors, adding "night curtains" which can be pulled down when the retail store is not open for customers, can also provide significant savings of around 20%.

The example of the doors illustrates the value of insulation in general. Insulation in refrigerated cases and cold rooms, be it for the walls or the floor, is critical in reducing or eliminating heat flow from the surrounding areas into the cold space, just like a door does. Cold rooms, regardless of their temperature, are insulated and only in rare cases would a floor of the room not be insulated. Insulation also helps to keep the moisture out and thus prevent the formation of frost on the cooling coils. Frost on the coils reduces the efficiency of heat transfer from the refrigerant to the air and decreases the thermal capacity of the refrigeration system. Periodic defrosts – timed or on demand and always terminated by temperature is beneficial to keep the system operating at its peak efficiency.

In cold rooms and refrigerated display cases, anti-sweat heaters on doors and lighting are also a source of electrical energy consumption. On demand anti-sweat heaters, supported by proper humidity control in the retail space, as well as LED lights can improve this by as much as 10-20%.

[13] (Reference: https://www.airah.org.au/Content_Files/Resources/Trial-Retrofit-of-Doors-on-Open-Refrigerated-Display-Cabinets.pdf).

2.6 Medium and Large Air Conditioning Systems for Comfort Cooling (not including industrial or data centres)

Larger air conditioning systems can be classified as either unitary direct expansion (DX) systems or chilled water systems:

- DX systems are designed to condition a single space or multiple spaces from a location within or adjacent to the space. Such a system is also known as local self-contained system. DX systems are usually for small and medium sized buildings requiring up to around 300 kW of refrigeration capacity (Bhatia, 2012), and sometimes used for larger cooling and heating capacity buildings by applying multiple systems or larger capacity units. The standard packaged and split units are typical examples of unitary DX systems
- Chilled water systems are designed to condition several spaces from one base location. Chilled water is produced in a refrigeration plant located at one central location and pumped to multiple air handling units (AHU) or fan coils (FCU) spread all over the facility. Chilled water systems are usually used when refrigeration loads exceed 300 kW, although in some countries chilled water systems with much smaller capacity are common. Central chilled water system can supply chilled water to several adjacent buildings.

For larger air conditioning systems, compressor manufacturers often qualify their designs for multiple refrigerants with similar characteristics for example, R-410A, R-452B and R-454B eliminating the need for dedicated compressors for each refrigerant. This reduces the cost of compressors due to economies of scale, while providing equipment manufacturers with added flexibility when deciding on which refrigerant to use.

For all the equipment categories discussed, the efficiency of the systems can be enhanced by using variable capacity controls, electronically commutated motors (ECM) for fans, or microchannel heat exchangers without the loss of cooling capacity

Table 2.3 below shows the availability matrix of the large commercial air conditioning for both DX and chilled water systems. Equipment is classified into eight sub-categories (Five for DX systems and three for chilled water) depending on the refrigeration capacity and the type of compressors used. This is discussed individually in this section to give a better view of the technologies used and the limitation of use.
The table gives a comprehensive view of the availability of refrigerants for each sub-category, availability of compressors, and the conformity to safety standards for the different refrigerants including the refrigerant charge. Energy efficiency optimization opportunities for low-GWP refrigerants are available.

With the flammability of new refrigerants, the challenge is compliance with safety standard regulations in both A5 and Non-A5 countries. The maximum size of a refrigerant charge depends on the volume of the occupied space which limits the applications for certain capacity ranges depending on the flammability classification as shown in Table 2.3. Market readiness to use flammable refrigerants including training and certification is key to allow countries to accept flammable alternative fluids.

Table 2.3. Availability matrix for large air conditioning units

Item	System	High GWP refrigerants presently in use	Medium and low GWP Refrigerants Alternatives		Compressor availability	Refrigerant	LFL (m3/kg)	maximum volume m3 @ max kW for this capacity range	Refrigerant Allowed According ISO 5149 & EN DN 378 (human Comfort/ flammability allowance)	Approx. refrigerant Charge per stage (kg) and per kW of capacity	
			A3	A2L							
2.6.1	Split Units 10 kW to 17 kW	HCFC-22 R-410A (Mainly) HFC-134a (few) R-407C (few)	HC-290 refrigerant charge must not exceed safe limit	HFC-32 R-452B R-454B	Rotary/ scroll with or without invertor Recip.	R-410A	NA	289	No Restriction	5.1	300 g / kW
						HFC-32	0.307		16.8	4.3	250 g / kW
						HC-290	0.038		1.2	0.9	50 g / kW
2.6.2	Unitary Equipment Packaged & Split 10 - 85 kW	HCFC-22 R-410A HFC-134a (few) R-407C (few)	Refrigerant charge exceeds the safe limit	HFC-32 R-452B R-454B (With multi refrigerant circuit)	Rotary/ scroll with or without invertor Recip.	R-410A	NA	1,445	No Restriction	25.5	300 g / kW
						HFC-32	0.307		37.6	21.3	250 g / kW
						HC-290	0.038			4.3	50 g / kW
2.6.3	Unitary Equipment Packaged & Split > 85 to 340 kW	HCFC-22 R410A HFC-134a few (screw) R-407C (scroll & rotary)	Refrigerant charge exceeds the safe limit	HFC-32 R-452B R-454B (With multi-refrigerant circuit)	Scroll Screw with/without inverter	R-410A	NA	5,780		51	300 g / kW
						HFC-32	0.307			42.5	250 g / kW
						HC-290	0.038			8.5	50 g / kW
2.6.4	Unitary Equipment	R410-A HCFC-22	Refrigerant charge			R-410A	NA	10,880		96	300 g / kW

<table>
<tr><th rowspan="2">Item</th><th rowspan="2">System</th><th rowspan="2">High GWP refrigerants presently in use</th><th colspan="2">Medium and low GWP Refrigerants Alternatives</th><th rowspan="2">Compressor availability</th><th rowspan="2">Refrigerant</th><th rowspan="2">LFL (m3/kg)</th><th rowspan="2">maximum volume m3 @ max kW for this capacity range</th><th rowspan="2">Refrigerant Allowed According ISO 5149 & EN DN 378 (human Comfort/ flammability allowance)</th><th colspan="2" rowspan="2">Approx. refrigerant Charge per stage (kg) and per kW of capacity</th></tr>
<tr><th>A3</th><th>A2L</th></tr>
<tr><td rowspan="2"></td><td rowspan="2">Packaged & Split
> 340 kW</td><td rowspan="2">HFC-134a (rarely)</td><td rowspan="2">exceeds the safe limit</td><td rowspan="2">Refrigerant charge exceeds the safe limit</td><td rowspan="2">Scroll /Screw with/without inverter</td><td>HFC-32</td><td>0.307</td><td rowspan="2"></td><td rowspan="2"></td><td>80.0</td><td>250 g / kW</td></tr>
<tr><td>HC-290</td><td>0.038</td><td>16.0</td><td>50g / kW</td></tr>
<tr><td rowspan="3">2.6.5</td><td rowspan="3">Multi Split less than 20 kW
and VRF > 20 kW</td><td rowspan="3">R-410A</td><td rowspan="3">Refrigerant charge exceeds the safe limit</td><td rowspan="3">HFC-32 for capacity < 10 kW</td><td rowspan="3">Scroll unitary for < 10 kW</td><td>R-410A</td><td>NA</td><td rowspan="3">340</td><td>No Restriction</td><td>6</td><td>300 g / kW</td></tr>
<tr><td>HFC-32</td><td>0.307</td><td>18.2</td><td>5.0</td><td>250 g / kW</td></tr>
<tr><td>HC-290</td><td>0.038</td><td></td><td>1.0</td><td>50g / kW</td></tr>
<tr><td rowspan="3">2.6.6</td><td rowspan="3">Chilled water systems 10 kW to 85 kW</td><td rowspan="3">R-410A
HCFC-22</td><td rowspan="3">HC-290Availab le</td><td rowspan="3">HFC-32
R-452B
R-454B
HFO-1234ze</td><td rowspan="3">Scroll with or without invertor</td><td>R-410A</td><td>NA</td><td rowspan="3">1,445</td><td>No Restriction</td><td>25.5</td><td>300 g / kW</td></tr>
<tr><td>HFC-32</td><td>0.307</td><td>No Restriction</td><td>21.3</td><td>250 g / kW</td></tr>
<tr><td>HC-290</td><td>0.038</td><td></td><td>12.8</td><td>150 g / kW</td></tr>
<tr><td>2.6.7</td><td>Chilled water</td><td>R-410A (Scroll)</td><td>HC-290/HC-</td><td>HFC-32
R-452B</td><td>Scroll Screw</td><td>R-410A</td><td>NA</td><td>5,780</td><td>No Restriction</td><td>102</td><td>300 g / kW</td></tr>
</table>

Item	System	High GWP refrigerants presently in use	Medium and low GWP Refrigerants Alternatives		Compressor availability	Refrigerant	LFL (m3/kg)	maximum volume m3 @ max kW for this capacity range	Refrigerant Allowed According ISO 5149 & EN DN 378 (human Comfort/ flammability allowance)	Approx. refrigerant Charge per stage (kg) and per kW of capacity	
			A3	A2L							
	systems > 85 kW to 340 kW	HCFC-22 (Scroll & Screw) HFC-134a (Screw)	1270 Available < 100 kg refrigerant charge**	R-454B R-513 HFO-1234ze		HFC-32	0.307		No Restriction	85.0	250 g / kW
						HC-290, HC-1270	0.0380.04 6		No Restriction	51.0	150 g / kW
2.6.8	Chilled water system > 340 kW	R-410A (Scroll) HFC-134a (Screw centrifugal) R123 (centrifugal)	HC-290/HC-1270 available less than 100 kg refrigerant charge**	HFC-32 (Scroll) R-452B, R-454B, R-513A (screw) HFO-1234ze, HFO-1233zd, R-514A (centrifugal)	Scroll, screw, centrifugal or magnetic bearing centrifugal compressors	R-410A	NA	10,880	No Restriction	192	300 g / kW
						HFC-32	0.307		No Restriction	160.0	250 g / kW
						HC-290, HC-1270	0.0380.04 6		No Restriction	96.0	150 g / kW

**Authorized occupancy*

***Comply for outdoor installations or controlled mechanical rooms*

Notes:

1. *Charge calculation based on ISO 5149 and EN 378*
2. *Assuming refrigerant charge of 50 gram /kW for HC-290 and 300 gram/kW for R-410A and 250 gram /kW for HFC-32*
3. *Components that enhance EE such MHX or smaller tubes for heat exchangers and EC fans are available*
4. *Energy efficiency enhancement up to 20% with low and medium GWP refrigerants is possible optimisation*
5. *R-717 (B2L) and R-744 (A1, high pressure) chilled water systems are available for capacities above 70 kW.*

2.6.1 AC split units 10 kW to 17 kW

Alternative refrigerant-based systems for AC split units in the range of 10 kW to 17 kW and their components including compressors, refrigeration accessories, and ECM fans to enhance energy efficiency are widely available. The market share of HFC-32 units in 2018 for Europe and China is shown Figure 2.1 below. The market continued to evolve since then with a growth in the use of HFC-32 in both Europe and China.

The United States have stricter restrictions on the use of flammable refrigerants; nevertheless, smaller capacity units up to 7 kW with HFC-32 refrigerant have been introduced in the United States (JARN magazine issue 636 volume 54, No.1). Larger capacity units are not yet approved for use in the USA because of safety regulations.

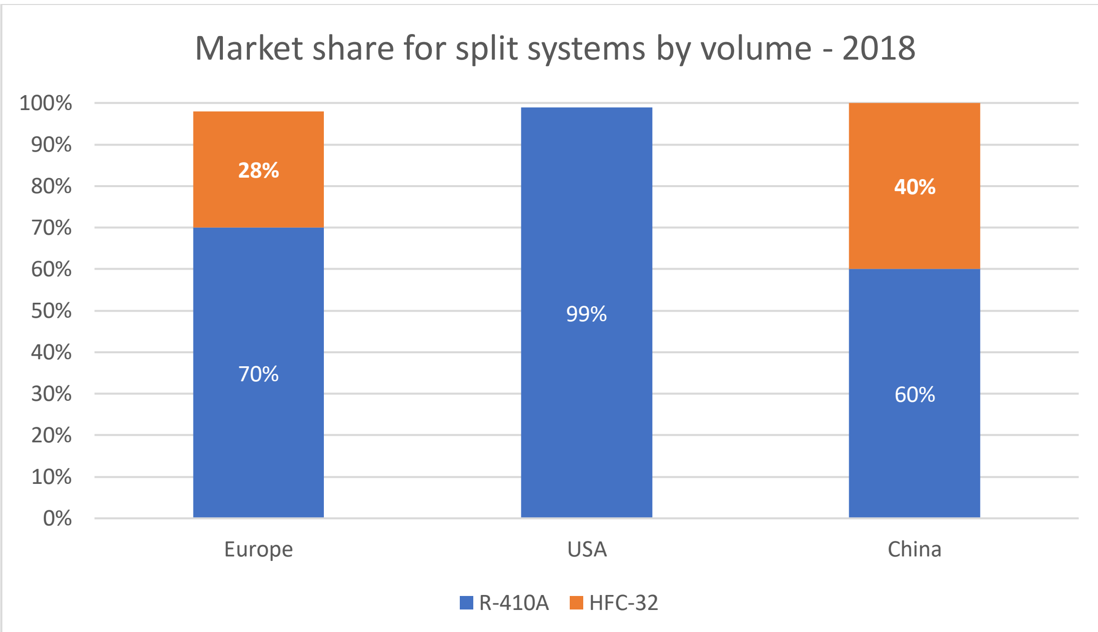

Figure 2.1. Market for HFC-32 units compared to R-410A in selected markets (source BSRIA)

Most of the available alternative refrigerant units in the 10 to 17 kW capacity range use scroll compressors with or without inverters. Units with inverter compressors have better efficiency than fixed speed, especially at partial loads. Reciprocating compressors are still used but in limited quantities since the compressor efficiency for reciprocating compressors is less than the scroll compressors. Rotary compressors are available up to 10 kW maximum.

2.6.2 Packaged and Central Split units (ACCU +AHU) (Unitary Equipment) 10 to 85 kW

Cooling and heating split and packaged units in this capacity range mostly use scroll compressors with or without invertor and very rarely the less efficient reciprocating compressors. Components for lower GWP applications for this capacity range are widely available. Some manufacturers are building compressors to be used with more than one type of refrigerant type, example R-410A and R-454B.

2.6.3 Packaged and Central Split units (ACCU+AHU) > 85 KW up to 340 kW

This capacity range has the lowest demand in number of units. . The units in this range use single large capacity scroll compressors or multiple smaller capacity compressors. In some capacity ranges, screw compressors are used, but rarely any reciprocating compressors. The majority of units with scroll compressors use R-410A and very rarely R-407C. Reciprocating compressors use either HFC-134a or R-

407C, and screw compressors use mainly HFC-134a. Higher energy efficiency scroll, and screw inverter compressors are available for this capacity range.

The new alternative refrigerants for this cooling capacity range are mainly HFC-32, R-454B, and R-452B. All these refrigerants have better efficiencies than R-410A. Split units however are not available because they would exceed the maximum allowable refrigerant charge. Safety regulations do not allow higher refrigerant charges than those listed in ISO standard 5149. However, some manufacturers have designed units with multiple compressors to reduce the amount of refrigerant charge per circuit.

2.6.4 Packaged and Central Split Units (ACCU+AHU) >340 kW

In this capacity range, multiple scroll compressors are used, the majority using inverter technology. Screw compressors, single or multiple, are used for larger capacities. Screw compressors can be either with inverter or with a slide valve mechanism for capacity control, both provide higher efficiencies than other types of compressors, especially reciprocating.

Scroll compressors mainly use R-410A, with the recent introduction of HFC-32, R-454B, and R-452B. Many systems in the Middle East have units with HFC-134a refrigerant although the efficiency is lower than the scroll compressors using R-410A.

Screw compressors run on the recently introduced R-513A and HFO-1234ze refrigerants.

2.6.5 Multi-split and Variable Refrigerant Flow Systems (VRF)

Multi split units have one outdoor condensing unit connected to up to five indoor units with cooling and heating capacity range up to 12 kW. Systems use scroll or rotary compressors and use R-410A a with several manufacturers already offering multi-split systems in Europe using HFC-32.

VRF variable refrigerant flow systems (VRFs) are more efficient than constant flow. VRFs have a larger capacity with single or multiple (up to four) outdoor condensing units with a max capacity per unit of 90 kW connected to max 64 indoor units. Currently most of these systems use R-410A, with some manufacturers offering small capacity VRFs with HFC-32. Systems with HFC-32 are available with extra measures such as leak detectors, forced ventilation, and shut-off valves.

2.6.6 Chilled Water Systems (Chillers) Air Cooled and Water Cooled 10 kW to 85 kW

In this category, higher capacity chillers are the most common, using either scroll or reciprocating compressors. Scroll compressor units mainly use R-410A and R-407C and sometime HFC-134a. Reciprocating compressors mainly use R-407C and HFC-134a. Alternative refrigerants HFC-32, R-454B, R-452B are available for use with scroll compressors. Some manufacturers are using R-513A in this capacity range; however, its efficiency is less than that of HFC-32 (which also has a higher efficiency than R-410A). Chiller units are available with HC-290 but with limited sales because of the market readiness to use flammable refrigerants. For capacities above 70 kW, R-744 chillers have been introduced in certain parts of the market with moderate or cold climates. R-717 chillers are available for comfort cooling above 70 kW, however higher initial cost impacts the decision on their application.

2.6.7 Chillers 85 kW to 340 kW

The chiller systems in this medium capacity range use single or multiple screw compressors with invertor or slide valve capacity control or scroll compressors with or without invertors. Screw compressors use HFC-134a, while scroll use R-410A. Recent analysis showed that in 2019, inverter chillers contributed to 29% of the global market share by volume (source BSRIA).

Refrigerants used in this range are HFC-32, R-452B, R-454B for scroll compressors and R-513A, HFO-1234ze, HFO-1234yf and R-717 for screw compressors and R-744 with reciprocating compressors. HC-290 is available for both scroll and screw compressors. Compressors for these refrigerants are wildly available.

2.6.8 Chillers > 340 kW

This range of chillers of largest capacity uses mainly multiple screw compressors, but occasionally multi-scroll. Centrifugal chillers are mostly used for capacities above 1000 kW. Smaller capacity magnetic bearing centrifugal compressors are mainly used in water-cooled applications, and some air-cooled applications in low ambient temperature countries.

Screw compressors mainly use HFC-134a. Alternative zero/low GWP refrigerants such as HFO-1234ze, HFO-1234yf, R-717, and R-744 are being introduced along with medium GWP R-513A. Centrifugal compressors are mainly using low pressure HFO-1233zd refrigerant which is non-flammable. Chillers using HC-290 are available in this capacity range within the maximum refrigerant charge dictated by safety standards. Once the systems are optimised, newer refrigerants show better efficiency.

2.6.9 Research

Most of the research on larger capacity air conditioners is done by the major manufacturers. In 2018, UNIDO ran a demonstration project with a local manufacturer in Jordan funded by the MLF[14], to test large capacity packaged units (up to 400 kW cooling capacity) using alternative refrigerants HFOs, HFC-32, and HC-290. The units with HC-290 showed better performance in comparison with baseline units with R-407C at three ambient conditions ranging from 2% to 6% and energy efficiency ratio EER values from 4% to 11% higher than the baseline units. Test results for HFC-32 and HFOs also showed improved efficiencies for all tested refrigerants compared to the baseline R-410A refrigerant. The project also included demonstration of safety measures for the prototypes and a cost analysis for the low GWP refrigerant components used in the manufacturing of the prototypes.

2.7 Not in Kind and District Cooling

Not-In-Kind (NIK) technologies are cooling /heating technologies that do not utilize mechanical vapour compression to provide the cooling/heating effect. In this section, widely commercially available technology means that several companies are producing it while commercially available technology means that at least one company is producing it. There are also emerging technologies that have passed the R&D stage and are being set up prior to being commercially availability. Finally, there are technologies that are still in R&D stage which are not yet totally established.

In order to establish the benefit of NIK technologies, the operational lifetime cost (OLC) should be established. The OLC has units of USD/TR.hour[15] and can be calculated as

$$OLC = \frac{NPV(Capex + Opex)}{NPV(TCE)}$$

Where NPV is the net present value of the system in USD, CAPEX, is the capital cost over its expected operational lifetime in USD, OPEX is the operational cost over its expected operational lifetime in USD, and TCE is the total cooling energy over its expected operational lifetime in tons of refrigeration-hours.

2.7.1 Widely available NIK technologies for Central air conditioning/heating and DC.:

There are seven NIK technologies widely available with lower OLC than vapour compression.

- Absorption and geothermal energy
- Adsorption and geothermal energy
- Exhaust recovery and adsorption
- Solar energy and absorption

[14] Decision 81/61 - UNEP/OzL.Pro/ExCom/81/58 – June 2018
[15] TR = Tone of refrigeration. One ton = 3.517 kW

- Direct/indirect evaporative cooling
- Exhaust recovery absorption
- Deep sea/lake cooling

A description of the technologies is available in the RTOC assessment report.

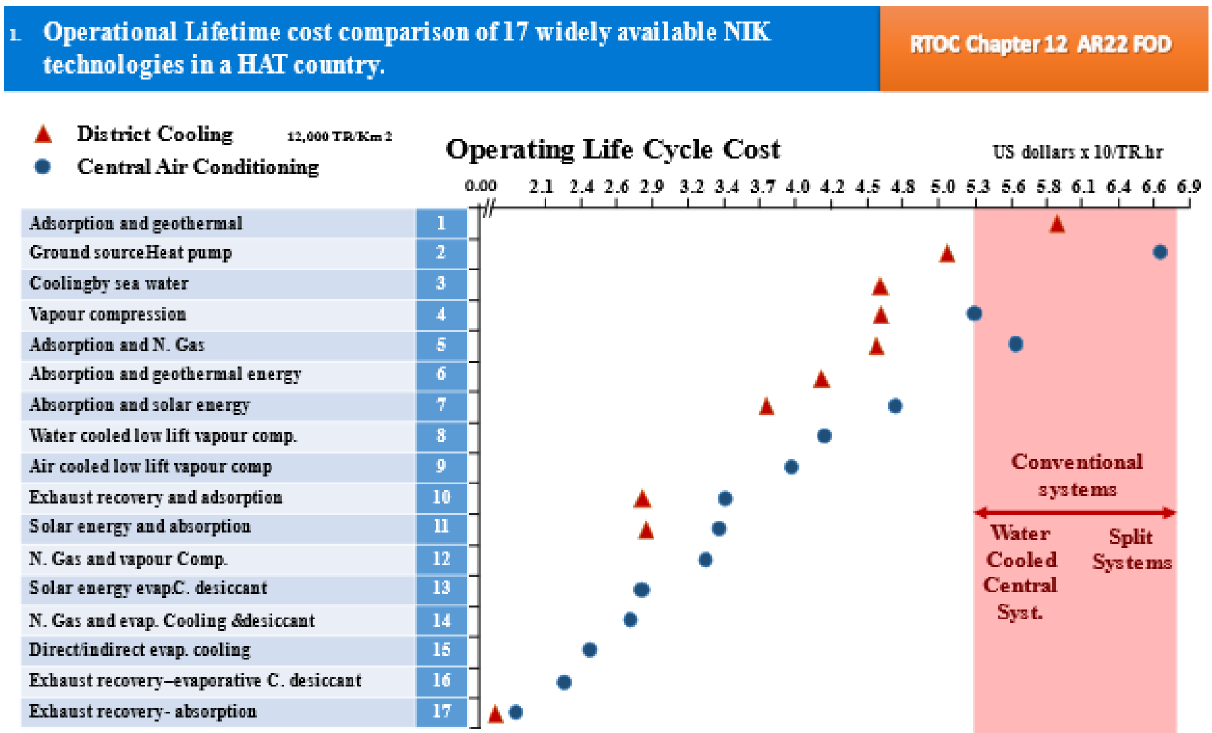

Figure 2.2. Operational lifetime cost comparison of widely used NIL technologies

The use of absorption or adsorption units, fired by geothermal energy, when available, has a better OLC when compared to vapour compression systems, although their capital cost is higher. The use of absorption chillers, direct fired or indirect fired by exhaust heat is an energy efficient solution when recovered heat is available. The OLC of the system is much improved when compared to vapour compression systems, but their capital cost is higher. Solar energy fired absorption systems have a better OLC than vapour compression systems, although their capital cost is much higher, and the space needed for solar collectors may be quite large.

Direct/Indirect hybrid evaporative cooling (IEC) is an attractive solution, especially in dry climates with low OLC compared to vapour compression systems, although the availability of water for its operation can sometimes be restrictive. Finally, Deep Sea Cooling (DSC) especially when coupled with district cooling, provide one of the better OLC values but its capital cost is higher than that of vapour compression cooling techniques.

2.7.2 District Cooling and the availability of Low GWP Technologies that maintain or Enhance Energy Efficiency

A district cooling system is a central air conditioning system that produces and distributes chilled water from a plant(s) to buildings, thus centralizing the production of chilled water and maximizing economy of scale. District cooling has a better overall cost effectiveness during its lifetime compared to systems in individual buildings. It is more reliable, more energy efficient, and has a lower carbon footprint.

District cooling was introduced in Hartford, Connecticut (USA), in 1963 by the Connecticut Natural Gas company to utilize natural gas for air-conditioning. District cooling has benefited from improvements in technologies that have resulted in a renewed interest as an important technology for providing cooling such as:

- Improvement in the efficiency of new chillers
- Improvement in the efficiency of distribution systems pumping
- Better prefabricated, pre-insulated piping suitable for direct burial, thus cheaper distribution systems
- Increased importance of cogeneration systems that have a higher thermal efficiency (70%–85%)

Asia and the Middle East are showing an increasing interest in district cooling, especially around the Gulf region, where it has grown exponentially since the 1990s. Gulf Cooperation Council (GCC) countries are expecting cooling capacity needs to triple between 2010 and 2030. Figure 2.3 shows an expected increase from 127 to 352 million kW (36–100 million TR). The potential district cooling expected additions in three GCC countries totals to 85.43 million kW (24.27 million TR):

- KSA: 44.88 GW[16] (12.75 million TR)
- UAE: 30.20 GW (8.58 million TR)
- Qatar: 10.35 GW (2.94 million TR)

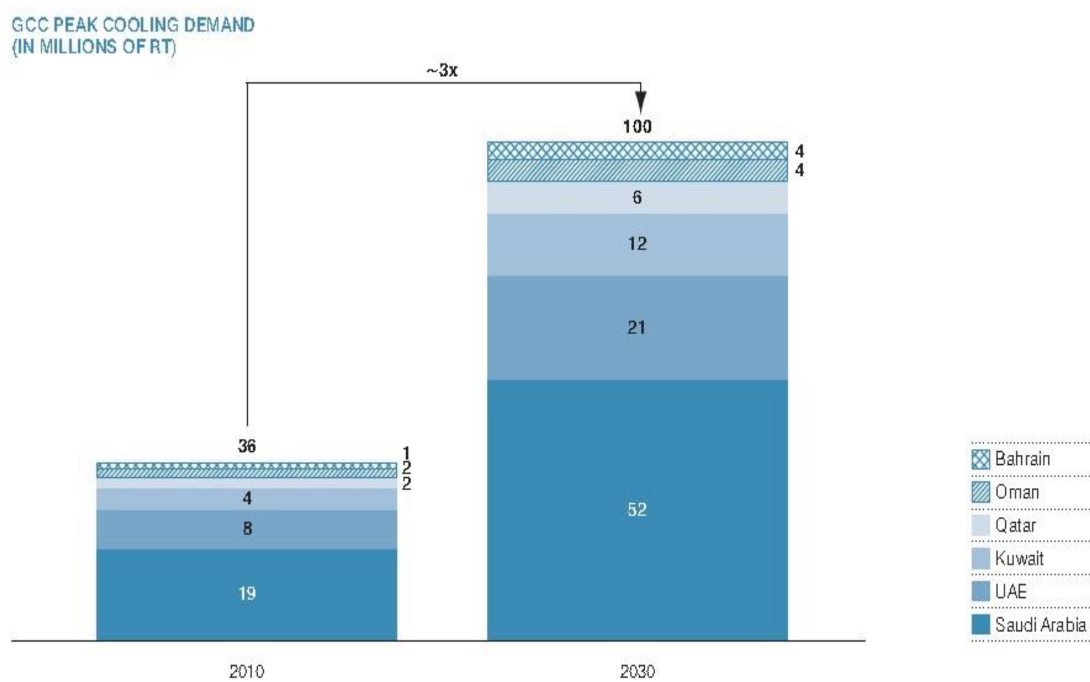

Figure 2.3. GCC peak cooling demand, millions of Refrigeration Tons (TR).

[16] GW = Gigawatt = 1 million kW

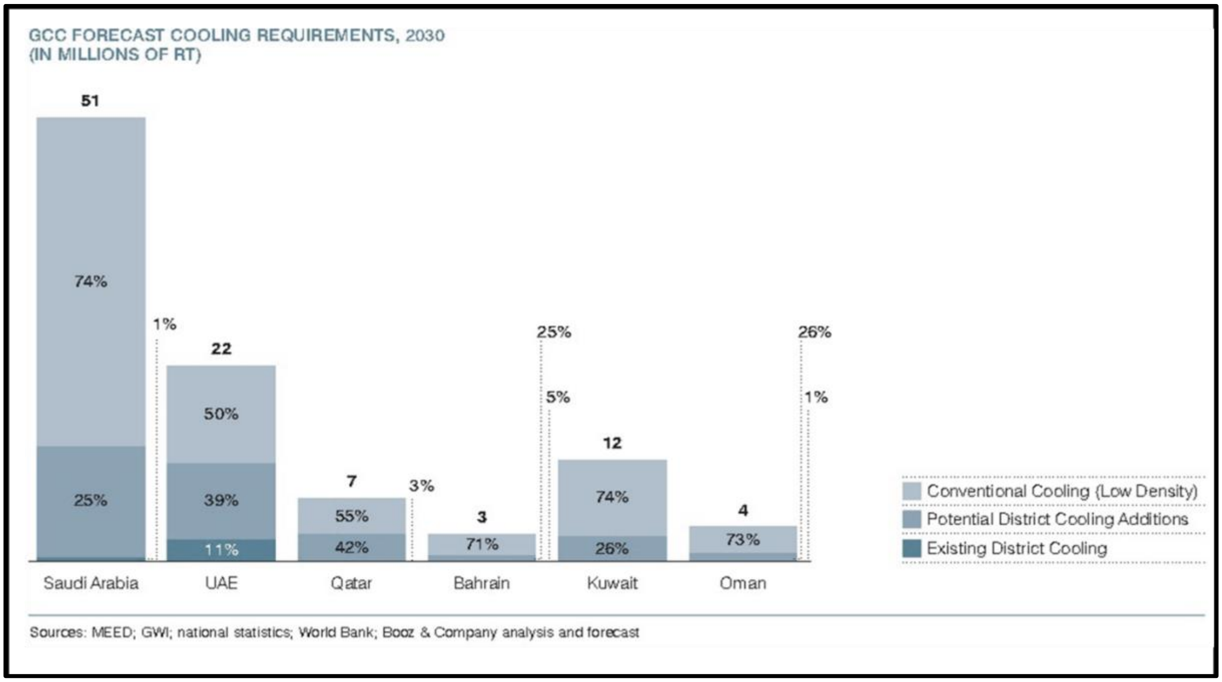

Figure 2.4. Forecast potential district cooling addition in GCC by 2030 (from T. El Sayed et al 2012.

In Europe, more projects are contemplating district cooling, especially now that an increased awareness of environmental issues has shed light on the benefits of district energy and the recognition that district energy can be an alternative solution to these issues.

The United States is the pioneer of district cooling and heating and has set the pace for many years with innovative technologies. Many U.S. states are deregulating their electric utilities. A building owner is capable of buying electricity from producers other than their local provider. Utilities are creating subsidies for electric-driven district cooling systems, offering customers an alternative service using electric power. Demand for district cooling is expected to increase with these measures.

The cooling and heating loads of individual buildings peak at different times. This is why the coincident overall peak demand of a district cooling system varies from the sum of each individual building peak demand. Diversity factors are used to calculate the overall peak load of a district cooling system. Those diversity factors may be as low as 0.6 or 0.7 of the sum of individual building peaks demands, in applications where there is a great diversity of use.

Because of its use of diversity factors, district cooling stations have a smaller bank of refrigerants than distributed in-house central systems, thus minimizing the refrigerant charge. When district cooling is combined with Thermal Energy Storage (TES) it reduces the on-peak need of cooling capacity, so that the District Cooling plant(s) can have lower capacity and refrigerant bank, as well as reducing overall energy cost.

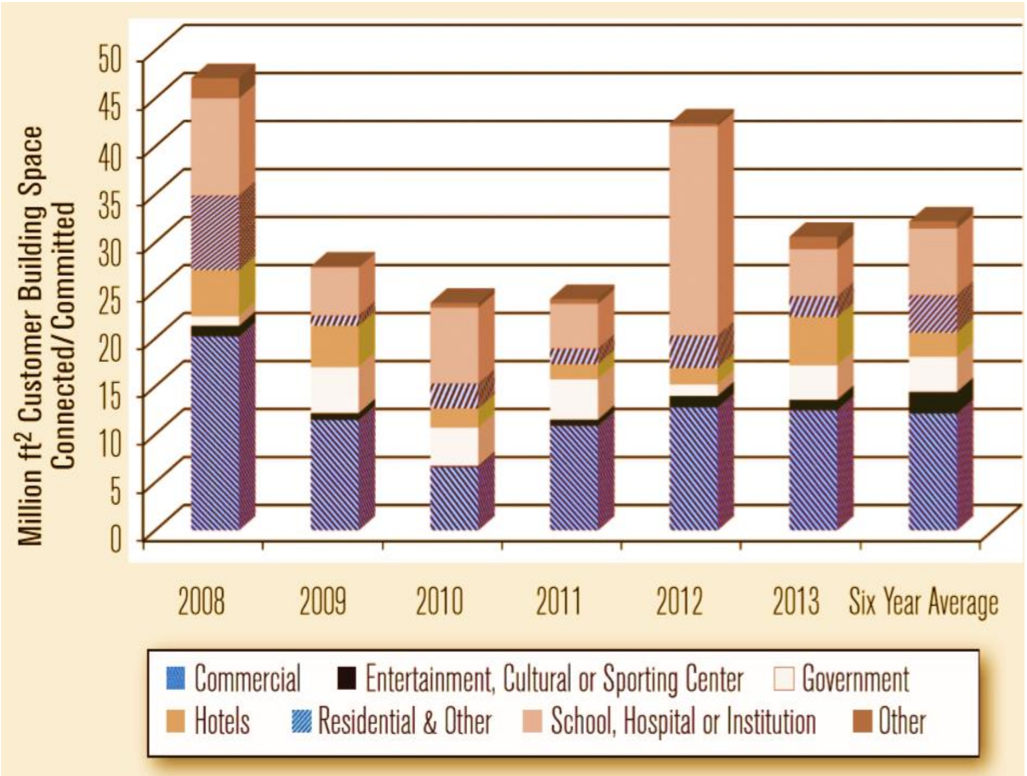

Figure 2.5. Growth of DC in North America (S. Tredinnick et al, 2015)

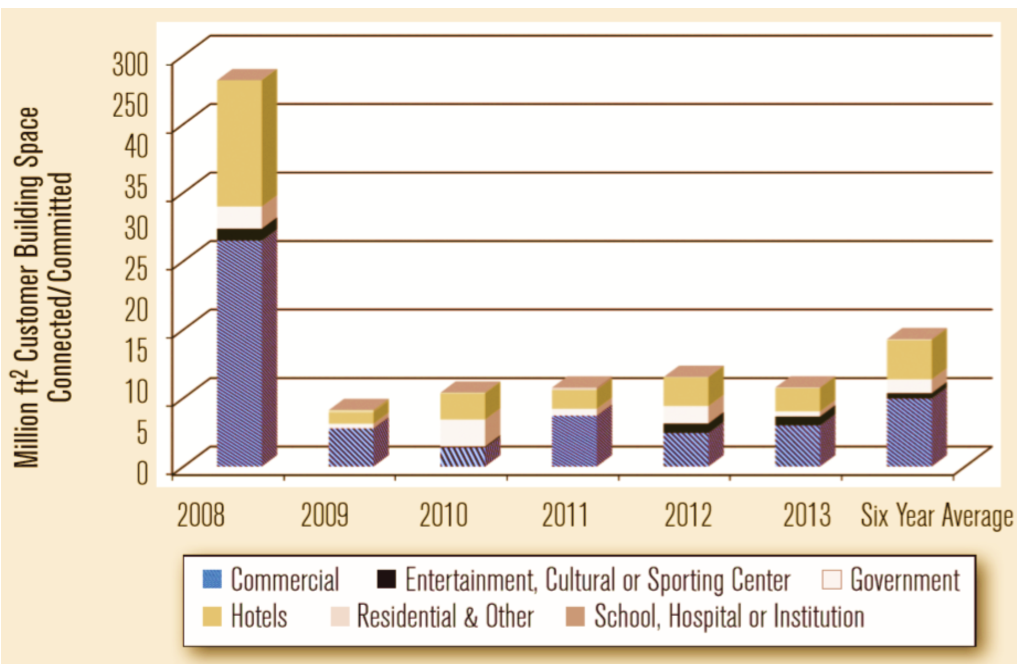

Figure 2.6. Growth of DC in the World except North America, in the same period (S. Tredinnick et al 2015)

2.7.3 Availability of Absorption lithium bromide/water chillers/heaters utilizing water as a refrigerant that maintain or Enhance Energy Efficiency

Absorption chillers/heaters are widely available technologies utilizing ammonia (NH_3) or water (H_2O) as refrigerant, both are natural refrigerant with zero GWP. There are two absorption systems NH_3- water and water- lithium bromide. The denominations of both systems are listed in Figure 2.7 below.

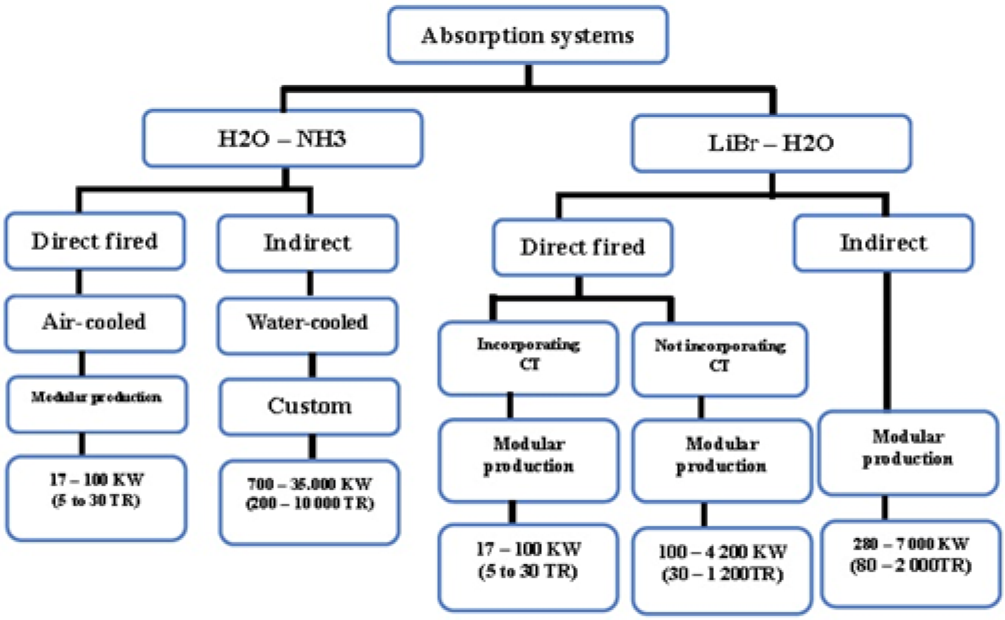

Figure 2.7. Denominations of absorption systems

Recent improvement in absorption chillers

The COP of absorption chillers/heater have improved over the years through the introduction of new technologies. Figure 2.8 shows the improvement in COP in absorption chillers/heaters with the introduction of new technologies. It is important to note that the COP of an absorption unit is a heat ratio and cannot be compared to the COP of an In-Kind unit since the other is a ratio of net refrigeration effect divided by the work exerted. To compare both values, the COP of the In-kind system has to be multiplied by the efficiency of the system providing the electrical energy from the power station all the way to the refrigeration plant.

Rather than raising the COP, the current practice for double effect lithium bromide-water absorption chillers is to decrease electrical consumption of the solution pump by about 50 % and the cooling water pump for the condenser and absorber by about 70 % and thus improving overall performance of the chiller.

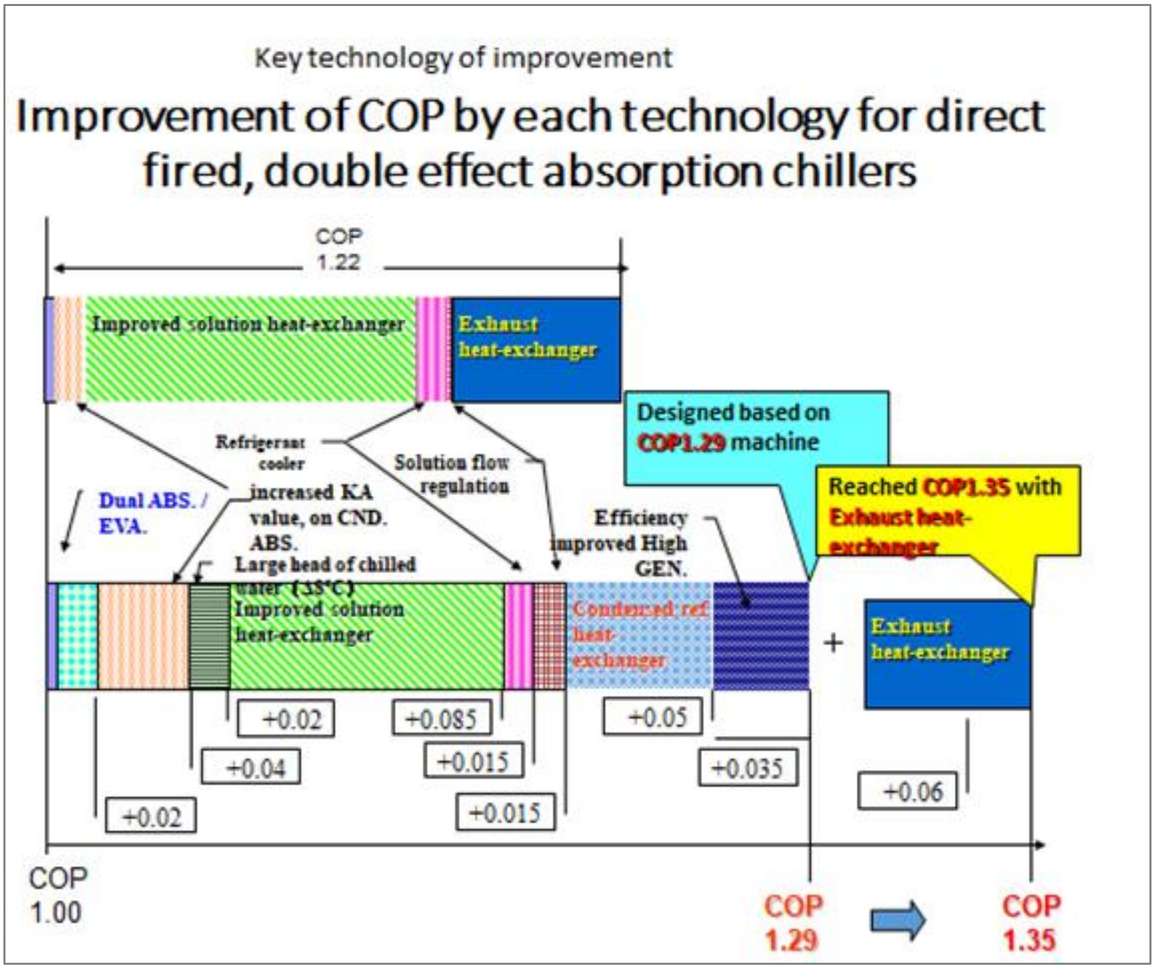

Figure 2.8. Improvement of COP by technology for absorption chillers.

3 Cost of Equipment Using Low and Medium GWP Refrigerants whilst Maintaining or Enhancing Energy Efficiency

Key messages:

- There is a wide range of RACHP equipment and a diversity of refrigerant options (low and medium GWP), which makes it necessary to evaluate material cost impact on a case-by-case basis.
- Refrigerant characteristics play an important role in the design of RACHP equipment in specific relation to maintaining or enhancing energy efficiency. The two main factors which influence the material cost of equipment are refrigerant thermodynamic characteristics (pressure, density, cycle COP etc.) and refrigerant safety characteristics (e.g., flammability/toxicity/pressure). Other factors may also play a role such as material compatibility.
- Flammability and/or toxicity characteristics may limit the acceptable amount of refrigerant for safety reasons and thus limit the cooling or heating capacity and/or energy efficiency that can be achieved. Reducing the refrigerant charge may be possible using different technologies such as microchannel heat exchangers but these can also bring technical and application challenges.

3.1 Introduction

This chapter aims to provide an overview of the cost impacts to RACHP equipment when shifting to the use of an alternative refrigerant (low or medium GWP) while maintaining or improving energy efficiency. It will focus on cost issues that are relevant for most of the RACHP sectors.

Numerous thermophysical properties and their interaction with the system components and operating conditions dictate the system performance Similarly, it is these properties as well as the chemical, safety and some other characteristics that affect the costs associated with the system. This is true for any refrigerant selection. However, when shifting to a low or medium GWP refrigerant for the same RACHP application, these characteristics may be different from the original selected refrigerant, and as such influence the costs.

There are many transactions in the lifetime RACHP equipment causing social and economic costs (from raw materials extraction up to destruction or recycling), which need to be covered somewhere by the "buyers" in the lifetime chain (private costs) and/or by third parties (external costs). Several cost-related aspects were already discussed in previous EETF (2020 and 2021) reports. In this current Decision XXXIII/3 (2022), the EETF task will focus on "material costs" only, based on three steps.

- Step 1: Selecting an alternative (low or medium GWP) refrigerant, at the same RACHP capacity
- Step 2: maintaining energy efficiency, at least linked to the country specific MEPS levels
- Step 3: increasing the energy efficiency to a higher level: Maintaining benchmark refrigerant at the same capacity, and enhancing energy efficiency, which factors are influencing the material costs of equipment?

Equipment transitions may combine a shift to both low or medium GWP refrigerant **and** higher energy efficiency at the same time, but for a good understanding of influencing cost factors it is better to make comparisons based on one variable step at a time.

Implications on material costs will be presented in general terms, to show the direction of change and to some extent the scale of change (e.g., in weight or number of components). Actual material costs impacts would have to be done on a case-by-case basis and can be very complex. Such actual cost analysis was not possible in the remit of this EETF, since there is a vast range of different RACHP equipment and a wide variety of low and medium GWP refrigerants.

Material costs are important considerations from a manufacturing perspective and ultimately result in end user price. It is much more difficult to make comparisons based on the actual price that consumers pay for the equipment (capex) because there are too many other factors in the supply chain (not related to material costs) which determine the ultimate end-user price. Examples are labour costs, patents and royalties, energy prices for manufacturing, transport costs, sales pricing policies of traders, incentives, tax policies, etc. There is also a whole host of other costs – training, service equipment, production line equipment, R&D time, modifications to labs, conferences, establishing new supplies, new product literature etc that are beyond the scope of this report.

Such factors usually fluctuate a lot over time as well as geographically and can therefore distort the link between material cost and final capex, they are therefore not further elaborated on.

Figure 3.1 illustrates why material costs are relevant considerations in the transition to lower GWP refrigerants. The picture shows two types of equipment for small supermarkets (convenience stores), delivering refrigeration (for display cases) as well as comfort cooling and heating (for the total retail space). While both the refrigeration/cooling/heating capacities and the energy efficiency of the two systems are the same for EU average climate conditions, the refrigerant used in the solution at the left (units 1+2 combined) is R-744 (CO_2 - GWP 1) and in the right (unit 3) is R-410A (GWP 2088). The weight of the CO_2 units is 736 kg (unit 1= 173 kg, unit 2= 563 kg) while the R-410A unit 3 weighs 370 kg. The difference in dimensions and mass is due to the different thermodynamic characteristics of the two refrigerants, an issue which will be further detailed in this chapter. When performing a comparison of the two system on basis of a TEWI analysis, the R-744 unit outperformed the R-410A.

Figure 3.1: For illustrative purposes only: comparison of material costs (in size and weight) for a RACHP convenience store solution (different refrigerant, same capacity, and same energy efficiency for EU average climate conditions).[17]

[17] https://www.naturalhvacr4life.eu/

3.2 Cost of low or medium GWP equipment that maintain energy efficiency (at the same capacity)

This section addresses the impact of material costs when RACHP equipment is developed for low and medium GWP refrigerants, assuming that thermal capacity and energy efficiency is maintained at the same level as the original equipment (cfr. step 1 + step 2 mentioned above)

Obtaining the same energy efficiency levels for a given application when converting to any new refrigerant (in this specific case a low or medium GWP refrigerant) will influence the material costs. This is affected by the need for different circuitry, additional or fewer components, component dimensions, necessary surface areas, wall thicknesses and so on. There are added implications arising from different safety characteristics of alternative refrigerants which further impact costs. In combination, assessing the impact of all these factors on the cost of specific systems, let alone product groups or refrigerating systems in general, is extremely complex.

The overall cost is also dependent upon the component and product range applicability (i.e., the impact of economy of scale). In some cases, this can be dependent on the characteristics of the refrigerant itself, and the range of sectors/products that it can be applied to.

Section 3.2.1 gives an explanation of the impact of thermodynamic refrigerant characteristics, followed by an explanation of the impact of choices related to safety characteristics (3.2.2), and, lastly, a variety of other aspects are elaborated upon such as material use (3.2.3)

3.2.1 Impact due to thermodynamic characteristics of the refrigerant

From a thermodynamic point of view, important refrigerant characteristics that influence material costs are cycle efficiency, compressor displacement, compression ratio, discharge temperature, circuit pressure losses and heat transfer properties. A summary of different refrigerants thermophysical properties on material mass requirements is given in Table 3.1. More detailed explanations on the different aspects can be found in Annex 9.3.

Table 3.1: Summary of factors influencing cost

Aspect	Remark	Cost considerations
Thermodynamic cycle efficiency	Higher pressure refrigerants generally have lower theoretical thermodynamic cycle COP. This is offset by other design features which means that there is no direct relationship with actual system efficiency.	Can cancel out due to other effects; depending upon how these are handled in specific applications, costs can be increased or reduced.
Compressor displacement	Higher pressure refrigerants have smaller displacement. Lower pressure refrigerants have a larger compressor.	Usually, no effect on cost; larger displacement offset by thinner walls. If the compressor size is smaller than the motor size, the cost impact is small, but if the refrigerant requires a larger compressor compared to the motor, the cost impact can become significant
Compression ratio	Higher pressure refrigerants have lower compression ratio which helps improve compressor efficiency.	Helps offset lower cycle efficiency.

Aspect	Remark	Cost considerations
Discharge temperature	Higher temperatures can have positive and negative effects on performance and thus cost. There is a maximum discharge temperature associated with a given refrigerant.	May lead to slightly higher or lower Heat exchanger size (and thus cost) or compressor features.
Circuit pressure losses	Pressure losses degrade efficiency and lower pressure refrigerant suffer more as they generally exhibit higher pressure loss (for the same cooling capacity and pipe/component size) than higher pressure refrigerants. However, thermophysical properties of individual refrigerant can have a significant impact, offsetting the negative aspects of lower pressure.	Lower pressure refrigerants either use small (low cost) components and efficiency suffers or use larger piping and components to maintain efficiency but at a higher cost.
Heat transfer	Overall, refrigerants with low molecular weight have better heat transfer. Higher heat transfer coefficients benefit system efficiency, but correct HX design is highly complex and must account for various other aspects.	High heat transfer coefficients may be utilised to design compact and effective heat exchangers with lower cost.

3.2.2 Impact due to safety characteristics of the refrigerant (toxicity/flammability, pressure safety)

Ensuring the requisite safety of RACHP equipment and products involve a wide variety of considerations including

- Pressure (most systems operate under several or tens of atmospheres) This may be more challenging in HAT countries.
- Impact – external surfaces should not injure users or workers
- Electrical – avoidance of shock and fire
- Toxicity – construction materials should not impose toxicity risk or chemical reaction
- Rotating hazards – moving parts
- Combustion/flammability – should not catch fire
- Noise – within acceptable levels
- … etc.

The entity placing the RACHP equipment into use must ensure that the risk posed by all applicable hazards are suitably mitigated during the entire lifecycle of the equipment (not only the use phase) and this is usually demonstrated through risk assessment.

All these considerations are routinely accommodated into the design of RACHP equipment and often have a cost associated with it. In this section, only the additional hazards associated with alternative refrigerants are further addressed.

Examples of refrigerants with corresponding additional hazard are included in *Table 3.2* as well as general mitigation measures required in order to offset the additional risk posed by the additional hazards of the refrigerant.

Table 3.2: Summary of mitigation measures for addressing additional hazards.

Additional hazard	Examples	Mitigation measures
Higher toxicity	R-717	Refrigerant quantity limits, charge minimisation, limited releasable charge, leak detection, ventilation, alarms, increased system tightness, instructions/marking
Flammability	HC-290, HFC-152a, HFC-32	Refrigerant quantity limits, charge minimisation, limited releasable charge, leak detection, airflow/ventilation, alarms, no ignition sources, increased system tightness, instructions/marking
Higher pressure	R-744	Thicker system wall material, additional pressure safety devices, instructions/marking

The means to achieve the various mitigation measures can be highly varied across different types of systems, applications, etc. below is a brief description of some general principles for mitigation measures in RACHP. The reader is referred to Annex9.4 9.4 for additional details.

Refrigerant quantity limits: Refrigerant quantities may be limited according to an "allowable charge limit" (ACL), that is based on the size of the space that the system is located within, installation characteristics of the system and auxiliary equipment and the flammability and/or toxicity characteristics of the refrigerant. Further, there may be an "upper charge limit" (UCL) which is a capped quantity that overrules the ACL. Implementing this measure does not necessarily demand additional hardware. However, further design tasks may be required such as charge minimisation (see below), limited releasable charge techniques (see below) and/or multiple refrigerant circuits. Costs involved are associated with the R&D activities to minimise charge (see below) or applying limited releasable charge techniques (see below), as and when required. Splitting the system into two or more circuits can result in a significant cost increase, up to 1.5 times the cost of the original system.

Refrigerant charge minimisation: refrigerant charge may be minimised through many techniques, such as avoidance of liquid receivers (or if necessary to handle alternate operating modes, reduced to a necessary volume), smaller heat exchanger tubes, smaller diameter interconnecting tubing and compressors with reduced internal volumes and lubricant charge. This typically has a negative cost impact (I.e., cost saving) through reduced refrigerant costs, both at manufacture and in-use, but also reduced construction material costs by means of smaller or lighter components. Additional costs are largely associated with R&D resources involved with sourcing and trialling alternate components.

Limited releasable charge: There are passive and active ways to reduce the released refrigerant, whereby overall risk can be reduced, and refrigerant quantity limits can be more easily satisfied. This can be achieved either using "passive" limited releasable charge (PLRC), which typically accounts only for the mass retained in refrigerant oil and the system volume at atmospheric pressure or "active" limited releasable charge (ALRC), which employs features such as safety shut-off valves to hold charge within the outdoor unit or for an integral system, splits the system internal volume into parts. For PLRC, no additional hardware is required, only to quantify the releasable charge. For ALRC, additional components may be needed. For PLRC, the costs are solely associated with the resources necessary to quantify the releasable charge. The same applies to ALRC and possibly an additional solenoid valve(s), the cost of which is dictated by the tube diameter and may range from a few dollars upwards.

Extract ventilation: Ventilation is required to extract a hazardous mixture and discharge it safely to the open air. Rate of ventilation usually depends upon the quantity of refrigerant that may potentially be released, the objective parameter (flammability limit or toxicity limit) and the volume of the space or enclosure. Ventilation only requires a suitably sized fan, motor and wiring and in some cases ducting to the appropriate external location. This comes at the cost of added development and component costs. It may be approximated as a proportion of the system cost; perhaps <2%.

Integral airflow: Integral airflow can be used to mix a leak with the surrounding air to ensure that the concentration remains below the lower flammability limit (LFL). Airflow is achieved with a fan that is part of the system, a condenser and/or evaporator. Ordinarily, no further costs are involved, except for the resources to check the effectiveness of the existing airflow. Otherwise, additional costs may be a small incremental cost for a larger fan/motor.

Warning alarms: Alarms may be used to warn occupants and workers of a potentially hazardous release of refrigerant and may be audible (siren) or visual (flashing lights) initiated by a leak detection system. Equipment required are primarily alarm speaker units, lamps, cabling, and instruction for occupants to guide their response to the alarm. Costs can be in the tens of dollars upwards.

Leak detection: leak detection system is often required as part of the arrangement involving ALRC, extract ventilation, integral airflow, and warning alarms. A leak detection system involves one or more sensors and a signal processor and controller. There are a wide variety of different sensors and often more than one may be needed. Costs can vary extensively. Gas sensors can be catalytic or metal oxide type, ranging from a few dollars upwards, to infra-red or laser gas detection, which can cost in excess of $1000. Reliability and precision are reflected in the cost. It is expected that economy of scales can drastically reduce the cost of reliable and precise sensors. Ultrasonic sensors are significantly more reliable and are extremely low cost (<$1), although several sensors may be needed, depending upon the equipment they are applied to. Sensors for measuring system parameters include pressure transducers and thermocouples. Whilst the latter have a negligible cost (and may be used anyway) pressure transducer can be in the order of tens of dollars and upwards. Signal processing and control units usually have negligible cost and can nevertheless be integrated into existing electronics of the RACHP equipment.

No ignition sources: to minimise the possibility of igniting leaked flammable refrigerant within the RACHP equipment we must avoid the presence of potential sources of ignition such as electrical arcs and excessively hot surfaces. There is a wide variety of options for avoiding ignition sources. Usually, there will be additional plastic enclosures or dividing plates, depending upon the type and size of equipment and refrigerants involved. Most component manufacturers offer products (compressors, valves, etc.) approved for use with flammable refrigerants. Additional costs can range from negligible to thousands of dollars (e.g., for large industrial installations). In most cases, economically effective approaches have been adopted.

Pressure system materials: pressure-containing walls of piping and components must be of suitable materials and requisite thickness to withstand the refrigerant pressure. In general, a component using a refrigerant of double the saturation pressure will require an additional third of wall material (for the pressure-containing parts). The cost implication depends upon the thermal capacity and the physical size but could be in the order of $5 – 10 per kW of thermal capacity.

Pressure safety devices: pressure safety devices are required on larger systems, where the greatest of any part of the system exceeds a certain value based on the product of the maximum pressure and the volume of the part (pipe, compressor, valve, etc.). Additional pressure limiting switch and/or pressure relief valve may be required. Pressure switches cost upwards of a few dollars and pressure relief valves cost upwards of a few tens of dollars.

Improved system tightness: likelihood of leakage and the possibility of larger leak holes can be reduced by introducing appropriate design and construction measures. Requirements may include better system components and fittings, avoidance of constructional circumstances likely to lead to leakage, more rigorous testing and leak checking and quality control programmes. Some tested and approved components and fittings will be higher cost than basic ones; however, with economy of scale, additional costs should become negligible. More rigorous leak testing requires additional equipment and procedures for production lines and quality control programmes demand additional resources of workers. However, provided the output of a production facility is large enough, additional costs become negligible (per unit produced). Furthermore, regardless of whether the refrigerant is conventional or a more hazardous alternative refrigerant, reduced leakage has significant advantages in terms of better system reliability, lower lifetime service costs and consequent reputational benefits.

Instructions/marking: Information about safe practices needs to be relayed to workers and to users. This additional information usually involves instructions in manuals and marking or signage on the equipment. This would result in additional pages in manuals and adhesive stickers. Material costs are negligible, the main cost implication being associated with sourcing and drafting the relevant information.

Table 3.3 Summary of costs associated with safety measures

Specific mitigation measure	Cost
Refrigerant quantity limits	n/a
Charge minimisation	Negative
Limited releasable charge	Negligible up to cost of sensors and valve(s)
Extract ventilation	Fan/motor assembly and sensors
Integral airflow	Negligible up to cost of sensors
Warning alarms	Sensors, lamps, buzzer/speaker
Leak detection	Sensors, controller
No ignition sources	Negligible up to $1000s, depending upon strategy
Pressure system material	Variable
Pressure safety devices	Variable
Improved system tightness	Negligible
Instructions/marking	Negligible

3.2.3 Impact due to other refrigerant characteristics

Other than the effect of different thermophysical properties and safety characteristics, refrigerants differ according to their chemistry. These may also have an impact on the costs and selection of materials, specifically:

- Metals for piping, heat exchangers, compressors, and other components
- Compressor oils/lubricants

3.2.3.1 Metals for components

Commonly used refrigerants are compatible with copper, steel, aluminium, and particular alloys, broadly known as bronze or brass (e.g., copper, tin, lead, and zinc). Whilst pure R717 is compatible with copper (and alloys), presence of small quantities of moisture can result in corrosion and therefore ammonia systems avoid the use of copper. The need for steel results in the use of heavier refrigerant pipes - which are seamed - and in the use of special accessories, requiring specialized skilled people for fitting and welding, resulting in higher costs for ammonia systems.

3.2.3.2 Compressor oils/lubricants

Compressor oils and additives are carefully selected to suit the refrigerant, compressor type and often, operating temperature range. Common types of oil for different types of refrigerants are:

- HFCs (and unsaturated/HFO) generally use polyol ester oils (POE) and sometimes polyvinyl ether oil (PVE), although the viscosity grade differs.
- HCs may use poly alkylene glycol (PAG) or poly alpha olefin oil (PAO) or conventional mineral oils (MO).
- R744 may use POEs or PAG.
- R717 uses hydrocracked mineral oils (HMO), MO, PAO, and alkyl benzene (AB) oils.

Generally, mineral oils are the cheapest, whilst the synthetic oils are more costly. POE are about double the cost of MO, PAO, and AB about 2.5 times the cost and PAG up to five times.

The quantity of oil depends upon the type and size of compressor. It can be closely linked to the compressor mass and thus independent of the refrigerant type. For instance, for rotary compressors a typical quantity if about 0.03 litres per kg of compressor. In other words, whether a refrigerant is high or low pressure, the quantity of compressor oil is about the same for a given nominal capacity and type of compressor. Thus, any cost impact is primarily associated with the selected oil type, which may or may not be different for a given refrigerant.

3.2.4 Price impact of material mass and refrigerant charge

3.2.4.1 Refrigerant charge

The cost of refrigerant is increasing. In some regions, legislation and quotas can limit the amount of refrigerant available for an industry to use. Safety and environmental justifications also encourage system producers to minimise refrigerant charge.

Refrigerant charge quantity depends on many parameters: temperature levels, refrigerant, energy efficiency, piping length (and diameter), HX design, use and size of liquid receivers and suction accumulators and even compressor selection and oil type. In general, fluorinated refrigerant charge vary in the range of 0.2 to 0.4 kg per kW (of nominal cooling capacity) for air conditioning applications, 0.3 to 0.6 kg per kW for medium-temperature refrigeration and 0.5 to 1.0 kg per kW for freezer temperatures.

Fluorinated refrigerant prices fluctuate depending upon many factors e.g., where and how much is being purchased; market demand versus supply; whether recycled and reclaimed; whether there is a quota system in place; import duties, VAT, etc. The low GWP refrigerants R-744, R-717 and HCs, e.g., HC-290, are in general low-cost refrigerants.

For additional refrigerant cost consideration, the reader is encouraged to refer to the TEAP Report, Decision XXXI/7: for continued provision of information on energy efficient and low GWP technologies, see section 2.1.6.

3.2.4.2 Material choice

RACHP equipment typically use steel, copper, aluminium in the refrigerant circuit (compressors, piping, heat exchangers, etc.). For refrigerants other than R717 (and R744 to an extent), copper is widely used due to its ease of manipulation. Similarly, steel is used for compressors for strength and suitability for manufacturing. Depending upon the type of HX, copper, copper and aluminium, aluminium and steel may be used. For example, finned-tube HX are usually copper tube and aluminium fins, plate HX are steel, shell and tube HX are steel, tube and wire HX are usually steel, pressed-channel HX are aluminium and tube-in-tube HX are usually copper. Choice of material for each type of HX is usually selected to suit the manufacturing process, structural requirements and to some extent, heat transfer and cost, where possible. Aluminium microchannel heat exchangers reduce the quantity of refrigerant and copper needed in RACHP systems are increasingly being used. However, there are several challenges related to their application in certain types of systems, such as, shorter component lifetime particularly in coastal areas and in cities with severe air pollution due to accelerated oxidation, defrosting cycle in heating mode, effective performance in reverse cycle mode and air-side clogging in dusty environments.

Depending upon the type of system, the material cost may contribute to between 10 – 30% of the manufacturer product price, where more complex or higher quality systems and those with wider functionality generally cost more so contribution of material cost is lower. The remaining 70 – 90% of the cost is attributed to production costs – both of the system itself and the components, controls and functional technology, storage and distribution, R&D and, of course, profit. As such, it is estimated that a 10% change in mass of construction material would lead to about 1 – 3 % change in manufacturer product price. Labour and other related costs due to manufacturing, storage, and distribution my result in further increase in manufacturer product price and could only be estimated on a case-by-case basis.

3.3 Cost of enhancing energy efficiency (for same capacity and same type of refrigerant)

In theory, the energy efficiency of RACHP systems can be optimized for any kind of refrigerant to approach the theoretical maximum. However, the practical energy efficiency that can be reached will differ between refrigerants and between equipment types. Accordingly, the costs for energy efficiency improvement are different and difficult to quantify.

Previous EETF reports (2019, 2020, 2021) elaborated on how changes to RACHP equipment designs could further improve energy efficiency, with an indication of the potential impact on component costs. While examples given were mainly related to room air conditioners and self-contained commercial refrigeration equipment, they can also be applicable to other types of RACHP equipment.

Examples given of potential energy efficiency measures given previously include:

- Higher efficiency compressors (multi- stage, inverter driven)
- Optimized fan shapes and fan motors
- Heat exchanger optimisation
- Electronic expansion valves
- Pipe insulation
- Head pressure controls
- Occupancy Sensors
- Considering humidity in comfort considerations
- Smart controls through software
- Condenser air precooling
- Doors on refrigerated display cases

Higher energy efficiency can require larger refrigerant charges, for example because of the increase of the heat exchanger volume. However, how much the heat exchanger can be enlarged may be constrained by installation limitations (indoor as well as outdoor space), while the required increase of refrigerant charge may also be constrained due to flammability and/or/ toxicity limitations. For example, some buildings (depending on climate conditions and building insulation level) may require higher cooling or heating capacities to be installed, thus requiring higher capacity units with larger refrigerant charges, or multiple separate units. In addition, installation characteristics, such as long piping lengths between indoor and outdoor unit also increase the refrigerant charge. This means the maximum potential energy efficiency improvement can be different for applications depending upon cooling/heating loads and piping lengths.

3.4 Examples

Current system designs provide an indication of which refrigerant related material cost impacts for different types of systems. For example,

- Domestic refrigerators almost ubiquitously use R600a, which is a low-pressure refrigerant, yet high efficiency is achieved. One key aspect related to this is that small (reciprocating) compressors can have higher efficiency with lower pressure refrigerants because manufacturing tolerances are easier to achieve.
- Very large chillers often use very low-pressure refrigerants (previously CFC-11 and HCFC-123, nowadays, HFO-1234ze(E), etc. With these, high speed centrifugal or axial compressors can be used and despite potentially high pressure drops, short (wide) pipe runs do not adversely affect cost.
- Large distributed commercial (retail) refrigeration systems use medium-high pressure refrigerants, such as R-744, where the consequence of very long pipe runs can be more easily tolerated with regards to the detrimental effect on efficiency.
- Due to the need for additional safety measures such as detectors, shut off valves and ventilation, VRF systems using HFC32 are less cost-effective compared to R410A VRF systems, whereas the use of HFC32 in small Split AC, residential hydronic heat pumps and scroll compressor chillers result in lower material costs than R410A.

4 Cost Benefit Analysis of Low GWP Technologies and Equipment that Maintain or Enhance Energy Efficiency

Key Messages:

- The Parties to the Montreal Protocol have agreed to maintain or enhance energy efficiency while phasing down HFCs under the Kigali Amendment to the Montreal Protocol. However, in practice, it is difficult to decide what level of energy efficiency is optimal in any particular case, both at a project level and at an economy wide level, for example when setting minimum energy performance standards for equipment.
- Parties may choose to conduct economy-wide or project-specific cost-benefit analyses to maximize benefits to consumers and society from energy efficiency improvement as has been done historically in many economies.
- The US Department of Energy and EU Ecodesign typically conduct in-depth cost-benefit analyses to optimise the level of energy efficiency of equipment.
- Such studies vary in their depth, analytical rigor, and cost from multi-year studies with detailed engineering analysis to short market studies. However, such studies are crucial for understanding the value of energy efficiency particularly in the context of considering investments that may have varying benefits to consumers and manufacturers as well as varying environmental benefits.
- Regardless of the level of energy efficiency invested in, it is very likely that co-ordinated investment in energy efficiency and refrigerant transition will cost manufacturers and consumers less than if such investments are made separately.
- In order to conduct an in-depth cost-benefit analysis of concurrent refrigerant transition and energy efficiency improvement, detailed data is necessary including incremental capital and operational costs.
- General lessons from previous case studies suggest that:
    - Energy Efficiency is more valuable under cases with high hours of use and high electricity prices
    - Lifecycle CO2 savings are higher in cases with high hours of use and high grid CO2 intensity
    - Lifecycle cost savings can far outweigh higher first cost of more efficient equipment
    - In the case of large investments an in-depth analysis is essential.
    - Manufacturers may find higher cash flow and revenue through efficiency improvement

4.1 Methodology

Many economies undertake analyses of various types to support decision makers in setting policies such as minimum energy performance standards (MEPS) or energy efficiency labels.

These vary in their depth, analytical rigor, and cost from multi-year studies with detailed engineering analysis to short market studies. However, such studies are crucial for understanding the value of energy efficiency particularly in the context of considering investments that may have varying benefits to consumers and manufacturers as well as varying environmental benefits.

In particular, cost benefit analyses are conducted by the US Department of Energy and also by the EU Ecodesign to support setting such standards for the United States and the European Union requirement. Below we show two examples of the detailed methodology used in the US and EU context for these analyses.

4.2 US Department of Energy Rulemaking Process

Under the US' Energy Policy and Conservation Act (EPCA), any new or amended energy conservation standard must be designed to achieve the maximum improvement in energy efficiency that the US Department of Energy (DOE) determines is technologically feasible and economically justified. (42 U.S.C. 6316(a)[18]; 42 U.S.C. 6295(o)(2)(A)[19]). DOE evaluates the significance of energy savings on a case-by-case basis, taking into account the significance of cumulative national energy savings, the cumulative emissions reductions, and the need to confront the global climate crisis, among other factors.

The EPCA requires that DOE determine whether the benefits of the standard exceed its burdens by considering, to the greatest extent practicable, the following factors:

- The economic impact of the standard on the manufacturers and consumers of the products subject to the standard;
- The savings in operating costs throughout the estimated average life of the covered products compared to any increase in the price, initial charges, or maintenance expenses for the covered products that are likely to result from the standard;
- The total projected amount of energy (or as applicable, water) savings likely to result directly from the standard;
- Any lessening of the utility or the performance of the products likely to result from the standard;
- The impact of any lessening of competition that is likely to result from the standard;
- The need for national energy and water conservation (42 U.S.C. 6316(a)[20]; 42 U.S.C. 6295(o)(2)(B)(i)(I)-(VII)[21])

EPCA requirement	**US DOE Analysis**
Significant Energy Savings	• Shipments Analysis • National Impact Analysis • Energy and Water Use Analysis
Technological Feasibility	• Market and Technology Assessment • Screening Analysis • Engineering Analysis
Economic Justification: 1) Economic impact on manufacturers and consumers 2) Lifetime operating cost savings compared to increased cost for the product 3) Total projected energy savings 4) Impact on utility 5) Impact of any lessening of competition 6) Need for national energy and water conservation	• Manufacturer Impact Analysis • Life-Cycle Cost and Payback Period Analysis • Shipments Analysis • Markups for Product Price Analysis • Energy and Water Use Analysis • Utility Impact Analysis • Employment Impact Analysis • Emissions Analysis • Regulatory Impact Analysis

Typically, for the US DOE such analyses are presented in a technical support document (TSD), which is

[18] https://www.govinfo.gov/link/uscode/42/6316
[19] https://www.govinfo.gov/link/uscode/42/6295
[20] https://www.govinfo.gov/link/uscode/42/6316
[21] https://www.govinfo.gov/link/uscode/42/6295

then subject to comments and amended based on the comments received from consumers, manufacturers, environmental and consumer advocates and civil society.

4.3 EU Ecodesign Process

The Methodology for Ecodesign of Energy-related Products (MEErP henceforth) consists of a techno-economic-environmental assessment of a specific product group. This assessment is the main analytical step in the potential implementation of the Ecodesign Directive on a specific product group.

Concerning the identification and the level of stringency of the (potential) Ecodesign requirements for a certain product group, the most important part of the analysis takes place within the techno-economic assessment, at the point when the life cycle cost curve is determined, and the Least Life Cycle Cost (LLCC henceforth) is defined. On the basis of the LLCC and related product environmental impact, Ecodesign requirements for a certain product can be set, aiming to gradually – and sustainably - push the market towards the LLCC. Once the requirements are defined, it is left to individual manufacturers to choose how, and with which technologies, to produce a compliant product (in line with the principle of technological neutrality). The LLCC is unique to each product category, and it provides the optimum level from a regulatory perspective because it minimises the total cost of ownership for the consumer and it pushes all manufacturers, at the same time, to make improvements to their products with existing technologies.

The MEErP is open, iterative, transparent, and utilises a tool (the EcoReport tool) that is free at the point of use and is simple to use whilst being sufficiently complex/ complete in order to capture the main inputs and outputs at product specific level. The EcoReport is a streamlined life cycle-based tool that is openly available, with no presumption or requirement of prior purchase of a commercially available Life Cycle Assessment package.

This methodology was developed to allow evaluating whether and to which extent various energy-related products fulfil certain criteria according to Article 15 and Annex I and/or II of the Ecodesign Directive that make them eligible for implementing measures.

4.3.1 MEErP tasks

Typically, MEErP involves the following 7 tasks with an optional Task 0 as described below.

- Task 1 – Scope (definitions, standards, and legislation);
- Task 2 – Markets (volumes and prices);
- Task 3 – Users (product demand side);
- Task 4 – Technologies (product supply side, includes both BAT and BNAT);
- Task 5 – Environment & Economics (Base case LCA & LCC);
- Task 6 – Design options;
- Task 7 – Scenarios (Policy, scenario, impact, and sensitivity analysis).

Tasks 1 to 4 can be performed in parallel, whereas 5, 6 and 7 are sequential. Task 0 or a quick scan is optional to Task 1 for the case of large or inhomogeneous product groups, where it is recommended to carry out a first product screening. The objective is to re-group or narrow the product scope, as appropriate from an ecodesign point of view, for the subsequent analysis in tasks 2-7. This process is illustrated in Figure 4.1.

4.3.2 Involvement of stakeholders

The European Commission gives stakeholders the opportunity to provide input to this study thereby creating a transparent and open process. This website is the main information exchange platform between the study-team, the Commission, and the stakeholders.

All documents will be freely available through this website. Registered stakeholders receive notifications on website updates. Furthermore, stakeholders can provide direct feedback to draft reports published on this website and make suggestions for energy-related products. Comments and suggestions may be made public on this website. Stakeholders can also provide other non-public comments directly to the study team.

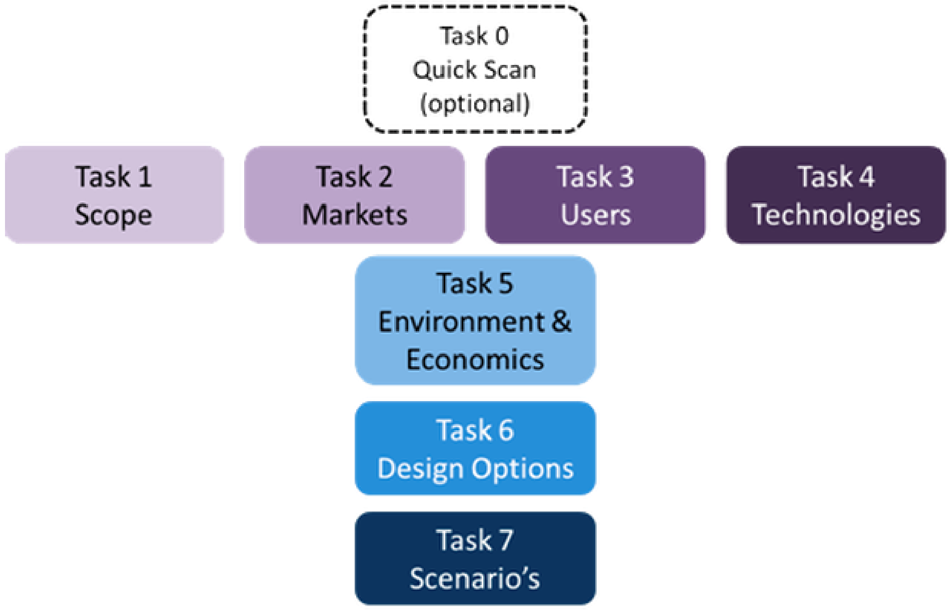

Figure 4.1. Revision of the MEErP methodology.[22]

4.3.3 MEErP Structure

The overview of all activities foreseen in the MEErP is presented in the Annex under MEErP Methodology Structure. The relevant parts are repeated at the outset of each of the following chapters, but this complete overview also serves to provide the Commission with a comprehensive format for administrative purposes.

4.4 Data needs

In order to conduct a cost-benefit analysis to determine the level of energy efficiency that is economically justified in terms of affording consumers the least lifecycle cost or shortest payback period, various types of data are needed as follows:

- Cost vs Efficiency (Engineering analyses)
    a. Energy savings estimates from more efficient components (these can be obtained from experimental measurements and also from appropriately validated design simulation models)
    b. Cost estimates for more efficient components
- Retail prices for baseline and efficient equipment (These typically include manufacturer and retailer markups and any applicable sales taxes)
- Installation cost estimates

[22] https://susproc.jrc.ec.europa.eu/product-bureau/product-groups/521/home

- Energy use estimates (These typically include hours of use, load, climate (e.g., cooling or heating degree days) and other related parameters used to estimate annual energy consumption for baseline and more efficient equipment)
- Electricity prices and price trend or forecasts
- Product lifetime (or survival function)
- Discount rates
- Price indices (consumer and producer)

Additionally, in order to conduct a manufacturer impact analysis and calculate the investment need for manufacturers additional data estimates are needed as follows:

- Tax rate
- Working capital
- R&D costs
- Depreciation
- Cost of capital

4.5 Benefits of Co-investment in energy efficiency and HFC phasedown

The Parties to the Montreal Protocol have agreed to maintain or enhance energy efficiency while phasing down HFCs under the Kigali Amendment to the Montreal Protocol. Regardless of the level of energy efficiency investment, it is likely that coordinated investment in energy efficiency and refrigerant transition may cost manufacturers and consumers less than if such investments are made separately. Figure 4.2 conceptually illustrates this possibility.

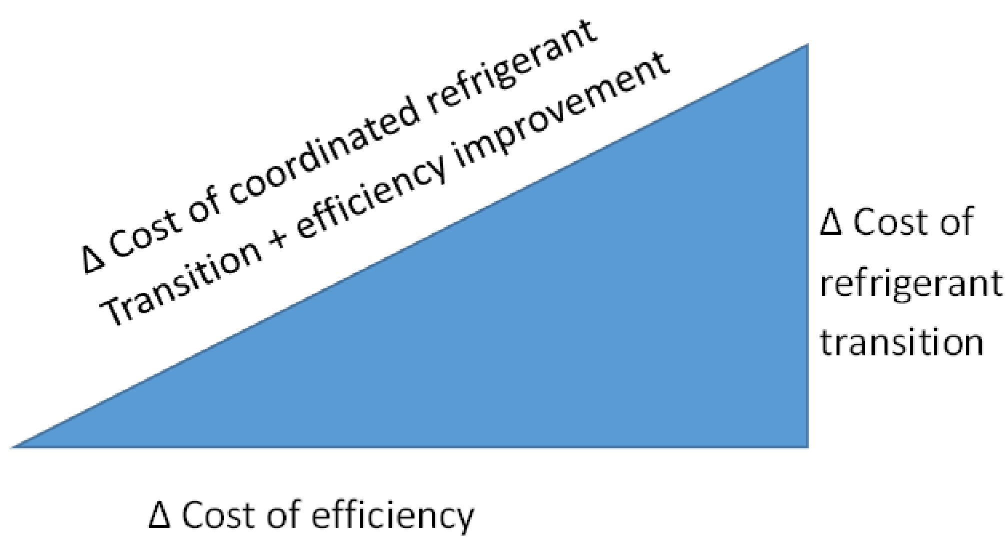

Figure 4.2. Illustration showing the benefit of coordinated refrigerant transition and efficiency improvement.

Sufficient data is not available to perform an “apples-to-apples” comparison of the combined benefits of coordinated investment in energy efficiency and refrigerant transition with the same investments conducted separately. However, prior Task Force reports have estimated the costs of combined energy efficiency and refrigerant conversion in selected cases.

The following are a few categories of conversion costs that may be reduced if coordinated investments are made in simultaneous energy efficiency improvement and refrigerant conversion versus separate investments in each.

- Equipment design and optimization costs
- Prototyping costs
- Testing costs
- Component and conversion costs for heat exchanger and compressor assembly lines
- Opportunity costs due to stoppage of manufacturing lines

4.6 Case Studies

While presenting the full results of the many cost-benefit analyses on energy efficiency of RACHP equipment done in recent years are beyond the scope of this report, we present a few examples of the results of such studies for policymakers for a few different geographies and equipment types to highlight a few common themes for the consideration of the Parties.

4.6.1 Mini-split ACs - (India Example)

Table 4.1 shows the cost of efficiency improvement for mini-split ACs of 1.5 tons (5.27 kW) cooling capacity in India, with the costs of higher efficiency components shown in Indian Rupees (Rs) (1 rupee = 0.0156 USD in 2015). (Shah et al, 2016). The "UA value" is the combined area and effectiveness of the heat exchangers (condenser and evaporator) where U ($W/m^2/K$) is the overall heat transfer coefficient and A is the area. These costs are then used to estimate the cost of manufacturing higher efficiency equipment at various energy efficiency levels.

Table 4.1. Incremental costs of efficiency improvement for 1.5 Ton (5.27kW) minisplit ACs in India in 2015. (Shah et al, 2016)

Component	Energy Savings from Base Case[1]	Incremental Manufacturing Cost (Rs)		Retail Price Increase from Base Case (Rs)[2]	
		Baseline	Range (50% lower to 50% higher than baseline)	Baseline	Range
Baseline Compressor (2.8 EER), 1.5 TR Cooling Capacity	-	-		-	
3.0 EER compressor	5.5%	200	100-300	480	240-720
3.2 EER compressor	10.5%	400	200-600	960	480-1440
3.4 EER compressor	15.0%	575	280-860	1,380	690-2070
Alternating Current Compressor variable speed drive	21.0%	3,600	1800-5400	8,640	4320-12960
Direct Current Compressor variable speed drive	23.0%	5,400	2700-8100	12,960	6480-19440
Variable speed drives for fans and compressor	26.0%	6,300	3150-9450	15,120	7560-22680
UA value of both heat exchangers increased by 20%	7.5%	1,470	735-2200	3,528	1760-5290
UA value of both heat exchangers increased by 40%	13.5%	3,240	1620-4860	7,776	3880-11660
UA value of both heat exchangers increased by 60%	17.5%	4,210	2100-6310	10,104	5050-15150
UA value of both heat exchangers increased by 80%	21.0%	6,080	3040-9120	14,592	7300-21890
UA value of both heat exchangers increased by 100%	24.0%	7,350	3675-11000	17,640	8820-2640
Thermostatic Expansion Valve	3.5%	250	125-375	600	300-900
Electronic Expansion Valve	6.5%	1500	750-2250	3600	1800-5400

Table 4.2 shows the results of the cost-benefit analysis for two energy efficiency levels, at 3.5 and 4 ISEER (Indian Seasonal Energy Efficiency Ratio) (W/W). As can be seen in this example, for higher hours of use the higher lifetime energy savings lead to a lower payback period over the lifetime of the energy efficient equipment, thus justifying an investment in higher energy efficiency. Similar sensitivity analysis would show lower payback periods for higher electricity prices as well.

Table 4.2. Range of retail price increase bill savings and payback period for 3.5 and 4 ISEER mini-split ACs in India.

ISEER (W/W)	Retail price increase required to cover the cost of efficiency improvement (Rs. %)	Bill savings per year for 1000 & 1600 hours of use (Rs.)	Bill savings over lifetime for 1000 & 1600 hours of use (Rs.)	Simple payback period for 1000 & 1600 hours of use (years)
3.5	4900, ~15%	2625 -4200	18300 -29400	1.9-1.2
4	9360, ~27%	3950- 6300	27500-44100	2.4-1.5

4.6.2 Commercial AC (China)

Table 4.3 shows the cost of efficiency improvement for variable refrigerant flow (VRF) AC systems in China in 2020, with the costs of higher efficiency components shown in Chinese Yuan (1 yuan = 0.145 USD in 2020) (Karali et al, 2020). As in the previous example, these costs are then used to estimate the cost of efficiency improvement at various energy efficiency levels. Figure 4.3 shows the estimated bill savings and net benefit over the lifetime of the system at various energy efficiency levels in terms of Annual Performance Factor (APF) in thousands of Yuan.

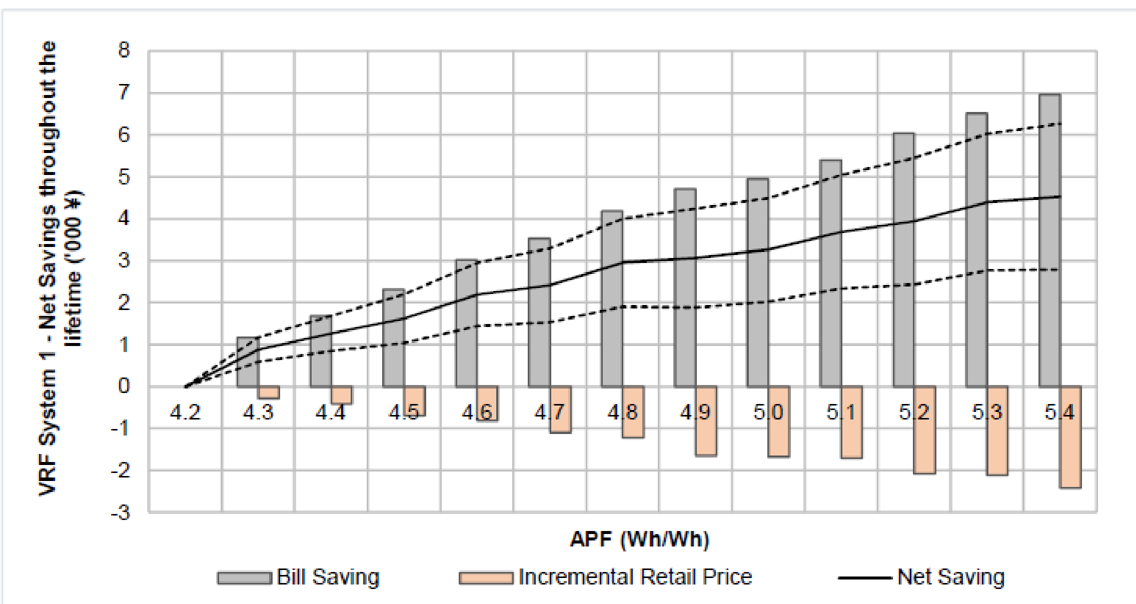

Figure 4.3. Estimated bill savings and net benefit over the lifetime of the system for different efficiency (APF) levels.

Table 4.3. Incremental Manufacturing Cost and Energy Savings for high efficiency components for Variable Refrigerant Flow (VRF) air-conditioning systems in China

	Component	Manufacturing Cost (¥)	Energy Savings from Baseline
Compressor			
Baseline Compressor	with DC inverter, i.e., VSD	2,300	-
Efficient Compressor 1	with DC inverter, i.e., VSD	2,470	5.9%
Efficient Compressor 2	with DC inverter, i.e., VSD	2,830	11.0%
Efficient Compressor 3	with DC inverter, i.e., VSD	3,190	15.5%
Multiple Compressors 4-7	DC+DC VSD compressors for each design options listed above	2x for each design options listed above	24.0%
Multiple Compressors 8-11	DC VSD + FSD compressors for each design options listed above	1.4x for each design options listed above	19.2%
Inverter			
All DC inverter	DC inverter for fans	460	5.3%
Heat Exchanger (HE)			
Baseline HE	-	1,216	-
Efficient HE 1	UA of both HEs increased by 20%	1,459	8.3%
Efficient HE 2	UA of both HEs increased by 40%	1,702	14.2%
Efficient HE 3	UA of both HEs increased by 60%	1,946	19.0%
Efficient HE 4	UA of both HEs increased by 80%	2,489	22.3%

Source: Costs are based on inputs from Chinese VRF system manufacturers. Energy savings are adjusted from Riviere et al. (2009) based on reported savings change between capacities.
Note: U ($W/m^2/K$) is the overall heat transfer coefficient, A (m^2) is the total heat exchange area. The VRF system with the baseline compressor has a system rating of 3.3 EER.

4.6.3 Heat Pump Case Study (EU)

A preparatory study for space and combine space and water heating was conducted as part of the revision of the Ecodesign and Energy labelling regulations in 2019 (EcoDesign, 2019). Heat pumps are included as one of the multiple technologies for heating. As in the previous examples, various energy efficiency improvement options were studied, and the cost of energy efficiency improvement was estimated for different "design options," i.e., combinations of more efficient components. Figure 4.4 shows the lifecycle costs and annual energy consumption for various design options for heat pumps in the EU.

Figure 4.4 shows that the least lifecycle cost occurs for a different design than the least energy consumption due to different incremental costs of manufacture of the design options. Hence, this example also shows the importance of conducting a cost-benefit analysis to estimate the most cost-effective level of energy efficiency to aim for maximizing the benefits to consumers, which may not coincide with the highest technically feasible energy efficiency.

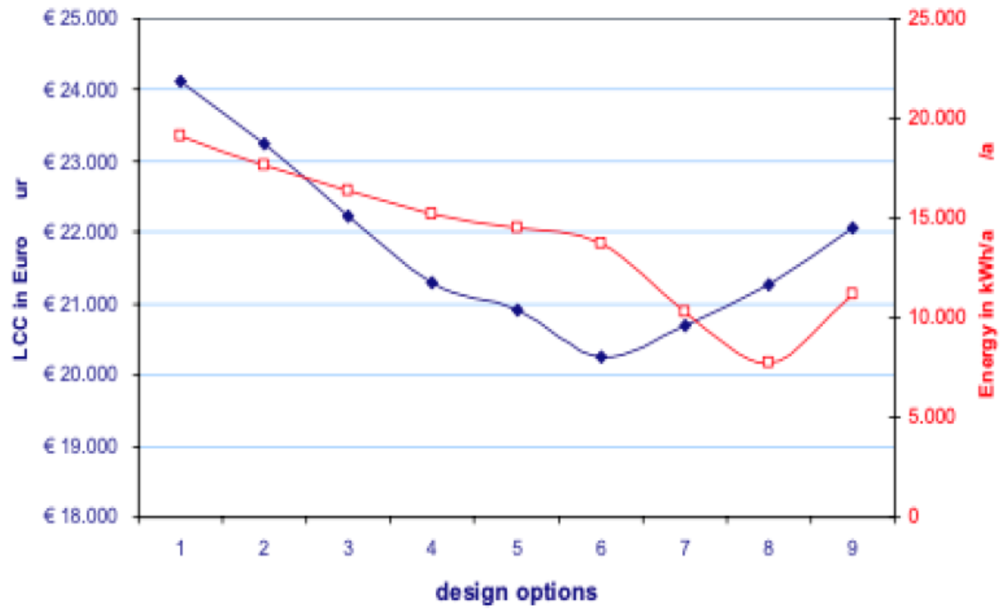

Figure 4.4. Life cycle cost and annual energy consumption for different design options.

4.6.4 Mini-split ACs - Brazil

A regulatory impact analysis led by ICS and LBNL was used to support revision of the MEPS for residential mini-split ACs in Brazil (Letschert et al. 2019), and found the revision, technically feasible and economically justified. Some results are highlighted below, further details can be found in the published study.

Through an estimate of the manufacturer costs and industry net present value (INPV) of setting higher MEPS, the study showed that the change in INPV was highly positive, meaning that manufacturers will benefit by switching their production to higher efficiency technology. According to the study results, similar investments would be required for achieving more modest efficiency levels, which manufacturers do not recover through future revenues. Higher MEPS also provide larger consumer and national benefits. Manufacturers cost, based on different scenarios are presented in Table 4.4. Life-Cycle Cost and Payback Period Results can be seen in the following Table 4.5.

Table 4.4. Manufacturers Cost Impact Analysis (Letschert et al., 2019)

	MEPS EER* = 3.23	**MEPS EER = 3.44**	**MEPS EER = 3.50**	**MEPS EER = 3.98**	**MEPS EER= 4.8**
CSPF**	3.64	3.77	5.36	6.84	8.65
Manufacturing Costs (million R$)	7.7	26.6	43.7	45.7	45.7
Capital Conversion Costs (million R$)	16.3	56.2	73.9	86.6	86.6
Total Investment needed (million R$)	24.1	82.8	117.6	132.4	132.4
INPV variation (million R$)	-18.3	-26.9	243.6	397.7	916.7

** EER is the energy efficiency ratio, W/W*

*** CSPF is the cooling season performance factor*

Table 4.5. Life-Cycle Cost and Payback Period Results for 1-RT, Mini-split ACs. (Letschert et al., 2019)

Efficiency Level (EL)	Market-Weighted CSPF	Average Purchase Price	UEC (Unit Energy Conservation)	Average Electricity Bill	Average LCC	LCC Savings	Payback Period
	W/W	R$*	kWh/year	R$	R$	R$	years
BAU (3.02)	3.60	1,258	469	309	3,411	-	-
MEPS at CSPF= 3.43	3.64	1,261	463	306	3,388	23	0.7
MEPS at CSPF= 3.65	3.77	1,289	447	295	3,342	69	2.10
MEPS at CSPF= 5.34	5.36	1,474	313	206	2,910	501	2.13
MEPS at CSPF= 6.83	6.84	1,578	243	160	2,692	719	2.14
MEPS at CSPF = 8.65	8.65	1,897	191	126	2,773	637	3.5

** The US dollar quotation ended 2018, the year the study was performed, at R$3.88 to US$1*
Note 1: Life-cycle cost and payback-period calculations use an electricity rate of R$0.66/kWh, which is a weighted average between residential and commercial customers (ANEEL, 2018a; ANEEL, 2018b; Mitsidi Projetos, 2018). The life cycle cost calculation uses a 10.5 % discount rate and assumes a lifetime of 10 years based on stakeholder feedback. We adjusted UECs based on ACs being used 3.1 hours per day in the residential sector and 3.9 hours in the commercial sector (Mitsidi Projetos, 2018), from UEC results in accordance with the ISO 16538 method based on 1,817 hours per year (about 5 hours per day)'

The ICS/LBNL study also indicated that “at the highest level analysed (i.e., at the estimated technical potential), Brazilian consumers save R$27 billion through 2035, and the power sector avoids 4.5 GW of demand (worth an additional R$30 billion) – representing R$400 in consumer/national benefits for every R$1 invested in manufacturing high efficiency ACs. In addition, higher MEPS result in substantial national CO2 reductions, which could be increased further by simultaneously and cost-effectively transitioning to refrigerants with low global warming potential (GWP) in accordance with the goals of the Kigali Amendment to the Montreal Protocol”

4.7 Lessons Learned

While one case study does not fit all cases that will be encountered by Parties in conducting cost benefit analysis to determine the level of energy efficiency that is cost effective in any particular economy or for any particular equipment type, in reviewing case studies mentioned above and also others in various economies a few general lessons can be learned as follows:

- Energy Efficiency is more valuable under cases with high hours of use and high electricity prices
- Lifecycle CO_{2eq} savings are higher in cases with high hours of use and high grid CO_{2eq} intensity
- Lifecycle cost savings can far outweigh higher first cost of more efficient equipment

5 Short Term Roadmap for Adoption of Energy-Efficient Technologies While Phasing Down HFCs

Key messages:

- Roadmaps for adopting energy-efficient technologies while phasing down HFCs will vary based on national circumstances. These approaches can benefit from a common set of policies that would support these technology transitions. These include sector-specific and cross-cutting policies like integrated energy and refrigerant performance standards and labelling, best practice performance metrics and test procedures, enabling building energy and safety standards, support for ongoing service sector training, and monitoring, compliance, and enforcement. Several country specific case studies are provided in Annex9.5
- The technology transition would be supported by coordination between National Ozone Units and national energy and climate authorities especially through the integration of lower GWP HFC standards into energy efficiency standards and labelling policies
- Raising awareness across government institutions and community-based consumer programmes can speed adoption of energy-efficient and low-GWP equipment, and increase access to additional financing mechanisms, such as through electricity utility efficiency programs and bulk procurement programs.
- Where A5 parties do not have the capacity to prescribe and enforce laws to prohibit shipping of obsolete products, the local and global harms inflicted as a result of increased environmental dumping in these most-vulnerable jurisdictions necessitate that non-A5 exporting parties share responsibility with A5 recipient countries to prevent the environmental dumping of obsolete products.

5.1 Brief overview of chapter and links to other chapters

The 2019 EETF report highlighted in Chapter 5 the importance of enabling policy for supporting market transformation to energy-efficient and lower-GWP equipment. This chapter provides a brief overview and example roadmap of these enabling policies by sector. The latest HFC alternative technologies will be assessed in a TEAP report due in 2022.

We will briefly elaborate on what is contained with the table for each sector, including discussion on relevance to Parties that have manufacturing enterprises for the sector or are importing only. Case studies pointing to examples of policies and implementation welcome, including list of relevant international standards and links, where relevant. The description of the different sectors is provided in Annex 9.2\9.2

The following list is a summary of the 8 Case Studies presented in Annex 9.5:

- Case Study 9.5.1 Integrating EE and refrigerant (GWP) performance in labels, Germany and Brazil
- Case Study 9.5.2 Integrating refrigerant in endorsement labels: US Energy Star adds lower GWP refrigerant filter, United States and Canada
- Case Study 9.5.3 Introduction of Standards and Labelling, breaking the price myth, Ghana
- Case Study 9.5.4 Brazil: Kigali Network- Civil Society Engagement and Awareness, Brazil
- Case Study 9.5.5 Super-Efficient Room Air Conditioner (SEAC) Programme, India
- Case Study 9.5.6 Linking refrigerant transition to utility energy efficiency obligations, United States (California and Washington)
- Case Study 9.5.7 Trigeneration integration in Data Centres across India, India
- Case Study 9.5.8 Market-based financial mechanism for domestic refrigerators and air conditioners in sub-Saharan Africa. Senegal, Ghana, and Rwanda

5.1.1 Mini-splits and room ACs

Air-to-air split air conditioners and heat pumps are a large and growing sector both in terms of energy and refrigerant demand (Sachar et al., 2018), with Africa topping the growth forecast with over 4% growth by volume (BSRIA, 2021). Coordination among ozone and energy efficiency policy makers is key to managing the transition to energy efficient and lower-GWP equipment in this sector. Tables 5.1 and 5.2 summarizes the main enabling policies for this transition. The role of policy in influencing the availability of low GWP and high efficiency equipment in markets can be seen in the comparison of the types of equipment produced in China for the domestic market and export markets (Figure 5.1). Fixed-speed room ACs are generally lower efficiency and use higher-GWP refrigerants, including HCFC-22 and R-410A. A 2019 analysis found that none of the variable-speed compressor models identified used HCFC-22 (Nicholson and Booten, 2019).

Best practice policies include integrated energy efficiency and refrigerant GWP performance labels, such as the United 4 Efficiency model regulations, use of seasonal energy efficiency performance metrics, and GWP thresholds (see EETF 2021 Case Study 4.1). Voluntary programs, such as endorsement labels, can also integrate energy efficiency and refrigerant information to help consumers identify more climate-friendly products (see Case Studies 9.5.1 and 9.5.2), and can be used by utility obligation schemes and procurement specifications (see Case Studies 9.5.5 and 9.5.6).

Visible and enforced standards and labelling policies can assist market transformation and counter the perception of high cost (see Case study 9.5.39.5.7). The success of these policies depends on exporters respecting national regulations (see Section 5.4.7).

Previous chapters and EETF reports describe the continuing improvements in energy performance and increasing availability and access to these technologies. A best practice to increase access to more efficient technologies as performance improves is the regular revisiting and strengthening of performance standards and levels. Figure 5.2 provides an illustration of the ratcheting up of performance requirements over time in the United States as an example. Countries or regions with multiple climate zones have also adopted performance levels appropriate to regional climates, with an example from the United States shown in Figure 5.2.

As the industry moves to alternative options to replace high-GWP HFC refrigerants, it is likely that A2L as well as A3 flammability class refrigerants will be used. As refrigerant alternatives become increasingly available (see Chapter 2), updating building codes and safety standards are another set of important enabling policies that have been under development for many years, and need local implementation to support the transition (see Table 5.2).

5.1.2 Heat Pumps

Heat pumps are increasingly used to enhance and improve the overall buildings' efficiency and to enable larger adoption of renewable and/or clean electricity to provide heating and cooling in buildings. As discussed earlier in chapter 2, heat pumps currently employ high GWP HFC refrigerants such as R-410A. However, there is a growing effort to transition to medium and lower GWP refrigerants such as HFC-32, R-454B, HC-290 and R-744 in Europe and Asia. As such, it is important for ozone and energy policymakers to pay attention to this growing category of refrigerant-using equipment in the context of the phasedown of high-GWP HFCs

5.1.3 Commercial HVAC

5.1.3.1 Packaged Ducted Air Conditioners

The efficiency metrics for packaged ducted AC is the Integrated Energy Efficiency Ratio (IEER) (Table 5.2), which has encouraged industry to improve energy efficiency, with growing interest to expand to cover heating and free cooling options which can improve overall efficiency by as much as 40%.

5.1.3.2 Transition towards low and medium GWP refrigerants

Most of "packaged" commercial HVAC has used R-410A, but A2L refrigerants are being introduced. However, because these are direct systems (generally "in a box," see Figure 5.3), safety standards and codes limit the charge of A2L and recently A3 flammability class and category B toxicity. Considerable work has been done to evaluate the use of A2L refrigerants in commercial as well as residential direct systems and new standards IEC60335-2-40 and UL60335-2-40 have been developed to define how to adapt the units for safe application of A2L refrigerants (see Tables 5.2). This includes control of ignition sources, charge management and active mitigation of a potential refrigerant leak. In support of this transition, industry, manufacturers, and safety organizations, including UL FSRI and the fire marshals, have collectively invested over US$10 million in research. At the same time efficiency continues to improve, with assessment in part load metrics.

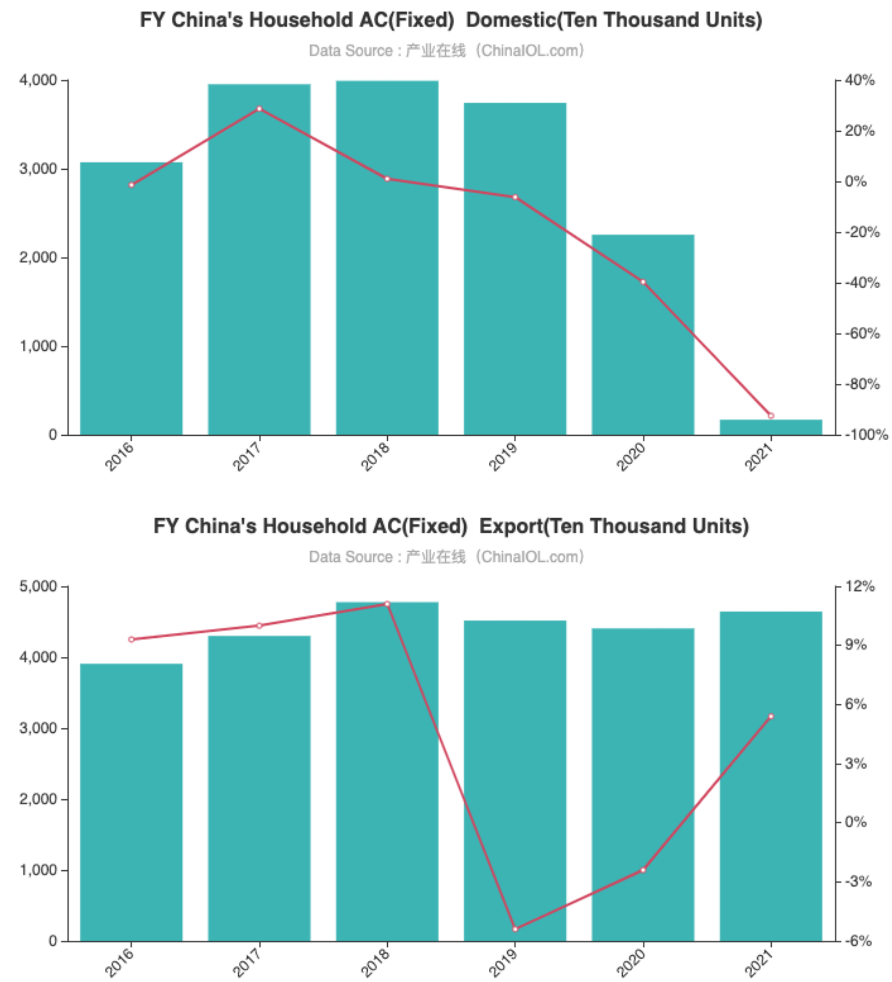

Figure 5.1: Top: Annual production in China of fixed-speed room air conditioners for the domestic market. China released the Green and High-Efficiency Cooling Action Plan in 2019 and revised the energy performance standard for room air conditioners in 2020 (see TEAP EETF 2021 Case Study 1.3).Bottom: Annual production in China of fixed-speed room air conditioners for the export market. Source: ChinaIOL (http://data.chinaiol.com/ecdata/index#, last visited 6 May 2022)

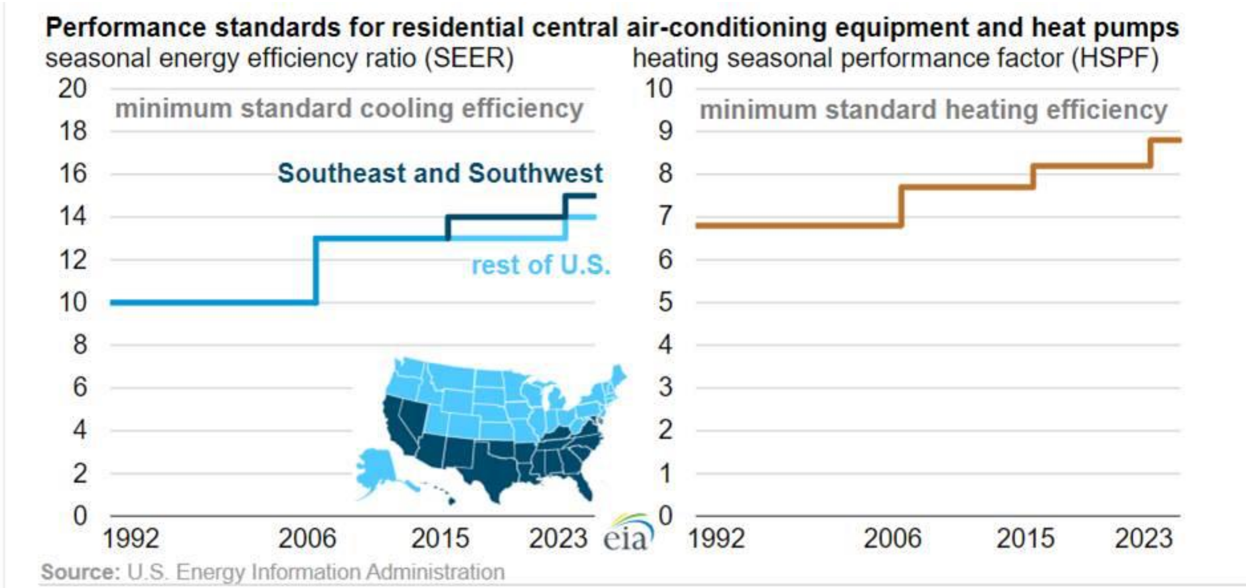

Figure 5.2: Example from the United States of ratcheting up of performance standards over time and incorporation of different performance levels by climatic zone. Source: Energy Information Administration. [*https://www.eia.gov/todayinenergy/detail.php?id=40232*](https://www.eia.gov/todayinenergy/detail.php?id=40232), [*https://www.energy.gov/sites/prod/files/2015/11/f27/CAC%20Brochure.pdf*](https://www.energy.gov/sites/prod/files/2015/11/f27/CAC%20Brochure.pdf)

Figure 5.3: Illustration of main RACHP safety standards and types of products to which they apply. Reproduced with permission from D. Colbourne.

5.1.4 Engineered Commercial HVAC

Chapter 2 describes types of engineering commercial HVAC and availability of low GWP and high-efficiency systems. From a roadmap perspective, it is important to consider building performance requirements and safety standards for this sector. Many larger buildings are cooled with applied commercial chilled water systems that can range from 10 tons (35 kW) to 5,000 tons (17,500 kW) and even larger as the chillers are applied in multiples with 2 or 3 chillers. This allows some redundancy as well as load diversification, with performance assessment focussed on part load and annualized performance (Table 5.2). Most equipment is designed to manage extreme heating or cooling demand (that occurs at 1% or lower frequency) (i.e., 1% or 0.4% design conditions) and then typically oversized by 15%. To manage this excess capacity for most of the year, equipment uses either tandem compressor, compressor staging, or inverter driven compressors and variable speed.[23]

With water being an issue in many regions around the world, there has been increased use of air-cooled chillers with sizes now as large as 500 tons (1,750 kW). Evaporative cooling can offer significant reductions in condensing temperature. As a result, there is interest in adiabatic precooling as well as hybrid cooling towers to reduce the use of water, while maintaining high efficiency.

With the move to renewable electricity, there is growing interest in using chillers for heating. New rating standards, metrics and efficiency levels have been developed for air-to-water, water-to-water, and chillers with heat recovery. In many commercial buildings there is demand for both cooling and heating simultaneously, and many new buildings are being designed to use a heat pump chiller to replace a fossil fuelled boiler, as well as a lead chiller that both heats and cools during the transition seasons.

In addition, there is growing focus to not only look at the chiller, but to look at the complete system including cooling towers, pumps, air handlers and over controls and sequencing. New approaches like Total System Performance Ratio (TSPR) and full map certification are being implemented to allow for overall system modelling and analysis.

Large chillers using screw and centrifugal compressors have started to use HFOs with GWP's less than 1. These include HFO-1233zd(E) which is an A1 refrigerant, R-514A which is a B1 refrigerant, and HFO-1234ze(E) which is an A2L refrigerant. There is also R-513A which is a refrigerant that can be used to retrofit HFC-134a which is one of the common refrigerants used in large chillers. These refrigerants are being implemented in advance of the proposed phase down regulations.

Smaller scroll chillers will essentially follow the same refrigerant selections as the packaged units and products using HFC-32 and R-454B. Such units are being introduced especially in Europe, where the phase down regulations are already well underway.

If chillers are well maintained to limit refrigerant leak rates and refrigerant is captured at the end of life, then indirect emissions from power use will be the dominant source of emissions from chillers and efficiency and energy performance should be a focus. The new refrigerants described in Chapter 2 allow for improved efficiency, and when combined with variable speed and oilless compressor there has been significant improvements in annualized efficiency. Natural refrigerants like CO2 although shown to be acceptable for refrigeration are not viable for comfort cooling and would result in significant decreases in energy efficiency, but there is interest in natural refrigerants and there are some class A3 applications in chillers, but require appropriate designs, application, and service practices to ensure safety. Furthermore, the use of natural refrigerants such as R-744 (CO2) and R-717 (NH3) provide some additional advantages when considering integrated heat pump designs – i.e., when cooling and heating loads are simultaneous.

For engineered commercial HVAC, government and industry investments in flammability research has led to updates to international safety standards and regional building codes (Figure 5.2) and will be complete in non-A5 parties in the 2024- 2026 timeframe. Parties may wish to include in roadmap planning adopting updates to relevant safety standards and regional building codes this decade to support compliance with Kigali phasedown requirements.

5.1.5 Self-Contained Commercial Refrigeration Equipment (SCCRE)

SCCRE with low-GWP refrigerants are increasing where there is regulatory environment that encourages this transition. For example, the European Union has seen an increase in the sales of higher energy

[23] Please refer to further discussion in section 6.1.

efficiency low-GWP refrigerated storage cabinets because of the combination of the Ecodesign Regulation EU 2015/1095, the Energy labelling regulation 2015/1094, and the EU F-Gas regulations. In March 2021, the European Union also introduced additional Ecodesign Regulation (EU 2019/2024) alongside an energy labelling regulation (EU 2019/2018) for refrigerating appliances with a direct sales function (i.e., both SSCRE and remote units). Other countries with a mandatory regulation for these products are Australia, China, Iran, Mexico, New Zealand, Switzerland, the United States and Vietnam. However, in many countries, these products continue to be unregulated, with no incentive to improve the products' energy efficiency or introduce low-GWP refrigerants.

5.1.6 Large Commercial Refrigeration

Large commercial refrigeration systems, found in food retail and food storage facilities are characterized by refrigerating capacities of equipment varying from hundreds of watts up to 1.5 MW (see Chapter 2). Since the systems are individually designed for the facility, they vary in how and where they are applied, in refrigerant charge size, and energy consumed by the equipment. These systems are installed, refrigerant charged and commissioned on site and operate throughout the year. As a result, these systems are more vulnerable to the quality of materials and workmanship than factory-built systems.

The HFC phase down being implemented by various non-A5 parties is causing a shift from non-flammable high-efficiency and high-GWP HFCs to low-GWP fluids in these applications as well. In non-A5 parties, manufacturers have to meet MEPS, which can be challenging and motivate design and engineering innovations. Industry is using the opportunity to rethink the design, installation, and use of the equipment in order to meet both goals of the HFC phasedown and MEPS. If these same standards in non-A5 parties can be replicated in A5 party contexts, improvements in energy efficiency can be expected to follow. The key is to set efficiency standards and let the industry respond with design and use of the equipment to meet those standards.

5.2 Cross-cutting issues

5.2.1 Integrating energy and refrigerant performance in standards and labelling

Ozone, climate, and energy efficiency officials have an opportunity to work together towards Integrated Standards and Labelling Programmes (ISLPs), which provide an effective policy to improve energy efficiency, reduce GHG missions and integrate non-ODS lower-GWP refrigerants as a part of standards and labels (see Case Study 9.5.1). The programme has the potential of overcoming information asymmetry by providing the consumer with energy and environmental performance information relevant to lifetime operation cost, which can help overcome the high first-cost barrier that is often associated with new high efficiency and/or low ODS/lower-GWP equipment through a market driven approach. The integration of zero-ODP and lower-GWP refrigerant in energy performance standards would maximise the energy, climate, and ozone benefits.

A robust ISLP backed by a strong awareness programme (see Case Study 9.5.4) could overcome the high first cost barrier (see Case Study 9.5.3) and help accelerate market transformation. HPMP implementation would attempt to calibrate the phase-out schedules with the energy performance and add to it the GWP thresholds. An ISLP will provide comparative pictorial labels, based on energy consumption and low-GWP refrigerant. The labels, e.g., ranging from 1 STAR to 5 STAR, are given in the decreasing order of energy consumption *and* lower GWP refrigerant as assessed using lifecycle climate performance metrics. An integrated ISLP will have the following components:

- An institutional entity to be identified to manage the program under the guidance of an Implementation Committee that will comprise of all stakeholders including the manufacturers, their associations, consumer bodies, testing laboratories.
- Manufacturers and importers will:

- test their equipment and self-declare the rating level.
- print and affix labels as per the label design, manner of display, and the rating plan prescribed for the particular equipment.
- Be responsible for accuracy of the information displayed on the label or any public claim for label level and quality of equipment.

- The institutional entity will conduct verification tests on a regular basis to verify the accuracy of labels.
  - The label can be challenged by other Importers, consumer associations, etc.
  - If the equipment is incorrectly labelled, and Importers do not rectify the errors as directed, then the institutional entity will inform the consumers through wide publicity and penalty may be enforced.
  - Monitoring, verification, and enforcement programs can be funded by governments and supplemented by registration or other fees.

5.2.2 Framework for Energy Efficient zero-ODP Low- or Medium-GWP refrigerants based Economic Development

A framework for energy-efficient, zero-ODP and low- and medium-GWP RACHP would include promotion of market based accelerated replacement of old equipment through Energy Service Company (ESCO) delivery mechanisms. The ESCO mode of delivery through performance contracts could not only increase demand but also could overcome the twin barriers of higher costs and information asymmetry that any new technology has to usually overcome. In addition, a mandatory programme for public procurement of higher STAR labelled equipment is recommended to not only demonstrate the Government's resolve but also to encourage manufacturers/importers towards higher quality and efficiency products. Consumer-facing standard and labelling approaches work well for residential and small commercial equipment. For larger commercial equipment, such as chillers, deep freezers, vending machines, etc., a combination of regulatory and market-based instruments such as "buyers' clubs" and ESCO delivery mechanism are effective approaches. The main elements of this framework could be:

- Increasing demand for replacement to higher efficiency and lower GWP products through government-orchestrated programmes, for example setting public procurement requirements in government-operated buildings and services.
- Enhancing capacity of ESCOs by creating a pool of trained manpower.
- Providing innovative financial instruments like risk guarantees funds, venture capital funds that could attract ESCOs.
- Review of entry barriers for investment by international ESCOs in the country.
- Mandating that all procurement by government and its allied agencies will be restricted to higher efficiency and lower GWP equipment in sync with the HPMP and KIP.
- Survey of all government establishments for replacement of identified equipment appliances and announcement of their replacement within a pre-defined time frame.

5.2.3 Building Sector Interventions

The building sector presents an opportunity in nudging technology choices related to air-conditioning, heat pumps and foam insulation by promulgating building codes. Most air-conditioning, heat pumps and foam insulation are used in buildings. Energy efficiency of the building sector is an important policy tool that could provide stimulus to zero-ODP, low- or medium-GWP refrigerant based technologies. This is particularly useful for large cooling systems using technologies like Vapour Absorption, Trigeneration, etc. (see Case study 9.5.7). Building codes could specify use of zero-ODP, low- or medium-GWP refrigerants to promote these technologies in the market. The main issues that need to be included are:

- Develop energy efficiency codes/ green building codes and fiscal incentives or tariff incentives to promote use of zero-ODP lower-GWP technologies in air-conditioning, heat pumps and foam insulation.
- Encourage market-based rating systems – linkages with international systems like Leadership in Energy and Environmental Design (LEED).
- Develop curriculum for architects/ engineers for energy efficiency codes/ green building codes integrated with choice of refrigerants. This should include training on how to integrate heat pumps into building designs to maximise efficiency.
- Awareness and outreach for stimulating demand. Capacity building of policy makers/ contractors/ building developers.

5.2.4 Enhanced Awareness and Outreach

Enhanced awareness and outreach capacity building are essential ingredients of standards and labelling programs (see Case study 9.5.4). A comprehensive media strategy would evolve based on the need to create awareness about energy conservation and efficiency along with the objectives of HCFC phase out and HFC phasedown. The strategy should focus on motivating stakeholders to not only save energy by its rational use but also on the irreversible damage that high GWP gases could cause to climate and the environment. Piggybacking on such umbrella messages could be the campaign on making the label a lifestyle brand. The essential ingredients of the media strategy could include:

- Identification of the target group (primarily industry stakeholders) and segregation in terms of their respective socio-economic parameters.
- Messages for communication will be tailored in a manner that is most effective for different strata of society - for instance for the middle class, cost saving is an effective communication strategy while for the upper classes, lifestyle branding or saving environment are usually better than cost saving communications.
- Media will be chosen appropriately to target different consumer and stakeholders. While television is a good medium for lower and middle classes, internet, mobile SMS have better acceptability in the higher classes.
- Simple messages usually are accepted better, and the strategy will focus on this.
- A combination of television, print and internet will be taken, in terms of their relative reach followed by radio, which usually has a good recall value.
- A consumer survey will form the basis of preparation of the media strategy, media plan and communication strategy.
- Initiating a capacity building programme aimed at retailers and distributors. This should include a broad framework of the ISLP, its advantages to consumers and society, comparative performance of higher STAR labelled equipment, etc. A standard module may form the basis of this outreach with expert trainers. Easy to understand tip sheets and flyers must be prepared which could help the retailers to inform the consumers. This could compliment the awareness programme.

5.2.5 System Level and Annualized Metrics

Over the years the primary approach for efficiency metrics has been to focus on full load metrics and some nominal rating condition. The is beginning to change in the following areas:

- Regional Metrics – The world is not a uniform design temperature. ASHRAE 169 has divided the world into 19 climate zones ranging from very hot climate zone 0 to very cold climate zone 8, further subdivided the thermal zones into A for humid, B for dry and C for marine. With this background there is growing interest and regulations focused on regional specific metrics ranging from residential systems thru commercial. In combination with this most of the focus is on annualized performance metrics which are more representative of the efficiency of the application.
- Model Based Design – Model based design tools have continued to evolve and improve but still only 20% of buildings are modelled and then typically only larger buildings. Looking at the complete system with a full model allows for further optimization of the energy. New tools and standards are under development by ASHRAE 205 to allow for more accurate representation of equipment. Standards are also evolving, and Europe has been working for years on a systems approach using the second European Directive. ASHRAE 90.1 as well as ASHRAE 189.1 have continued to enhance and improve full building modelling approaches with changes to appendix G in ASHRAE 90.1 and Appendix D in ASHRAE 189.1. There are also subsystems approaches being developed and ASHRAE 90.1 is currently developing the Total System Performance Ratio (TSPR) to allow for system level compliance path for HVAC systems.

5.2.6 Standards

5.2.6.1 Safety standards and building safety regulations

With the increasing use of A2L, A2 and A3refrigerants significant work has been done – and is continuing – to develop improved requirements for their extended use in all types and systems and applications.

Modifications have been made to IEC60335-2-40 (and derived national and regional standards for air conditioners and heat pumps and the IEC60335-2-89 (and derived national standards for commercial refrigeration appliances. Similarly, extensive work is ongoing with ISO 5149, EN 378, ASHRAE 15, and CSA B52 to widen their applicability to flammable refrigerants

National building safety and fire regulations and codes are extremely varied in terms of their scope, format, and functionality. Whilst in some countries, such regulations are fairly generic in nature and lay down conceptual approaches and principles and may refer to safety standards, others are highly prescriptive and detailed. In these latter cases, regulations may include specific rules associated with the safe use of refrigerating systems and refrigerants and as such, may need to be revised to reflect the modern application of (medium and low GWP) alternative refrigerants; often this can be lengthy bureaucratic process.

5.2.6.2 Energy efficiency standards

Energy Efficiency Standards have been in use since the 1970s. These standards continue to evolve in developed countries and new standards are being added in developing countries with unique requirements for the local climate conditions and building designs. These standards cover the overall design of the building including envelope, lighting, RACHP. Some new standards have also developed for high performance buildings as well as green building design which include site selection, renewable energy, and waste reduction management. Often these standards include the following approaches;

- **Mandatory requirements** – Specific requirements that must be complied with and can include HVAC&R equipment efficiencies and specific design and application requirements. These continue to expand with new products and new metrics as well as expanded scope for both new and existing buildings
- **Prescriptive requirements** – These are typical requirements that may include options, and most be complied with thru one of multiple optional paths.
- **Optional paths** – Many of standards have evolved to include optional paths. One of the common ones is a full performance approach using advanced modelling tools. Efforts have been underway to increase the use of modelling tools. Most tools are not accurate enough for absolute energy but are used to compare a minimum reference building to a proposed building. Work is underway to simplify the work with a fixed baseline building and performance improvement requirements. Work is also underway to improve the equipment modelling with standards like ASHRAE 205. There are also new approaches to allow for subsystems compliance as well as the use of additional credits approaches to allow for selective features to comply with energy efficiency

But there is a lot of local interest in country and seasonal efficiency requirements and building codes which add complexity to ratings and certification programs and there is an opportunity to try to harmonize standards global, but they will require regional specific requirements.

5.2.7 Service sector and supply chain: access to parts, chemicals, trained and skilled workforce

The availability of a trained workforce that can handle technologies with flammable or toxic refrigerants, or those requiring special skills, such as when working with CO_2, could be a barrier to entry of energy efficient equipment using these refrigerants, or an excuse for suppliers not to market those products. Training and education of technicians has been the basis of Montreal Protocol capacity building activities for some time and continues to be the emphasis of strategies and plans. The success of training depends on two factors:

- The timing factor, or the synergy of the provision of training with equipment availability in the market since the effect of training will gradually be lost if the principles learned are not being applied on a daily basis.
- The reach factor, in other words, who gets trained. Training is mostly concentrated on the formal sector, i.e., those technicians who are registered and known to the organizers. It is not unusual for technicians in the informal sector to be left out and to continue operating in the dark. Technicians with no experience in new low-GWP, energy-efficient technologies would discourage their customers from buying newer, more efficient technologies because they are not able to service them. Certification and training of technicians, with appropriate reward for an upskilled technicians is effective in moving technicians from the informal sector to a stable formal sector which can evolve alongside the technology.

Chapter 6 provides an in-depth look at the effect of service on maintaining energy efficiency, as well as competency requirements.

5.2.8 Shared exporter-importer responsibility is critical to prevent environmental dumping of new and used cooling appliances

Environmental dumping of refrigeration and air conditioning equipment includes:

1) Export of technology that cannot legally be sold in the country of export as a consequence of failure to meet environmental, safety, energy efficiency, or other product standards; and

2) Export of technology that is unusable in the country of export because refrigerants are no longer available because of national regulation or phaseout and phasedown control schedules under the Montreal Protocol.

From the perspective of recipient countries, environmental dumping involves the introduction into recipient markets of products rendered “obsolete” in the country of manufacture (Andersen et al., 2018). “Obsolete” in this context is defined as appliances (and the refrigerants that these appliances use) with no value in use, even if still functional, taking into consideration self-interest and public interest. Appliance obsolescence occurs when a next-generation product can be purchased and operated for lower annual costs and/or when the operation of the old product exposes owners and the global community to unacceptable environmental and safety risks.

Environmentally harmful dumping of products, from the perspective of the exporting countries, can be interpreted as lawful fulfilment of purchaser specifications when the products in question do not violate the recipient-country standards or other requirements. However, engaging in environmental dumping, through introduction of obsolete products in this situation, strengthens the barrier in the market to adoption and uptake of energy-efficient products using new refrigerants that are safe for the stratospheric ozone layer and less damaging to climate.

Dumping results in the availability on the market of cheaply priced products that take advantage of purchaser psychology, where purchasers opt for cheaper “first cost” inefficient products that are actually more expensive in the long run, diverting finances away from other critical developing-country household needs. Inefficient product dumping eventually crowds out efficient products from the market. Developed countries (Non-A5 Parties) have existing capacity to reach their HFCs phase out targets earlier than anticipated. History confirms that manufacturers in these countries are inclined to dump obsolete products on Article 5 Parties. Mindful of the fact that dumping makes it increasingly difficult for importing countries to meet their international obligations, both exporting and importing countries should have laws in place prohibiting the movement across borders of environmentally harmful products. Non A5 Parties should have mechanisms in place to help ensure that their manufacturers respect importing-country laws prohibiting the shipping of obsolete products to A5 parties. Even where A5 parties do not have the capacity to prescribe and enforce laws to prohibit shipping of obsolete products, the local and global harms inflicted as a result of increased dumping in these most-vulnerable jurisdictions necessitate that non-A5 exporting parties share responsibility with A5 recipient countries to prevent the dumping of obsolete products (Agyarko et al., 2022). Furthermore, non A5 parties possessing superior recycling technologies should not use recycling facilities established in A5 countries as a reason to pressure A5 parties to continue accepting obsolete products.

5.2.9 Cold chain

Cold chain is an important and growing sector which requires attention to enable the adoption of sustainable technologies and systems and avoid locking in high-GWP refrigerants with high energy costs. An energy efficient cold chain is climate-friendly and contributes towards food security by providing controlled temperatures to preserve products along the food value chain.

A study carried on in 2010 in Europe[24] found out that the average specific energy consumption in cold stores is 50 kW/m^3, which compared to the best-in-class of 10 kW/m3 of systems already in use at that time tells how inefficient some of the cold stores operating in Europe are. Considering that 50 kW/m3 is only the average, it means that almost half the stores are operating at 10 times the level of the best-in-class.

According to estimates by the International Institute of Refrigeration (IIR) 12% of the food produced globally in 2017 was lost due to an insufficient cold chain. A more extensive cold chain would limit the

[24] ASHRAE Journal Podcast Episode 11 | ashrae.org

need to increase agricultural production to compensate for these losses and avoid the corresponding CO_2 emissions; however, could the additional CO_2 emissions resulting from the implementation of a more extensive cold chain be greater than the emissions avoided by reducing food losses due to a lack of refrigeration? To answer this question, modelling by IIR has shown that an energy efficient cold chain would allow a reduction of almost 50% of the CO_2 emissions of the current cold chain and avoid 55% of the food losses attributed to the current cold chain (IIR, 2021). Figure 5.4 shows the CO_2 emissions from the current cold chain by stage (or sector) and emission source including refrigerants. Refrigerants contribute to 22% of the total emissions with the largest portion coming from the retail sector.

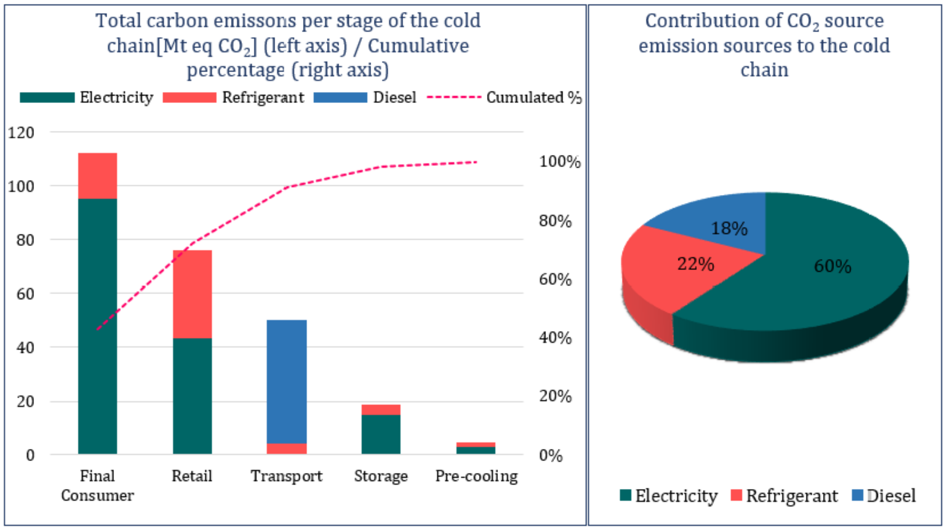

Figure 5.4. Total CO_2 emissions of the current global cold chain per stage and emission sources (Source IIR 7th Informatory Note)

Experience from Egypt where a study was carried out by the World Bank aiming to reduce loss and waste of fresh produce by improving the dynamics that govern the cold chain from harvesting, to refrigerated transport, logistic centres, cold storage, and to distribution to the local market or export. The study showed the gaps in the cold chain and where efforts should be directed to improve it and mainstream good practices of preservation into the daily activities of farmers. The eventual aim is the provide readily accessible pre-cooling services, on a pay-as-you-go basis, a few hours after harvesting to extend the shelf life from days to weeks thus increasing production efficiency and sustain the cold chain all the way to logistic centres and cold storage facilities.

India Cooling Action Plan addresses not only the space cooling and heating but also the cold chain. The cold chain, unlike space cooling, has to address a broad spectrum of equipment from pack houses, bulk storage, reefer trucks, cold storage as hub, ripening chambers, all the way to retail through which positive and negative temperature conditions are maintained for food safety. The plan includes the adoption of low-GWP refrigerants, the development of standards for toxic and flammable refrigerants, MEPS program for commercial refrigeration products, retrofit of cold rooms with energy efficient alternatives, standardized design, construction, and associated specification for cold chain components, and adopting renewable technologies and phase change materials. The plan also covers building training facilities for the cold chain professionals and creating awareness for a better utilization of cold rooms and monitoring of food produce

5.3 Market-based policies and programs for adoption

5.3.1 Market Pull Mechanisms: Bulk Procurement and Buyers Club

Bulk purchasing is a means of product procurement that involves large orders of the same item. Manufacturers often reduce the unit price per item based on how many items are sold together. Buyers' club is referred to an organization or group working towards increasing benefits of bulk purchase via price reduction and better quality of standardized products. Buyers' club programmes envisage bulk procurement practice to enable lowering the product price for consumers.

Bulk Procurement and Buyers clubs are important schemes that lead to increasing demand for and access to low-GWP products at end user/consumer side, as they can bring the volume, from the consumer to the manufacturing side, which makes the programme economically feasible. By providing a partner buyer (private bank, a public institution, big chain/store that sells ACs etc.) with a significant number of units to be purchased, it provides manufacturers with the volume needed to supply the low-GWP/energy efficient products in quantities that will transform the market and reduce dependence of high-GWP HFCs for servicing.

Organizing public or private bulk procurement or Buyers clubs is a way to overcome information and other barriers to create and aggregate demand and get access to climate-friendly cooling technologies (see Case Study 9.5.5).

5.3.2 Utility obligations

Utility financed and/or operated energy efficiency schemes are highly effective in delivering substantial, sustained, and cost-effective energy savings and associated reductions in CO_2 emissions. Programs with GHG reduction goals can also integrate incentives for transitioning to lower-GWP refrigerants and management of ODS and high-GWP banks (see Case Study 9.5.6).

A key component of programme impact, including cost-effectiveness, is the effective alignment of utility commercial incentives with the delivery of energy savings. There are essentially two new elements of the recent utility energy efficiency schemes: i) mandated energy savings obligations and ii) the flexibility to trade the obligations. The mandated savings obligation, when linked to a suitable non-compliance penalty structure, seems to be an especially effective means of ensuring that public policy objectives for energy efficiency are met (Waide and Buchner, 2008). According to Waide and Buchner (2008), the importance of allowing obligations to be traded for programme success is not yet clear and will require more time before proper longitudinal evaluations can be attempted.

Local governments can work with electric and gas utilities and other program sponsors—potentially including third-party efficiency program administrators, state energy offices, regional energy efficiency alliances, and other organizations—to design efficiency programs for homes and businesses, and to improve the efficiency of their own facilities. Utilities and other third-party efficiency program administrators such as public benefit programs may also help local governments understand the energy sector and the energy consumption patterns in their jurisdictions. In addition, local governments can leverage the valuable relationships that utilities have with trade groups such as home builders, home energy raters, contractors, and energy service companies.

Examples of successfully implemented collaboration between government and utilities in the USA[25] are:

- Appliance Recycling
- Building Codes and Appliance Standards
- Building Labelling/Disclosure

[25] https://www.epa.gov/statelocalenergy/local-utilities-and-other-energy-efficiency-program-sponsors

- Financial Incentives/Rebates
- Lead by Example/Non-Residential Programs
- Residential Retrofit Programs
- Residential Weatherization and Direct Install Programs

In Brazil, of all the energy efficiency and energy conservation programs, two stand out for their magnitude: the National Electric Energy Conservation Program (PROCEL) and the Energy Efficiency Program (PEE). The first, coordinated by the Ministry of Mines and Energy (MME) and executed by Centrais Elétricas Brasileiras S.A (Eletrobrás). In 2015, PROCEL actions alone resulted in energy savings of 11.6 TWh or 2.5% of the country's energy consumption (www.procelinfo.com.br). The savings are equivalent to the annual energy production of a 2801 MW power plant, or consumption of 6 million houses.

The second, the PEE, is regulated by the National Electric Energy Agency (ANEEL) and carried out by the electric energy distribution concessionaires/utilities. Regarding the PEE and as determined by specific legislation, in particular the Law number 9991 (24 July 24, 2000), the electric energy distributors/utilities, must apply a minimum percentage of net operating revenue (NOR) on Energy Efficiency, according to regulations of ANEEL. The minimum percentage of the utilities' NOR for the PEE can change according to law and normative resolution published by ANEEL (www.aneel.gov.br). Currently, utilities allocate 0.5% of the NOR to energy efficiency projects/programmes, with 0.1% going to PROCEL. Several projects and calls for proposals are under way and can be found at ANEEL site mentioned.

Both programs resulted in the improvement of energy efficiency in Brazil and thus prolonged the need to create new energy sources, resulting in the reduction of environmental impacts and investments for the creation of new plants.

5.4 Example policy roadmap

5.4.1 Enhancing awareness amongst policy makers and key stakeholders

A first step is to organize workshops and seminars to enhance awareness and understanding of policy makers and key stakeholders of the unique opportunity that HPMP and KIP implementation presents to maximize environmental gains and avail of the three benefits by adopting and promoting energy efficiency of RAC appliances. The benefits are:

- Accelerated HCFC phaseout and preparation for transition to low-GWP alternatives.
- Energy (and cost of energy) savings due to enhanced energy efficiency of appliances and RAC equipment.
- GHG emissions reductions, both due to enhanced energy efficiency as well as use of low-GWP refrigerants.

5.4.2 Implementation of the carbon negative action plan

Governments with climate targets and action plans should include projections for emissions from growing uses of RACHP equipment (apart from Transport and industry) in the country, taking into consideration the carbon intensity of power generation.

5.4.3 Strengthening institutional and regulatory framework

The national authority responsible for implementing ozone, energy, and climate mitigation strategies, in many cases would benefit from capacity building for developing a strengthened framework for energy efficiency linked to HPMP. Overarching legal and regulatory framework for energy efficiency, integrated energy policy with HPMP and KIP implementation as a vehicle or low carbon growth strategy and fiscal and policy incentives to promote integrated approach to ozone, energy and climate are some of the measures that could be taken.

5.4.4 Graded implementation of integrated standards & labelling programme (ISLP)

The need for standards for RACHP equipment is urgent. Initially it could be linked with Minimum Energy Performance Standards (MEPS) followed by an integrated ISLP with limits of GWP of refrigerants. See for example U4E model regulations (2021 EETF Case Study 4.1).

5.4.5 Linking import policies under HPMP and KIP with ISLP

The fact that all of RACHP equipment are imported into many countries provides opportunity to the government to implement MEPS/ISLP and then link them to import policies being developed for RACHP equipment under HPMP and KIP. Mandatory application of MEPS/ISLP will ensure only compliant RACHP equipment in national markets.

5.4.6 Identification of sector specific barriers and ways to overcome them

Markets for energy efficiency have failed in several parts of the world as a result of several barriers. International experience suggests that targeted regulatory and policy measures need to be implemented in order to successfully overcome these barriers and stimulate market transformation in favour of energy efficiency. The barriers that the countries are facing at present to make the right technology choice for climate friendly alternatives to HCFC and high-GWP HFCs are very similar. Information exchange about policy and regulatory best practices in markets like the USA (in particular California, see Case Study 9.5.6), EU, Japan and most recently India in the appliances sector, could help the countries efforts to overcome these barriers and maximize the benefits of accelerated HCFC phaseout and preparation for the transition to low-GWP alternatives. The barriers that are common are:

- High cost of climate friendly technologies thereby limiting demand (see Case Study 9.5.3)
- Absence of regulatory and policy push towards adoption of climate friendly technologies
- Inadequate information about the comparative advantages of using energy efficient non-ODS low-GWP refrigerant based technologies in terms of achieving the objectives of accelerated phaseout, energy savings and GHG mitigation.
- Low availability of climate friendly technologies

5.4.7 Integrating green building policies with HPMP

The building sector is a major user of RACHP equipment. Guidelines, codes for promoting green/ energy efficient building design and construction using climate friendly alternatives of HCFC in RACHP as well as building insulation could be useful policy tool for achieving accelerated phaseout objectives. This intervention is vital to balance the growth in building sector simultaneously with economic development.

5.4.8 Promoting public procurement policies

Government procurement policies could be amended to encourage RACHP equipment that are energy efficient, zero-ODP, low-GWP. The emphasis could be on procurement based on life cycle cost assessment as against least cost procurement.

Table 5.1: RACHP safety standards and the allowable refrigerant charge.

Standard	Title	Application	Factors that dictate allowable charge limit	Flammable Ref. Charge Limit
IEC 60335-2-24	Particular requirements for refrigerating appliances, ice-cream appliances and icemakers	Domestic refrigeration, freezers, and ice makers	Sealed system	Up to 150g of flammable refrigerant per circuit
IEC 60335-2-89	Particular requirements for commercial refrigerating appliances with an incorporated or remote condensing unit or compressor	Any refrigeration appliances used in commercial situations	Minimum room size, LFL, sealed system, fan airflow, design, and construction of product	A2L and A2 ~1.2 kg A3 ~ 0.5 kg
IEC 60335-2-40	Particular requirements for electrical heat pumps, air conditioners and dehumidifiers	Any air conditioning and heat pump systems	Minimum room size, LFL, lowest release height, maximum releasable charge, leak detection system, circulation airflow, ventilation	A2L ~ 80 kg A2 ~ 3.5 kg A3 ~ 1 kg
ISO 5149	Mechanical refrigeration systems used for cooling and heating - safety requirement	Any refrigeration, air conditioning and heat pumps: domestic, commercial, and industrial	Varies by access category and location classification, LFL, release height, ventilation, leak detection systems, alarms	Numerous; ranging from 150 g to unlimited, depending upon the situation

Table 5.2: Mapping enabling policies by sector

Sector / Policy	Mini/ducted split	HP (hydronic)	Commercial HVAC	Engineered HVAC (chillers/chilled water systems)	SCCR	Large Commercial Refrigeration
Minimum Energy Performance Standard (MEPS) / Labels with GWP threshold – with regular revisiting; consensus body to bring together regulators and industry to inform performance standards	X Ex. U4E model regulations	US, ecodesign, Japan, China	US, EU, China, India, RSA MEPS	AHRI 340/360	US, ecodesign, etc. Ex. U4E model regulations	US, EU MEPS for both components UL, AHRI testing standards 1. display case 2. back-end equipment (e.g., condensing units)
Best practice test procedures and metrics (i.e., seasonal, systems)	Seasonal efficiency (e.g., SEER, sCOP, APF)	HSPF, sCOPh, APF	Part load efficiency (e.g., IEER) Seasonal efficiency			AWEF walk-in coolers Ex. ASHRAE best practice guide
System Energy Performance standards	AHRI 210/240		Ex. Building performance e.g., ASHRAE 90.1 - appendix G AHRI 310/380			X Leak tightness requirements beneficial from EE POV and prevents food loss/waste [requirements for leak sensors, safety valves] [avoid prescriptive mode] Recommissioning (e.g., XX) Ex.

Sector / Policy	Mini/ducted split	HP (hydronic)	Commercial HVAC	Engineered HVAC (chillers/chilled water systems)	SCCR	Large Commercial Refrigeration
Importing Used/refurbished equipment import bans	X iPIC Ex. Ghana				iPIC	Jurisdiction LED requirement example? Performance stds CARB ex (energy performance?) Recycling/retirement
Safety standards	IEC 60335-2-40 ISO 5149 UL 60335-2-40 EN 378	IEC 60335-2-40 ISO 5149 UL 60335-2-40 UL 60335-2-89 EN 378	IEC 60335-2-40 ISO 5149 UL 60335-2-40 EN 378	EN 378 ISO 5149	IEC 60335-2-89 ISO 5149 UL 60335-2-89 EN 378	IEC 60335-2-89 ISO 5149 UL 60335-2-89 ASHRAE 15 EN 378
Service sector and supply chain	Certification requirements Ongoing accreditation to keep up with tech innovation	Certification requirements Ongoing accreditation to keep up with tech innovation	Certification requirements Ongoing accreditation to keep up with tech innovation		Certification requirements Ongoing accreditation to keep up with tech innovation	Certification requirements Ongoing accreditation to keep up with tech innovation
Monitoring, compliance, and enforcement						

6 Options to Maintain and Enhance Energy Efficiency through Best Practices in Installation, Servicing, Maintenance, Refurbishment and Repair

Key Messages:

- Design upgrades to meet energy efficiency levels require a higher level of knowledge and training for safe and effective installation and servicing. These new topics include units with variable speed drives, controls with self-diagnostics and remote-control features which all require improved skills including knowledge of electronics.
- Energy efficiency degradation is affected by the severity of use and operating conditions, as well as corrosive environments. Improper installation and maintenance accentuate the loss of EE, and high quality and frequent planned maintenance minimise the loss of EE.
- Refrigerant leakage impacts EE. Reducing leakage continues to be a service priority for optimised systems using low-GWP refrigerants with reduced refrigerant charge.
- End-user environmental awareness is driving them to demand lower CO_2-eq emissions from the operation of their systems. Preventive and eventually predictive maintenance are becoming a priority for both operators and service providers.
- Rigorous service requirements drive higher training, certification, and specialisation with improved rewards. This will tend to lower technician turnover and consolidate/spread good practices.

6.1 Introduction

Design upgrades to meet energy efficiency levels require a different approach to installation and servicing. Units with variable speed drives, controls with self-diagnostics, and remote-control features all require new skill sets and ongoing training to install and maintain. Energy efficiency degradation is affected by the severity of operating conditions and the type of use; moreover, improper installation makes the impact of these factors more severe and quicker.

Improving energy efficiency is getting more difficult at the component level. After 30 years of component efficiency improvements, the industry is now challenged with looking at the complete system with energy based on a system level; not just at full load, but on an annualized basis. This may also include hybrid systems as well as efforts to reuse and reclaim energy.

The need to maintain and improve energy efficiency has driven a change in the service landscape where preventive, and eventually predictive maintenance, becomes a priority for both customers and service providers. Lower-GWP refrigerants and design optimisation requiring smaller refrigerant charges encourage better energy efficiency through closer monitoring for leaks. The impact of leaks on the loss of performance and efficiency is true whatever the charge. Moreover, the products and systems are getting more complex and have to adapt to the building control as well as the grid requirements; consequently, initial commissioning as well as recommissioning are growing in importance. This is resulting in new skills and ongoing training being required for service and installation and maintenance technicians.

Higher energy bills and environmental awareness is increasingly driving end-users in some regions to demand a lower carbon footprint from the operation of their systems. The quest for higher EE systems with low climate impact is becoming of equal importance to customers for both environmental and financial considerations. Customers are not willing to compromise on the life cycle sustainability of the products and systems.

Rigorous service requirements drive specialization, and specialization reduces high technician turnover and consolidates good practices. Technicians have to cope with the changing service landscape, and training curricula needs revisiting to integrate EE; ongoing certification is therefore a must. There is also a need for new tools and aids for service and commissioning.

6.2 Servicing Landscape

The product landscape is changing to meet higher energy efficiency levels. New technological introductions like the transition to lower GWP refrigerants, variable speed technology or digital capacity control, microprocessor controls with more advanced features and logic, microchannel condensers, and evaporators, flooded and falling film evaporators for chillers, and electronic expansion devices and ECM motors are increasingly used across all product lines. The industry is also moving from a full load focus to optimized system level annualized performance, and all of these make systems more complex for installation and servicing. These new technologies are constantly evolving and require on-going training of technicians. Additionally, installation and commissioning practices and tools for new high-end integrated technologies require on-site optimization and adjustments for maximum performance and efficiency. This is driving a change in the servicing landscape requiring technicians with mechanical and/or electronic engineering background.

Modern servicing is changing from preventive to predictive. Microprocessor-based controllers and remote monitoring are aiding in maintaining the efficiency of systems and can pinpoint faults before they occur. Factors that affect the performance of systems can be analysed and the risk of failure reduced.

Commercial refrigeration systems installed in supermarkets are one of the highest leaking systems due to the individual nature and complexity of the systems. With the increased emphasis on food security, refrigeration is becoming an increasingly challenging sector from a servicing point of view.

The RACHP service sector can be divided into two groups: organized (formal) and unorganized (informal). Formal service companies have all the infrastructure facilities necessary to complete RACHP related services, organize workshops for training and employ engineers, supervisors, and technicians. The informal sector, which is predominant in some A5 countries, can be seasonal and/or unregistered and even unknown by the authorities which can lead to shoddy practices and catastrophic results.

One of the factors driving owners to switch to more efficient units is the advice they receive from a service technician who provides personal experience on the benefits and value of EE as well as a lower GWP refrigerants. Awareness and training of technicians on EE and its attributes ensures the adequacy of their knowledge which otherwise would act as a barrier to the introduction of new technologies that can be a challenge to untrained technicians especially in the informal sector. Additionally, the use of lower GWP refrigerants requires capacity building and training initiatives to address the specific issues related to the installation, operation, and maintenance of equipment in a safe and secure way.

6.3 Service Requirements

Servicing includes design, installation, operation, maintenance, and repair services for RACHP equipment which can suffer significant capacity and efficiency performance loss depending on how the components are sized, assembled, installed, and subsequently field maintained. During this process, technicians use procedures such as refrigerant recovery, recycling, reprocessing, and reusing, leak testing, brazing, pressure testing, vacuuming, flushing refrigeration circuits, refrigerant charging *etc*. which need to be performed with skill for optimum results. There is also a growing need to recover more refrigerant at the end of life. Many of the new lower GWP refrigerants will be lower flammability (A2L) refrigerants and some small systems will move to highly flammable (A3) refrigerants which require new training for proper use of flammable refrigerants. Also, many of these refrigerants will be mixtures and require new procedures for charging and maintenance.

For the **design** aspects and when considering new equipment, the designer must consider the service and maintenance aspects along with the appropriate selection of components and system configuration and optimization and provide features and controls that will help ensure good operating EE throughout the life of the system. The energy savings associated with proper design and installation are considerable and there is room for additional energy efficiency improvements at a system level.

Installation and operation need monitoring and operational measurements for a performance evaluation. Good monitoring and control systems as well as energy dashboards can help the plant operator or maintenance technician check performance and correct any wasted energy faults; this needs instruments such as energy meters or by performing key measurements of temperature and pressure.

Maintenance is either "predictive maintenance" with, based on the condition, the inspection of equipment at regular intervals, or "preventive maintenance" with, based on time, the reconditioning or replacement of the product or its components at regular intervals, regardless of its current state. With real time monitoring possibilities, preventive maintenance can be migrated from fix time to real time based on the working parameters. Preventive maintenance programmes of RACHP systems are necessary to maintain equipment in appropriate condition and to reduce refrigerant emissions and energy consumption that ultimately increase the life span of systems. Technicians also perform "detective maintenance" or troubleshooting, or "corrective or rupture maintenance" replacing parts once they have failed. There is also a growing interest in larger systems to use digital twins[26] to analyse the measured performance relative to the digital twin model and help in the diagnostics. Collecting data on energy use helps in justifying maintenance intervention by measuring against the performance modelling used during the design stage[27].

When **servicing** a system, the use of refrigerants that are not compatible with the system, both for top-up charging and full replacement, increases energy consumption and reduces system efficiency. The proliferation of replacement refrigerants can put into jeopardy the certainty of efficient operation. Illegal refrigerants that are not suitable or compatible with the machines in which they are being introduced can cause safety issues in addition to loss of energy efficiency. There is also the increased use of flammable refrigerants in appliances and commercial systems. In addition, many of the new refrigerants will be mixtures that require proper consideration when charging the system and analysis performance for service.

Tools are necessary to do the job safely and efficiently. Different refrigerants might require different tools in regard to leaks, flammability, brazing, charging, etc. Refrigerants with zero/very low GWP, such as HCs in small applications can be vented rather than recovered but pose the risk of venting highly flammable refrigerants that are heavier than air. The industry is transitioning from simple mechanical tools to digital tools and apps that require new skills but can also significantly improve the sustained operation and efficiency of the products and systems.

Training has to encompass various aspects such as installation, operation, safety, maintenance, repair and servicing in order to provide technically sound service. Training involves both theoretical and practical aspects of good management practices including data communication. With the new refrigerants there has already been considerable training that is available in the industry using on-line tools.

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[26] Digital Twin – A digital twin for buildings is a computer model that is created to simulate the building design and systems such that it can be run using measured ambient conditions and other load attributes in a diagnostic tool for measured building data. It can allow virtual dissection of the building systems to determine issues and actions for service and recommissioning.

[27] https://www.ashrae.org/news/ashraejournal/ashrae-journal-podcast-episode-11

6.4 Competence standards

With the focus on new alternative GWP refrigerants, some of which are flammable, coupled with continued improvements in efficiency and the use of smart connect buildings, there is a continuous need for the standards, guidelines, and building codes to change and update.

Indirect emissions dominate the emissions for RACHP products in buildings; consequently, just maintaining efficiency should not be the goal as most regulations are focused on at least 5% efficiency improvements in every revision cycle to reach carbon neutral in the long term.

Research has been conducted to evaluate over 10 million substances on the safe application of these refrigerants resulting in updates to many standards and guidelines as well as new training materials aligned with these standards. The following is some of the work that has been done or is in process.

- IEC60335-2-40/UL60335-2-40 has been updated and significantly revised to address the new refrigerants including the safe application of A2L and A3 refrigerant in systems. These standards cover the requirements for comfort cooling equipment design and certification. New sections have been added on service practices as well competences for service technicians. The United States is close to releasing the 7th edition of the US UL60335-2-40 derived version of the IEC standard the 4th edition of which has been updated and should be released by September 2022.
- For refrigeration systems, IEC60335-2-89 and UL60335-2-89 standards have also been updated and are published.
- The application standards including ISO 5149, the US ASHRAE 15, new residential ASHRAE 15.2, Canadian B52 and the European EN 817 also being updated for the new refrigerants.
- Supporting guidelines and training are also being updated. The NATE[28] Examination and Certification Program has been updated for the new refrigerants and has been rolled out in some regions. In addition, new training efforts on refrigerants are also being shared through industry-run training organizations and with many new webinars and on-line training. The industry has adapted well to the pandemic to make the conversion from the typical classroom training to on-line training and webinars.

Several standards organizations are also working on new guidelines and training to insure the proper installation and maintenance of high-performance systems. Some these were mentioned above for refrigerants but there are activities also underway in the following areas:

- European standard EN 13313:2010 “Refrigerating systems and heat pumps - Competence of personnel” This standard defines the activities related to refrigerating circuits and the associated competence profiles and establishes procedures for assessing the competence of persons who carry out these activities;
- An ISO version of the standard, benefiting from EN13313, is under preparation under ISO Technical Committee TC86/SC1 as standard ISO/DIS 22712 - Refrigerating systems and heat pumps - Competence of personnel[29]. This standard contributes to the Sustainable Development Goal 9: “build resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation”. ISO Standard 22712 provides guidance for personnel skill assessment on installation, operation, and servicing. Improper installation and servicing of cooling system can lead to less energy efficiency as well as higher leakage rates of refrigerants. Proper qualification of RACHP technicians minimizes environmental risks, increases energy efficiency, and ensures the creation of a future oriented workforce;

[28] NATE = North American Technician Excellence. NATE tests represent real-world working knowledge of RACHP systems and validate the professional competency of service and installation technicians
[29] www.iso.org/standard/73739.html

- British Refrigeration Association is releasing an updated "Guidance for the Service of Hydrocarbon Refrigerant Equipment in A Retail Environment" and also a "Guide to Flammable Refrigerants;"
- Australia has done considerable work in the training and safe application of new refrigerants and released a document covering the "Safety Considerations when Using Flammable Refrigerants;"
- AHRI has developed considerable training including fourteen webinars and training materials on new refrigerants that can be viewed at www.AHRInet.org
- UL FSRI (Fire Safety Research Institute) did tests to study the impact of the new refrigerants on building and structure fire fighting for the education of the fire services. UL FSRI has released training reports and videos for the purpose;
- ASHRAE has also supported research and released several reports. There are also working on new standards for evaluating building HVAC in the new ASHRAE 221 standard "Test Method to Field-Measure and Score the Cooling and Heating Performance of an Installed Unitary HVAC System". ASHRAE is also in the process of a new ASHRAE 228 Standard "Method for Evaluating Zero Net Energy and Zero Net Carbon Building Performance".

6.5 Role of Technicians in the Synergy between Energy Efficiency and Refrigerant Phase-Down

The training and certification of technicians on alternative refrigerants for HCFC phase-out, HFC phase-down, and on maintaining EE are convergent and should not conflict each other. The process of training is an on-going one and has to be coupled with the practical use of the material trained in actual day-to-day work otherwise it will be lost. Technicians have to maintain equipment spanning in age from zero to more than 30 years old, and in applications from room AC to large commercial chillers, and with a wide variety of refrigerants. Training needs to include new equipment (heat exchanger, compressor), new developments (system controls, duct free, VRF, large commercial heat pumps, dedicated outside air systems etc) and many new refrigerants and blends; alongside the demand for improved efficiency in response to the strengthening of MEPS standards. This can only happen if it is designed in an integrated way to encompass all the different factors.

Including EE in training and technical school curricula ensures sustainability of initiatives undertaken during HPMP and KIP. This requires coordination between the ozone offices and the competent ministries or authorities. Curricula can sometimes differ between technical schools in the same country. The harmonization of curricula is essential and doable; it is among the first steps to be undertaken to support Kigali Implementation Plans (KIP).

Technicians taking the lead in bringing awareness about maintaining EE during service will also drive new higher efficiency products being put on the market. Untrained technicians can conversely delay energy efficient product introductions, especially if they perceive the new products as a threat to their jobs. Technicians, rather than salespeople, are seen as the trusted advisors on decisions to upgrade or replace systems. To qualify for this role, technicians need to be experts on the various aspects of the system and be conversant on the effects and benefits of energy efficiency.

Well trained, competent, and certified technicians play a key role in achieving the compliance in reducing environmental emissions and impact and certification makes the level of knowledge of technicians measurable. The target is for energy efficient systems with alternative low-GWP refrigerants that have varying properties i.e., flammability, toxicity, and high pressure.

Examples of RACHP efficiency opportunities through improved operation and maintenance can be found in table 6.1 below. Losses up to 30% of energy efficiency can be avoided through preventive actions, while other actions improve efficiency.

Table 6.1 Impact or preventive maintenance on energy efficiency. Compiled by authors with adaptation from (ExCom 2021)

Preventive action	***Mitigation effect – The preventive actions will avoid degradation of performance and the increase of energy consumption***	***Impact – Avoided increase in energy consumption***
Cleaning condenser and evaporator coils	Every 1°K (Kelvin) rise in condensing temperature may reduce evaporator capacity by 1 to 2 % and increase power consumption. A dirty evaporator coil would result in reduced system duty.	up to 20%
Eliminating refrigerant leaks	This can also include routine leak check as well as continuous smart monitoring of refrigerant charge. Low refrigerant charge increases compressor running time with loss of capacity and eventual failure.	up to 30%
Checking condenser pressure controls	Condenser fan cycling/speed controllers and dampers not set correctly could cause over, or under, condensing resulting in poor efficiency and longer compressor running time. Under-condensing would result in higher running current. Many new products are using variable speed to enhance the condenser heat pressure control.	up to 20%
Cleaning or replacing filters regularly	Dirty filters will result in 2 to 4% reduced system duty for every 1 ⁰K reduction in evaporator temperature.	up to 25%
Checking operations and settings controller	Ensuring appropriate mode is used, temperature set correctly, fan speed suitable, and that each function operates correctly.	up to 10%
Actions that improve performance		
Variable Speed	With the rapid growth of variable drives many units are using variable speed on the compressor, condenser fans, and indoor fans to improve the annualized energy savings. This complicates the controls, the setup, and the commissioning of the units and systems.	These variable speed approaches and controls can improve annual performance in excess of 30 to 40%

6.6 Retrofit

Systems losing performance or efficiency can be corrected in one of several ways:

- Repair and recharge with the same refrigerant recognizing that material compatibility and operation can be impacted by a refrigerant change as well as safety standards approval. Changes should be checked before recharging a refrigerant;
- Repair and use a new refrigerant as a drop-in. Note that most safety standard do not allow retrofit of a new refrigerant which affects safety classification (i.e., from A1 to A2L);
- Retrofitting, i.e., repair, change some components, and fill with new refrigerant, or
- Redesign, i.e., repair and add the same refrigerant, but also make other improvements to improve reliability and efficiency.

Retrofit comes with a price tag with increased risks and responsibilities. A system is the sum of its components; however, replacing several components can cost more than a brand-new factory assembled system because of economies of scale. There is a trade-off point between retrofit and replacement which a proper audit can pinpoint before starting the retrofit work. In addition, a retrofitted system may enhance energy efficiency up to a certain point while a new design based on new technologies can reach higher efficiency levels.

The risks associated with retrofit are either safety related due the flammability of refrigerants, or compatibility related where the selection of components does not ensure the proper functioning of the system.

Retrofits also pass on the warranty responsibilities to the entity doing the retrofit. Service providers need to take notice that this carries financial risks beyond the termination of work on site.

MOP Decision VII/25 allows financing of eligible retrofitting projects, in sectors vital to LVC economies on a case-by-case basis where this can be shown to be the best approach.

Multilateral Fund Executive Committee Decisions 72/17 and 73/34 (ExCom 2014) regarding retrofitting to hydrocarbons, stress the need for caution due to risks related to flammability. Caution, refrigerant retrofits with different safety classification refrigerants are not approved by most safety standards!

Energy efficiency can be maintained through the application of proper service; however, retrofit can in specific cases and at an added cost enhance energy efficiency beyond original design conditions. The impact of retrofit on EE depends on the scope of work and the size of the equipment, the larger the scope and the size of equipment the more viable is the return on investment to cover the extra costs. Note that older equipment may be worth retiring early if the payback period for retrofit is long.

6.7 Best Practices

Good servicing is enhanced by sharing best practices to increase the effectiveness and reduce the cost of programme implementation which benefits both country and the private sector. This section shares best practices from around the world with emphasis on A5 countries. There are two general cases and four country-specific ones.

6.7.1 Incentives to reduce energy demand

The use of incentives to reduce energy demand can motivate operators to operate plants more efficiently. Incentive programs related to energy efficiency have proven their effectiveness in many countries.

The Home Efficiency Rebate initiative in Canada offers homeowners all across Ontario up to CN$5,000 in-home renovation rebates. This results in an immediate payback and lower electricity bill. There are additional rebates to upgrade the heating and cooling systems.

6.7.2 New Energy Efficiency Approaches

ASHRAE 90.1 in the US as well as the IECC standard are considering a new systems level alternate compliance approach at a model-based evaluation of the complete HVAC System called Total System Performance Ratio (TSPR). It is in public review but is targeted to be updated for ASHRAE 90.1 in 2022 and for the IECC Standard in 2024.

Country specific cases:

6.7.3 Egypt's New Code on Refrigerants, Certification, Training, and Enforcement

The code was published in 2020. The code's goal is to provide guidance to stakeholders in RACHP for selecting energy efficient, lower GWP refrigerants as substitutes for HCFC-22 and R-410A. It also provides guidance for retrofitting refrigerants, handling natural refrigerants, and guidance in the handling of lower GWP refrigerants. The code also provides templates for keeping records and forms for refrigerants. The code is written in the format: Must Do, Avoid, and Recommended. The code has six chapters plus appendices:

Chapter 1: Relevant International and National Commitments
Chapter 2: Characterization and Classification of Refrigerants
Chapter 3: Cylinders and Containers for Refrigerants
Chapter 4: Selection Criteria for Refrigerants
Chapter 5: Requirements for the Containment and Proper Use of Refrigerants
Chapter 6: Management Records and Forms for Refrigerants

The appendices list all new refrigerants characteristics and physical properties.

Two Training sessions were organized in 2021 to explain the code to Stakeholders. Currently emphasis is on creating a certification program using the code as the source of the syllabus for the certification course. The aim of the code eventually is to be the cornerstone of an enforcement program for implementation in the RACHP field.

Kuwait has, with the help of ASHRAE, been developing a similar guide entitled "Guide for Safely Transitioning to Low GWP Refrigerants." The guide is going through the final editing and should be published this summer

6.7.4 India Cooling Action Plan Sets Goals on Energy Efficiency and Service Training

The India Cooling Action Plan (ICAP) was launched on March 19, 2019, by Ministry of Environment, Forest, and Climate Change (MoEF & CC) which is the nodal ministry. ICAP looks at 20-year perspective of the cooling requirements of India starting from 2017 with short-term as 5 years, medium-term as 10 years, and long-term as 20 years. The thematic areas considered are space cooling in buildings, air-conditioning technology, cold chain and refrigeration, transport air-conditioning, refrigeration and air-conditioning servicing sector, refrigerant production demand and innovation.

A holistic approach was taken in the development of ICAP considering cooling as a development need required across different sectors of the economy for human health, well-being, productivity, and economic development. It is based on the premise that the low penetration of cooling equipment will increase due to economic growth, urbanization, and increase in per capita income. ICAP also looks at three international commitments i.e., Kigali Amendment to the Montreal Protocol, Paris Agreement under United Framework Convention on Climate Change (UNFCCC), and Sustainable Development Goals of 2030. This led to an integrated long-term approach towards addressing cooling requirement across all the sectors such as estimating and reducing cooling demand, refrigerant transition to comply with the Kigali amendment, enhancing energy efficiency, and advancing cooling technology options.

The study shows that the demand for air-conditioners in cooling capacity is expected to grow eight times by 2037. The targets are taken to reduce the demand by 2037 with interventions such as:

- Reduction in cooling demand by 20 to 25%
- Reduction in refrigerant demand by 25 to 30 %
- Reduction in energy consumption for cooling by 25 to 40 %
- Training of 100,000 service technicians by 2022

ICAP has recognized the need for integrating the enhancement in energy efficiency with the training of service technicians as major factors to attain the overall goals.

6.7.5 Rwanda Centre of Excellence

The cold chain is badly neglected in many A5 countries resulting in large losses in fresh produce and other important commodities. Codes need to be written, taught, training courses made, certification programmes written and enforced. A cold chain with mechanical refrigeration improves food sustainability but burdens the electrical grid with the corresponding emissions. This emphasizes the role of EE in the development of cold chains. Regional cooperation is an improvement on individual efforts.

The Africa Centre of Excellence for Sustainable Cooling and Cold chain (ACES) was established in 2020 to advance sustainable development priorities and ambitions for enhanced collaboration across the African continent. Technical and business assistance on sustainable low-carbon design services and renewable energy will mitigate climate impacts of the additional cooling capacity needed to preserve food and reduce wastage.

6.7.6 Armenia Centre of Excellence

The goal is to create a centre of excellence for technical and engineering personnel in the safe handling of low GWP refrigerants. The beneficiaries are experts from A5 countries in Europe and Central Asia.

The centre creation project includes the development of training programs and certification of personnel and companies involved in maintenance, repair or production equipment and products that use or contain fluorinated gases or refrigerants with low GWP. The centre also serves as a demonstration centre and a knowledge base of alternative (natural) refrigerants. The main objective of the center is to promote widespread adoption of low-GWP refrigerants in A5 countries, the improvement of procedures of service of refrigeration and HVAC equipment, and reducing emissions of fluorinated gases.

The main functions of the centre are education, qualification, and certification of technical personnel of RACHP sector as well as providing free consultation and examination, in particular on the modification of the refrigeration and climate control systems and their components in order to reduce climate impact. The centre runs demonstration projects of refrigeration and climate control systems running on low GWP refrigerants.

7 How to Assess the Benefits of Integrating Energy Efficiency Enhancements with the HFC Phase-Down

Key Messages:

Modelling tools can support the analysis of the potential to reduce energy related indirect GHG emissions from RACHP at the same time as phasing down use of HFCs and reducing direct HFC emissions.

Some important insights from modelling are discussed – these include:

- The relative importance of direct and indirect GHG emissions can vary considerably in different countries. This has an impact on the choice of policy to support an integrated approach. For countries with high electricity generation carbon factors, reducing energy use is the key priority. For countries with low carbon factors, a greater focus on reducing HFC emissions is beneficial.
- The relative importance of direct and indirect GHG emissions can also vary considerably across the wide range of different RACHP technologies and applications. There are many different pathways available to achieve the Kigali Amendment targets. Combining early action for HFC mitigation actions with simultaneous energy efficiency actions can lead to significant reductions in cumulative GHG emissions between now and 2050 and at the lowest cost. Grid decarbonisation also makes a vital contribution to reduced emissions.
- Using heat pumps in place of fossil-fuels for space, water and process heating will be essential for heating decarbonisation. The avoided fossil fuel emissions from the use of heat pumps will massively outweigh any direct and indirect emissions from the heat pumps.
- Ensuring that new RACHP equipment is as efficient as possible, and that existing equipment is operated and maintained for high efficiency makes a very cost-effective contribution to the path to net zero GHG emissions.
- There is a significant lack of reliable data on refrigerant banks and equipment stocks by sector which is needed optimise the outputs of modelling. Better t data would improve modelling at national and regional levels.

7.1 Introduction

7.1.1 Background

Decision XXXIII/5 included a requirement to: "*Provide detailed information on how the benefits of integrating energy efficiency enhancements with the hydrofluorocarbon phase-down measures can be assessed*".

This section addresses this requirement. A review of key points from the last EETF report is provided in Section 7.2.2. Insights from modelling of the whole RACHP market are given in Section 7.3 and examples of modelling of specific initiatives were given above in Section 4.

7.1.2 Key points from previous EETF Report

The May 2021 Energy Efficiency Task Force report included a significant discussion about modelling the benefits of enhancing energy efficiency while phasing down HFCs – see Section 5 of the 2021 EETF report. It was shown that integrated modelling of the direct (refrigerant-related) GHG emissions and indirect (energy-related) GHG emissions from refrigeration, air-conditioning, and heat pump (RACHP) markets provides valuable insights into the importance of linking improvements in energy efficiency with the HFC phase-down.

There is significant potential for both direct and indirect emission reductions, with the indirect energy-related emission reductions estimated to represent around three-quarters of the avoided emissions. An assessment by UNEP and the IEA of the climate benefits of efficient and climate friendly cooling by 2060

(Dreyfus, G., et al, 2020) showed that the world could avoid the equivalent of up to 210-460 Gt CO2-eq over the coming four decades through efficiency improvements and the refrigerant transition (Shah et al. 2019).

The requirements of good modelling were discussed. For "bottom-up" modelling of the whole RACHP market it was emphasised that the same stock data must be used for modelling both the direct and indirect emissions in an integrated model. This includes using the same estimates of current stock levels and of future growth. It was also stressed that the RACHP market is complex and that providing realistic analysis required good "granularity," with sufficient technology sectors to represent the range of equipment types and applications.

Creating a single stock model with good granularity enables the assessment of:

a) **HFC mitigation actions** that lead to a phase-down in HFC use and emissions

b) **Energy efficiency actions** that lead to a reduction in energy usage and peak power requirement.

c) **Grid decarbonization actions** that reduce the CO_2 emissions from the energy being used.

A number of modelling initiatives were reviewed including the HFC + Energy Outlook Model, the LBNL JIF model, the Green Cooling Initiative, MEPSY and U4E Country Savings Assessments.

7.2 Modelling HFC phase-down and EE improvements in whole RACHP market

Modelling of the whole RACHP market can be carried out using bottom-up models such as HFC + Energy Outlook. It is possible to model individual countries, larger regions or the whole global RACHP market. In this section, insights from the modelling of single countries and larger regions using HFC + Energy Outlook are discussed.

7.2.1 Split between direct and indirect emissions, national level

Total GHG emissions from RACHP systems are the sum of the direct refrigerant-related emissions and the indirect energy-related emissions. Many previous publications state that energy-related emissions are dominant, representing between 75% and 80% of the total. This is true in some circumstances, but modelling shows that the split between direct and indirect GHG emissions is a country-specific issue and highly variable.

The key parameter that affects the balance of emissions is the electricity grid carbon emissions factor. Countries that are heavily dependent on coal electricity generation might have grid carbon factors in the range 0.8 to 1.1 kg CO_2 per kWh. Countries with significant renewable resources or nuclear power might have grid factors over 90% lower i.e., in the range 0.05 to 0.1 kg CO_2 per kWh. These different grid factors have a big impact on the balance of GHG emissions from RACHP.

Figure 7.1 shows data from a regional model for 3 different grid carbon factors. The modelled refrigerant emissions and the energy used to operate the RACHP are the same in all three cases. With a grid factor of 1 kg CO_2 per kWh, energy-related emissions are 85% of the total but this falls to only 34% of the total for a grid factor of 0.1 kg CO_2 per kWh. Figure 7.2 displays the same data in a different format showing that direct emissions are constant and that indirect emissions for a constant energy use are influenced by the grid factor.

Key message: For countries with high grid factors, reducing energy use is the key priority. For countries with low grid factors, a greater focus on reducing HFC emissions is beneficial.

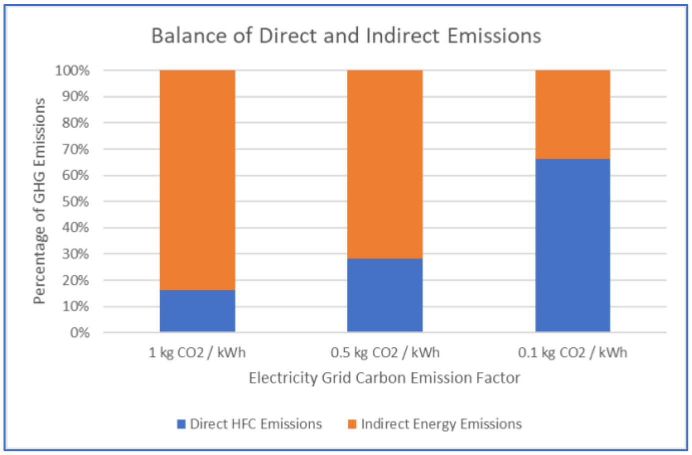

Figure 7.1. Balance of RACHP emissions for different grid carbon factors

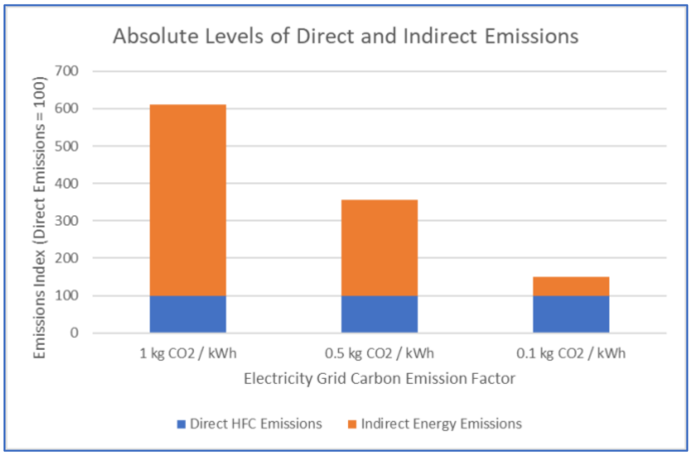

Figure 7.2. Magnitude of RACHP emissions for different grid carbon factors

7.2.2 Split between direct and indirect emissions, technology level

Modelling also shows clear differences of the split of emissions between different technology types. Some examples are shown in Figure 7.3, which is based on a fixed grid carbon factor of 0.5 kg CO_2 per kWh:

a) Small factory-built refrigeration equipment (e.g., residential refrigerators and small stand-alone retail displays) have low leakage rates and are operated constantly. Even if HFC refrigerants are used, direct emissions are low. With long operating hours the energy use is high, hence the indirect energy emissions are usually >95% of the total. This type of equipment is well-suited to hydrocarbon (HC) refrigerants; with HCs the direct emissions are negligible, and the indirect emissions can be >99% of the total.

b) Large, site constructed refrigeration equipment (e.g., large supermarket central systems or industrial systems) often have quite high leakage rates, which makes the direct emissions more important. A popular HFC used in these applications is R-404A, with a very high GWP (3,922); leakage emissions are especially important. Figure 7.3 shows that a large supermarket chilled food central system could have over 60% direct emissions.

c) Similar types of equipment operating at different temperature levels will usually have equal direct emissions but the indirect emissions for low temperature systems are greater than higher temperature systems. For example, frozen food display cabinets use more energy than an equivalent chilled food cabinet.

d) Some RACHP equipment only has limited operating hours per year. For example, car air-conditioners. Most cars are used for a very small proportion of the year. A typical private vehicle usage is less than 10,000 miles per year. This probably equates to less than 300 hours per year of car use. The energy-related emissions only occur during operation and are relatively low. Refrigerant leakage emissions can occur both during operation and when a vehicle is stationary, hence these emissions are less influenced by the low running hours.

Key message: Policy makers need to recognise the complexity of the RACHP market and develop different policies for different applications.

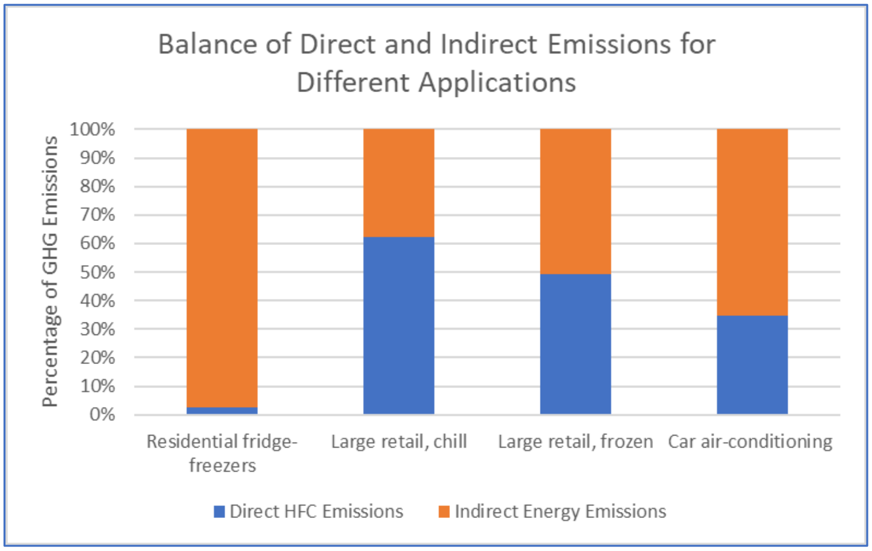

Figure 7.3. Emissions for various applications (for constant grid carbon factor of 0.5 kg CO2 / kWh)

7.2.3 Understanding sources of direct refrigerant emissions

Refrigerant emissions can occur at different parts of the lifecycle of a piece of RACHP equipment. The HFC Outlook model includes estimates of emissions during:

1) New equipment manufacturing and installation
2) Operating life
3) At end-of-life

Figure 7.4 shows modelling of sources of emissions from the whole RACHP market of a single country and from two different types of food retail equipment (stand-alone units and large central systems). Emissions during manufacture and installation are only a tiny percentage of the total (0.5% for all RACHP in this example). Leakage emissions during life are dominant 75% for all RACHP. For small, sealed equipment (including residential refrigerators and freezers and stand-alone retail systems) the proportion of end-of-life emissions are more significant (80% of emissions from stand-alone retail equipment).

Key message: actions taken to reduce operational leakage (e.g., through regular leak tests and better maintenance) can significantly reduce direct emissions in some market sectors. Gas recovery at end-of-life is also important to minimise emissions.

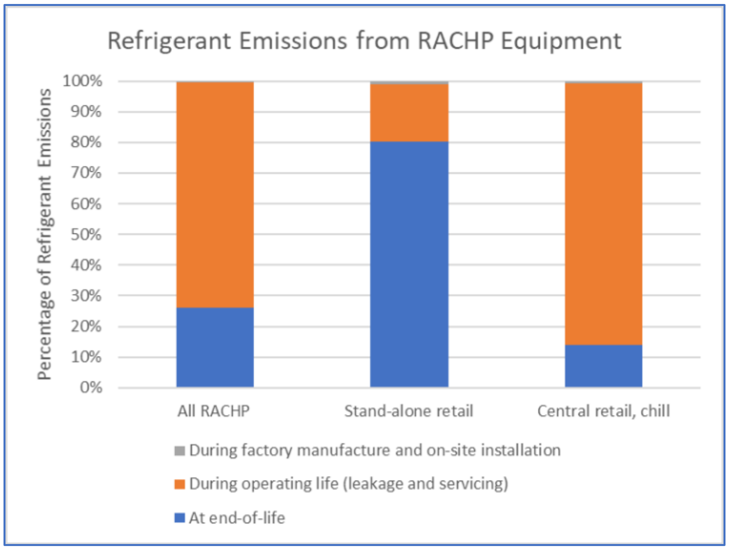

Figure 7.4. Refrigerant emissions during RACHP equipment lifecycle

7.2.4 Understanding Core Actions for Reducing Direct and Indirect Emissions

To forecast future reductions in GHG emissions, bottom-up models like HFC Outlook need to:

a) Estimate the likely growth of stock in each RACHP market

b) Model a range of actions that will reduce direct emissions

c) Model a range of actions that will reduce indirect emissions

d) Model the interaction/synergy of integrated actions to reduce direct and indirect emissions

Policy makers need to consider the types of action that will reduce emissions and then implement suitable policies to support the implementation of these actions. The core actions to reduce GHG emissions are summarised in Table 7.1.

It is important to note that the correct actions taken prior to selecting new equipment will reduce both direct and indirect emissions. If you minimise the need for cooling (e.g., by fitting doors to retail displays) prior to refrigeration equipment selection then the required equipment will be smaller, using less refrigerant and using less energy.

Key message: It is important to be aware of the actions that reduce direct and indirect emissions and to recognise that if they are tackled together, it is likely that the greatest emissions reductions will be achieved with lowest cost.

Table 7.1 Core actions to minimise GHG emissions

<table>
<tr><th></th><th>Actions to minimise direct refrigerant emissions</th><th>Actions to minimise indirect energy emissions</th></tr>
<tr><td>Prior to selecting new equipment</td><td colspan="2">Consider all opportunities to minimise the need for refrigerated cooling e.g.:
• Doors on retail display cabinets
• Passive building design measures to reduce heat gains (e.g., shading)
Consider the appropriate temperature level for cooling – higher temperatures are more efficient e.g., avoid putting loads with different temperatures on a single refrigeration system.
Consider the range of operating conditions to be encountered through the year and how the cooling equipment can be optimised to maximise efficiency under all common conditions e.g., make sure the plant is efficient under low part load conditions.</td></tr>
<tr><td>When selecting new equipment</td><td>Use lower GWP refrigerants.
Ensure new equipment is designed to minimise leakage.</td><td>Select highest efficiency equipment.
Ensure design is efficient at all common operating conditions.
Fit relevant monitoring e.g., kWh meters, pressure, and temperature sensors.</td></tr>
<tr><td>When operating existing equipment</td><td>Minimise leakage with regular leak tests and good maintenance.
Recover and re-use refrigerant during major plant maintenance activities.
Retrofit systems using very high GWP refrigerants (e.g., R-404A) with lower GWP alternatives.</td><td>Optimise controls to minimise energy use.
Carry out regular maintenance to ensure design efficiency is maintained.
Regularly monitor energy use and operating conditions to check performance.</td></tr>
<tr><td>At end-of life</td><td>Ensure refrigerant is recovered.
Reprocess recovered refrigerant for re-use in other RACHP systems.</td><td>Ensure recycling of all valuable components (e.g., all metals).</td></tr>
</table>

7.2.5 Need for early action on HFC phase-down

The modelling of HFC phase-down clearly shows that in some Article 5 countries actions are needed in 2022 and 2023 to comply with the Kigali Amendment HFC freeze in 2024. Figure 7.5 shows historic HCFC and HFC consumption for a single country, together with a forecast of HCFC phase-out and 2 possible forecasts of HFC consumption. The “Just compliant” scenario does not “turn the corner” away from the reference scenario until the end of 2023 – there is non-compliance with the freeze in 2025 to 2027 and also non-compliance with the first phase-down step in 2029.

Key message: to avoid non-compliance early HFC mitigation actions are required.

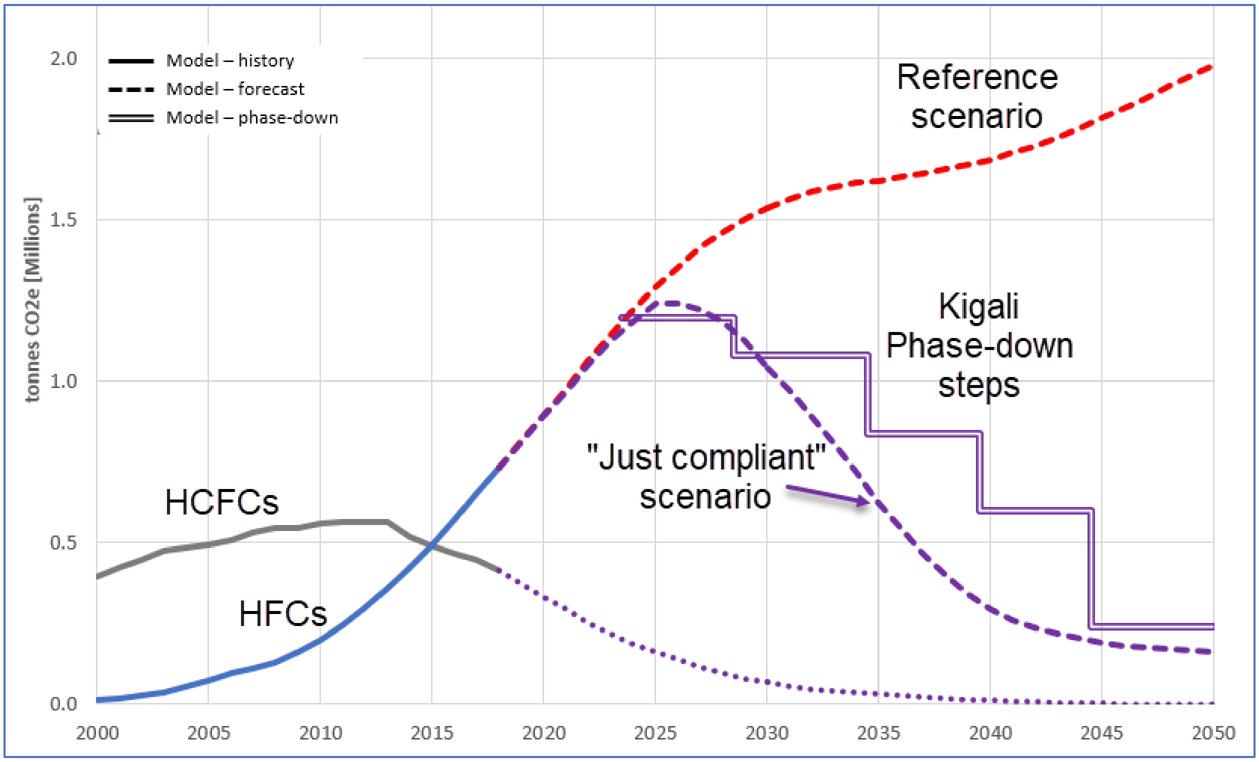

Figure 7.5. Early action to avoid non-compliance with first Kigali steps

7.2.6 Assessing Different Pathways to Reduce Direct and Indirect Emissions

It is important to compare different pathways that will lead to the reduction in total GHG emissions from RACHP equipment. Analysis of pathways can help policy makers identify the best ways to encourage the uptake of lower GWP and more efficient RACHP systems. In this section a comparison of pathways for a typical Article 5 Group 1 country is provided. The actual pathways for individual countries can vary considerably – this example gives indicative figures.

The starting point is to recognise that there is expected to be considerable growth in the amount of cooling provided in most countries. In addition, in order to decarbonise heating systems there is expected to be growth in the use of heat pumps. Figure 7.6 illustrates the possible growth rate of cooling and heating delivered between 2020 and 2050. In this example the 2050 amount of cooling and heating delivered is 2.8 times higher than in 2020.

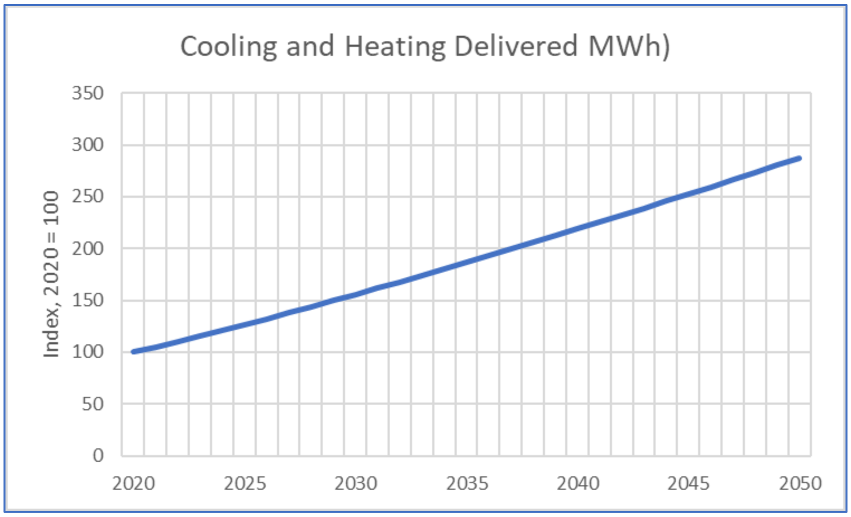

Figure 7.6. Forecast of growth of RACHP Cooling and Heating

Models can then show different pathways for both direct HFC emissions and for indirect energy emissions.

Figure 7.7 shows 3 pathways for HFC emissions from the RACHP sector. Without Kigali, the "No Action" pathway forecasts that direct emissions grow by a factor of 2.5. The "Just Compliant Scenario" is a pathway that reaches the Kigali target level of HFC consumption by 2045 (an 80% cut in HFC consumption for an A5 Group 1 country). Under the Just Compliant pathway the cumulative GHG emissions between 2022 and 2050 are approximately 50% of the No Action level. Low GWP refrigerants are available for most RACHP sectors and if these are implemented more quickly than under the Just Compliant pathway there are significant extra environmental benefits. The "Best Possible" pathway has cumulative emissions between 2022 and 2050 that are 40% lower than Just Compliant.

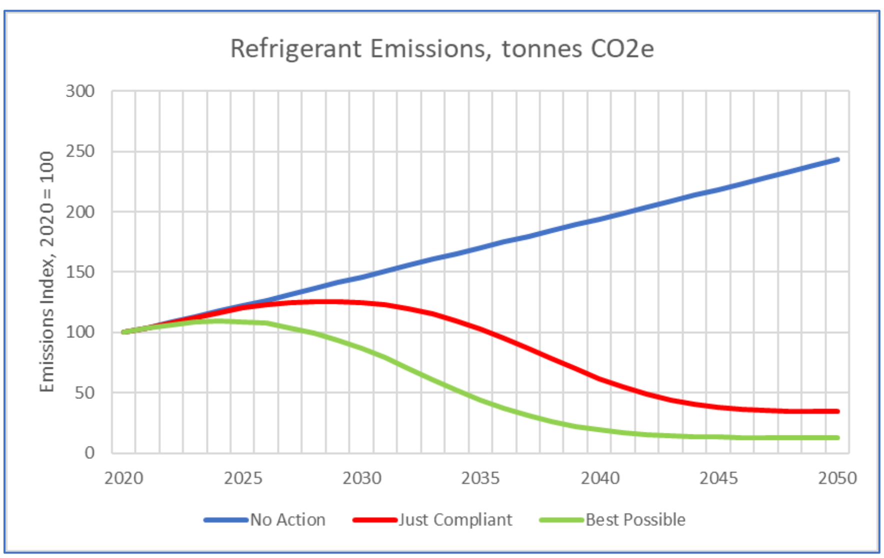

Figure 7.7. Forecast of future RACHP refrigerant emissions

Figure 7.8 shows four different pathways towards the use of more energy efficient equipment. This data is based on the MWh of electricity and fuel used to operate all the RACHP equipment in a country. The "No efficiency gain" pathway assumes no improvements in energy efficiency from the levels achievable in 2020. The other 3 pathways model different levels of ambition to improve the efficiency of new RACHP equipment, using the core actions shown in Table 7.1. The No efficiency gain scenario results in a doubling of energy use by 2050, as the stock as RACHP equipment is growing (as shown in Figure 7.6). With high levels of ambition, the 2050 energy use is forecast to fall to 75% of the 2020 value, despite a 280% increase in the amount of cooling and heating delivered.

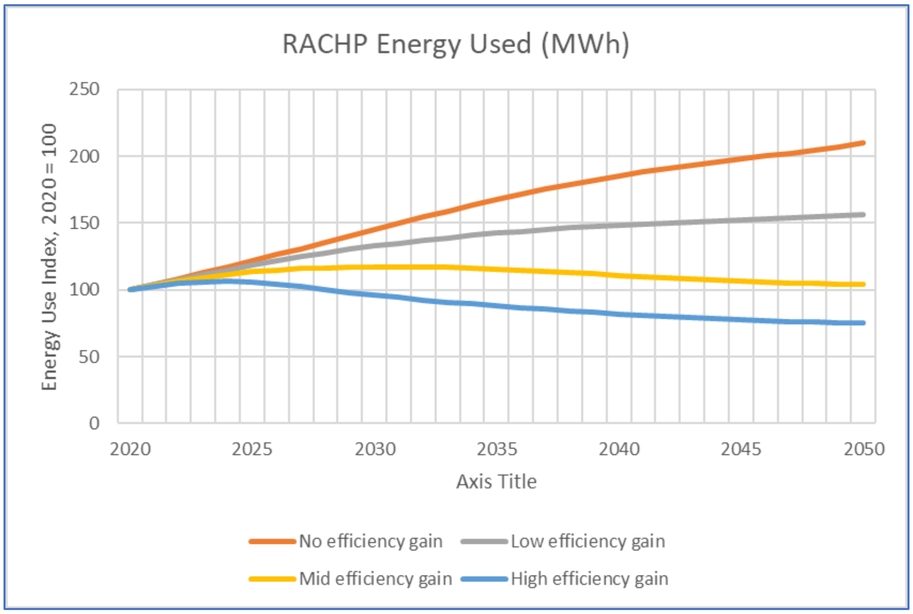

Figure 7.8. Forecast of future RACHP energy consumption

The final step in this analysis is to estimate the indirect energy related CO_2 emissions. This can vary considerably between different countries depending on (a) the current electricity grid emissions factor and (b) the pathway to lower carbon electricity. The impact of different electricity grid emissions factors was illustrated in Figures 7.2 and 7.3. Figure 7.9 shows an example based on a 2020 grid factor of 0.75 kg CO_2 per kWh. This is a typical 2020 factor in many A5 and non-A5 countries.

For the "No efficiency gain" pathway, the grid factor is assumed to remain at this value. For the other 3 pathways the grid factor reduces linearly between 2020 and 2050. In the left-hand chart, the grid factor is assumed to reduce to 0.4 kg CO_2 per kWh by 2050 (which is a low ambition pathway). In the right-hand chart the grid factor is assumed to reduce to 0.1 kg CO_2 per kWh by 2050.

The cumulative indirect emissions between 2022 and 2050 for the best scenario (High efficiency gain and grid factor of 0.1 kg CO_2 per kWh by 2050) are 70% lower than under the No efficiency gain scenario.

Key message: there are many different pathways available to achieve the Kigali Amendment targets. Combining early action for HFC mitigation actions with simultaneous energy efficiency actions can lead to significant reductions in cumulative GHG emissions between now and 2050. Grid decarbonisation also makes a vital contribution to reduced emissions.

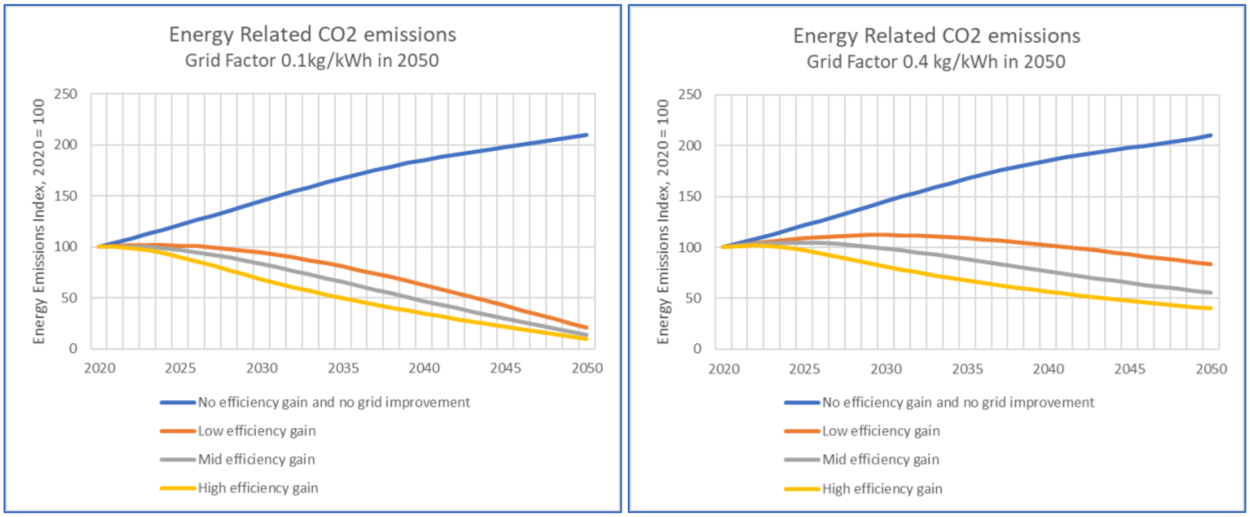

Figure 7.9. Forecast of future RACHP energy related CO_2 emissions for two electricity decarbonisation pathways

7.2.7 Heat Pump Benefits

Most existing heating systems (for building space heating, for water heating and for industrial process heating) use fossil fuels and make a significant contribution to CO_2 emissions. The decarbonisation of heating is a crucial aspect of the path to net zero.

A significant proportion of heat demand can be supplied using electric heat pumps. This is the most efficient way of providing heat with electricity as heat pumps make use of "free heat" in a waste heat stream or from the environment (from air, water, or the ground). The heating markets that are well suited to heat pumps include:

- Residential: space heating and hot water heating
- Commercial: Commercial and public sector buildings, space heating and water heating
- Industrial: low temperature process heating (below 130ºC) and industrial building space heating

Modelling of the growth of heat pumps in the EU shows the significant contribution to GHG emission reductions created by the use of efficient heat pumps. Figure 7.10 shows estimates of the direct and indirect emissions from heat pumps together with the abated fossil fuel emission. This represents the fossil fuel emissions that would have occurred if the heat pumps had not been used (based on heating with natural gas in 95% efficient boilers). This shows that the abated fossil fuel emissions in 2050 are **40 times greater** than the heat pump emissions. This analysis is for the EU where the forecast electricity grid carbon factor in 2050 will be close to zero.

Key message: the avoided fossil fuel emissions through the use of heat pumps will massively outweigh any direct and indirect emissions from the heat pumps (especially in regions where there is a low carbon electricity grid factor).

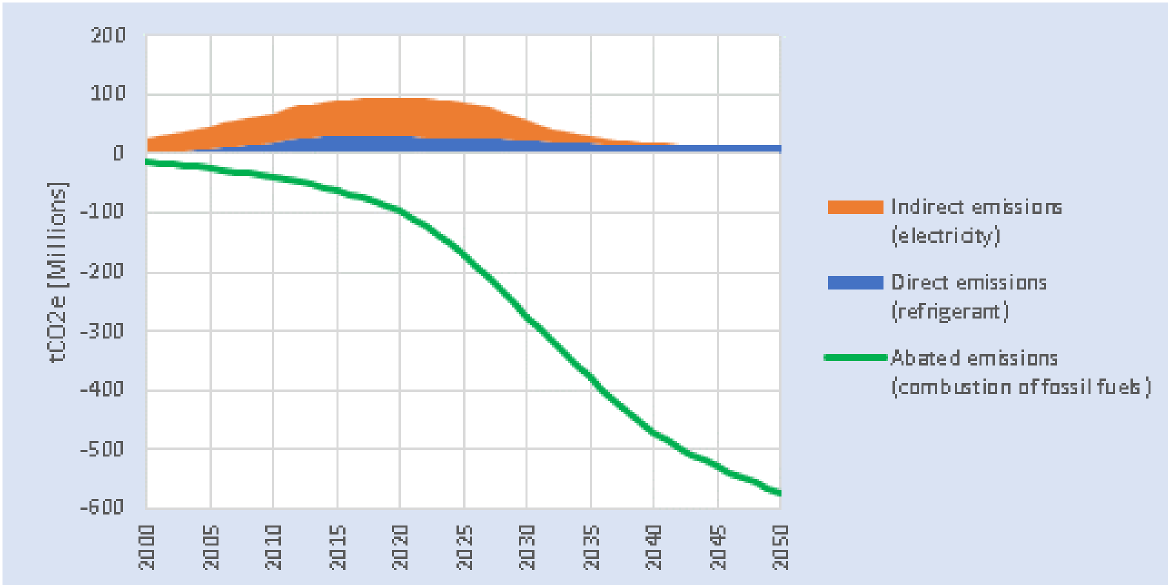

Figure 7.10. Avoided GHG Emissions through use of Heat Pumps in the EU

7.2.8 Energy Efficiency First

If a country has achieved decarbonisation of the electricity grid (through use of renewables or nuclear power) then it is possible to argue that energy efficiency of RACHP equipment is not important, as indirect GHG emissions will be zero.

Whilst this is true for a few countries that already have a low electricity carbon emission factor (e.g., Lesotho and Bhutan, which both have very large hydro resources), most countries rely on a significant amount of fossil fuel for electricity generation and will need to make large investments to decarbonise their electricity. Modelling of the relative costs of new zero carbon generating capacity or improving the efficiency of RACHP equipment indicates that it is usually more cost effective to reduce electricity peak demand through RACHP efficiency investments than to simply invest in more zero-carbon generation.

For example, studies carried out by the European Commission has led the EU to specify the "Energy Efficiency First" principle. It means "*taking utmost account of cost-efficient energy efficiency measures in shaping energy policy and making relevant investment decisions. It is a far-reaching guiding principle that should complement other EU objectives, in particular sustainability, climate neutrality and green growth*."

Key message: Ensuring that new RACHP equipment is as efficient as possible, and that existing equipment is operated and maintained for high efficiency makes a very cost-effective contribution to the path to net zero GHG emissions.

7.2.9 End-of-life refrigerant recovery and re-use

Models can show how much refrigerant is entering the waste stream every year. As shown in Figure 7.4, end-of-life emissions represent an important part of total direct refrigerant emissions. Policy makers can use modelling data to consider the potential benefits of ensuring that refrigerants are recovered from old equipment. Maintenance technicians need appropriate training on how to recover refrigerant and they need access to refrigerant recovery machines. Many countries have already introduced regulations to make refrigerant recovery mandatory at end-of-life and during maintenance.

Following refrigerant recovery, the recovered gas can either be destroyed or re-used. Under the Montreal Protocol, re-use of gas is outside of the phase-down or phase-out process, so there is a commercial incentive to re-use recovered gas. The gas needs to be re-processed to ensure it is of sufficient quality. This requires a suitable infrastructure to collect recovered gas cylinders and for re-processing. In small Article 5 countries that might be difficult to establish, and it is worth considering regional initiatives across several countries.

Key message: venting HFC refrigerants to atmosphere during maintenance or at equipment end-of-life is highly undesirable and steps should be taken to maximise refrigerant recovery. Recovered refrigerants can be re-used if there is a suitable infrastructure for re-processing.

7.2.10 Understanding Equipment Operating Hours

Modelling of refrigerant consumption and emissions is simpler than modelling RACHP energy consumption. The key variables for modelling refrigerant use from a piece of RACHP equipment are refrigerant type, refrigerant charge, in-life leak rates and end-of-life recovery rate. The consumption and emissions of refrigerant does not have a strong link to equipment usage patterns.

For energy modelling a fundamental variable relates to usage patterns. For certain types of equipment, the pattern is simple. For example, residential refrigerators need to run 24 hours per day to ensure the stored product remains cold. However, for air-conditioning equipment there is a lot of "user-choice" to define operating hours and temperature set points. These both have a significant impact on the annual energy use. There is probably a relationship between wealth and operating hours, although this is not well researched. If a user can afford to pay for electricity, they may decide to use their air-conditioning equipment for 24 hours a day to maximise comfort levels. However, if electricity is too costly or if supplies are unreliable, the air-conditioning unit might only be used for limited hours per day.

Key message: equipment usage patterns have a big impact on energy use and indirect emissions. More research is needed to understand operating patterns of different categories of RACHP equipment in different climates and in countries with different levels of wealth.

7.2.11 Lack of good data for modelling

As discussed in 7.3.9, there is a lack of data on RACHP usage patterns. It is important to note that for many countries there is a significant lack of data for all aspects of modelling. Some examples where better data would improve modelling:

1) Stock of RACHP equipment in the wide range of different technology categories. There is sometimes some stock data available for residential refrigerators, car air-conditioning and for small room air-conditioners. However, for commercial and industrial refrigeration and for larger air-conditioning systems (e.g., used in offices, hotels, public buildings etc.) data is usually unavailable.
2) Refrigerant leakage rates.
3) End-of-life refrigerant gas recovery rates.
4) Average energy efficiency of equipment being placed on the market.
5) RACHP usage patterns.
6) Impact of poor operation and maintenance on energy efficiency.

Key message: better data is needed to improve modelling at national and regional levels.

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9 Annexes

9.1 Acronyms

A5	Article 5
AC	Air conditioner
ANSI	American National Standards Institute
ASEAN	Association of Southeast Asian Nations
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATEX	ATEX relates to 2 different EU directives addressing the risks of potentially EXplosive ATmospheres (derived from French): one directive covers the safety of workers, and the other covers requirements for equipment intended to be used in explosive atmospheres.
BEE	Bureau of Energy Efficiency
CaaS	Cooling as a Service
CDV	Committee Draft Vote
CO_2-eq	Carbon Dioxide Equivalent using 100-year Global Warming Potential, unless otherwise noted
COP	Coefficient of Performance
ECM	Electronically Commutated Motor
EE	Energy Efficiency
EER	Energy Efficiency Ratio
EESL	Energy Efficiency Services Limited
EETF	Energy Efficiency Task Force
EGYPRA	Egyptian Programme for Promoting Low-GWP Refrigerants' Alternatives
EU	European Union
FDD	Fault Detection and Diagnostics
GCP	Global Cooling Prize
GHG	Greenhouse Gas
GWP	Global Warming Potential
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons
HPMP	HCFC Phase-out Management Plan
Hz	Hertz
IATA	International Air Transport Association
ICC	Incremental Capital Cost
IEC	International Electrotechnical Commission
IGU	Insulated Glazing Unit
IOC	Incremental Operating Cost
IOT	Internet of Things
IPCC	The Intergovernmental Panel on Climate Change
ISO	International Standardisation Organisation
JRAIA	The Japan Refrigeration and Air Conditioning Industry Association
KIP	Kigali Implementation Plan
LCC	Life Cycle Costs

LED	Light Emitting Diode
LLCC	Least Life Cycle Costs
LVC	Low Volume Consuming
MCHX	Microchannel Heat Exchangers
MEPS	Minimum Energy Performance Standards
NCP/NCAP	National Cooling Plan or National Cooling Action Plan
NOU	National Ozone Unit
ODS	Ozone Depleting Substance
OEM	Original Equipment Manufacturer
PRAHA	Promoting low GWP Refrigerants for Air-Conditioning Sectors in High-Ambient. Temperature Countries
RAC	Room Air Conditioner
RACHP	Refrigeration, Air-Conditioning, and Heat Pumps
RDL	Refrigerant Driving License
RTF	Replenishment Task Force
RTOC	Refrigeration Technical Options Committee
SCCRE	Self-Contained Commercial Refrigeration Equipment
SEER	Seasonal Energy Efficiency Ratio
SME	Small and Medium Enterprise
TEAP	Technology and Economic Assessment Panel
U4E	United 4 Efficiency
VIP	Vacuum Insulating Panels
W	Watt

9.2 Background note on RACHP applications

9.2.1 Mini-splits and room ACs

Air-to-air split air conditioners and heat pumps are a large and growing sector both in terms of energy and refrigerant demand. Coordination among ozone and energy efficiency policy makers is key to managing the transition to energy efficient and lower-GWP equipment in this sector. Table 5.1 summarizes the main enabling policies for this transition. Best practice policies include integrated energy efficiency and refrigerant GWP performance labels, such as the United 4 Efficiency model regulations, use of seasonal energy efficiency performance metrics, and GWP thresholds (see EETF 2021 Case Study 4.1). Voluntary programs, such as endorsement labels, can also integrate energy efficiency and refrigerant information to help consumers identify more climate-friendly products (see Case Studies 9.5.1 and 9.5.2), and can be used by utility obligation schemes and procurement specifications (see Case Studies 9.5.5 and 9.5.6). Visible and enforced standards and labelling policies can assist market transformation and counter the perception of high cost (see Case study 9.5.3). The success of these policies depends on exporters respecting national regulations (see Section 5.4.7).
Previous chapters and EETF reports describe the continuing improvements in energy performance and increasing availability and access to these technologies. A best practice to increase access to more efficient technologies as performance improves is the regular revisiting and strengthening of performance standards and levels. Countries or regions with multiple climate zones have also adopted performance levels appropriate to regional climates (Figure 5.1).

As the industry moves to alternative options to replace high-GWP HFC refrigerants it is likely that A2L as well as A3 flammability class refrigerants will be used. As refrigerant alternatives become increasingly available, updating building codes and safety standards are another set of important enabling policies that have been under development for many years, and need local implementation to support the transition (see Tables 5.1 and 5.2).

9.2.2 Heat Pumps

Heat pumps have become a very attractive option with the advent of renewable energy. Air-to-air heat pumps have been used in milder climates for many years, but there is growing interest to expand to colder climates. In the US, the Department of Energy has challenged the industry to develop a cold climate heat pump and efforts are well underway. They use variable speed compressors for enhanced performance at low ambient temperatures.

Heat pumps may be insufficiently responsive to produce more heat under very cold conditions. Dual fuel heat pumps where auxiliary heat is provided by gas at peak times may reduce the overall energy while maintaining comfort. Geothermal heat pumps are becoming available, but installation costs are high.

For domestic water heating the market has expanded to use heat pump water heaters that have significant efficiency improvement over electric based water heating.

Typically heat pumps have been limited to smaller sizes less than 20 tons (70 kW) but larger air-to-air, air-to-water and water-to-water heat pumps are being developed and applied. The larger heat pumps in commercial buildings allow for reuse of energy where part of the building is in cooling and another part is in heating. Similar concepts are also being used for high energy demand buildings like data centres to allow for the rejected heat to be repurposed and reused to heat other nearby buildings or even processes and growing facilities.

9.2.3 Commercial HVAC

9.2.3.1 Packaged Ducted Air Conditioners

Packaged air conditioners have been widely used in North America for the heating and cooling of commercial and residential units, with growing use in other regions around the world due to the low installed cost. They are typically located outside the occupied space either on the roof or at ground level. The size of the units ranges from 3 tons (10 kW) to over 150 tons (525 kW). They are offered in constant volume as well as variable volume. Indoor fans have been modified to two speed fans to reduce fan power consumption by more than 60% and also improve humidity control. The features of the units increase to include options like economizers, exhaust air energy recovery, zoning systems, and advanced microprocessor-based controls

9.2.3.2 Duct Free Air Conditioners

An alternative to the ducted air conditioners is duct free and variable refrigerant flow (VRF) systems where local fan coils allow for zoning and elimination or reduction in ductwork. They also offer the opportunities to both heat and cool and in moderate to cold climates.

9.2.3.3 Dedicated Outside Air Units

There is growing use of dedicated outside air units that are designed to provide higher dehumidification capabilities. The use of these products is expanding and require a systems approach to the building design. With the pandemic the challenge is how to increase ventilation without significant increases in energy use. In commercial buildings 25% to 30% of the building energy consumption may be attributed to ventilation air conditioning.

9.2.4 Engineered Commercial HVAC

Many larger buildings are cooled with applied commercial chilled water systems that can range from 10 tons (35 kW) to 5,000 tons (17,500 kW) and even larger as the chillers are applied in multiples with 2 or 3 chillers. This allows some redundancy as well as load diversification, with performance assessment focussed on part load and annualized performance (Table 5.1). Most equipment is designed to manage extreme heating or cooling demand (that occurs at 1% or lower frequency) (i.e., 1% or 0.4% design conditions) and then typically oversized by 15%. To manage this excess capacity for most of the year, equipment uses either tandem compressor, compressor staging, or inverter driven compressors and variable speed.[30]

With water being an issue in many regions around the world, there has been increased use of air-cooled chillers with sizes now as large as 500 tons (1,750 kW). Evaporative cooling can offer significant reductions in condensing temperature. As a result, there is interest in adiabatic precooling as well as hybrid cooling towers to reduce the use of water, while maintaining high efficiency.

With the move to renewable electricity, there is growing interest in using chillers for heating. New rating standards, metrics and efficiency levels have been developed for air-to-water, water-to-water, and chillers with heat recovery. In many commercial buildings there is demand for both cooling and heating simultaneously, and many new buildings are being designed to use a heat pump chiller to replace a fossil fuelled boiler, as well as a lead chiller that both heats and cools during the transition seasons.

In addition, there is growing focus to not only look at the chiller, but to look at the complete system including cooling towers, pumps, air handlers and over controls and sequencing. New approaches like Total System Performance Ratio (TSPR) and full map certification are being implemented to allow for overall system modelling and analysis.

Large chillers using screw and centrifugal compressors have started to use HFOs with GWP's less than 1. These include HFO-1233zd(E) which is an A1 refrigerant, R-514A which is a B1 refrigerant, and HFO-1234ze(E) which is an A2L refrigerant. There is also medium GWP R-513A which is a refrigerant that can be used to retrofit HFC-134a which is one of the common refrigerants used in large chillers. These refrigerants are being implemented in advance of the proposed phase down regulations.

Smaller scroll chillers will essentially follow the same refrigerant selections as the packaged units and products using medium GWP refrigerants HFC-32 and R-454B. Such units are being introduced especially in Europe, where the phase down regulations are already well underway.

Chiller emissions are dominated by indirect emissions from the power used. Chillers are typically well maintained and have low refrigerant leak rates and high end of life recovery, so it is extremely important to focus on efficiency. The new refrigerants mentioned above allow for improved efficiency, and when combined with variable speed and oilless compressor there has been significant improvements in annualized efficiency. Natural refrigerants like CO_2 although shown to be acceptable for refrigeration are not viable for comfort cooling and would result in significant decreases in energy efficiency, but there is interest in natural refrigerants and there are some class A3 applications in chillers, but require appropriate designs, application, and service practices to ensure safety. Furthermore, the use of natural refrigerants such as R-744 (CO_2) and R-717 (NH_3) provide some additional advantages when considering integrated heat pump designs – i.e., when cooling and heating loads are simultaneous, but R-744 has also been introduced in the market of water chillers.

For engineered commercial HVAC, government and industry investments in flammability research has led to updates to international safety standards and regional building codes (Figure 5.2) and will be complete in non-A5 parties in the 2024- 2026 time- frame. It is anticipated that these safety standards and regional building codes will be adopted by A5 parties during the 2020s driven by the Kigali phasedown requirements.

9.2.5 Self-Contained Commercial Refrigeration Equipment (SCCRE)

SCCRE with low-GWP refrigerants are increasing where there is regulatory environment that encourages this transition. For example, the European Union has seen an increase in the sales of higher energy efficiency low-GWP refrigerated storage cabinets because of the combination of the Ecodesign

[30] Please refer to further discussion in section 6.1.

Regulation EU 2015/1095, the Energy labelling regulation 2015/1094, and the EU F-Gas regulations. In March 2021, the European Union also introduced additional Ecodesign Regulation (EU 2019/2024) alongside an energy labelling regulation (EU 2019/2018) for refrigerating appliances with a direct sales function (i.e., both SSCRE and remote units). Other countries with a mandatory regulation for these products are Australia, China, Iran, Mexico, New Zealand, Switzerland, the United States and Vietnam. However, in many countries, these products continue to be unregulated, with no incentive to improve the products' energy efficiency or introduce low-GWP refrigerants.

9.2.6 Large Commercial Refrigeration

Large commercial refrigeration systems, found in food retail and food storage facilities are characterized by refrigerating capacities of equipment varying from hundreds of watts up to 1.5 MW (see Section 2.5). Since the systems are individually designed for the facility, they vary in how and where they are applied, in refrigerant charge size, and energy consumed by the equipment. These systems are installed, refrigerant charged and commissioned on site and operate throughout the year. As a result, these systems are more vulnerable to the quality of materials and workmanship than factory-built systems.

Two broad classifications in large commercial refrigeration systems are *Remote Condensing Units* and *Centralized or Distributed Systems*. The outdoor ambient temperature and humidity play a significant role in the energy performance of this type of equipment, as the heat removed from the space being refrigerated is ejected to the outdoor ambient environment.

No two large commercial refrigeration systems are alike. First, their application or use is not alike, and second, due to the effect of the outdoor ambient conditions on energy performance, two similar pieces of equipment in different geographies will not draw the same power. For this reason, it is important that energy efficiency regulations are performance-based minimum requirements and not prescriptive, i.e., not requiring specific components or technology. For example, EU Regulation 2019/2024 for refrigerating appliances with a direct sales function sets minimum energy requirements and an energy label for remote cabinets. It addresses one part of the entire refrigeration system to avoid cold losses inside the stores.

The HFC phase down being implemented by various non-A5 parties is causing a shift from non-flammable high-efficiency and high-GWP HFCs to low-GWP fluids in these applications as well. A non-flammable alternative that has gained significant interest is R-744. In the start the development was made primarily for medium temperature climates, but now systems for high ambient climates have been developed.

In non-A5 parties, manufacturers have to meet MEPS, which can be challenging and motivate design and engineering innovations. Industry is using the opportunity to rethink the design, installation, and use of the equipment in order to meet both goals of the HFC phasedown and MEPS. If these same standards in non-A5 parties can be replicated in A5 party contexts, improvements in energy efficiency can be expected to follow. The key is to set efficiency standards and let the industry respond with design and use of the equipment to meet those standards.

9.3 Effect of refrigerant choice on cycle performance

In this annex we provide detailed thermodynamic analysis for the impact of refrigerant choice on the cycle parameters. This study is done across the range of alternative refrigerants where thermodynamic properties differ, thus yielding dissimilar performance parameters. Key performance parameters include:

- Cooling & Heating coefficient of performance (theoretical cooling and heating COP)
- Compressor displacement
- Pressure ratio
- Discharge temperature
- Critical temperature

COP represents cycle efficiency, compressor displacement translates as the volumetric flow rate of refrigerant around the circuit, pressure ratio is the ratio of discharge to suction pressure and relates to compressor efficiency. Higher discharge temperature can be considered disadvantageous or not, depending upon the function of the system, but nevertheless is undesirable from the perspective of compressor reliability. The level of each of these performance parameters can infer an impact on system cost.

9.3.1 Relation of pressure ratio versus theoretical cooling and heating COP

Figure *9.1* depicts the theoretical cooling COP of almost all the refrigerants listed within ISO 817 (2021) according to their saturated vapour pressure at 0°C (selected as a nominal reference condition). Certain alternative refrigerants have been assigned coloured markers to help gauge the data. These show that approximately, refrigerants with a lower saturated vapour pressure tend towards higher theoretical efficiencies. For some refrigerants, there is wide deviation ("stragglers"), however, these refrigerants are with very wide temperature glides and divergence in COP could be reduced through selection of "mid-point" conditions, more consistent with the shape of their temperature glide. In order to normalise efficiencies, those with higher cycle COPs can (in theory) benefit from smaller heat exchangers and vice versa for those with lower cycle COPs.

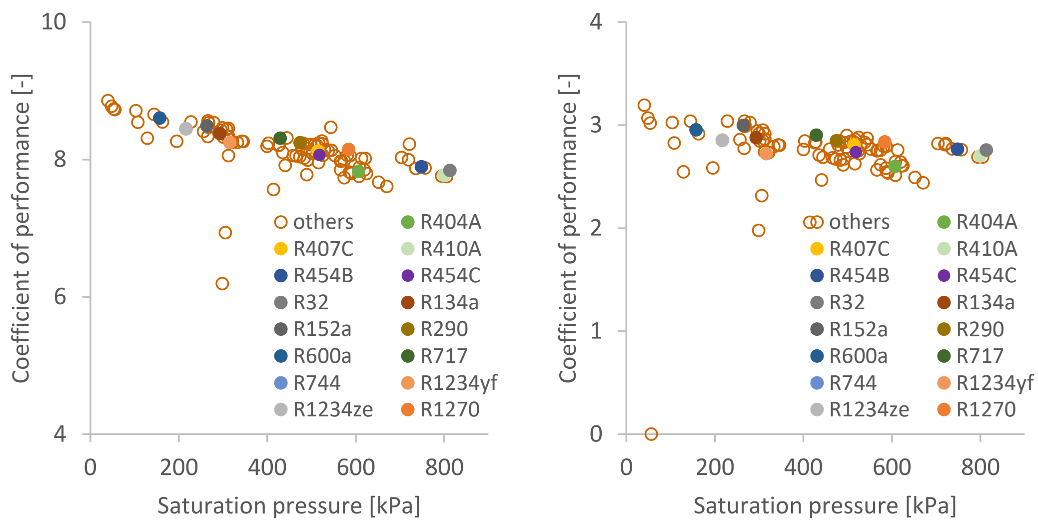

Figure 9.1: Variation of theoretical cycle COP of refrigerants listed in ISO 817 (2021) over saturated vapour pressure at 0°C; condensing temperature of +40°C, evaporating at +10°C (left) and -25°C (right

The theoretical heating COP is provided in *Figure 9.2*, which also shows higher efficiency with lower pressure refrigerants, albeit with more scatter than for cooling COP.

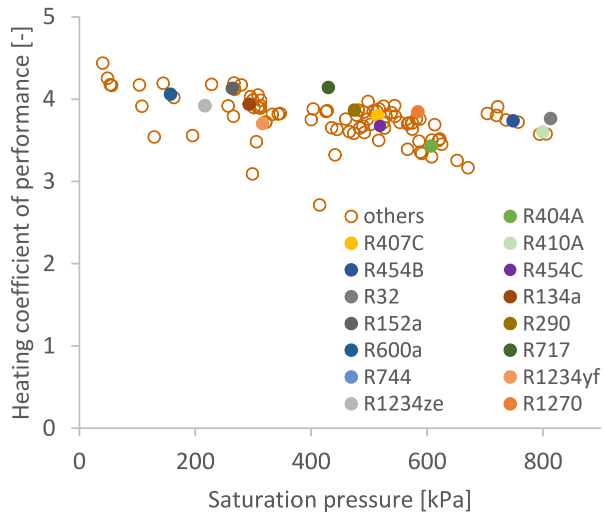

Figure 9.2: Variation of theoretical heating COP of refrigerants listed in ISO 817 (2021) over saturated vapour pressure at 0°C, based on evaporating at -5°C and condensing at +60°C

It must however be emphasised that the stated efficiencies are purely theoretically based. In practice one would design the system for the refrigerant considered. Then a lot of other factors will play in and offset the theoretical COP figures by various characteristics of the refrigerant and different design features. This means that there is no direct relationship with actual system efficiency. Please refer to Table 3.1 and the examples given in section 3.4. It must also be mentioned that R-744 has a saturation pressure at this condition of 3500 kPa, and the characteristic of this fluid defers very much from the other fluids, thus not suited for such simplified cycle calculations.

9.3.2 Relation of pressure ratio to Compressor displacement

Compressor displacement (Figure 9.3) represents the volumetric flow of refrigerant for a cycle, where there is a strong dependence upon saturation pressure. In terms of compressor cost, this does not infer a notable impact on cost (see below) within a certain range, however, it can indicate an impact on required tubing size, both for piping and heat exchangers. Thus, those refrigerants towards the right of the x-axis can tolerate smaller components (pipes, heat exchangers, etc.) without adversely affecting the cycle performance.

Whilst lower pressure refrigerants require a larger compressor volumetric displacement, this does not have a significant impact on the mass of materials used for the compressor. For instance, *Figure 9.4* shows the “specific mass” (compressor total mass per kW of nominal cooling capacity) for rotary compressors with higher and medium-pressure refrigerants. There is no distinguishable tendency for compressor mass across refrigerant pressure levels. Whilst some elements of the compressor may be larger (greater mass) for the lower pressure refrigerants, these are offset by the thicker casing material required to handle the higher-pressure refrigerants. This same observation can be seen amongst different manufacturers’ products and other compressor types. Some deviation might be expected for very low-pressure refrigerants, but usually in these cases different types of compressors with higher speeds are used, so a direct comparison is not possible.

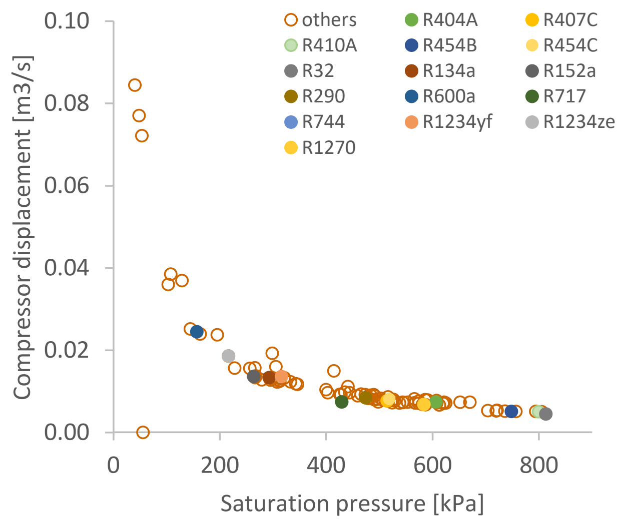

Figure 9.3: Variation of theoretical compressor displacement of refrigerants listed in ISO 817 (2021) over saturated vapour pressure at 0°C

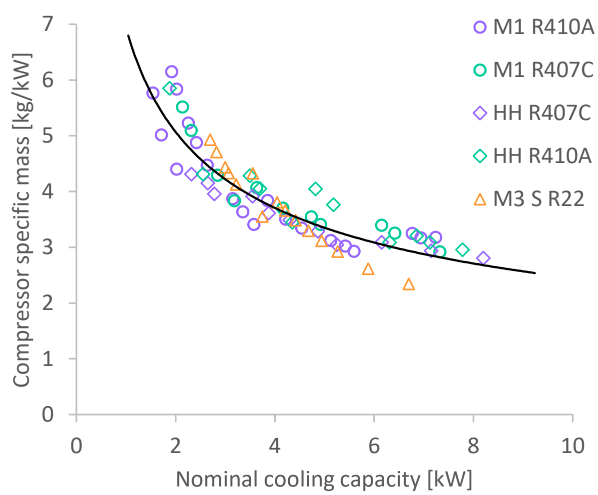

Figure 9.4: Variation of compressor mass with refrigerant type and nominal capacity

Figure 9.5 illustrates how lower pressure refrigerants have higher pressure ratios. Compressors for refrigerants towards the right of the x-axis can have higher efficiency to those towards the left. Conversely, for refrigerants with high pressure differences, internal leakage can to an extent be higher which goes some way to offset the benefits of lower pressure ratios to compressor efficiency. Type of compressor may also play a role with respect to influence of internal leakages, as an example a reciprocating compressor may have less internal leakage than a corresponding scroll compressor.

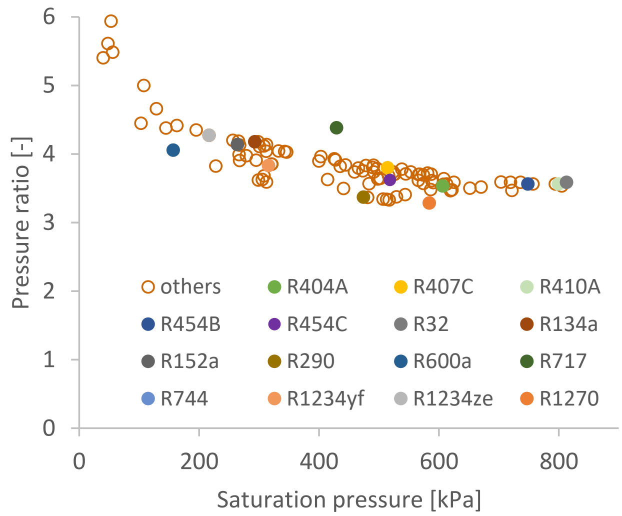

Figure 9.5: Variation of pressure ratio (left) and pressure difference (right) of refrigerants listed in ISO 817 (2021) for an evaporating temperature of -5°C and condensing at +40°C, over saturated vapour pressure at 0°C

9.3.3 Relation between pressure ratio versus discharge temperature

Variation of discharge temperature across refrigerants is shown in Figure 9.6. Generally, those with higher pressure have higher discharge temperature, although the trend is much more scattered. As mentioned, in some cases a higher discharge temperature can be advantageous, i.e., where the higher temperature is useful for the application. Apart from additional considerations of materials to address impacts on longevity of components, discharge temperature has limited impact on costs.

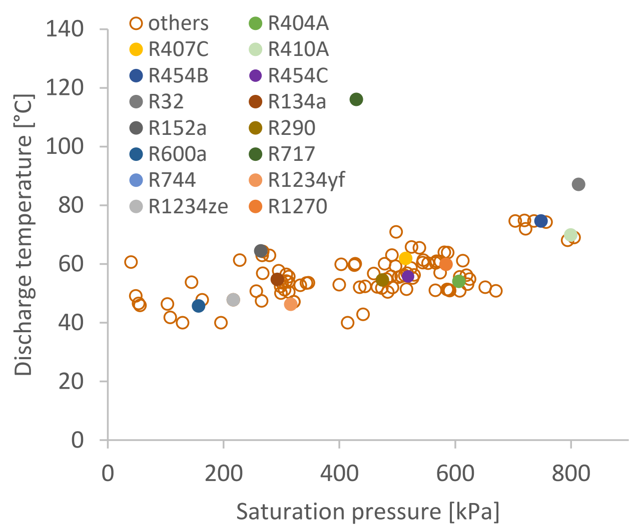

Figure 9.6: Variation of discharge temperature of refrigerants listed in ISO 817 (2021) for an evaporating temperature of -5°C and condensing at +40°C, over saturated vapour pressure at 0°C

9.3.4 Relationship between pressure ratio and critical temperature

When the operating pressure approaches the critical pressure, the thermo-physical cycle efficiency decreases. This is why in high ambient temperatures, high pressure refrigerants with low critical temperature often are avoided. With R-744, having a very low critical temperature, the operation is switched from subcritical high pressure to a supercritical high pressure at certain operating conditions, thus running a transcritical cycle, in order to gain efficiency. At very high ambient temperatures efficiency of the cycle may further be enhanced by use of e.g., parallel compression or using ejectors to recover some work during expansion, the latter however with additional costs.

Refrigerant	**R-410A**	**HFC-32**	**HFO-1234ze**	**HC_290**	**R-744**	**R-717**
Critical temperature (°C)	72.5	78.1	109.4	96.8	31.1	132.5

As can be seen, the various performance parameters associated with theoretical refrigeration cycles differs significantly amongst refrigerants. In some respects, lower saturated vapour pressures imply advantages, in others higher pressure refrigerants benefit.

9.3.5 Effect of refrigerant pressure losses

As a refrigerant flows though piping and components, frictional and other pressure losses (acceleration and gravitational) occur. This results in corresponding increase in discharge or condensing pressure (temperature) and reduction in suction or evaporating pressure (temperature). Accordingly, as pressure losses increase, saturated suction and discharge temperature diverge, and cycle efficiency reduces. Thus, minimisation of pressure losses leads to higher efficiency (for all refrigerants).

Most refrigerant's cycle COP degrades at about 1.5% per K of saturated temperature increase (condenser) or decrease (evaporator) due to pressure loss. Specifically, pressure loss should be assessed in terms of temperature change corresponding to saturated pressure change, rather than pressure change itself (i.e., in kPa). The graph in *Figure 9.7* helps illustrate the point: lower pressure refrigerants experience a small pressure loss per K change in saturation temperature, whereas higher pressure refrigerant experiences the opposite. Practically, this means that to limit degradation in COP to, say 3%, a higher-pressure refrigerant can tolerate double the absolute pressure loss (i.e., in kPa) that a lower pressure refrigerant could. Broadly, this translates as the lower pressure refrigerant having to use a larger diameter tube (of the same length).

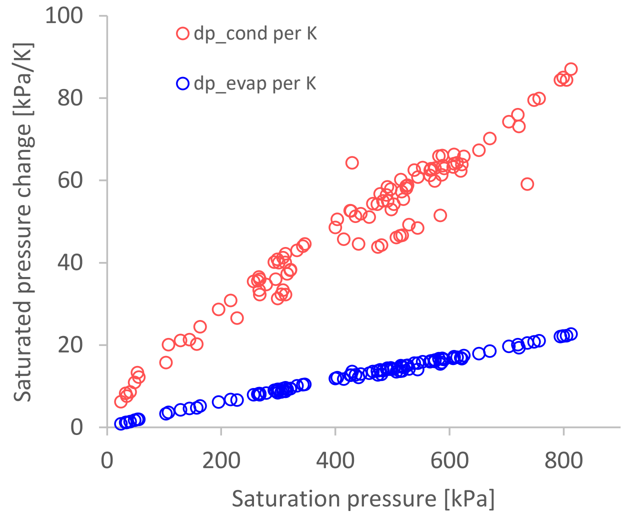

Figure 9.7: Variation of compressor mass with refrigerant type and nominal capacity

Actual pressure losses are a function of refrigerant thermophysical and transport properties: latent heat (which dictates mass flow rate), density (affecting velocity), and viscosity. The higher the latent heat, higher the density and lower the viscosity, the lower the pressure loss. The weighting of these elements also depends upon whether the flow is liquid, vapour or two-phase.

Figure 9.8 illustrates the variation in pressure loss, expressed as change in saturation temperature, per m of pipe. Apart from the unique case of R717, higher pressure refrigerants exhibit smaller pressure losses.

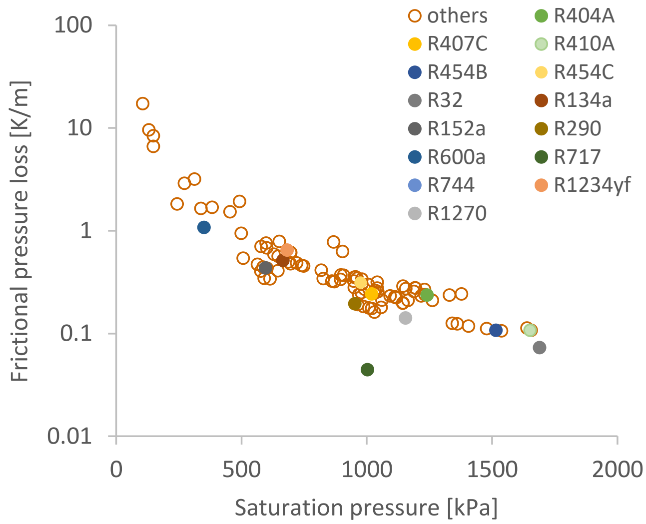

Figure 9.8: Pressure loss of vapour flow corresponding to change in saturated temperature change in a 10 mm inside diameter pipe

Figure 9.9 provides an example of how much the theoretical cycle COP is degraded by pressure loss of vapour through 1 m of 10 mm diameter tube. For refrigerants with a vapour pressure above 1000 kPa, the degradation is small, but as the saturation pressure of the refrigerant reduces, the impact becomes more severe. In these cases, the need for much larger diameter, or shorter pipe lengths is evident.

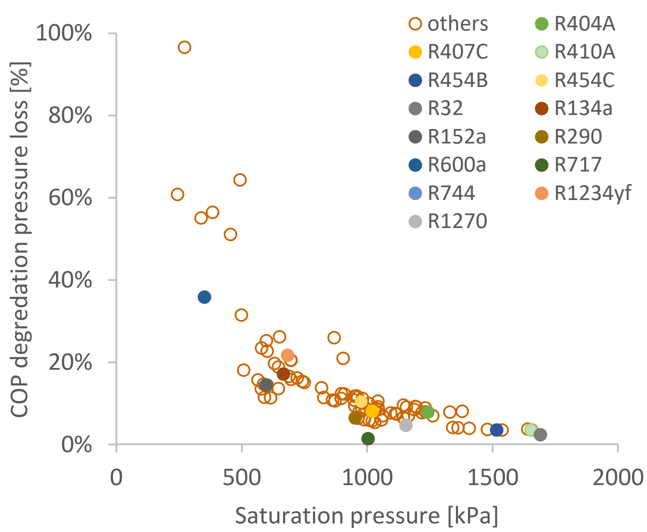

Figure 9.9: COP degradation due to pressure loss of vapour flow in a 10 mm inside diameter pipe

However, as with the case of compressors, piping for lower-pressure refrigerants can have smaller wall thicknesses and this can offset the mass of material ordinarily expected with larger diameter tubes. In *Figure 9.10*, the mass of copper per m of piping is shown for different refrigerants, according to saturated vapour pressure at 0°C. The pipe diameter is sized to give a pressure drop equal to 0.1 K per m and the corresponding tube thickness is calculated according to standard procedures. Overall, lower pressure refrigerants generally use less material, however, there is a wide scatter across any pressure level, arising from the individual refrigerants thermophysical properties; those with lower viscosities and lower volumetric flow rates tend towards the bottom of the band. In practical terms, the situation is less clear since tube thickness cannot be specified so precisely, where for a given diameter, tubing may only be available in two, three or four thicknesses. To put these values in context, for a refrigerant requiring 0.1 kg/m of piping compared to one requiring 0.05 kg/m, the additional cost for 20 m would be about $15.

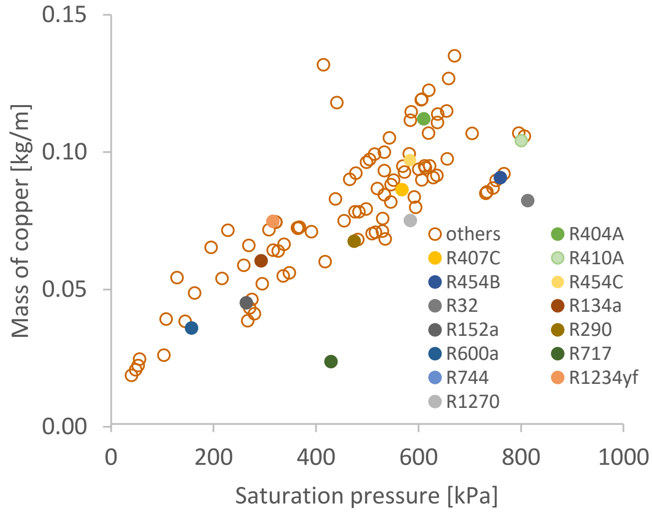

Figure 9.10: Influence of refrigerant pressure and pressure drop on piping material mass

Although not specifically assessed, the consideration should also be given to line components: expansion valves, pressure regulating valve, liquid-suction heat exchangers, solenoid valves, filter-dryers, distributors, sight-glasses and so on.

Generally, these components will be based on the size of the piping they are connected into, but the mass of material is not closely linked to the internal pressure, since the material required for its structure and functionality will override pressure aspects. The data in *Figure 9.11* (based on liquid piping for 10 kW cooling capacity and 0.1 K per m pressure loss) shows that, except for very low-pressure refrigerants, the variation in pipe diameter – and an indicator of component mass – is dependent not only on refrigerant saturation pressure, but other thermophysical and transport properties.

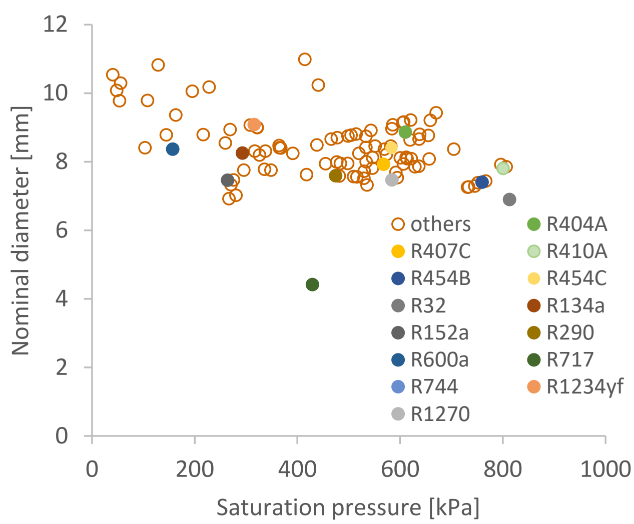

Figure 9.11: Influence of refrigerant pressure and pressure drop on liquid piping diameter

Higher pressure refrigerants allow for smaller refrigerant volume flows, allowing for example more compact compressor designs. How well the positive effect of smaller volume flows at higher pressures are possible to be realised in compressor designs will vary depending on compressor type and application. As an example, reciprocating higher pressure compressors for R-744 have shown to be significantly more compact and efficient than corresponding R-717 compressors for the same application in low temperature cascade stage of industrial refrigeration plants. For other types of compressors, the advantage has shown to be more challenging to realise in full.

Higher operating pressures, as is the case for instance for R-744, may have the benefit of smaller dimensions of tubing. The tube wall thickness can thus be in the same range as for a low-pressure refrigerant and resulting in a lighter tube for a given length, even if the pressure is higher. This can be a significant advantage where tube lengths are long, for instant for centralised refrigeration plants within commercial refrigeration.

In summary, higher-pressure refrigerants typically contribute to lighter weight / lower mass equipment designs, thus leading to lower material costs. more compact equipment designs (thus leading to lower material costs) because these refrigerants have a higher density and so less volume needs to be pumped through the vapor compression cycle to achieve the same capacity and efficiency. However, this is not the case when the refrigerant needs to run in transcritical mode or near critical condition.

9.3.6 Impact of heat transfer

Heat transfer within a RACHP system is fundamental to the cycle operation and has different levels of influence at different parts of the cycle. Refrigerant thermophysical properties affect heat transfer characteristics, some directly, some indirectly. Moreover, the design of components, including materials and surfaces usually have a dominant influence on the heat transfer. Separating the effect of refrigerant properties and component design is difficult, although in general components are (or should be) designed to maximise the potential gain that can be achieved with any refrigerant's properties. As knowledge and experience with a particular refrigerant increase, so does engineer's expertise with exploiting a refrigerant's properties.

Refrigerants with smaller molecules typically have better heat transfer characteristics. For example, R717 tends to have higher heat transfer coefficients, while unsaturated HFCs exhibit lower ones. Refrigerant blends with "temperature glides" similarly show poorer heat transfer coefficients during phase-change, compared to single component refrigerants or azeotropic blends; generally, the larger the glide, the greater the degradation in heat transfer coefficient. Certain design measures can be adopted to help alleviate this degradation, but it cannot be offset entirely.

Further implications arise when considering that some HCs are designed specifically for a given refrigerant and product (or product group), whereas with other systems, HXs may simply be those selected from a catalogue. In the latter case, optimal design for the refrigerant used and system integration may be achieved to a lesser extent. Whilst characterising the impact of pressure loss is relatively straightforward, analysing the impact of heat transfer is considerably more complex.

Whilst the effect of heat exchangers (condenser, evaporator) is dominant, heat transfer in most interconnecting piping has a negative impact on system performance; more heat transfer in suction lines and delivery lines reduces cycle efficiency. Heat transfer within the compressor, between discharge and suction parts similarly reduces efficiency.

Note that the entire discussion above is based solely upon the refrigerant. However, in most systems, oil circulates with the refrigerant, which generally has a negative impact upon pressure loss and heat transfer. However, the degree of solubility of the oil with the refrigerant can have a notable effect on this interaction.

9.4 Detailed cost impact due to safety characteristics of the refrigerant (toxicity/flammability, pressure safety)

9.4.1 Introduction

Ensuring the requisite safety of RACHP equipment and products involved a wide variety of considerations including

- Pressure (most systems operate under several or tens of atmospheres)
- Impact – external surfaces should not injure users or workers
- Electrical – avoidance of shock and fire
- Toxicity – construction materials should not impose toxicity risk or chemical reaction
- Rotating hazards – moving parts
- Combustion/flammability – should not catch fire
- Noise – within acceptable levels
- … etc.

Ultimately, the entity placing the RACHP equipment into use must ensure that the risk posed by all applicable hazards are suitably mitigated and this is usually demonstrated through risk assessment.

All these considerations are routinely accommodated into the design of modern RACHP equipment and often have a cost associated with it. For the purposes of the current discussion, only the additional hazards associated with alternative refrigerants will be addressed further.

Specific to implementation of alternative refrigerants, additional hazards not hitherto widely relevant are:

- Higher toxicity
- Flammability
- Higher operating pressures
- Certain alternative refrigerants encompass more than one of these hazards.

Examples of applicable refrigerants are included in Table 9.1as well as general mitigation measures which are often required in order to offset the additional risk posed by the additional hazards of the refrigerant.

Table 9.1: Arrangements and general categorisation of HPs

Additional hazard	Examples	Mitigation measures
Higher toxicity	R-717	Refrigerant quantity limits, charge minimisation, limited releasable charge, leak detection, ventilation, alarms, increased system tightness, instructions/marking
Flammability	HC-290, HFC-152a, HFC-32	Refrigerant quantity limits, charge minimisation, limited releasable charge, leak detection, airflow/ventilation, alarms, no ignition sources, increased system tightness, instructions/marking
Higher pressure	R-744, R-410A	Thicker system wall material, additional pressure safety devices, instructions/marking

Mitigation measures are generally offered by RACHP sector safety standards, although corresponding measures are equally sought from standards and guidelines of other industry sectors which also handle such substances. The means to achieve the various mitigation measures can be highly varied across different types of systems, applications, etc. While there are too many variations to address in detail here, we describe some general principles in RACHP.

9.4.2 Refrigerant quantity limits

Description: For flammable refrigerants, the possibility of a leak being ignited by an uncontrolled potential source of ignition within the wider area needs to be minimised. This is achieved by limiting the quantity of refrigerant that can leak out such that potentially flammable mixture will not form beyond the RACHP equipment itself. For higher toxicity refrigerants, the possibility of a leak forming a toxic concentration in spaces where occupants may be present must be minimised and is done so by limiting the quantity of refrigerant that can leak out such that potentially toxic mixture will not form beyond the RACHP equipment itself. Thus, refrigerant quantities may be limited according to an "allowable charge limit" (ACL), that is based on the size of the space that the system is located within, installation characteristics of the system and auxiliary equipment and the flammability and/or toxicity characteristics of the refrigerant. Further, there may be an "upper charge limit" (UCL) which is a capped quantity that overrules the ACL.

Materials: Essentially, implementation of the quantity limit does not necessarily demand additional hardware. However, where a manufacturer or installer wishes to use a certain refrigerant in a situation with restrictive quantity limits further design tasks may be required such as charge minimisation (see below), limited releasable charge techniques (see below) and/or multiple refrigerant circuits.

Costs: Whilst there are no direct costs associated with refrigerant quantity limits, practically, any costs involved are associated with the R&D activities to minimise charge (see below) or applying limited releasable charge techniques (see below), as and when required. Splitting the system into two or more circuits can result in a significant cost increase, up to 1.5 times the cost of the original system.

9.4.3 Refrigerant charge minimisation

Description: In order to comply with refrigerant quantity limits, or indeed to lower the risk associated with a given system, charge minimisation may be exercised. Historically, little consideration was given to the reduction of refrigerant charge and indeed, often oversized refrigerant reservoirs were applied to prolong the duration that a leaky system would operate for without the need of a service or "topping-up" of the refrigerant. Nowadays, systems may be designed with numerous features, such as avoidance of liquid receivers (or if necessary to handle alternate operating modes, reduced to a necessary volume), smaller heat exchanger tubes (as associated total internal volume), smaller diameter interconnecting tubing and compressors with reduced internal volumes and lubricant charge. It should be noted, though, that within the constraints of current technologies, there is likely a limit of how far charge reduction can go, whilst maintaining a certain efficiency level of a system.

Materials: Generally, a charge reduction corresponds to a less system materials, whilst individual component's function essentially remains unchanged. In some cases, construction materials may change, for example, when switching from a finned (aluminium) tube (copper) to micro-channel heat exchanger (all aluminium).

Costs: Charge minimisation typically has a negative cost impact (cost saving) through reduced refrigerant costs, both at manufacture and in-use, but also reduced construction material costs by means of smaller or lighter components. Additional costs are largely associated with R&D resources involved with sourcing and trialling alternate components.

9.4.4 Limited releasable charge

Description: Ordinarily, it is assumed that the leaked amount of refrigerant equals the charged amount. However, there are passive and active ways to reduce the released refrigerant, whereby overall risk can be reduced, and refrigerant quantity limits can be more easily satisfied. Limited releasable charge falls into two categories:

"Passive" limited releasable charge (PLRC), which typically accounts only for the mass retained in refrigerant oil and the system volume at atmospheric pressure. Additionally, for refrigerants with very high latent heats, the releasable charge may be limited by depression of the residual liquid refrigerant pressure. In particular, with R744, self-blocking of the leak hole can occur as a leak solidifies.

"Active" limited releasable charge (ALRC), which employs features such as safety shut-off valves to hold charge within the outdoor unit or for an integral system, splits the system internal volume into parts, in response to leak detection, usually being activated in response to leak detection.

Materials: For PLRC, no additional hardware is required, only to quantify the releasable charge. This may be done by calculation or test or a combination of both. For ALRC, additional components may be needed. For a system with a reciprocating compressor and liquid line solenoid valve, or a rotary compressor with a reversing valve and electronic expansion valve, or similar arrangements, no additional hardware is necessary. Otherwise, additional solenoid valve(s) may have to be fitted.

Costs: For PLRC, the costs are solely associated with the resources necessary to quantify the releasable charge. The same applies to ALRC and possibly an additional solenoid valve(s), the cost of which is dictated by the tube diameter and may range from a few dollars upwards.

9.4.5 Extract ventilation

Description: Ventilation of a room or an enclosure that houses the refrigeration system can be ventilated in order to extract a hazardous mixture and discharge it safely to the open air. Rate of ventilation usually depends upon the quantity of refrigerant that may potentially be released, the objective parameter (flammability limit or toxicity limit) and the volume of the space or enclosure. It may be operating continuously or upon demand of a leak detection system.

Materials: Usually, ventilation only requires a suitably sized fan, motor and wiring and in some cases ducting to direct the ventilated air to the appropriate external location.

Costs: Apart from the resources for design and selection of the equipment, the fan and motor have a cost. Since these are approximately linked to the size of the system (refrigerant charge), it may be approximated as a proportion of the system cost; perhaps <2%. For flammable refrigerants, fan/motor assemblies must not act as a potential source of ignition so there can be additional costs involved (see below).

9.4.6 Integral airflow

Description: Typically for flammable refrigerants, integral airflow can be used to mix a leak with the surrounding air to ensure that the concentration remains below the lower flammability limit (LFL). It is not intended to exhaust the mixture from the space, only dilute it.

Materials: Airflow would usually be achieved with a fan that is part of the system, a condenser and/or evaporator fan, provided the airflow rate and discharge velocity are high enough to disperse a leak. Depending upon the assumed leakage rate, most condenser and/or evaporator fans usually supply sufficient airflow. In the event that this is not the case, either a larger fan/motor assembly or an additional fan may be needed to satisfy the criterion.

Costs: Ordinarily, not further costs are involved, except for the resources to check the effectiveness of the existing airflow. Otherwise, additional costs may be a small incremental cost for a larger fan/motor.

9.4.7 Warning alarms

Description: Alarms may be used to warn occupants and workers of a potentially hazardous release of refrigerant and may be audible (siren) or visual (flashing lights). They will be initiated by a leak detection system.

Materials: Equipment required are primarily alarm speaker units, lamps, and cabling. Additionally, instruction for room occupants to guide their response to the alarm.

Costs: Such equipment costs in the order to tens of dollars upwards.

9.4.8 Leak detection

Description: A leak detection system is often required as part of the arrangement involving ALRC, extract ventilation, integral airflow, and warning alarms. The type of leak detection may employ gas detection, ultrasonic sensors, system operating parameters (pressure, temperature, etc.) or other means such as liquid level sensing, liquid flow fractions, etc. Once the detection system identifies a leak indicator, a signal is sent to initiate the applicable measure.

Materials: A leak detection system involves one or more sensors and a signal processor and controller. There are a wide variety of different sensors and often more than one may be needed.

Costs: Costs can vary extensively. Gas sensors can be catalytic or metal oxide type, ranging from a few dollars upwards, to infra-red or laser gas detection, which can cost in excess of $1000; generally, reliability and precision is reflected in the cost. However, if the use of gas detection proliferates throughout the RACHP sector, there is no reason why more reliable and precise technologies cannot drastically reduce in cost. Ultrasonic sensors are significantly more reliable and are extremely low cost (<$1), although several sensors may be needed, depending upon the equipment they are applied to. Sensor for measuring system parameters include pressure transducers and thermocouples. Whilst the latter have a negligible cost (and may be used anyway) pressure transducer can be in the order of tens of dollars and upwards, again depending upon the refrigerant and component size and similarly for liquid level sensors. Signal processing and control units usually have negligible cost and can nevertheless be integrated into existing electronics of the RACHP equipment.

9.4.9 No ignition sources

Description: It is necessary to minimise the possibility of igniting leaked flammable refrigerant within the RACHP equipment and this is achieved through ensuring against the presence of potential sources of ignition. These may be electrical arcs from switching components, excessively hot surfaces from heaters or naked flames. There are numerous ways and means of achieving avoidance of ignition sources, such as high ventilation rates or repositioning of electrical components so flammable concentrations are avoided at such locations, using sealed enclosed to prevent ingress of flammable concentrations, limiting size of gaps within enclosures so flames cannot propagate outwards to the larger mixture and ensuring electrical current and voltage is below certain values such that sparks have insufficient energy to ignite a flammable mixture. Additional aspects are usually necessary, such as suitably robust housing materials and good quality parts, to guarantee protection against ignition for the lifetime of the equipment.

Materials: Given the wide variety of options for avoiding ignition sources there are a similarly extensive number of material implications. Usually, there will be additional plastic enclosures or dividing plates, depending upon the type and size of equipment and refrigerants involved.

Most component manufacturers now offer products (compressors, valves, etc.) that are approved for use with flammable refrigerants, against the applicable safety standards.

Costs: Similarly, additional costs can range from negligible to thousands of dollars (e.g., for large industrial installations), although in most cases, economically effective approaches have been found.

9.4.10 Pressure system materials

Description: To withstand the elevated pressure of refrigerant, the pressure-containing walls of piping and components must be of suitable materials and requisite thickness. Whilst higher-pressure refrigerants tend to have smaller pressure drops (corresponding to change in saturated refrigerant temperature), this is not sufficient to offset the effect of the higher pressure.

Materials: As a general approximation, a component using a refrigerant of double the saturation pressure will require an additional third of wall material (for the pressure-containing parts), be this copper for piping or steel for compressor shells.

Costs: The cost implication depends very much upon the thermal capacity of the system and the physical size, moreover, whether specific piping and components have been tuned to the particular refrigerant or whether those of nominal “off-the-shelf” wall thickness have been used. This could be in the order of $5 – 10 per kW of thermal capacity, with smaller values for lower temperature application or larger for higher temperature applications.

9.4.11 Pressure safety devices

Description: Pressure safety devices include pressure limiting switches and pressure relief valves. They are required on larger systems, where the greatest of any part of the system exceeds a certain value based on the product of the maximum pressure and the size of the part (pipe, compressor, valve, etc.). Thus, higher pressure refrigerants reach this certain value sooner and for those that are higher toxicity and/or flammable, the value is set lower. Although higher pressures imply smaller dimensioned parts, this does not offset the effect of the higher pressure in the product of the pressure and part size.

Materials: Additional pressure limiting switch and/or pressure relief valve may be required.

Costs: Pressure switches cost upwards of a few dollars and pressure relief valves cost upwards of a few tens of dollars.

9.4.12 Increased system tightness

Description: By introducing appropriate design and construction measures to the refrigerating system, the likelihood of leakage and the possibility of larger leak holes can be reduced. Various safety standards and guidelines include such measures and are referred to as “enhanced tightness refrigeration systems” and “hermetically tight systems.” Requirements may include better system components and fittings, avoidance of constructional circumstances likely to lead to leakage, more rigorous testing and leak checking and quality control programmes.

Materials: System components and fittings that have been tested and approved to the applicable standards.

Costs: Whilst some tested and approved components and fitting will be higher cost than basic ones, as more and more manufacturers adopt the regime, additional costs should become negligible. More rigorous leak testing requires additional equipment and procedures for production lines and quality control programmes demand additional resources of workers. However, provided the output of a production facility is large enough, additional costs become negligible (per unit produced). Furthermore, regardless of whether the refrigerant is conventional or a more hazardous alternative refrigerant, reduced leakage has significant advantages in terms of better system reliability, lower lifetime service costs and consequent reputational benefits.

9.4.13 Instructions/marking

Description: Information about safe practices needs to be relayed to workers (such as technicians) and to users. Additional information may relate to the hazardous characteristics of the refrigerant. This additional information usually involves instructions in manuals and marking or signage on the equipment. Examples include details about safe handling of the refrigerant during servicing of the equipment and “flammable refrigerant” warning triangles.

Materials: Additional pages in a manuals and adhesive stickers.

Costs: Material costs are negligible, the main cost implication being associated with sourcing and drafting the relevant information.

9.5 Case Studies Referred to in Chapter 5 of this EETF Report

This Annex includes 8 Case Studies as listed below:

- Case Study 9.5.1 Integrating EE and refrigerant (GWP) performance in labels, Germany and Brazil
- Case Study 9.5.2 Integrating refrigerant in endorsement labels: US Energy Star adds lower GWP refrigerant filter, United States and Canada
- Case Study 9.5.3 Introduction of Standards and Labelling, breaking the price myth, Ghana
- Case Study 9.5.4 Brazil: Kigali Network- Civil Society Engagement and Awareness, Brazil
- Case Study 9.5.5 Super-Efficient Room Air Conditioner (SEAC) Programme, India
- Case Study 9.5.6 Linking refrigerant transition to utility energy efficiency obligations, United States (California and Washington)
- Case Study 9.5.7 Trigeneration integration in Data Centres across India, India
- Case Study 9.5.8 Market-based financial mechanism for domestic refrigerators and air conditioners in sub-Saharan Africa. Senegal, Ghana, and Rwanda

9.5.1 Integrating EE and refrigerant (GWP) performance in labels

Geography: Germany, Brazil

Policy type: Endorsement labelling programs

Product type: Room air conditioners and stationary air conditioners.

Product source: NA

Description:

In Germany, the **Blue Angel** has been the ecolabel of the German Federal Government for more than 40 years. It is an independent and credible label that sets stringent standards for environmentally friendly products and services. To enable reductions in greenhouse gas emissions, the label for air conditioners specifies the use of natural refrigerants and the efficiency of the device. An indicative life cycle assessment, completed as part of the development process for the Basic Award Criteria for the use of air conditioners in Germany, illustrated that environmentally friendly and energy efficient air conditioners using the refrigerant propane (R290) generate around 30% less greenhouse gas emissions than conventional devices using the refrigerant R410A.

To be awarded the Blue Angel label, the air conditioners must have a seasonal energy efficiency ratio (SEER) for an average climate of SEER $\geq$ 7 and must be free of refrigerants containing halogens. In addition, it is not permitted to use ammonia as a refrigerant.

In Brazil, the **Procel Seal (voluntary)** is managed by the Brazilian National Electricity Conservation Program (Procel) and was originally launched in 1995, with specific policies for window air conditioners in 1996 and for split-type air conditioners in 2004. The label is well-recognized and substantially influences consumer behaviour; 91% of consumer recognize the label and 68.3% say that they would pay 10% more for a product bearing the Procel Seal.[31] Until recently, the criteria for the Procel Seal was aligned with the criteria for the top labelling class on the comparative label managed by the mandatory Brazilian Labelling Program (PBE), coordinated by Instituto Nacional de Metrologia, Qualidade e Tecnologia, INMETRO[1].

Enabling institutional infrastructure and capabilities:

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[31] BRACIER. "USO DE ETIQUETAS DE CONSUMO DE ENERGIA GERÁ ECONOMIA DE R$ 2,9 BI EM DEZ ANOS." 2015. Available online at: http://bracier.org.br/noticias/brasil/5288-uso-de-etiquetas-de-consumo-de-energia-gera-economia-de-r-2-9-bi-em-dez-anos

Under Brazilian law, the Procel Seal may not be a required criteria for public procurement, as the law does not allow for a voluntary label to be made mandatory for participation in a government procurement process. However, privately-owned electricity distribution utilities in Brazil are required to spend 0.5% of their national operation revenues (NOR) on energy efficiency programs, including appliance replacement programs. For these utilities, the Procel Seal has often served as a convenient and easily identifiable criteria for participation in appliance replacement programs.

Additional insights and lessons learned:

As of now, there is only one model listed in the Blue Angel database that complies with the requirements – a 12000 Btu/h split-type room air conditioner using R290, underscoring the lack of availability of room ACs using natural refrigerants. However, the approach used by the Blue Angel label highlights an opportunity to use endorsement labels as a mechanism to identify air conditioning equipment with the lowest climate impacts.

In Brazil, one of the Procel's key lessons from administering the Seal over the years is that the alignment with the top efficiency class on the comparative label administered by the Brazilian Labelling Program has led consumers to view the two labels as interchangeable. This approach decreased the Procel Seal's incremental effectiveness over the comparative label. Procel is now looking to change this by adopting more stringent criteria for the Procel Seal and by launching a marketing study to begin differentiating the Seal from the comparative label.

References and web-links:

BLUE ANGEL The German Ecolabel for Stationary air conditioners. Basic Award Criteria Edition August 2016. Available online at: https://produktinfo.blauer-engel.de/uploads/criteriafile/en/DE-UZ%20204-201608-en%20Criteria-2020-01-10.pdf

Lists of eligible products for the Blue Angel program. Available online at: https://www.blauer-engel.de/en/productworld/kein-kurzname-gesetzt

BRACIER. "USO DE ETIQUETAS DE CONSUMO DE ENERGIA GERÁ ECONOMIA DE R$ 2,9 BI EM DEZ ANOS." 2015. Available online at: http://bracier.org.br/noticias/brasil/5288-uso-de-etiquetas-de-consumo-de-energia-gera-economia-de-r-2-9-bi-em-dez-anos

Data/visualization:

Figure 9.12: Image of blue angel label and its environmental and health benefits

Figure 9.13: PROCEL Seal

9.5.2 Integrating refrigerant in endorsement labels: US Energy Star adds lower GWP refrigerant filter

Geography: United States and Canada

Policy type: Endorsement labelling programs

Product type: Residential Refrigerators, Residential Freezers, Room Air Conditioners, Commercial Ice Machines, Commercial Refrigerators and Freezers, Vending Machines, Lab Grade Refrigerators and Freezers, and Clothes Dryers (heat pumps)

Product source: Global

Description: The U.S. Environmental Protection Agency (EPA) administers the ENERGY STAR® program, which is a government-backed energy efficiency endorsement label.

Providing refrigerant information on energy efficiency labels is a critical way to help consumers select efficient products that use climate-friendly refrigerant. In North America, ENERGY STAR has begun offering this information through its Product Finder tool.

ENERGY STAR is a globally recognized brand helping consumers identify energy efficient equipment. Thousands of industrial, commercial, utility, state, and local organizations—including nearly 40% of the Fortune 500®—partner with the U.S. Environmental Protection Agency (EPA) to use the ENERGY STAR brand. EPA ensures that refrigerators, air conditioners, freezers, and other products that earn the label are independently certified to deliver the efficiency performance and savings that consumers have come to expect. In 2019, more than 300 million ENERGY STAR certified products were sold, with a market value of more than $100 billion, and 7 billion ENERGY STAR-labelled products have been sold since 1992.

On January 26, 2022, the U.S. Environmental Protection Agency sent the following notice to stakeholders:

"In response to stakeholder interest in products that contain lower global warming potential (GWP) refrigerants, EPA has added new filters to the relevant ENERGY STAR product finders to highlight products that make use of lower GWP refrigerants. The filter is now available for Clothes Dryers (heat pumps), Residential Refrigerators, Residential Freezers, Room Air Conditioners, Commercial Ice Machines, Commercial Refrigerators and Freezers, Vending Machines, and Lab Grade Refrigerators and Freezers. EPA will add this filter to additional product finder pages as additional lower GWP refrigerants are approved and are available in ENERGY STAR models. For ENERGY STAR product listings that do not currently include refrigerant information, brand owners may work with their certification body to update their listings with this information. To complement the enhanced product listings, there is also new educational information for consumers on why to look for and buy products with lower GWP refrigerants."

Enabling institutional infrastructure and capabilities:

Providing refrigerant information on energy labels is an easy, low-cost way to give people and businesses greater control over the greenhouse gas emissions of the products that they purchase. Absent this information, customers may not know if they are purchasing a product that uses a refrigerant that is harmful to the environment. Ozone officers should consider working with mandatory and/or voluntary energy labelling programs to include information about refrigerants.

Additional insights and lessons learned:

Asking for refrigerant information can spur manufacturers to pay greater attention to refrigerant used in their products and equipment, while also providing regulators with vital information to help assess domestic uptake of low-GWP alternatives to HFCs.

References and web-links:

ENERGY STAR product finder: **https://www.energystar.gov/productfinder/**

9.5.3 Introduction of Standards and Labelling, breaking the price myth

Geography: Ghana

Policy type: Standards and Labelling

Product type: Room air conditioners (RAC)

Product source: imported (100%)

Description: In 2003, the Ghana government, the highest consumer of RACs, began preparation to introduce minimum energy performance standards (MEPS) and labelling for RACs, as part of the measures to check rising demand for electricity and rising operating cost of RACs. Importers, the major stakeholders, were not pleased with the proposed policy that would require them to import only RACs that met the MEPS. The importers posited that the introduction of the standards would make RACs too expensive and beyond the reach of the average Ghanaian and the policy would not inure to the benefit of the nascent market. With their high price theory, the importers thus constituted the first barrier to be scaled. Their case was that standards come with a premium.

Enabling institutional infrastructure and capabilities.

The Energy Commission, the implementer of the policy and the Energy Foundation, a public-private partnership that promotes energy efficiency, conducted a market survey to gather the necessary data for the formulation and the implementation of the policy, specifically, the minimum energy efficiency standards of RACs in the country. Name plate data of 100 units were collected from RAC on the market to determine their level of efficiency. The supplier price data and Customs data were gathered as part of the needed information for the data analysis. Four categories of cooling capacity were considered;

<12,000 Btu/hr

12,000 < 18,000 Btu/hr

18,000 < 24,000 Btu/hr

≥24,000 Btu/hr

The findings of the survey, among other things, helped to determine the energy efficiency levels of the RACs on the market. The survey found that the major determinant of price on the market were: 1) brand, 2) size and 3) popularity, not energy efficiency levels. There was absolutely no correlation between price and energy efficiency levels (Figures 1 and 2). In fact, the most expensive brand, which was selling for $1,800 at the time, had an energy efficiency ratio (EER) of 2.0. On the other hand, a low-cost brand, selling for $600, recorded EER of 3.0. It is instructive to note that, until the introduction of standards and labels, energy efficiency did not factor in pricing RACs. Prices went up after the introduction of energy efficiency standards and labels had become household symbols, but soon fell because of competition. The short-term price increase was occasioned by limited supply as a few importers braved the storm to bring in the energy efficient RACs that met the standards and thereby took advantage to skim the market. Consumer awareness had also been created to position consumers in anticipation of energy efficient RACs soon to be available on the market and that worked out well for the importers because of the availability of new, labelled, and efficient RACs on the market as opposed to the unlabelled ones whose efficiencies were not known.

The outcome of the survey succeeded in breaking of the price-efficiency myth and that paved the way for a smooth introduction of the policy. The importers dropped their resistance and subsequently cooperated in the implementation of the policy. The nascent RAC market began to see steady growth, especially with the introduction of the ban of the importation of used RACs. The market growth, competition and lowered prices vindicated the policy because importers and the consumers were the ultimate beneficiaries.

Additional insights and lessons learned

In terms of market size, Ghana is insignificant, but the introduction of the policy left importers with no option other than to comply with the energy efficiency policy. Certain giant brands in the cooling appliance industry came to Ghana to negotiate for exemptions from the policy on the grounds of market size, the likelihood of price increase and the fact that the brand is an international brand. The labelling puts energy efficiency levels from one star to five stars, with one star being the minimum with EER of 2.8 and five stars being the maximum with EER of 4.0 or more. Contrary to what the importers wanted us to believe, the RAC market is thriving, and prices have fallen drastically (Figure 3). The top range and most expensive 24,000 Btu/hr energy efficient RAC, rated 4 stars, is currently selling for $1000 compared with same size but inefficient model which sold for $1,800 in 2003, a drastic reduction. Competition has played a key role in driving down the prices and the myth surrounding the introduction of standards and labelling has been broken. Ghanaians have now moved from one star, the entry point, to desiring high-efficiency RACs. Neighbouring countries have adopted the Ghana Standards and Labelling scheme and the Ghanaian label has been seen on cooling appliances in neighbouring Togo and Benin.

Graphics

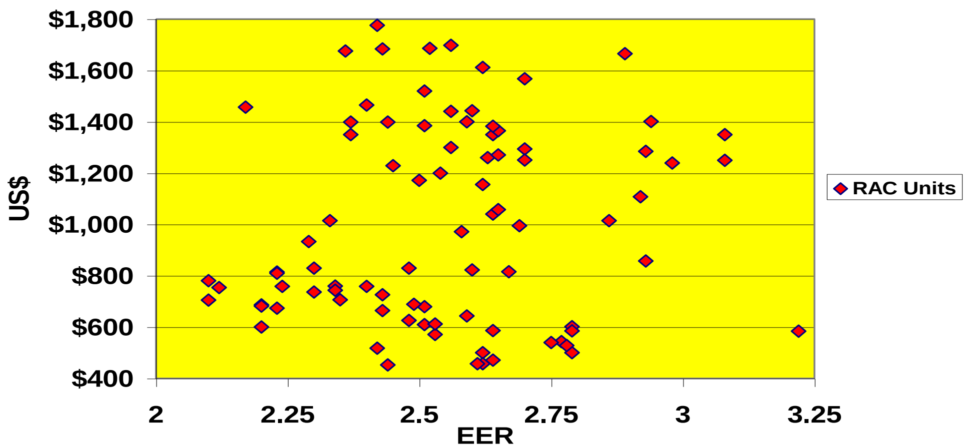


Figure 1. Diagram showing the price of RAC vs. efficiency levels. There was no correlation between price and efficiency levels.

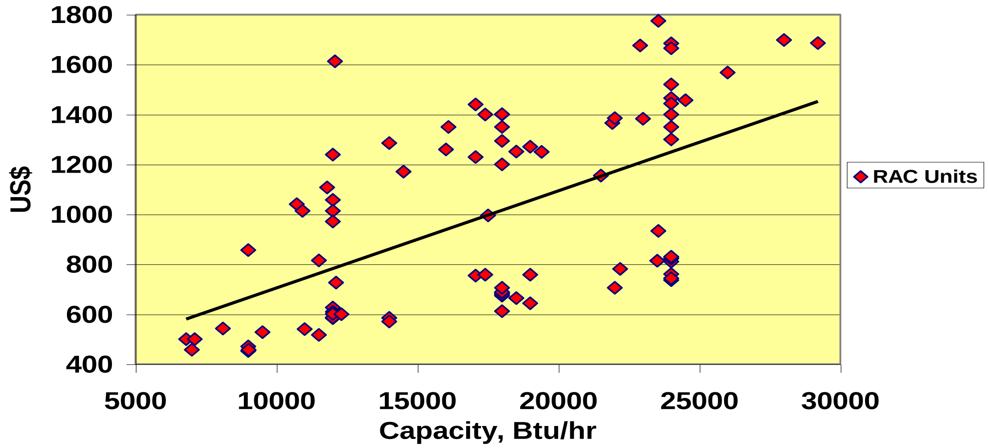
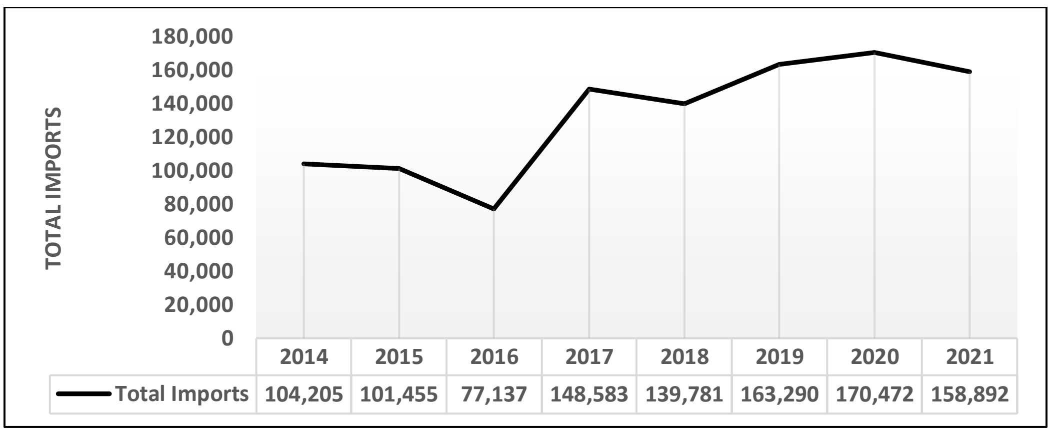


Figure 2. Diagram showing size and prices of RAC units showing a strong correlation between prices and sizes



	2014	2015	2016	2017	2018	2019	2020	2021
Total Imports	104,205	101,455	77,137	148,583	139,781	163,290	170,472	158,892

Figure 3: Diagram showing the growth of RAC imports since 2014

9.5.4 Brazil: Kigali Network- Civil Society Engagement and Awareness

Geography: Brazil

Policy type: Awareness

Product type: residential air conditioner

Product source:

Description: The Kigali Cooling Efficiency Programme (K-CEP) funded in 2017 a project in the residential air conditioning sector in Brazil named Kigali Project, implemented by the Instituto Clima e Sociedade, ICS [https://www.climaesociedade.org/]. At that time, the majority of Brazilian air conditioners (AC) in the local market were low-efficiency fixed-speed ACs using HCFC-22, with an increasing number using R-410A. The Project focused on supporting regulatory as well as consumer-facing actions, including enhancing Energy Efficiency (EE) level of standards, such as, Minimum Energy Performance Standards (MEPS), and Labelling; development of new testing methodology; market driven actions to increase accessibility to low GWP refrigerant fluids; actions to enable Brazil to speed ratification of the Kigali Amendment of the Montreal Protocol. Equipment energy performance testing methodology also required change to consider variable-speed compressors (inverters) and seasonal variances. (See EETF 2021 Case Study 4.4)

Enabling institutional infrastructure and capabilities.

Policy and Regulatory Framework: Brazil's Energy Efficiency Law (number 10295 of 17 October 2001) provides for the National Policy for the Conservation and Rational Use of Energy, attributing the execution to the federal government (Minister of Energy) and giving it the power to establish maximum levels of energy consumption or minimum energy performance levels of machines and appliances manufactured or sold in Brazil. Decree number 4059, 19 December 2001, regulated Law 10295 and created the Energy Efficiency Indicators Management Committee-CGIEE. The committee guarantees that: a) minimum level of energy efficiency is established according to specific regulations, b) the process is based on impact assessment and prioritization, conformity assessment criteria and supported by accredited laboratories for tests and trials, and c) mandatory public hearings are held.

Brazilian government implements another key policy for appliances' energy efficiency – the Brazilian Labelling Program (PBE), coordinated by Instituto Nacional de Metrologia, Qualidade e Tecnologia, INMETRO[1]. Most part of cooling appliances must hold an energy efficiency mandatory label that aims to provide key information for consumers' best decision, such as: energy consumption and energy efficiency rating (varying mostly from E, the worst efficient, to A, the most efficient).

As a complementary policy, Brazil also provides an endorsement voluntary label, called Selo PROCEL[2], which purpose is to inform consumers the top of the class energy efficient appliances which are available in the market. Selo PROCEL is coordinated by Eletrobras, a government owned energy company. (See Case Study 7.1)

Revisions of the MEPS and Labelling were long due and the majority of residential AC commercially available in Brazil were in the "A" category. The equipment falling in this performance category had low efficiency when compared to the same model in the rest of the world. The support provided by the Project and based on a study of impact of the MEPS revision and costs associated to manufacturers and consumers, done in partnership with Lawrence Berkeley National Laboratory, LBNL[3], and CLASP[4] confirmed the urgency to update MEPS and labelling in Brazil.

Additional insights and lessons learned

Civil Society Engagement: According to national regulations, the government had to establish a public hearing before taking the decision to update the MEPS. Public hearings are an important vehicle to hear from stakeholders, including civil society organizations. However, these civil society groups were generally left unheard, mostly for lack of information and technical knowledge regarding the Montreal Protocol Kigali Amendment and links to energy efficiency, the opportunities for low CO_2 emissions and energy conservation in the refrigeration and air conditioning sector.

ICS project team recognized an opportunity to tackle public awareness and bring the voice of civil society into the public debate. This was accomplished by supporting and strengthening a network of NGOs able to pressure for improved MEPS and labelling revision, as well as the ratification of the Kigali Amendment by the National Congress. The team adopted diversified advocacy strategies, such as national media coverage, consumer engagement and awareness campaigns.

The creation of the Kigali Network (Rede Kigali) was the way to bring key civil society organizations/institutions to understand and discuss matters related to both Energy Efficiency, Kigali Amendment ratification and related actions to enable access to energy efficient and ozone and climate friendly technologies and use media and market driven mechanisms to increase access to low carbon emission technologies in the residential AC sector.

In addition to ICS, the following organizations were part of the Kigali Network: International Energy Initiative (IEI Brasil), Instituto Brasileiro de Defesa do Consumidor, IDEC (Consumer Protection), Engajamundo (composed by youth climate leaders), Healthy Hospitals Project (an organization that promotes sustainability at the health sector), and Mitsidi Projetos (a consultancy focused on providing technical assistance for energy efficiency measures).

The strong technical and media support allowed the execution of consumer awareness campaigns (such as Black Friday, to reduce selection of HCFC-22 low efficiency air conditioners) to succeed, increase technical credibility of the project team with government officials and industry, facilitated reaching out to industry associations supporting energy efficiency improvements and ratification of the Kigali Amendment, and the submission of evidence-based contributions to public hearings by civil society. The results can be seen in the figure below.

The work in partnership brought to ICS the "K-CEP Strongest Collaborators Award" awarded by the Kigali Cooling Efficiency Programme in 2021.

The Kigali Network continues its work focusing on achieving Kigali ratification in 2022 and working to support the enhancement of energy efficiency standards and labels (mandatory and voluntary) programs in order to bring to consumers the appliances in Refrigeration and Air-Conditioning sectors that can save energy and are climate friendly at a price they can afford.

Figure 1. Summary of progress engaging civil society and improving policies enabling access to efficient and low-GWP equipment.

[1] https://www.gov.br/inmetro/pt-br

[2] Programa Nacional de Conservação de Energia Elétrica, PROCEL- http://www.procelinfo.com.br

[3] https://www.lbl.gov

[4] https://www.clasp.ngo

9.5.5 Super-Efficient Room Air Conditioner (SEAC) Programme

Geography: India

Policy type: Aggregation, Bulk Procurement, Replacement programme

Product type: Room Air Conditions

Product source: Domestic (100%)

Description: According to the "India Cooling Action Plan" (ICAP, see EETF 2021 Case Study 1.2), the aggregated nationwide space cooling requirement, in tons of refrigeration (TR) where 1 TR is 3516.85 Watts, is projected to grow around 8 times, i.e., from 130 million TR in 2017-18 to nearly 1000 million

TR by 2037-38. Within space cooling in buildings, Room Air Conditioners (RAC) constitutes the dominant share. As per ICAP, 81% of the total refrigerant-based cooling equipment is constituted by room air conditioners. Approximately 8% of Indian households had room air conditioners during year 2017-18. This is anticipated to rise to 21% and 40% in 2027-28 and 2037-38, respectively. The air conditioner stock in Indian market is close to 30 million units with approximately 5 million units sold in FY'2017. The projected rise in the penetration levels of room air conditioners in Indian households will result in a steep growth in the room air conditioner stocks to about 350 million by 2037-38.

The electricity consumption for room air conditioners accounts for 42% of the total consumption in space cooling and approximately 4.3 % of the country's total electricity consumption. Currently the average efficiency level of room air conditioner stock in the Indian market is around 3.2 ISEER (Indian Seasonal Energy Efficiency Ratio) which is well below the current efficiency levels of 5.4 ISEER available in the Indian room air conditioner market. Therefore, the efficiency intervention for room air conditioners presents a huge potential for electricity savings.

The second critical factor linked with the growing room air conditioners stock is the increase in refrigerant demand. Most of the refrigerants used in room air conditioners have Global Warming Potential (GWP) and / or Ozone Depleting Potential (ODP).

Energy Efficiency Services Limited (EESL) joined hands with the leading power distribution companies of Delhi NCR - BSES Rajdhani, BSES Yamuna and other utilities to give out 50,000 high-efficiency variable speed and climate friendly air conditioners with the following specifications:

5.4 ISEER rated inverter driven air conditioners (with 20% better efficiency than the 5-star rated AC sold currently in the market) of 1.5 TR capacity. The current average efficiency of the RAC conditioner market in India is ~ 3.2 ISEER, as close to 60% of the market is of 3-star (or below) rated RAC's (as per India Bureau of Energy Efficiency data and industry reports).

Global Warming Potential (GWP) < 700 (which is almost 1/3rd the value of refrigerants prevalent in Indian market). The most prevalent refrigerants in the room air conditioner market are R-410A and R-22, which have high GWP.

The methodology was to undertake bulk procurement, create awareness through partners (utilities) and reduce transaction cost through a digital marketing platform. The price reduction was to be passed on to consumers.

Enabling institutional infrastructure and capabilities:

EESL has designed innovative business models that are transparent, scalable, flexible, and are able to seamlessly embrace different and emerging technologies in a manner that incentivizes all stakeholders. The simplicity and flexibility of the business models is such that it avoids the requirement of public funds as enablers, has incentives for all stakeholders, and delivers outcomes in a time-bound manner. The business models have the power to unlock demand in sectors where none existed. By doing so, EESL drives large-scale initiatives to create a market for transformative future ready solutions. It partnered with utilities to ensure that there is information dissemination (through call centres, emails, information on electricity bills, etc) and support. EESL created an online digital marketplace "EESLmart.in" where consumers could purchase the SEAC and SLAs were inked with the suppliers of SEAC to deliver and install ACs within a pre-specified time.

Additional insights and lessons learned:

Bulk procurement reduced costs of SEAC by about 35-40% from their showroom costs. The demand for ACs started to rise as awareness campaigns took effect. However, the programme could not become scalable because of:

In India, 70-80% of AC sales occur during February-May every year. In the year of launch (2019), there were general elections in India and EESL could not, by election code of conduct, take this project

Next 2 years, the pandemic stuck and thereby the take-off was very slow.

The lesson learnt is that timing of the intervention plays an enormous part in success of a project particularly when buying behaviour is skewed as in this case.

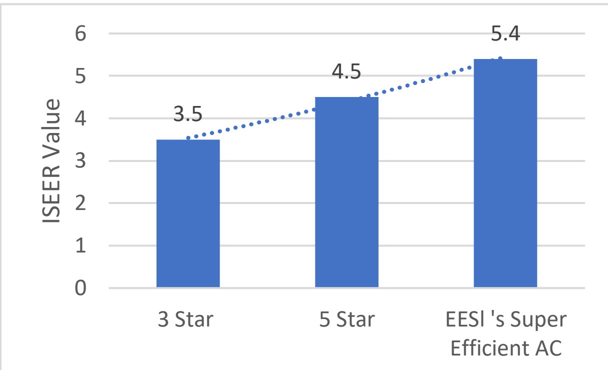
References and web-links:

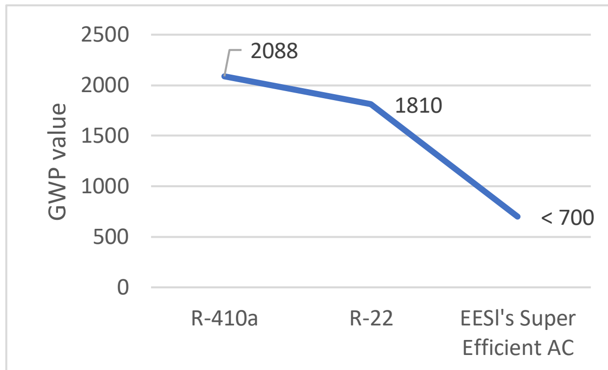
https://eeslmart.in/

eeslindi.org

Data/visualization:

Comparison of average AC ISEER and GWP value sold in India, the best in class as per regulations and EESL’s SEAC





Description	Value
1. Total number of RACs to be deployed in 3 years	3.5 m
2. Regions covered	All metro cities and tier 2 cities
3. Cumulative Energy Savings (GWh)	11,640
4. Cumulative GHG emissions reduction (Million tCO2)	10
5. Total demand reduction (MW)	7275
6. ODP reduction (ODP Tonnes)	254

9.5.6 Linking refrigerant transition to utility energy efficiency obligations

Geography: United States (California, Washington)

Policy type: Utility obligation

Product type: All stationary RACHP

Product source: import and domestic

Description: The California Public Utilities Commission (CPUC) regulates the electricity and gas companies (utilities) that operate in the state of California. California and other US states with energy efficiency resource standards require utilities to fund energy efficiency programs. Utility energy efficiency spending in the US totals about USD 5-10 billion every year.

A 2018 law, the California Cooling Act, authorized the CPUC to develop a strategy to promote low-GWP refrigerants in equipment funded by energy efficiency programs it oversees. Specifically, the law said: "76002. *The Public Utilities Commission shall consider developing a strategy for including low-GWP refrigerants in equipment funded by the energy efficiency programs overseen by the Public Utilities Commission."* The State of Washington recently passed a bill encouraging utilities to address refrigerants as well, House Bill 1050, in 2021.

In California, the CPUC responded by:

1. Developing a refrigerant calculator and ordering efficiency program administrators to use it to evaluate refrigerant GHG impacts and the avoided costs from reducing refrigerant emissions;

2. Updating their evaluation tools, such as the Cost Effectiveness Tool (CET), to include refrigerant; and

3. Ordering utilities and energy efficiency program administrators to seek out all cost-effective opportunities to mitigate refrigerant emissions starting in 2022 (CPUC decision D.21-05-031).

Laws like this are significant because they can unlock funding to manage refrigerant emissions and address refrigerant banks while promoting energy efficient equipment. They can also potentially increase cost-effectiveness of utility energy efficiency programs in areas where energy regulators have a dual mandate of increasing efficiency and reducing building GHG emissions, a win-win for both efficiency and refrigerant regulators.

Enabling institutional infrastructure and capabilities:

Governments are increasingly establishing goals to reduce greenhouse gas emissions from buildings (sometimes referred to as 'building decarbonization'). This often includes promotion of heat pumps and other refrigerant-using devices to replace gas appliances. Energy efficiency, utility, and building professionals charged with reducing building GHG emissions are increasingly realizing that it is insufficient to only examine the emissions associated with electricity or fuel consumption: as the California Public Utilities Commission put it, "tracking and managing refrigerant leakage is key to achieving building decarbonization and GHG reduction goals" as well (CPUC, 2021). Ozone officers have the opportunity to work with energy efficiency officials to ensure that low-GWP refrigerants are prioritized in energy efficiency incentive programs. Doing so can help unlock additional funding to assist with the phase-down of high-GWP refrigerants. The laws, regulations, and evaluation tools created in the US State of California could be adapted for use in other states or regions as well.

References and web-links:

· SB 1013 (California Senate Bill 1013, Fluorinated Refrigerants, also known as the California Cooling Act). 2018. (signed into law by governor on September 13, 2018). https://leginfo.legislature.ca.gov/faces/billStatusClient.xhtml?bill_id=201720180SB1013

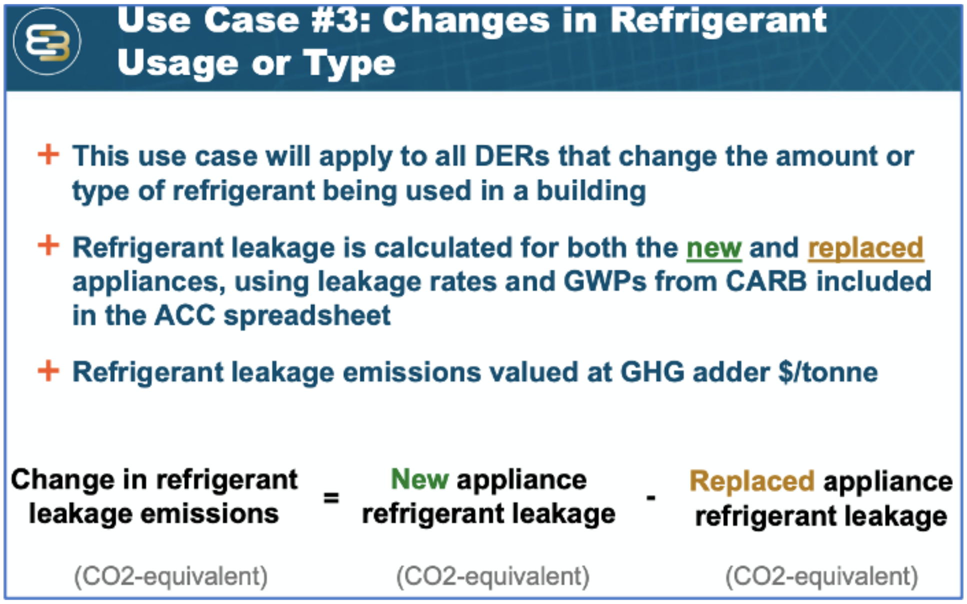
· CPUC (California Public Utilities Commission). August 26, 2021. *CPUC Refrigerant Policy Developments* https://efiling.energy.ca.gov/getdocument.aspx?tn=239468

· CPUC (California Public Utilities Commission). Decision 21-05-031 (26 May 2021) ASSESSMENT OF ENERGY EFFICIENCY POTENTIAL AND GOALS AND MODIFICATION OF PORTFOLIO APPROVAL AND OVERSIGHT PROCESS

https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M385/K864/385864616.PDF

· Morgenstern, J. and Mantegna, G. 2020. *IDER 2020 Avoided Cost Calculator Update: Avoided Cost of High-GWP Gases.* Energy and Environmental Economics (E3). May 6, 2020. https://files.cpuc.ca.gov/gopher-data/energy_division/EnergyEfficiency/CostEffectiveness/High%20GWP%20Workshop.pdf

Data/visualization:



Formula for energy efficiency programs to calculate benefits from a change in refrigerant usage or type. Source: Morgenstern and Mantegna, 2020.

9.5.7 Trigeneration integration in Data Centres across India

Geography: India

Policy type: Energy Efficient and Order specific Customized model

Product type: Commercial cooling

Product source: Mixed Model (50% Domestic – OEM's & 50% International - Gensets)

Description: Data centres require significant high-quality energy and cooling. Trigeneration or combined cooling, heat, and power (CCHP), is the process by which some of the heat produced by a cogeneration plant is used to generate chilled water for air conditioning or refrigeration. An absorption chiller is linked to the combined heat and power (CHP) to provide this functionality. Trigeneration with waste heat recovery vapour absorption machine (VAM) containing "lithium monobromide or Ammonia" offers an energy efficiency and climate-friendly alternative to meeting cooling demand using conventional high-GWP refrigerants.

Growth and Size of the Indian Data Centre market: The size of the digital economy in India is estimated to grow from $ 200 billion in 2017-18 to a staggering $ 1 trillion by 2025. Currently, India has around 375 MW installed power capacity for Data Centre and as per projections, this may grow to three time by 2025. With the expected 5G implementation and data localisation norms, need for data storage to be closer to its users gains greater importance, with a view to measure down on latencies. The total 3rd party data centres industry is expected to move from the current 590+ MW to ~2,000 MW in the next 2-3 years. With an additional capital waiting in the wings to support development of ~520 MW of data centres, one should expect significant capacity addition in India soon.

Evaluation Metrics for Data Centres: Data centres are high electric energy consumers, resulting in very high electric power costs. They require high-quality energy in terms of reliability to ensure continuous operation. Future challenges for data centres are electric load densification and an increase in thermal dissipation of the servers. Thus, assessing the energy usage and energy efficiency is crucial and achieved by measuring metrics such as:

Power Usage Efficiency (PUE) - Ratio of total facility power to IT equipment power. Indian context witness unreliable power hence the usage of DG sets to power the equipment arises. Henceforth, it results in the **Low Loading & Low Efficiency.**

Data Centre Infrastructure Efficiency (DiCE) - defined as the fraction of the IT equipment energy divided by the total facility energy. It is the reciprocal of PUE.

Energy Consumption in Indian Data Centres: Data centres are the highly energy intensive premise and imposes high cost on the organization for the upkeep and its operation. Cooling is the largest energy demand in data centres in India (Figure 1). Increasing cost puts a lot of pressure on the developers of the data centre in designing an energy efficient data centre. Energy consumption in data centres is increasing at a very fast pace in India. India's sustainable growth is being challenged by the increased energy consumption of the data centres.

Data Centres generally hold two types of requirements:

Power Requirement

Chilling Requirement

Enabling institutional infrastructure and capabilities:

Energy Efficiency Services Limited (EESL) was set up under Ministry of Power, Government of India, to facilitate implementation of energy efficiency projects. EESL is a joint venture of NTPC Limited, Power Finance Corporation, Rural Electrification Corporation and POWERGRID. EESL is a Super Energy Service Company (ESCO) that seeks to unlock energy efficiency market in India, estimated to at $12 billion that can potentially result in energy savings of up to 20 per cent of current consumption, by way of innovative business and implementation models. EESL has undertaken large scale programmes in energy efficient lighting that led to distribution of 370 m LED bulbs, replaced 12 m streetlights and 10,000 government buildings on ESCO mode. In addition, it has taken up super-efficient ACs (see Case Study 5), decentralised solar plants, smart meter as a service and several other pathbreaking clean energy and energy efficiency initiatives.

EESL has designed innovative business models that are transparent, scalable, flexible, and are able to seamlessly embrace different and emerging technologies in a manner that incentivizes all stakeholders. The simplicity and flexibility of the business models is such that it has incentives for all stakeholders and delivers outcomes in a time-bound manner. The business models have the power to unlock demand in sectors where none existed. By doing so, EESL drives large-scale initiatives to create a market for transformative future ready solutions. It now owns Edina (UK) who are specialists in Trigeneration technologies.

Data/visualization:

Table 1: Comparison of CO_2 emissions from generating power and cooling from grid-sourced electricity and trigeneration technology.

Reduction in CO_2 Emission (Per MW) by implementation of Trigeneration Technology			
Description of Parameters	GRID	Trigen Technology	Savings Possible
Power of 1 MW	800	460	340
Chilling for 250 TR	200	0	200
Total			540

Note: Around 250 TR of chilling can be generated from 1 MW of Gas based Power Generation.

All the values mentioned above are in kg of CO_2/h

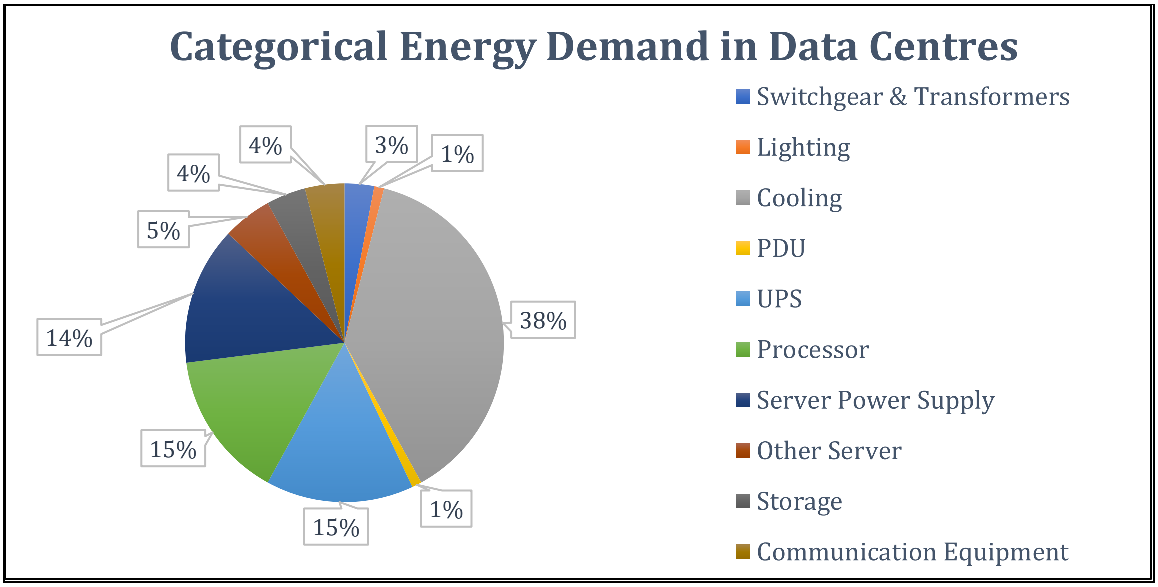


Figure 9.14 Energy Demand across Data Centre in India

Subscriber base has increased exponentially to around 700 million and size of the Digital economy.

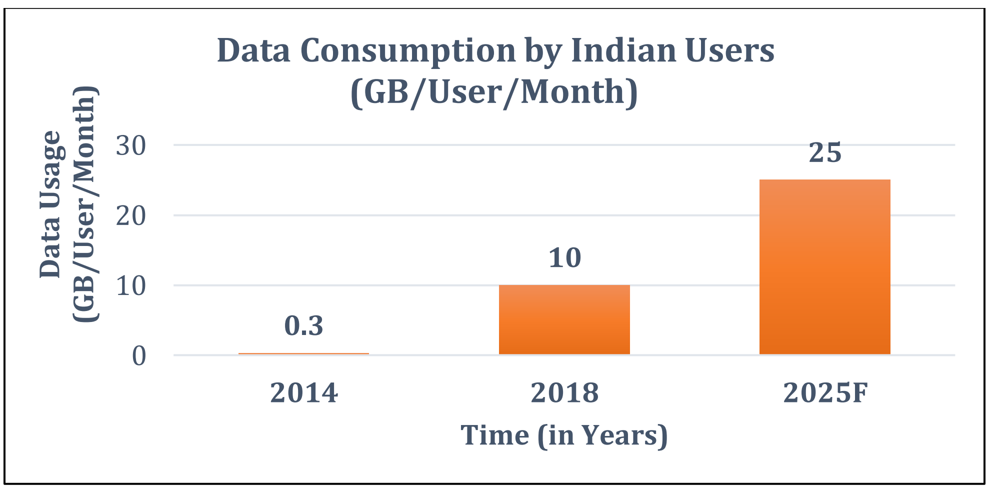


Figure 9.15: User driven data projection from 2014 till 2025(F) in India

9.5.8 Market-based financial mechanism for domestic refrigerators and air conditioners in sub-Saharan Africa.

Geography: Senegal, Ghana, and Rwanda

Policy type: Financial mechanism, Replacement programme

Product type: Refrigerating appliances and room air conditioners

Product source: imported (100%)

Description: According to the latest Chilling Prospects report[32], 776 million Africans face cooling access challenges, and around half are on the brink of purchasing their first air conditioner or refrigerator. Even though a high-efficiency appliance typically costs users much less over its lifetime (due to reduced energy consumption), the higher upfront cost is a significant barrier for consumers. Moreover, they have no incentive to consider which refrigerant is utilized, so inefficient products utilizing high-GWP refrigerants remain predominant.

The United Nations Environment Programme's United for Efficiency (U4E) initiative and the Basel Agency for Sustainable Energy (BASE) were competitively selected in 2020 by K-CEP (now the Clean Cooling Collaborative (CCC)) to support the transition to efficient, climate-friendly residential cooling in Ghana, Senegal, and Rwanda. The premise is to combine rigorous eligibility criteria adapted from U4E's Model Regulation Guidelines and orchestrate market-based financial mechanisms that address the first-cost barrier while incentivizing proper recycling of old, operable cooling appliances.

ECOWAS Refrigerators and Air Conditioners Initiative (ECOFRIDGES):

ECOFRIDGES was launched with the governments of Ghana and Senegal and the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) in late 2020 with a unique approach for each market. By 2023, ECOFRIDGES GO aims to unlock at least US$11 million in private finance (from a baseline of $0) to support the purchase of more than 15,000 efficient, climate-friendly cooling appliances that mitigate 86,184 tons of greenhouse gas (GHG) emissions relative to a business-as-usual (BAU) scenario.

In **Ghana**, ECOFRIDGES Green On-wage (GO) financing was developed as a bank loan product for public and private sector employees, where repayments for approved appliances are made via salary deductions. The employer acts as the loan's guarantor, reducing the need for stringent credit assessments and collateral. The initiative includes an array of local financial institutions and local equipment vendors to allow for competition and diverse offerings. In the first weeks of the scheme's availability on a pilot scale, over 500 ECOFRDIGES GO cooling appliances were sold, which helped inform improvements to the monitoring, reporting and verification system and prompted the full launch of the financing scheme to all eligible customers in late 2021.

In **Senegal**, ECOFRIDGES on-bill financing gives consumers the option to finance the purchase of an approved appliance through monthly charges on their prepaid electricity meters with SENELEC. Eligibility is determined through a simple review of electricity consumption and prepaid meter charge history and other basic information. Over the next three years, the aim is to unlock US$6 million in financing to support the purchase of more than 19,000 efficient, climate-friendly appliances that save over 31,000 tons of GHG emissions relative to BAU.

ECOFRIDGES includes a pathway for end-of-life collection and recycling, monitoring and verification, policy recommendations, capacity building, and awareness-raising campaigns.

[32] Analysis covers 31 countries in Africa that are considered 'high impact': https://www.seforall.org/chilling-prospects-2021/global-access-to-cooling/regional-trends

Rwanda Cooling Finance Initiative (RCOOL FI):

In 2018, U4E, BASE, and the Rwanda Environment Management Authority (REMA) launched the Rwanda Cooling Initiative (RCOOL) with CCC's support to aid the country's transition to efficient, climate-friendly cooling through a range of policy measures (including Africa's most ambitious MEPS and labels based on U4E's Model Regulation Guidelines). The scope was expanded in early 2021 to include the development of a financing initiative (FI), which is expected to unlock at least US$1 million in financing for 12,500 approved appliances by 2024. The initiative was informed by ECOFRIDGES and the GO financing approach of Ghana was selected as the most appropriate approach for the market, allowing public and private sector employees to use a bank loan to purchase approved appliances with repayments deducted from their salaries. Like ECOFRIDGES, RCOOL FI is comprehensive in addressing recycling, capacity building, awareness, and other aspects.

Additional insights and lessons learned:

Initial technical assistance by U4E and BASE entails integrated design and implementation with local partners from the public and private sector so that a smooth handover of responsibilities is orchestrated as early as practicable for a pathway toward self-sufficiency rather than a sudden change following the culmination of engagement by the technical assistance team. The emphasis is on models that are replicable in Africa and beyond where rising incomes and electricity access are driving ever greater adoption of mechanical cooling. It contends within the context of the challenges of local finance, including consumer loan interest rates often above 20%.

The technical team and government worked together to negotiate discounts off the manufacturer suggested retail price (MSRP) of participating products which covers the cost of financing and offsets the incentive for recycling. A robust set of well-enforced criteria (see Table 1), with ongoing monitoring and oversight, compelling marketing, and regular are key to keeping all parties aligned toward the success of the programme while retaining healthy competition across participants. Such financial mechanisms can achieve a triple win: improving consumer access to high-quality equipment; safeguarding the climate; and developing local financial intermediation services.

Enable electric grid-connected households and small enterprises (on-bill) and salaried employees (on-wage) to finance efficient refrigerators and air conditioning systems which otherwise are likely more expensive to purchase relative to inefficient competing products.

For officials, link with relevant development policy targets and agreements, minimum energy performance standards and labels, and opportunities to address energy security and economic competitiveness considerations.

Provide a common set of term and conditions that are agreed upon by all participating parties and monitor compliance to ensure a level playing field.

Offer capacity building for participating vendors, banks, utilities, government agencies and waste management companies to ensure they understand their roles and responsibilities – start with a pilot phase to test readiness.

Raise customer awareness through a dedicated marketing campaign.

Allow time for importation of products that meet the eligibility criteria, making the case through the anticipated market demand potential.

Relationship building is essential across participating actors to ensure smooth functioning, exchanges of information (e.g., applications).

Include a mix of competing vendors and banks to allow for diversity of options but with a suitable pipeline of opportunity where all can benefit.

References and web-links:

ECOFRIDGES project page https://united4efficiency.org/country-regional-activities/ghana-senegal/

ECOFRIDGES GO site by Ghana Energy Commission http://energycom.gov.gh/about-ecofridges-go1#

RCOOL FI project page https://united4efficiency.org/country-regional-activities/rwanda/

RCOOL FI launch https://www.facebook.com/RwandaCooling/videos/313614857375700/

Data/visualization:

Figure 1: Green On-wage business model

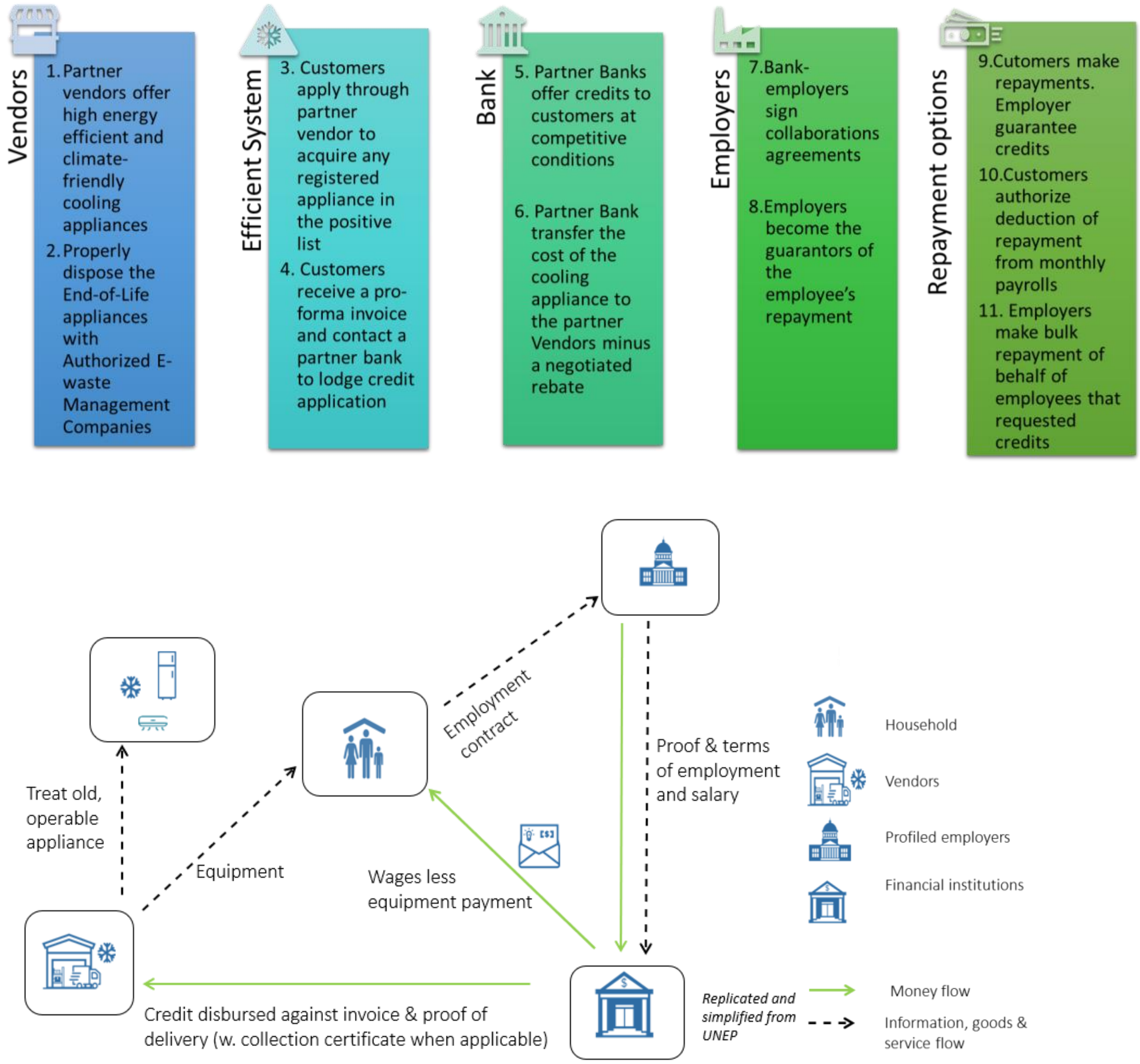


Table 1: Product eligibility criteria for ECOFRIDGES GO.

	ACs	**Refrigerating Appliances**
Type of products:	Ductless split air conditioners	Household refrigerators and refrigerator-freezers –freezers-only are excluded.
Age:	Only new products.	Only new products.
Product size:	nominal cooling capacity up to 5.3 kW	Between 90l to 500l
Refrigerants and	GWP[1] limit of 750.	GWP limit of 20, maximum charge of 0.15kg
Foam Blowing Agents	N/A	GWP limit of 20
Warranty:	Minimum 2-years	Minimum 2-years
Safety certification	Conform to safety regulations of both the manufacturing country and Ghana (e.g. IEC 60335-2-40)	Conform to safety regulations of both the manufacturing country and Ghana (e.g. IEC 60335-2-24:2002 /AMD:2017, or a subsequent revision)
Energy Efficiency:	Interim criteria until introduction of new MEPS & labels regulation: 3-star equipment as per current Ghanaian regulation: EER >3.45 Criteria following introduction of new MEPS & labels regulation: TCSPF $\geq$ 7 (see notes on evaluation below)	Interim criteria until introduction of new MEPS & labels regulation: 5-star equipment as per current Ghanaian regulation: Climate Class ST: I<30 Climate Class T: I<42 Criteria following introduction of new MEPS & labels regulation: EEI < 22 (see notes on evaluation below)

Additional criteria include at least 3-year post-sale servicing from manufacturers, limits on price above average retail price for similar products in same market, among others. For additional details, see: http://energycom.gov.gh/images/ECOFRIDGES-Ghana_product-eligibility-Final.pdf