MONTREAL PROTOCOL ON SUBSTANCES THAT DEPLETE THE OZONE LAYER

REPORT OF THE TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL

MAY 2023

VOLUME 1: PROGRESS REPORT

SUPPLEMENTARY REPORT

DECISION XXXIV/3 ENERGY EFFICIENCY WORKING GROUP REPORT

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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 2023

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SUPPLEMENTARY REPORT

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Foreword

The 2023 TEAP Report

The 2023 TEAP Report consists of three volumes:

Volume 1: *TEAP 2023 Progress Report*

Supplement to the TEAP 2023 Progress Report: Decision XXXIV/3 Energy Efficiency Working Group Report

Volume 2: *Evaluation of 2023 critical use nominations for methyl bromide and related issues - Interim Report – May 2023*

Volume 3: *Decision XXXIV/2: Assessment of the funding requirement for the replenishment of the Multilateral Fund for the period 2024-2026*

This is Volume 1 Supplementary report

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Key Messages

Chapter 2: Energy Efficiency: A Systems Approach

- To decarbonise heating and cooling in a cost-efficient manner, energy efficiency needs to go beyond a pure product-based approach. Taking an integrated approach to the energy system offers massive opportunities to reduce the need for energy generation, cost and emissions and to increase the resilience of the energy system. Analysing and optimising heating and cooling loads, energy sources and carriers, as well as the potential of waste heat recovery and thermal storage will pave the way for system-based energy and cost savings as well as increased emission reductions.
- Cold chains are a global challenge. Food production will need to increase significantly to feed the expected human population of 9.7 billion by 2050. In addition, food loss due to the lack of cold chains accounts for more than 1 gigaton of CO_2-equivalent emissions. Building up the cold chain with energy efficient equipment and low GWP refrigerants, combined with renewables-based electricity generation and increased use of electric vehicles will prevent food loss and significantly reduce emissions. To make it happen, all actors need to cooperate: governments, industry, academia and finance will be needed for research, skills development, new business models, and adoption at scale.
- According to the International Energy Agency (IEA), space cooling is responsible for around 10% of global electricity consumption and 5% of global greenhouse gas emissions. Energy-efficient HVAC equipment in buildings optimises energy usage in cooling and heating systems, resulting in significant energy and cost savings. Additionally, it enhances indoor air quality and extends equipment lifespan. Implementing building codes and regulations, working with industry associations and standards bodies, and considering lifecycle costs are all critical for encouraging the adoption of energy-efficient equipment.

Chapter 3: Energy Efficiency Associated with Improvements in Foams

- Continued efforts to reduce energy consumption in buildings and refrigerating appliances have encouraged increased use of insulating foams. Building codes and standard mandates, insulation performance standards, labelling mandates, and other policies establish requirements to reduce heating and cooling loads in both commercial and residential buildings and for refrigeration. Investment in decarbonization and infrastructure will drive increased use of insulation including several end-uses for foam products specially the high insulating ones like polyurethane, polystyrene and phenolic foams.
- Walls with appropriate foam thickness produced with low thermal conductivity and low GWP blowing agents can provide substantial benefits of insulation with superior energy efficiency with less CO2 emissions for applications in buildings and cold chain.
- High performance insulating foams improve energy efficiency by creating an air barrier and reducing heat transfer. Insulation foams applied in building reduce heat loss or heat gain which improves individuals' comfort and can lower energy costs. For cold chain, high performance foams also create an air barrier and reduce heat gain to keep temperature in storage, transport, consumption and conservation of food, medicines and a variety of products that need temperature control with reduced energy consumption and cost.

- The continuous improvement in foams technology to provide high insulatingBM:: materials in combination with more efficient refrigerating systems provide a notable improvement in energy efficiency. For example, the typical new refrigerator uses 75% less energy than a typical refrigerator 70 years ago while offering roughly 20% more storage capacity and other features. New refrigerator technology also eliminated ODS and high GWP blowing agents and refrigerants with a significant reduction of CO_2 emission in the manufacturing process.
- Foam insulation can create an air barrier making assurance of sufficient ventilation and possibly monitoring of air quality more important, as highlighted during the pandemic.

Chapter 4: Energy Efficiency Technologies: Availability and Accessibility

- RACHP and MAC equipment that are at, or below, the global average efficiency levels are still being manufactured and sold posing a problem to the adoption, implementation, and compliance of Minimum Energy Efficiency Performance Standards (MEPS) in many countries
- A 2023 IPCC report confirms that concerted efforts on Energy Efficiency (EE) measures and emissions mitigation measures can reduce costs and produce better results
- The availability of high energy efficiency technology in manufacturing countries does not automatically result in accessibility at the importing countries
- The assembly sector typically waits for a new technology to evolve, and the economies of scale to take place before they adopt. For a faster adoption of new technologies, the assembly sector could benefit from the demonstration of higher energy-efficiency low-GWP technologies through activities such as the creation of regional centres of excellence.
- Electrical voltage and frequency variation are often overlooked as a barrier to product availability and therefore, accessibility of products worldwide
- Product certification to stated performance and performance standards is one of the most important differentiators in a crowded market where consumers can make trusted choices on what they purchase
- Manufacturers are typically faced with the choice of either buying the EE technology/component or building the internal capacity to develop and manufacture it (make vs. buy). Scale, based on the production volume, and speed, based on the capital recovery period, play a role in deciding the business strategy
- The majority of refrigerants used in new car MAC is mainly HFC-134a (GWP 1430). HFO-1234yf (GWP 3) is used as a substitute by car manufacturers in some regions.
- The thermal management system with heat pump technology has been accepted as an energy-efficient solution for electric vehicles, which require refrigerants compatible with electrically driven compressors and can provide heating and cooling capacity. R-744, HC-290, and other new refrigerant blends are under assessment and gaining renewed attention.
- Cost of new technologies, supply chain issues, and lack of industry collaboration are existing barriers related to the availability and accessibility of low GWP refrigerants in MAC and mobile heat pumps in electric vehicles.
- Upgrading technicians' capacity and improving their awareness on advantages of labelling that could be communicated to their customers helps in achieving the energy efficiency benefits from the policy.

Chapter 5: Measurement Verification and Enforcement Tools

- Energy test methods are central to appliance standards and labelling programs to validate efficiency claims by manufacturers before products enter markets and to ensure that products continue to meet program requirements and identify non-compliant products once on the market.
- Energy test methods for cooling appliances have been developed by international standards organizations like the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO) and other regional and national standard bodies. Several international and national energy test methods are in use in different regions for the most common residential cooling equipment – domestic refrigerators and room air conditioners.
- Test method attributes can and should be evaluated on an ongoing basis as the products and technologies they are intended to evaluate continue to evolve.
- Appliance energy and performance testing requires qualified test facilities where the laboratory, test equipment, personnel training, and operating procedures are all appropriate for the product being tested. Testing is one of the most resource-intensive and time-consuming aspects of an energy efficiency program but there are approaches to conduct effective testing with limited resources.
- Certifying and enforcing compliance is critical to safeguard climate and cost savings from energy efficiency programs. Robust, cost-effective, and well-rounded compliance processes protect markets from inefficient and low-quality products. Common approaches for conformity assessment adopted by governments around the world include supplier's declaration of conformity and third-party testing and certification by independent parties or government agencies.
- Product Registration Systems are effective tools for tracking compliance. They document tested and certified products on the market and can support market surveillance and enforcement efforts.

Chapter 6: Barriers to Energy Efficiency

- The dumping of low energy efficient products in low-income countries coupled with the lack of knowledge and higher cost of purchase of energy efficient products contribute greatly to their low uptake.
- Barriers to the introduction of EE RACHP equipment can be overcome by:
    - education and consumer awareness campaigns,
    - reducing the investment risk through incentive schemes such as rebates and innovative financial mechanisms for the consumer,
    - stringent regulations and enforcement such as bans on the import of used equipment and products; the development of regulatory frameworks including MEPS for new and used equipment; investment in testing to provide consistency and clarity for consumers and businesses,
    - upgrading/ developing of training materials/ programs for RACHP technicians in vocational institutions and national associations, to incorporate the specialised knowledge and skills needed to install and maintain EE refrigeration systems.

Chapter 7: Potential Benefits of Energy-Efficient RACHP, Including Climate Benefits and Costs, while Phasing down HFCs

- Modelling shows significant potential for energy savings and reductions in peak power. By 2050, the difference in electricity use between "No efficiency gain" and "High efficiency gain" scenarios could be nearly 10,000 TWh per year. The High efficiency gain scenario leads to capital investment savings of USD 2 to 3 trillion by reducing the need to build new power station between now and 2050.
- The residential and commercial sectors dominate the use of electricity for cooling, representing around 44% and 42% of total consumption, respectively.
- Comfort cooling represents around 60% of electricity use, with refrigeration representing the remaining 40%.
- Reduction in the indirect energy related CO_2 emissions from RACHP systems will be driven by efforts to reduce cooling demand (e.g., through better building design), improved equipment efficiency and improved operation and maintenance. The decarbonisation of the electricity supply is also a crucial factor.
- In 2023, indirect emissions represent around 75% of RACHP GHG emissions, with direct HFC emissions representing the remaining 25%. Both direct and indirect emissions can be substantially reduced by 2050.
- The cost impact of energy saving measures need to be evaluated on a project-by-project basis as the cost effectiveness is influenced by a range of project-specific technical factors and also by the local conditions (e.g., cost of electricity and grid carbon factor).
- Modelling the costs of energy efficiency improvement can be difficult given that relevant data is proprietary and may involve design changes that manufacturers typically prefer not to disclose publicly.
- On a per-project basis, modelling such costs is crucial for understanding the value of energy efficiency investments that depend on factors such as climate, income, electricity prices, hours of use, CO2 intensity of the grid and the costs of labour and capital.
- Standards setting bodies such as the US Department of Energy or EU Ecodesign conduct analyses of the costs to manufacturers and consumers of the revision of 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.
- Lawrence Berkeley National Laboratory has designed the Joint Investment Framework (JIF) tool for providing initial estimates of the costs and benefits of efficiency improvement in parallel with the phasedown of refrigerants under the Montreal Protocol on a per-project basis using publicly available data. Initially developed as a spreadsheet-based tool and currently implemented in Python for room AC projects, it is being further refined.

Chapter 8: Range and Trends in GWP and EE of RACHP Equipment

- There is a general trend toward increasing adoption of Minimum Energy Performance Standards (MEPS) and Labelling programs globally for RACHP equipment.
- Many Parties lack regulatory capacity and testing infrastructure to design, implement and enforce stringent MEPS programs, so there is an ongoing need for improvement and potentially technical assistance and/or financing in these areas.

- In all applications, there is a general trend of increasing efficiency e.g., through increased adoption of inverter drives that save energy when operating at part load conditions
- Similarly, there is a global trend towards lower GWP refrigerants, driven by the Kigali Amendment, with the weighted average GWP trending downward significantly with increasing deployment of lower GWP refrigerants globally.
- More efficient equipment on a market at any particular time will show more efficient models typically cost more than entry-level models due to multiple reasons including the bundling of non-energy related features in premium models. Hence retail prices may not actually reflect the real cost of energy efficiency improvement.
- Costs of more efficient equipment and components tend to come down over time as a new technology becomes mainstream and due to economies of scale.

Chapter 9: Potential Approaches for Assessing Additional Costs for Improving EE while Phasing Down HFCs

- Additional costs associated with improving the energy efficiency of equipment alongside conversion to HFC alternatives are summarised drawing on information presented in previous EETF reports and presented as Additional Capital Cost (ACC) and Additional Operating Cost (AOC) to differentiate from the Incremental Capital Cost and Incremental Operating Cost.
- The EEWG presents a novel approach for assessing additional costs using an efficiency improvement-linked incentive index. This approach is contrasted with a traditional incremental cost approach. A key feature of the incentive index is that it focuses resources on those enterprises with the greatest need for capacity building and access to knowledge for designing and integrating lower-cost components into their products to improve from minimum to medium and better energy performance. Such an approach focused on where manufacturing EE capacity is most needed, would address a key barrier to access to higher energy efficient equipment in manufacturing and importing countries.

1 Introduction

1.1 Decision XXXIV/3: Enabling enhanced access and facilitating the transition to energy-efficient and low- or zero-global-warming-potential technologies

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

Recalling also paragraph 22 of decision XXVIII/2, in which the Executive Committee of the Multilateral Fund for the Implementation of the Montreal Protocol was requested to develop cost guidance associated with maintaining and/or enhancing the energy efficiency of low-global-warming-potential or zero-global-warming-potential replacement technologies and equipment, when phasing down HFCs,

Taking note of the *Scientific Assessment of Ozone Depletion: 2018* [1] report, which notes that improvements in the energy efficiency of refrigeration and air-conditioning equipment during the transition to low-global-warming-potential alternative refrigerants can potentially double the climate benefits of the Kigali Amendment,

Welcoming the reports of the Technology and Economic Assessment Panel in response to decisions XXVIII/3, XXIX/10 and XXX/5, inter alia, which provide valuable information on opportunities and pathways for enhancing or maintaining energy efficiency while phasing down HFCs,

Cognizant of the work under way by the Executive Committee to develop cost guidance on energy efficiency and further operationalise the aforementioned decisions, including decisions 89/6 and 90/50,

Taking note of the Technology and Economic Assessment Panel 2018 report [2] which indicates that coordinated investment in energy efficiency and refrigerant transition will cost manufacturers and consumers less than if such investments are made separately,

1. To request the Technology and Economic Assessment Panel to:
    a. Include in its 2023 progress report:
        i. Information on enhancements in energy efficiency associated with improvements in appliance foams;
        ii. Updates relating to the availability, accessibility, electrical compatibility, and cost of energy efficient products and equipment containing low- or zero-global-warming-potential refrigerants in the refrigeration, air-conditioning and heat pump sectors;
        iii. Information on testing equipment and procedures for validation of energy efficiency claims to enforce minimum energy efficiency standards and labels, and information on voluntary labelling programmes;
        iv. Information on barriers to consumer and business acceptance of the adoption of more energy-efficient products and equipment containing

low- or zero-global-warming-potential refrigerants, including barriers related to electrical compatibility of such products and equipment, and possible solutions for sustainable transition to such products and equipment;

v. Analysis of the potential benefits of introducing more energy-efficient refrigeration, air-conditioning and heat pump equipment, including costs and related climate benefits while phasing down HFCs;

vi. Information on the range of, and trends, in global warming potential and energy efficiency of refrigeration, air-conditioning and heat pump equipment, for which there are available data;

b. Integrate updates on energy efficiency while phasing down HFCs in the refrigeration, air-conditioning and heat pump sectors in its progress and quadrennial assessment reports from 2023 onwards;

2. To request the Executive Committee to take into consideration the information prepared by the Technology and Economic Assessment Panel in the preparation and finalization of the energy efficiency cost guidance in the context of the Kigali Amendment (decision XXVIII/2, para. 22), and to report on its progress in the context of the annual report of the chair of the Executive Committee to the Meeting of the Parties;

3. To request the Executive Committee to continue to support activities to maintain and enhance energy efficiency while phasing down HFCs in countries wishing to do so;

4. To request the Secretariat to:

   a. Organize a one-day workshop in 2023, back to back with the Meeting of the Parties, to share information, experiences and lessons learned, and assess challenges related to ways of improving availability and accessibility of energy-efficient equipment and equipment using low- or zero-global-warming-potential alternatives during the implementation of the Kigali Amendment;

   b. Prepare a report of existing policies addressing the interlinkages between phasing down HFCs and enhancing energy efficiency.

5. To encourage parties to:

   a. Enhance coordination between domestic energy and ozone officials to enhance energy efficiency while phasing down HFCs;

   b. Support upgrading domestic servicing, including related certification programmes and technician training to maintain and/or to enhance energy efficiency, reduce refrigerant leaks, and ensure proper installation and maintenance of refrigeration, air-conditioning and heat-pump equipment;

   c. When phasing down HFCs, to take into account, as appropriate, the information contained in volume 3 of the Technology and Economic Assessment Panel 2022 report responding to decision XXXIII/5.[3]

[1] World Meteorological Organization, *Scientific Assessment of Ozone Depletion: 2018*, Global Ozone Research and Monitoring Project – Report No. 58 (Geneva, Switzerland, 2018).

[2] Report of the Technology and Economic Assessment Panel, May 2018, vol. 3: Decision XXIX/10 – Issues related to energy efficiency while phasing down hydrofluorocarbons.

[3] Report of the Technology and Economic Assessment Panel, May 2022, vol. 3: Decision XXXIII/5 – Continued provision of information on energy-efficient and low-global-warming-potential technologies.

1.2 Previous Decisions

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
- 2021 - Decision XXXIII/5

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 four Energy Efficiency Task Forces (EETF) which reported in 2018 and 2019, 2020/21 and 2022. Please refer to previous EETF reports for more details.

1.3 Key Messages from the 2022 Energy Efficiency Task Force Report

The Energy Efficiency Working Group reviewed the previous Task Force Reports as a starting point for this 2023 update. This section summarises the conclusions from the 2022 TEAP Decision XXXIII/5 Energy Efficiency Task Force Report.

Climate benefits from the Montreal Protocol: 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 to 4 degrees by 2050, equivalent to ~25% of the mitigation of global warming. Future HFC Phasedown through the 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. 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 and near-term contribution to the path to net zero GHG emissions.

Availability, Accessibility, and Implementation: 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 A5 parties transition to new generation RACHP equipment.

Avoidable direct and indirect GHG emissions in A5 parties: Phase-down schedules agreed under Decision XXVIII/2 allow for continued import of high GWP HFCs in RACHP equipment at present. This will result in accumulating stock of RACHP equipment with operating lifetimes on the order of 10 to 20 years and is expected to be most significant in A5 parties (especially LVC importing countries) that are technology takers with limited access to RACHP equipment using low-GWP alternatives). This increasing stock will require continued consumption of high-GWP HFCs for the lifetime of the equipment for servicing needs and delay by 20 years the potential climate benefits through reduced direct emissions. In addition, if the high GWP HFCs were contained within inefficient RACHP equipment, this would create an economic burden of excess energy demand (indirect emissions) in A5 parties for the same period.

Common policy framework: Roadmaps for adopting energy-efficient technologies while phasing down HFCs can benefit from a common set of policies such as 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, monitoring, compliance, and enforcement.

Coordination of National Ozone Units (NOUs) with national energy and climate authorities: The technology transition would be supported by coordination between National Ozone Units and the national energy and climate authorities responsible for setting specifications for energy-using RACHP equipment. As result, the integration of lower GWP HFC refrigerant requirements into energy efficiency policies, such as, mandatory or voluntary labelling, and minimum energy performance standards (MEPS) will bring cost-effective and near-term contributions to the path to net zero GHG emissions.

Avoiding Dumping: Where A5 parties do not have the capacity to prescribe and enforce laws to prohibit shipping of obsolete products, the local and global harms, by 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.

Installation and Servicing; Training: Design upgrades to meet enhanced energy efficiency levels in new RACHP products require a higher level of knowledge and training for safe and effective installation and servicing. New skills include installation and maintenance of equipment with variable speed drives, controls with self-diagnostics, and remote-control features, requiring knowledge of electronics. Rigorous service requirements drive higher training and certification.

Modelling: Combining HFC mitigation with energy efficiency would lead to substantial reductions in cumulative GHG emissions between now and 2050, and at the lowest cost. Further synergy between energy efficiency and electricity generation decarbonisation makes a vital contribution to reduced emissions. Countries with high electricity generation carbon emission factors may wish to consider, reducing RACHP energy use as a key priority. For countries with low generation carbon factors, a greater focus on reducing HFC emissions is more beneficial.

Energy and Refrigerant Conservation: Demand for HFC refrigerants for servicing will be an increasing proportion of HFC production. Actions taken to conserve refrigerants through regular leak tests and improved maintenance, with recovery at end-of-life would significantly reduce direct emissions in the short and long term. Venting HFC refrigerants to atmosphere during maintenance or at equipment end-of-life is highly undesirable. Technicians should be enabled to collect high GWP refrigerants from equipment at end-of-life, and suitable infrastructure has to be available for re-processing.

1.4 TEAP Approach to Decision XXXIV/3

At the MOP in 2022, Decision XXXIV/3 “Enabling enhanced access and facilitating the transition to energy-efficient and low- or zero-global-warming-potential technologies” was adopted by parties. Paragraph 1 makes a number of requests from TEAP, and in paragraph b) specifically requests TEAP to “Integrate updates on energy efficiency while phasing down

HFCs in the refrigeration, air-conditioning and heat pump sectors in its progress and quadrennial assessment reports from 2023 onwards".

TEAP established an internal Energy Efficiency Working Group (EEWG) within the Refrigeration, Air Conditioning, and Heat Pump Technical Options Committee (RTOC) in addition to a co-Chair of TEAP and the Flexible and Rigid Foams Technical Options Committee (FTOC) with relevant expertise and experience related to providing information to parties on energy efficiency during HFC phasedown.

1.5 2023 Energy Efficiency Working Group: Membership

Co-chairs: Omar Abdelaziz EGYPT, Ashley Woodcock UK

Paulo Altoe	FTOC Co-Chair	BRAZIL
Ghina Annan	RTOC Member	LEBANON
Feng Cao	RTOC Member	CHINA
Ana Maria Careno	RTOC Member	COLOMBIA
Hilde Dhont	RTOC Member	BELGIUM
Gabrielle Dreyfus	FTOC Member, RTOC Member	USA
Bassam Elassaad	RTOC Member	LEBANON
Ray Gluckman	TEAP Senior Expert Member RTOC Member	UK
Herlin Herlianika	RTOC Member	INDONESIA
Mary Najjuma	RTOC Member	UGANDA
Roberto Peixoto	RTOC Co-Chair	BRAZIL
Rajan Rajendran	RTOC Member	USA
Leyla Sayin	RTOC Member	TURKEY
Nihar Shah	RTOC Member	INDIA
Andrea Voigt	RTOC Member	GERMANY

Brian Holuj from USA acted as a consulting expert to the working group.

1.6 Chapter outline

The 2023 EEWG has responded to the Decision by providing context to the energy efficiency of RACHP equipment, with new sections, "Comfort in Buildings" and "Cold Chain Systems". In addition, as requested, we provide updated information in the following chapters:

- Chapter 2: Energy Efficiency: a System Approach
- Chapter 3: Energy Efficiency Associated with Improvements in Foams
- Chapter 4: Availability, accessibility and cost of equipment containing low- or zero-global-warming-potential refrigerants
- Chapter 5: Testing equipment and procedures for validation of energy efficiency claims to enforce minimum energy efficiency standards and labels, and voluntary labelling programmes
- Chapter 6: Barriers to consumer and business acceptance of the adoption of more energy-efficient products and equipment containing low- or zero-global-warming-potential refrigerants, including barriers related to electrical compatibility of such products and equipment, and possible solutions for sustainable transition to such products and equipment

- Chapter 7: Analysis of the potential benefits of introducing more energy-efficient refrigeration, air-conditioning and heat pump equipment, including costs and related climate benefits while phasing down HFCs
- Chapter 8: The range of, and trends, in refrigerants' global warming potential and energy efficiency of refrigeration, air-conditioning and heat pump equipment, for which there are available data
- Chapter 9: Estimation for EE Cost while Phasing Down HFCs

2 Energy Efficiency: A System Approach

Key Messages

- To decarbonise heating and cooling in a cost-efficient manner, energy efficiency needs to go beyond a pure product-based approach. Taking an integrated approach to the energy system offers massive opportunities to reduce the need for energy generation, cost and emissions and to increase the resilience of the energy system. Analysing and optimising heating and cooling loads, energy sources and carriers, as well as the potential of waste heat recovery and thermal storage will pave the way for system-based energy and cost savings as well as increased emission reductions.
- Cold chains are a global challenge. Food production will need to increase significantly to feed the expected human population of 9.7 billion by 2050. In addition, food loss due to the lack of cold chains accounts for more than 1 gigaton of CO_2-equivalent emissions. Building up the cold chain with energy efficient equipment and low GWP refrigerants, combined with renewables-based electricity generation and increased use of electric vehicles will prevent food loss and significantly reduce emissions. To make it happen, all actors need to cooperate: governments, industry, academia and finance will be needed for research, skills development, new business models, and adoption at scale.
- According to the International Energy Agency (IEA), space cooling is responsible for around 10% of global electricity consumption and 5% of global greenhouse gas emissions. Energy-efficient HVAC equipment in buildings optimises energy usage in cooling and heating systems, resulting in significant energy and cost savings. Additionally, it enhances indoor air quality and extends equipment lifespan. Implementing building codes and regulations, working with industry associations and standards bodies, and considering lifecycle costs are all critical for encouraging the adoption of energy-efficient equipment.

Previous EETF reports focussed on equipment level energy efficiency and marginally considered the impact of the system on the energy consumption and associated emissions. In this report, we introduce the concept of the system level approach to RACHP equipment efficiency that looks at the whole process of delivering cooling and heating services, not just the individual components. By optimising the design, operation, and maintenance of the RACHP systems within the context of the overall facility which they service, the overall energy consumption and environmental impact can be reduced. This requires a holistic analysis of the cooling and heating loads, the RACHP equipment performance, the energy sources and carriers, and the potential for waste heat recovery and thermal storage. In this section, we present some examples of system level efficiency measures for cold chain and building industry applications.

2.1 Cold chain: a system level approach

Cold chains are critical infrastructure that underpin the delivery of multiple developmental goals and targets from food and health security through to poverty reduction. However, the level of cold chain development widely varies between countries. Cold chains are typically well established in high-income countries with the availability of modern equipment, reliable energy supplies, skills, and high-value market demand. In contrast, in many high ambient temperature (HAT) low-income countries where cold chains are really needed, they are often weak and fragmented, or even non-existent.

Previous interventions by governments and development institutions to establish refrigeration in developing countries have largely focused on cold storage. Critical elements of the chain and their inter-connectivity have been neglected, including the lack of energy and transport infrastructure, adequate policies and regulations, skills, finance, and business models to enable equitable uptake and longevity of appropriate solutions. As a result, most cold chain interventions have failed (e.g., many isolated cold stores in developing countries are unused), leading to inefficient allocation of resources and potentially higher long-term financial and environmental costs.

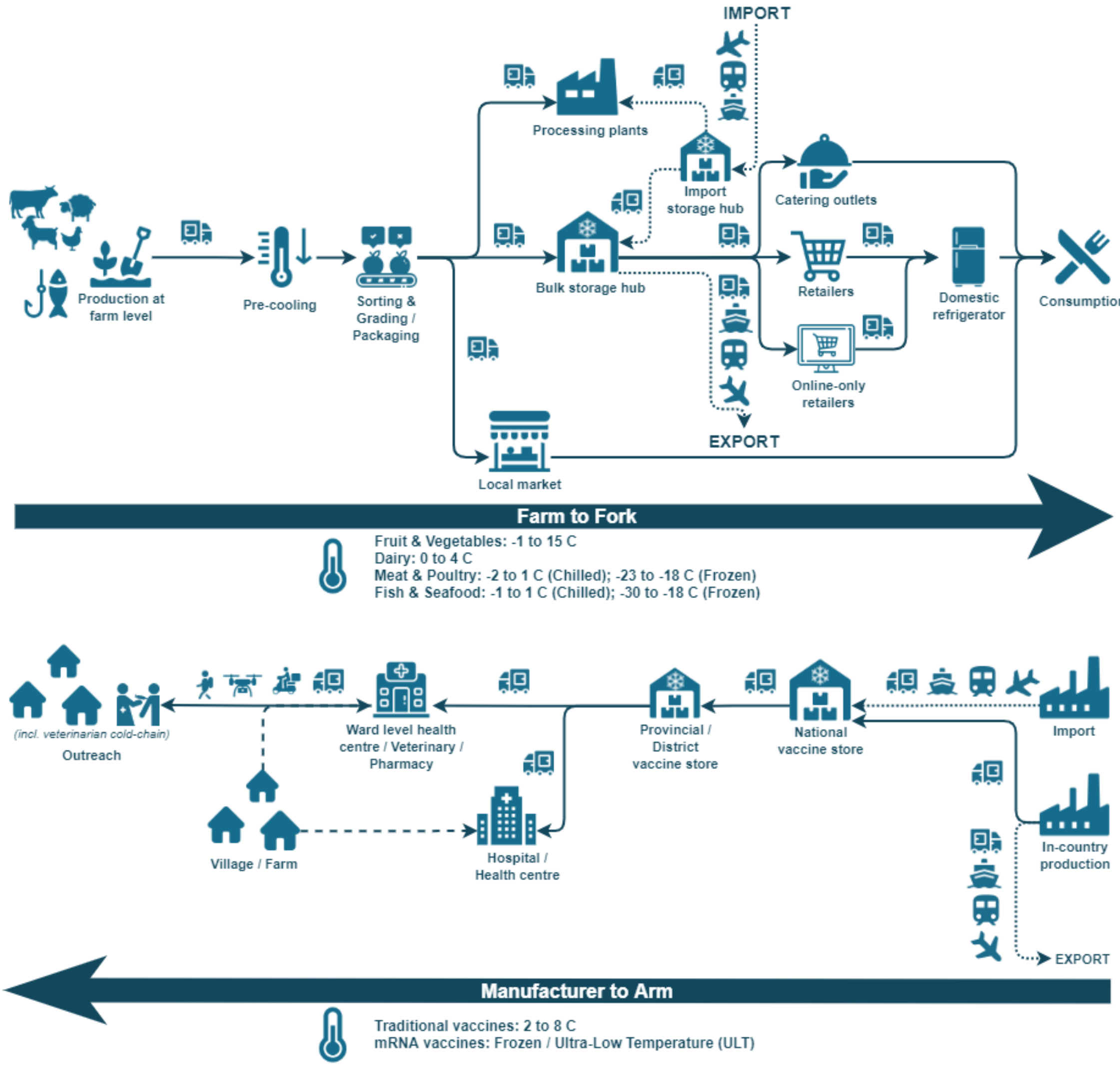

Figure 2-1. Typical cold chain flow from farm to fork, and from vaccine manufacturer to arm (Sayin L 2023)

Cold chains are complex, multi-dimensional, temperature-controlled supply chains that maintain perishable produce and/or temperature-sensitive products at their optimum temperature and environment from source to destination, preventing qualitative and quantitative product losses and ensuring their safety (Figure 1). Their seamless operation demands attention at multiple levels, including producers (e.g., farmers, vaccine manufacturers etc.), aggregators, processors, distributors, retailers, and consumers.

Food cold chains require optimisation at every stage (i.e., small to large scale) including primary processing (e.g., sorting and grading), packaging, precooling[1], refrigerated warehouses, cold storage at the wholesale/retail level, catering, refrigerated transport as well as domestic refrigerators. Most perishable produce is highly sensitive to the surrounding environment, such as temperature and humidity. Degradation processes start immediately after harvest, slaughter, or collection, and continues until the produce is spoiled or consumed.

Lack of effective food cold chains contribute to:

- the loss of over 500 million tons of food production annually (12% of the total food produced) at a cost of around $400 billion without considering social and health impacts
- In low-income countries, only 20% of food that needs refrigeration gets refrigerated, compared to 60% in high-income countries (IIF/IIR 2020)
- Poverty and hunger to small holding farmers who live on less than $2/day, but produce most of the food in e.g., sub–Saharan Africa
- 600 million people falling ill, and 420,000 deaths per year due to foodborne diseases (Afshin et al. 2019; WHO 2022)

Health cold chains have an inverse structure (i.e., large scale down to individual patients) with stages from national, provincial and district cold storage facilities, refrigerators at hospitals and health centres, mobile elements, such as refrigerated aircraft and trucks, as well as cold boxes or even drones for rapid outreach delivery, all of which cannot fail if the patient is to get treated. For example, vaccines may lose their efficacy if exposed to a temperature outside the recommended range[2] for inappropriate amounts of time, throughout the supply chain from vaccine manufacturer to arm.

Lack of effective medicine cold chains contribute to:

- Over 1.5 million people losing their lives due to vaccine-preventable diseases each year.
- Economic disadvantage: Every dollar spent on child immunization provides $44 worth of economic benefits in low- and middle-income countries (Ozawa et al. 2016)
- Vaccine wastage (~25%) estimated to cost $34.1 billion annually, not including the substantial physical burden and economic impact (Nagurney 2020).

2.1.1 Environmental impact

Food loss due to the lack of cold chains accounts for more than 1 gigaton of CO_2-equivalent emissions. However, conventional cold chains have also been energy intensive and polluting. The current GHG emissions of 261 million tonnes of CO_2-equivalent emissions globally in 2017 (IIF/IIR 2021). come from the leakage of refrigerants (direct emissions) together with power generation for the cold chain equipment and fuel for refrigerated vehicles and generators (indirect emissions). In addition, there are also hidden polluters in cold chains with

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[1] Precooling is an essential first step in the perishable food cold chain. It is often lacking in low-income countries with the focus on cold storage. Unlike cold storage, which is designed to maintain the temperature of products, precooling equipment is used for the controlled and rapid removal of heat from freshly harvested or slaughtered produce prior to storage or transport.

[2] Both higher and lower temperature excursions, even for very short periods of time, can render a vaccine obsolete.

health implications. For example, a transport refrigeration unit consumes up to 20% of a refrigerated vehicle's diesel and emits high levels of airborne pollutants.

In coming years, GHG emissions from optimised cold chains could be minimised through using low GWP refrigerants in efficient equipment, synergised with power generation from renewable sources, increasing use of electric vehicles and other solutions. When combined with reduced emissions from food loss, a systems approach to cold chain would produce a major win-win.

A study, developed by IIR, 2021, estimates the GHG emissions mitigation that could be achieved by having a global cold chain improved. Table 2-1 shows a strong reduction in CO_2 emissions associated with food losses due to a lack of refrigeration. These emissions go down from 1004 to 76 million tonnes CO_2eq for an improved cold chain[3], i.e., a reduction of 92%.

Table 2-1: GHG emissions reduction due to improved Food cold chain (IIR/IIR2021)

Designation	Cold Chain		Unit
	Current	Improved	
Food losses due to a lack of refrigeration	526	236	Million tonnes
CO_2 emissions associated with these food losses	1,004	76	Million tonnes CO_{2eq}
CO_2 emissions from equipment	261	589	Million tonnes CO_{2eq}
Total CO_2 emissions associated with the cold chain considered	1,265	665	Million tonnes CO_{2eq}

2.1.2 System-level thinking

Cold chains for food and health will need to expand and evolve globally to respond to emerging needs and changing demand patterns, but also to deliver socio-economic development and unlock growth especially in low-income economies. The multidimensional challenge at hand is that the cold chain development will need to be:

- equitable in terms of availability and access,
- future-proofed and resilient against changes to the system and future risks and disruptions,
- sustainable with minimum environmental impact.

Food cold chains in low-income countries are mainly owned and run by the private sector. As a result, cold chain investments often fail to deliver on food and nutrition security, fail to generate sustainable and equitable benefits for all, and instead exacerbate inequalities. Many previous interventions to assist under-served communities have disregarded the cold chain connectivity, technical training needs, and appropriate business models. As a result, they have not achieved their full potential, leading to inefficient allocation of resources and potentially higher financial and environmental costs in the long term.

The cold chain challenge in low-income countries is much more complex than deploying more equipment. For food, there is a need for a robust, seamless, temperature-controlled,

[3] The "improved" cold chain considered by the IIR model corresponds to the level of the cold chain currently existing in developed countries.

end-to-end connectivity from farm to fork through a systems-levels approach. Some key elements include:

1. fit-for-market and purpose technologies to meet the cold chain needs effectively and to avoid short lived solutions;
2. energy and transport infrastructure to ensure seamless operation and connectivity from source to destination;
3. policies and regulations to facilitate uptake of appropriate solutions at scale;
4. finance and business models to enable equitable distribution of risks and costs to overcome issues around affordability and viability as well as the value created from investments in cold chain equipment and infrastructure;
5. skills and capacity at all levels from farmers (and where relevant fishermen) to ensure uptake and improve post-harvest practices, to technicians/engineers to ensure adequate installation and maintenance of technologies;
6. avoiding conventional fossil fuel-based, inefficient and climate polluting technologies

The same should be ensured in reverse for medicines cold chains from production to point of use to deliver safe and effective vaccines, blood and other life-saving medicines at the right place, time and condition.

2.1.3 Future Proofing

The cold chain has to be future proofed through responsive development pathways which optimise investments and managing risks. Cold chain requirements change with climate, technologies, policies and regulations, social norms; food systems will change in the light of agricultural and technical innovations such as, alternative proteins and vertical farming. They also need to consider how vaccines, including those that require sub-zero cold chains, might evolve over time in targeting new variants of disease and new populations, and whether there is an opportunity to integrate food and health into a more synergistic strategy to develop both efficiency and resilience across the total cold chain. Understanding and planning for such changes and integrating them into development plans is critical to optimise investments and managing risks, given the equipment and infrastructure deployed during the rest of this decade will still be in operation in 10-20 years.

Inadequate cold chains are now a global challenge. Food production will need to increase significantly to feed the expected human population of 9.7 billion by 2050 (UN 2019). This will require closing the 56% gap in the global food supply between what was produced in 2010 and what will be needed in 2050 (WRI 2019). Reducing food loss and waste by 25% by 2050 could close the food gap by 12% (WRI 2019). With 60% of the world's uncultivated arable land lying in Africa, and the population growth focussed on this continent, unlocking this potential will require robust cold chains to sustain local populations as well as connecting to international markets.

Climate change coupled with increased population movement, will increase both the likelihood and impact of future outbreaks of infectious disease originating in low-income countries. It is important to develop a comprehensive global strategy for health cold chains to ensure that low-income countries can manage early outbreaks locally before they move to epidemic or pandemic scale.

The development of sustainable, resilient, and equitable global cold chains requires the establishment of a common viewpoint on shared goals and co-ordination, policies and regulations, among governments and industry working with academic institutions and developmental agencies. Finance is needed for research, skills development and innovation, new business models, and adoption at scale.

2.1.4 Case study: Africa Centre of Excellence for Sustainable Cooling and Cold Chain (ACES)

ACES is a regional collaboration which commenced in 2022, between the Governments of Rwanda and the United Kingdom, the United Nations Environment Programme, and a consortium of Universities in the UK and Rwanda, led by University of Birmingham. The ACES headquarters hub is at the Rubirizi Campus, Kigali and will have a number of Specialised Outreach and Knowledge Enterprises “SPOKES” as demonstration and training sites across Africa. Sister centres of excellence are also being established in Telangana and Haryana, India.

Aims

- Support the development and roll-out of sustainable, resilient, and equitable cooling and cold chain solutions in the agriculture and health sectors, ensuring a seamless, end-to-end connectivity from farm to fork, and from vaccine manufacturer to arm.
- Deliver against social need (including marginalised and displaced communities), food and health security, affordability and accessibility, business and economic opportunity, climate change mitigation and adaptation, decarbonisation and energy access, and resilience.

The programme will

- Encourage an innovative systems approach to cold chain development
- Provide the knowledge and support to a new inclusive self-sustaining community of cold chain stakeholders for the delivery of fit-for-market, user accepted solutions.
- Equip the next cohort of scientists and engineers, entrepreneurs and wider stakeholders with the tools, skills, knowledge, and expertise to develop the new technologies, systems, and business models.
- Train the trainers: develop curricula for training technicians along the length of the cold chains
- Present the evidence to reshape the policy, regulatory and finance environment.
- Provide policymakers and financiers access to agent-based modelling and forecasting to test solutions, quantify Return on Investment as well as test resilience against future risks.

2.2 Buildings: a system level approach

Energy-efficient heating, ventilation, and air conditioning (HVAC) equipment in buildings optimises energy usage in cooling and heating systems, resulting in significant energy and cost savings. Additionally, it enhances indoor air quality and extends equipment lifespan. According to the International Energy Agency (IEA), space cooling is responsible for around 10% of global electricity consumption and 5% of global greenhouse gas emissions, making this an important issue to address (IEA, 2022a).

Buildings with energy-efficient equipment may incur varying initial costs depending on the scope and type of the project and the equipment involved. LED lighting fixtures, for instance, are more energy-efficient than traditional incandescent or fluorescent bulbs, though they may cost more initially. Similarly, energy-efficient HVAC systems, such as those with a high

Seasonal Energy Efficiency Ratio (SEER) rating, may cost 30-50% more than conventional systems. However, they consume less energy to cool or heat a building, leading to long-term cost savings of up to 30% on energy bills (WBDG, 2016). Proper insulation, shading and reflective surfaces on buildings which reduces energy usage by minimising heating and cooling loads, may involve higher initial costs. Energy-efficient windows, such as double-paned windows, may also incur higher initial costs, but can save up to 25% on energy bills by reducing heat transfer and air leakage. Although mechanical and electrical building energy-efficient equipment has higher initial costs than conventional equipment, long-term savings from reduced energy usage can lower total cost of ownership. Hence, it is crucial to weigh lifetime costs and benefits before deciding.

Energy-efficient RACHP equipment can significantly mitigate climate change by reducing greenhouse gas (GHG) emissions. This is achieved through reduced energy consumption, low-GWP refrigerants, heat recovery, and optimization and control. According to the International Energy Agency (IEA), energy-efficient equipment can reduce global electricity demand by up to 10% by 2040, resulting in a reduction of 2.5 billion metric tonnes of carbon dioxide emissions per year. Furthermore, the widespread adoption of energy-efficient equipment could cut energy-related CO_2 emissions by 1.5 billion metric tonnes by 2030. New equipment using low GWP refrigerants usually has high efficiency due to technological developments. The IEA estimates that energy efficiency improvements can deliver over 40% of the CO2 emissions reductions needed to meet global climate goals by 2040. For instance, replacing older, less efficient air conditioning units with newer, more efficient models can save up to 50% on cooling costs and reduce associated greenhouse gas emissions by up to 50%, according to the U.S. Environmental Protection Agency (EPA).

Building energy codes, government incentives, and research and development can also contribute to reducing the use of HFCs and increasing energy efficiency. Building energy codes mandate energy-efficient equipment and low-GWP refrigerants. One example is · California's Title 24 Building Energy Efficiency Standards that requires the use of refrigerants with a GWP of less than 750 for new commercial and high-rise residential buildings, and less than 150 for new low-rise residential buildings.

Building envelope and thermal insulation are crucial components in achieving high levels of building energy efficiency. According to the U.S. Department of Energy, heating and cooling account for around 50% of the energy consumed by buildings in the United States, and a significant portion of that energy is lost through air leaks and poorly insulated walls and roofs. A well-designed building envelope with proper insulation can reduce energy consumption by 20-30%, (Al-Tamimi 2021) resulting in lower energy costs and reduced greenhouse gas emissions. Studies have also shown that investing in energy-efficient building envelope and thermal insulation can have significant economic benefits. For example, a recent study by IEA (IEA 2022b) showed that buildings-related emissions in the Association of Southeast Asian Nations can be reduced by 70% by implementing building energy efficiency improvements combined with electrification.

Promoting the use of energy-efficient equipment is crucial for mitigating climate change and achieving sustainable development. It has the potential to significantly reduce energy consumption and greenhouse gas emissions, resulting in lower energy costs, improved energy security, and a more sustainable future for all. Policymakers can set energy efficiency targets and standards for equipment manufacturers and buildings, while governments and businesses can provide incentives for the adoption of energy-efficient equipment such as tax credits, rebates, and low-interest loans. Moreover, education campaigns and public awareness initiatives can help to increase understanding of the benefits of energy efficiency and encourage individuals and businesses to take action.

Additionally, implementing building codes and regulations, working with industry associations and standards bodies, and considering lifecycle costs are all critical for encouraging the adoption of energy-efficient equipment. While energy-efficient equipment may have a higher initial cost, it can lead to significant savings over the life of the equipment in terms of energy costs and maintenance. Overall, promoting the use of energy-efficient equipment is a crucial step towards mitigating climate change and achieving sustainable development, and policymakers, businesses, and individuals all have a role to play in this effort.

2.2.1 Case Study: ASHRAE 90.1 Building Energy Standard

An example of successful system-level building level energy efficiency integration is the standard ASHRAE 2022. This building energy standard has undergone successive updates since its introduction in 1975. The 2016 version of the ASHRAE 90.1 results in more than 50% reduction in energy use compared with the 1975 version as shown in Figure 2-2 (Goel et al. 2021).

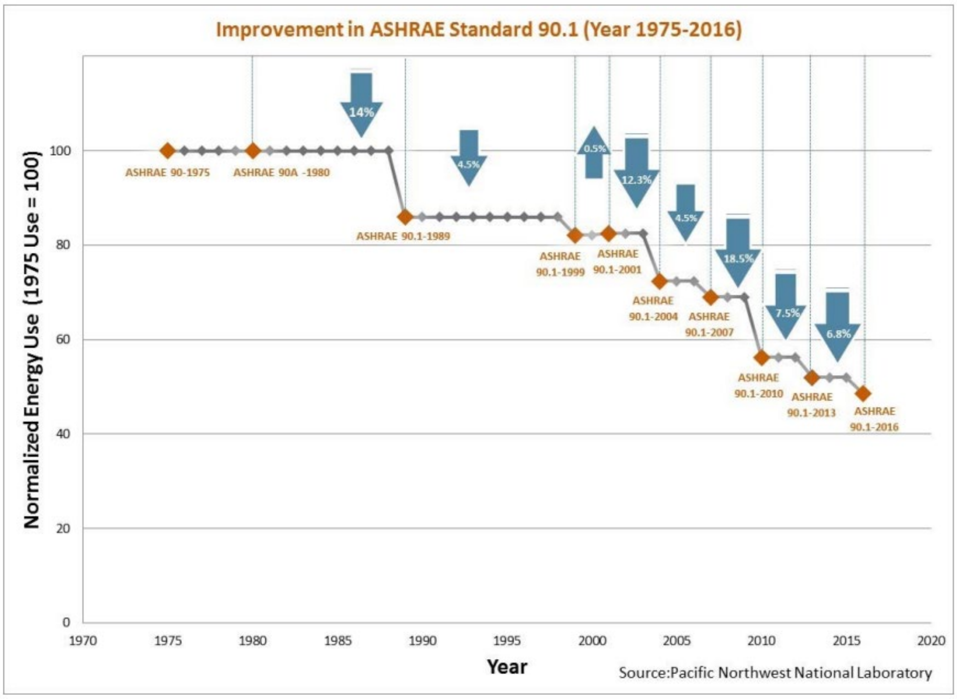

Figure 2-2. ASHRAE 90.1 normalised energy use reduction over the years.[4]

2.2.2 Case Study: Build-ME

Build-ME is a recently concluded project[5] (2016 – 2022) that focused on supporting the implementation of energy efficient buildings in the Middle East and North Africa (MENA) region through the implementation of renewable energy integration and energy efficient cooling and heating equipment in Egypt, Jordan, and Lebanon. The Build-ME project offers

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[4] https://www.constructioneconomicsresearch.com/post/building-standards-energy-codes-and-decarbonisation, https://www.ashrae.org/about/ashrae-task-force-for-building-decarbonization.

[5] https://www.buildings-mena.com/info/about

significant resources including training materials, tools, and case studies. Their system level approach for enviro-technoeconomic assessment of building-energy efficiency optimization is presented in Figure 2-3.

They used this approach to reduce the energy use intensity of a multi-family residential building in Egypt from 107.8 kWh/m^2.year to 26.3 kWh/m^2.year through a series of integrated building, equipment, and renewable energy measures.[6] These measures are presented in Table 2-2 and the corresponding results are presented in Table 2-3. The measures presented in Table 2-2 describe the different building envelope insulation levels for the roof, walls, and floor. The windows type and windows to wall ratios, the heating and cooling equipment efficiency (COP), the lighting technology – that reflects energy efficiency, the renewable energy integration, and changes in temperature setpoints.

- The Business-as-Usual (BAU) energy intensity was 107 kWh/m^2.year
- An improved “Design” could reduce the energy intensity to 80.6 kWh/m^2.year.
- An “Optimised” integrated systems level approach has the potential to reduce the energy intensity to 26.3 kWh/m^2.year.
- The final “Selected” and most cost-effective design had energy intensity of 31 kWh/m^2.year.

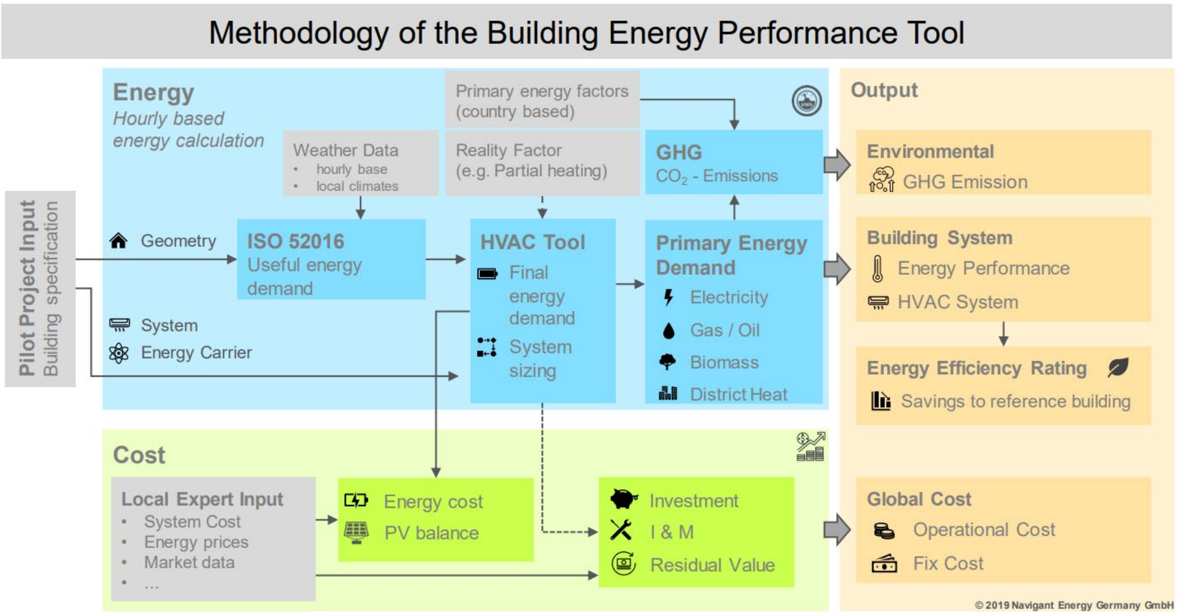

Figure 2-3. System level enviro-technoeconomic analysis for buildings.[7]

[6] https://www.buildings-mena.com/info/cairo-west-residence-egypt

[7] https://www.buildings-mena.com/files/EGY_PP1_AlDau.pdf

Table 2-2. Building energy efficiency measures.[7]

Parameter	"BAU"	"Design"	"Optimised"	"Selected"
Roof Insulation (U-Value, W/m^{2}K)	0.8	0.8	0.4	0.4
Wall Insulation (U-Value, W/m^{2}K)	2.4	2.4	0.38	0.5
Floor Insulation (U-Value, W/m^{2}K)	2.2	2.2	2.2	2.2
Windows (U-Value, W/m^{2}K/ G-Value)	5.8 / 0.85	2.8 / 0.7	2.8	2.8
Windows Fraction, %	37%	37%	15%	37%
Shading	No		Solar Glazing	
Heat Supply (COP)	2.5	2.5	5	3.2
Cooling Supply (COP)	2.5	2.5	5	3.2
Lighting systems	CFL	CFL	CFL	LED
Renewable energy	No		12 kWp	
Set temperature	Cooling: 23°C, Heating: 21°C		Cooling: 26°C, Heating: 21°C	

Table 2-3. Results for the different building designs.[7]

Parameter	"BAU"	"Design"	"Optimised"	"Selected"
Energy Use Intensity, kWh/m^2.year	107.8	80.6	26.3	31
Cooling	66%	59%	21%	36%
Heating	11%	10%	3%	5%
Water heating	13%	17%	44%	38%
Lighting	7%	9%	23%	12%
Other	4%	4%	3%	3%
PV	0%	0%	(4.9%)	(5%)
CO_2 emissions intensity, kg/m^2.year	3.4	2.4	0.6	0.7

For the optimised case, the insulation level was maximised for the roof and walls, the window-to-wall ratio was minimised, and the most efficiency heating and cooling equipment were selected; however, CFL lighting were still used.

The most cost-effective solution that was finally adopted had some trade-offs to make it affordable. The roof insulation was kept to a maximum, the wall insulation was reduced, the heating and cooling efficiency was reduced but the lighting was improved from the optimised case. However, it was a substantial improvement in building energy efficiency on the BAU.

Using this type of systematic approach, it is possible to reduce the overall emissions by ~75% cost effectively. The key is to create a synergy between optimal building envelope, equipment selection, renewable energy integration and smart control systems. By applying these principles, we can design and construct buildings that are energy efficient, comfortable and resilient.

2.3 Contribution of Foams to Energy Efficiency of Appliances and Buildings

Foam insulation provides a thermal barrier for both appliances and buildings, and to seal the envelope reducing the ingress of hot or cold air. Closed-cell polyurethane[8] (PU) foams are lightweight and durable, encapsulate the foam blowing agent (FBA), and have very low thermal conductivity. The choice of foam (and FBA) and thickness in buildings is a complex decision. Some foams can achieve adequate insulation performance at minimum thickness which saves space in buildings and cold chain applications.[9]

Continued efforts to reduce energy consumption in buildings and refrigerating appliances have encouraged increased use of insulating foams. Spray foam is used to retrofit older buildings with little or no insulation. Standards set requirements for minimum thermal resistance of insulation (e.g., a specific resistance for insulation in walls) or performance requirements of the entire building by setting a maximum allowed energy consumption for the building design. However, as of 2021, according to the International Energy Agency (IEA), at least 110 countries have no mandatory building energy codes or standards. IEA equates this to the equivalent of Spain's entire building stock.[10]

The combination of improved insulating materials and more efficient refrigerating systems has provided a notable improvement in energy efficiency. For example, the typical new refrigerator today uses 75% less energy than its 1973 counterpart while offering roughly 20% more storage capacity. Foam contributes to the efficiency of refrigeration equipment and enables equipment to meet minimum efficiency performance standards (MEPS). The thickness and thermal performance of the foam is a critical "design feature" in attaining MEPS. The foam quality and sealing means that manufacturers can reduce or replace other structural elements. New alternative FBAs such as HFOs can achieve similar or better thermal performance than that of existing HFC/HCFCs.[11] MEPS are not widely established for commercial refrigeration equipment which uses large volumes of polyurethane foam, and the choice of FBA is based on cost. MEPS for cold chain equipment are limited to applied systems (e.g., walk-in coolers and freezers, cold storage warehouses, and transportation) and are comparable to the requirements for some equipment (e.g., domestic refrigerators).

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[8] This document includes both polyurethane (PUR) and polyisocyanurate (PIR) in references to polyurethane (PU) foams.

[9] PU foams are the dominant insulation material for most of the cold chain. The cold chain includes refrigeration at farms and factories, cold storage warehouses, refrigerated marine, road, rail, and air transport, cold storage in retail facilities and restaurants, and residential refrigeration.

[10] Delmastro et al, Building Envelopes last accessed April 2023

[11] United Nations Montreal Protocol Technical and Economic Assessment Panel 2023 Flexible and Rigid Foams Assessment Report Advance Copy January 2023

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3 Energy Efficiency Associated with Improvements in Foams

Key Messages

- Continued efforts to reduce energy consumption in buildings and refrigerating appliances have encouraged increased use of insulating foams. Building codes and standard mandates, insulation performance standards, labelling mandates, and other policies establish requirements to reduce heating and cooling loads in both commercial and residential buildings and for refrigeration. Investment in decarbonization and infrastructure will drive increased use of insulation including several end-uses for foam products specially the high insulating ones like polyurethane, polystyrene and phenolic foams.
- Walls with appropriate foam thickness produced with low thermal conductivity and low GWP blowing agents can provide substantial benefits of insulation with superior energy efficiency with less CO2 emissions for applications in buildings and cold chain.
- High performance insulating foams improve energy efficiency by creating an air barrier and reducing heat transfer. Insulation foams applied in building reduce heat loss or heat gain which improves individuals' comfort and can lower energy costs. For cold chain, high performance foams also create an air barrier and reduce heat gain to keep temperature in storage, transport, consumption and conservation of food, medicines and a variety of products that need temperature control with reduced energy consumption and cost.
- The continuous improvement in foams technology to provide high insulating materials in combination with more efficient refrigerating systems provide a notable improvement in energy efficiency. For example, the typical new refrigerator uses 75% less energy than a typical refrigerator 70 years ago while offering roughly 20% more storage capacity and other features. New refrigerator technology also eliminated ODS and high GWP blowing agents and refrigerants with a significant reduction of CO_2 emission in the manufacturing process.
- Foam insulation can create an air barrier making assurance of sufficient ventilation and possibly monitoring of air quality more important, as highlighted during the pandemic.

This chapter is responding to the following: Decision XXXIV/3 requests TEAP to provide "information on enhancements in energy efficiency associated with improvements in appliance foams."

Polymeric foams are used in a wide range of products including thermal insulation. Spray foam and insulating panels for buildings and refrigerated appliances reduce cooling and heating loads and maintain safe temperatures for the storage and transport of foods, vaccines, and for other medical uses. Closed cell foams (polyurethane, polystyrene, and phenolic) foams trap the Foam Blowing Agent (FBA) in the polymer matrix which gives low thermal conductivity.

Insulation creates resistance to heat flow that reduces the heating and cooling load of buildings and refrigeration systems. Heat conductivity or "lambda value" or "k-factor" are used to describe the insulation properties of insulating foams. Polymeric foam insulation is used to seal building envelopes and refrigerated spaces from air infiltration, further reducing heating and cooling loads. The balance between thermal performance and cost is dependent on a number of factors including foam density, type of foam (open versus closed cell), and type of FBA.

Building science trends toward efforts to reduce cooling and heating loads increase the amount of foam and its associated FBA usage and selection. It should be noted that a careful balance of air infiltration and ventilation has been identified as a key aspect of "healthy buildings, and it is anticipated that more information will become available in the coming years.

FBAs are retained within the foam and are intrinsic to the thermal performance of polyurethane rigid foam insulation (Heinemann, 2000). A change in FBA selection can impact the thermal performance of the foam. Reductions in the use of better thermal performing FBAs to optimise systems for other reasons, such as to reduce cost, could result in an unintended impact to thermal performance. Extruded polystyrene (XPS) manufacturers have reported challenges in finding an alternative that allowed them to meet stringent thermal standards in the United States, as an example where foam design has been challenging for this transition.

There is a proliferation of blends of new FBAs with low GWP and zero ODP. Thermal performance, structural attributes, flow of foam systems, and cost of finished foams are key features for optimization, resulting in FBA with a range of thermal conductivities. Differences in factory size determine relative capital and operational costs and the choice of FBA. Table 3-1 compares the properties of older FBAs versus new alternatives. Comparing the thermal conductivities of blowing agents ranks CFC-11 as best, then HFOs, hydrocarbons and worst HFC-134a. HFOs have low thermal conductivity and less flammable but are significantly more expensive than hydrocarbons. Another important consideration is FBA solubility and diffusion in polyols – although some FBAs will be emitted soon after the foam is manufactured, sealed foams in equipment or buildings only lose 10-15% of their thermal performance through the lifetimes of the foams.

From a cost perspective, the price of the newer FBAs is higher, and the volume needed for a given amount of foam is greater because of higher molecular weights, which increases the cost of foam systems. This is because blowing agents are purchased based on weight, but they are used based on volume which is inversely proportional to molecular weight.

Water is added as a supplementary FBA to reduce costs. Water reacts with isocyanate during the foaming reaction creating carbon dioxide. Blends are used to optimise cost and physical properties of most low GWP, zero ODP for both gaseous and liquid FBAs. Cost is also impacted by capital investment needed to use flammable alternatives (See flash points in the tables below.).

Another important consideration is FBA solubility and diffusion in polyols and its impact on long-term thermal performance and some safety requirements. For example, some FBAs will be emitted sooner after the foam is manufactured. This is true for extruded polystyrene (XPS) foams, which are generally produced with gaseous FBAs, and are often carefully stored in warehouses to ensure that some high emitting, and sometimes flammable,[12] FBAs are emitted and to ensure that dimensional stability is maintained prior to shipment.

Finally, thermal resistance (lambda value) of FBAs is an important consideration especially for insulating foams. Foams may perform differently, depending on foam formulations and

[12] Low solubility blowing agents are not necessarily high emitters, 134a for instance. Also, not all flammable blowing agents are high emitters in XPS (isobutane, for example), but some as DME and ethanol are.

FBA blends. Some blends of FBAs seem to behave as azeotropes, much like refrigerant blends with low glide[13], and provide better performance than either component on its own. Optimising cost and other parameters may result in the limited adoption of insulation with lower thermal conductivity because of its cost or the availability of FBAs with better thermal performance. In addition, space limitations can limit additional layering of insulation, and optimization must be based on foam formulation and blowing agent selection, as well as elimination of thermal bridging.

For parties with standards for foam performance, building energy codes, and appliance standards, some transitions have taken longer because of the need to optimise foams to meet these requirements. For parties without these standards, there could be a change in performance that may be unanticipated.

Table 3-1. Properties of different Foam Blowing Agents

	CFC-11	HCFC-141b	HFC-134a	HFC-245fa	HFC-365mfc/227ea	Cyclopentane	Methylal	Methyl Formate	HFO-1336mzz-Z ǂ	HCFO-1233zd-E ≠	HCFO-1224yd-Z §
Chemical formula	CCl3F	CH_3CCl_2F	CF_3CH_2F	$C_3H_3F_5$	$CF_3CH_2CF_2CH_3$ CF_3CHFCF_3	C_5H_{10}	$CH_2(OCH_3)_2$	$C_2H_4O_2$	$CF_3CH{=}CHCF_3$	$ClCH{=}CHCF_3$	CF3-CF=CH-Cl
Molecular weight (g/mol)	137.4	116.9	102	134	149,4	70,13	76,09	60,04	164,1	130,5	148,5
Boiling point (°C)	22.7	32,9	-26,6	15,3	30	50	42	33	33.4	18.6	14
Vapor pressure (kPa) (@25°C)	107,1	79	482 *	122.7 *	85	53.3	58.6	63.4	60.4	130	151
Flammability Limit (Vo l%) #	No	7,6 - 17,7	No	No	No	1.5-1.8	1.6-17.6	4.5-23	-	-	-
Vapor density (Air = 1) kg/m3 §	4,7	5,02	5,18	5,96	6,54	2.42	2.63	2.07	4.21	7.19	9.19
Gas lamda @ 25 °C (mW/mK)	8,23	10.04	14.05	12.00	10.70	11.7	14.2	10.7	10.7	10.2	10.2
Flash Point (°C) (closed cup)	No	No	No	No	No	-42	-30.5	-32.3	None	None	None
ODP	1	0,11	0	0	0	0	0	0	0	~ 0	~ 0
GWP	4600	725	1300	950	1030	11	<25	-	2	1	<1

Source: TEAP Report 2006; TDS and SDS from suppliers and distributers; *ASTM E-681-79; # @20 (°C)

ǂ Opteon™ 1100, HFO-1336mzz-Z – Chemours https://www.opteon.com/fr/-/media/files/opteon/opteon-1100-push-bulletin.pdf New blends in Chemours´ product list Opteon™ 1100/1150 ;

≠ Arkema Forane™ 1233zd-E ; Honeywell Solstice ® 1233zd-E .

§ AMOLEA™ yd for HFCO 1224yd-Z (AMOLEA) https://www.agcce.com › refrigerants. (Used in Japan also for foams)

3.1 Life Cycle Analysis

Concern about climate change has created demand for FBAs with low GWP as well as improved thermal properties. A life cycle analysis can be used to fully understand the impact an FBA will have on life climate change potential (LCCP)[14] in spray polyurethane foam, panels, or refrigeration applications. For installations where thickness is constrained or set equal, optimised blends to maximise thermal performance can have lower CCP evaluated on a cradle-to-grave (CTGr) basis due to the lower GWP of direct emissions of FBA during installation, use, and at end-of-life due to lower energy requirements during the use phase. Generally, results remain consistent, showing lower CCP across changes to several variables, such as regional climates and FBA loading across sensitivity and uncertainty analyses with respect to FBA emissions during use and end-of-life, FBA formulation variability and life cycle inventory uncertainty, house size, and electricity grid mix. Direct emissions more than

[13] Some blends of FBAs seem to behave as azeotropes, much like refrigerant blends with boiling point reductions, a feature that provides better performance than either component on its own in low temperature insulation applications.

[14] Climate change potential or lifecycle climate change potential (LCCP) can be assessed using tools such as TRACI 2.1 (https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci).

off-set the energy benefits relative to water/CO_2 blown foam, leading to higher CTGr CCP (Krieger et al., 2012).

Life cycle analyses over the past decade have continued to confirm that the GWP of FBAs with GWPs less than 50 have less impact on the holistic life cycle GHGs of a foam while HFC-based blowing agent, the GWP values affect the overall lifecycle GHGs significantly heavily dominating the calculation compared to the embodied carbon of the foam. With efficient blowing agents and greater penetration of renewables into the electricity grid, the overall lifecycle GHG emissions may also be reduced further (Wysong et al.).

Some sector transitions have taken longer because of the need to optimise foams to meet building energy codes, and appliance standards. A transition to an alternative FBA, or to reduce cost, can reduce thermal performance, with for example extruded polystyrene manufacturers failing to meet stringent thermal standards in the United States and if space limits foam thickness.

3.2 New technical developments in Foams can improve Energy Efficiency

There is continued research and commercialization announcements of various uses of FBA. Generally, there has been testing and qualifying of new uses and work to improve thermal properties at minimum cost. There continue to be efforts to optimise the estimates of long-term thermal performance. Some novel technologies are noted below.

- Adoption of new Super Insulating Materials (SIM) usually with Vacuum Insulating Panels (VIP) and Advanced Porous Materials (APM) that are combined with foams to provide up to 20% improvement in insulating walls. These are used in Europe to retrofit buildings containing low efficiency foams.
- HCFO based foams have been tested as replacement of HFCs in refrigerated containers (Rider and Super, 2021),in relation to the stability of the polyol blend and long-term thermal performance. The high solubility of some FBAs in the polymer matrix may create challenges for compressive strength, dimensional stability, and poorer adhesion to metal and plastic. New catalysts and additive combinations may enable improved performance.
- Measuring long-term thermal performance (LTTR) – LTTR can be assessed in two ways, by predictive LTTR methods, or by observing actual use, and for different foam applications the correlation between the measures is variable. Spray foam (CPI, 2021a) using HFO-1336mzz-E isomer indicated a degradation in actual use of only 2.7% in insulation performance after 3.5 years compared to 16% predicted by the LTTR method. In contrast the LTTR method predicted long term performance in both filled wall cavities and in insulated metal panels.
- Co-blowing agents (e.g., methylal or dimethoxymethane) continue to be investigated to reduce costs and improve foam properties (CPI 2022). Performance in blends with HFOs/HCFOs (CPI 2021b) have focussed on dimensional stability.

Energy efficiency improvement in different settings.

- **Wall thickness and different insulating materials:** A study conducted in Sweden provided important information on optimising insulation measures to minimise the life cycle cost of buildings in need of renovation (Gustafsson, 2000). Another study found 63% decrease in CO_2 emissions under optimum conditions in different regions of China evaluating two different walls and three different FBAs (Yu et al., 2009, Yuan et al., 2017).

- **Alternate materials:** A study performed in Turkey, showed that when compared to fibrous materials, polymeric foams (EPS and XPS) provided substantial gains in EE (more than 50%) with low densities and low thickness. The tests were analysed with three different types of fuels in supplying energy or in the grid of energy matrix. It was also stated that the amortization of investment to implement the insulating walls is around 3.5 years (Kan, 2022).
- **High performance, Net-zero homes:** In Hawaii, Kaupuni Village homes were designed to have at least 40% lower energy consumption than the baseline. Energy efficiency measures included optimal building envelope with polymeric foam to insulate walls and roof, including Energy Star® appliances, high efficiency lighting and daylighting with good solar control, natural ventilation, high efficiency air conditioners, and solar water heating (UNT, 2012; Norton et al, 2013).

3.3 Foams in Countries with High Ambient Temperatures

In high ambient temperature countries, foam insulation is critical for minimising cooling load. However, there are some unique challenges faced by companies manufacturing foams in high ambient temperature (HAT) conditions. Additional information can be found in the F-TOC 2022 Assessment Report

- Hot temperatures affect raw material storage, product selection, method of application, and can impact foam quality. For example, dry conditions mean that moisture-curing, one-component foams may be challenging or impossible to use
- High temperatures mean that foam blowing agents will expand, increasing the pressure in storage drums alone or in blended polyol systems. Some distributors and manufacturers have cooling warehouses or partially load drums so that there is room for expansion.
- High temperatures may result in more complete foaming and larger cell size, with reduced thermal performance.
- Foam systems have a limited shelf-life that is shortened by high temperatures. Spray foam insulation components have a six-month shelf life, after which the catalyst may begin to degrade which may make the resulting foam more brittle.
- Some manufacturers caution against installing foam systems at temperatures greater than 49°C.

Although many of these challenges have been important in HAT parties and regions during previous transitions, they continue to be important factors in the design of new systems. A literature search by Wang et al. 2022, surmised that high ambient temperatures, in combination with varying volumes of FBA content, resulted in more complete foaming and larger cell size due to increases in the reactivity, polymerization and foaming rate resulting in more microporous structures. Different types of foam blowing agents were not identified to change the impacts of physical properties at high ambient temperatures.

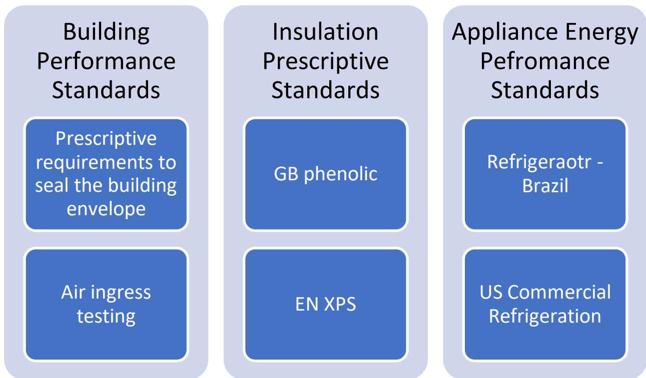
3.4 Maintaining Thermal Performance of Foams During the Foam Blowing Agent Transition

FBA and FBA blend selection is based on a number of factors including cost, balanced by other design features to promote energy efficiency, which is often mandated by regulation. To achieve a good balance of thermal insulation performance and cost, various co-blowing technologies are adopted. Many manufacturers use HFCs or HFO/HCFOs to co-blow with hydrocarbons. It should be noted that hydrocarbons are widely used in domestic refrigeration products with vacuum panels to provide better energy efficiency, but this increases manufacturing costs.

FBAs provide the primary contribution to the thermal performance of polyurethane rigid foam insulation (Heinemann et al., 2000). A change in FBA selection can impact the thermal performance of the foam. Reductions in the use of better thermal performing FBAs to optimise systems for other reasons, such as to reduce cost, could result in an unintended impact to thermal performance. There may be limitations to the adoption of insulation with lower thermal conductivity because of its cost or the availability of FBAs with better thermal performance. In addition, space limitations limit additional layering of insulation and optimization must be based on foam formulation and blowing agent selection, as well as elimination of thermal bridging.

For parties with standards for foam performance, building energy codes, and appliance standards, some transitions have taken longer because of the need to optimise foams to meet these requirements. For parties without these standards, there could be a change in performance that may be unanticipated.

Building codes and standard mandates, insulation performance standards, labelling mandates, and other policies establish requirements to reduce heating and cooling loads in both commercial and residential buildings, and for refrigeration. Investment in decarbonization and infrastructure will drive increased use of insulation including several end-uses for foamed products produced from polymeric MDI. For example, in China, the "Dual Carbon" vision (peaking carbon in 2030 and neutrality in 2060)– has further pushed for energy conservation. China's investment programme includes a range of opportunities for rigid foams and light-weight polyurethane composites in the cold chain, district cooling and heating, high speed rail, new electric vehicles (NEVs), and the construction of temperature-controlled data server centres.



Standards impact design and use of insulation

When mandated, foam and appliance manufacturers must provide the same performance in the finished product, as they select new FBAs. In addition, necessary foam performance is influenced by local market conditions and unique manufacturing conditions.

For example, historically, the importance of energy consumption in the US and Japanese markets led manufacturers to use formulations with higher levels of FBAs to achieve lower thermal conductivities than were required in European markets. The European Union (EU) and North America are currently the leading proponents of building codes to improve energy efficiency in the construction industry, while the global appliance industry continues to develop new more energy-efficient models. Many innovations are on-going to make thermal insulation products that meet the stringent fire standards in residential and commercial buildings.

Since FBAs contribute significantly to the thermal performance of foam insulation, and there are so many options available, a question arises in how building owners, end-users, and perhaps even policymakers can ensure that foam insulation containing low GWP, zero ODP alternatives meet desired thermal performance requirements. Adoption of performance standards for buildings and equipment may be one alternative while another is standards applied specifically to foam products, such as EN 13164, which is the thermal standard for insulation products for buildings for factory made extruded polystyrene foam (XPS) products. Another example is the China National Standard GB/T 20974 for rigid phenolic foam for thermal insulation. Appliance and building performance standards also offer a mechanism for ensuring that efficiency levels are maintained.

Foam insulation used in the cold chain and buildings represent an important contribution to reducing heating and cooling loads and energy consumption. Combining the use of state-of-the-art foams and newer more efficient HVAC systems, higher comfort and better temperature control can be achieved while lowering energy consumption for buildings, logistics process, cold storages, and food conservation in both A5 and non-A5 parties.

Minimum thermal standards for insulation and building energy performance standards can ensure that insulation is optimised throughout the foam blowing agent transition while reducing the need for additional electricity generation.

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4 Energy Efficiency Technologies: Availability and Accessibility

Key Messages

- RACHP and MAC equipment that are at, or below, the global average efficiency levels are still being manufactured and sold posing a problem to the adoption, implementation, and compliance of Minimum Energy Efficiency Performance Standards (MEPS) in many countries
- A 2023 IPCC report confirms that concerted efforts on Energy Efficiency (EE) measures and emissions mitigation measures can reduce costs and produce better results
- The availability of high energy efficiency technology in manufacturing countries does not automatically result in accessibility at the importing countries
- The assembly sector typically waits for a new technology to evolve, and the economies of scale to take place before they adopt. For a faster adoption of new technologies, the assembly sector would benefit from the creation of regional centres of excellence for the demonstration of higher energy-efficiency low-GWP technologies
- Electrical voltage and frequency variation are often overlooked as a barrier to product availability and therefore, accessibility of products worldwide
- Product certification to stated performance and performance standards is one of the most important differentiators in a crowded market where consumers can make trusted choices on what they purchase
- Manufacturers are typically faced with the choice of either buying the EE technology/component or building the internal capacity to develop and manufacture it (make vs. buy). Scale, based on the production volume, and speed, based on the capital recovery period, play a role in deciding the business strategy
- The majority of refrigerants used in new car MAC is mainly HFC-134a (GWP 1430). HFO-1234yf (GWP 3) is used as a substitute by car manufacturers in some regions.
- The thermal management system with heat pump technology has been accepted as an energy-efficient solution for electric vehicles, which require refrigerants compatible with electrically driven compressors and can provide heating and cooling capacity. R-744, HC-290, and other new refrigerant blends are under assessment and gaining renewed attention.
- Cost of new technologies, supply chain issues, and lack of industry collaboration are existing barriers related to the availability and accessibility of low GWP refrigerants in MAC and mobile heat pumps in electric vehicles.
- Upgrading technicians' capacity and improving their awareness on advantages of labelling that could be communicated to their customers helps in achieving the energy efficiency benefits from the policy.

This chapter is responding to the following: Decision XXXIV/3 requests the TEAP to provide "[updates] relating to the availability, accessibility, electrical compatibility, and cost of energy efficient products and equipment containing low- or zero global warming-potential refrigerants in the refrigeration, air-conditioning and heat pump sectors." Updated information is discussed in this chapter.

4.1 Introduction on scale, speed, and solutions for EE transformation

Industries with old, entrenched technologies contribute to the scale of the challenge and the speed at which the transformation to relevant solutions can take place (Wirth, 2023)[15]. RACHP and MAC equipment that are at, or below, the global average efficiency levels are still being manufactured and sold and pose a problem to the adoption of EE in many countries. With the increased demand for equipment, the scale of the problem will grow exponentially. In 2022, there were 3.6 billion cooling appliances in use, the number is estimated to grow to 14 billion in 2050. During this period US $1.2 trillion in power generation investment can be saved with more efficient air conditioners while cutting electricity costs in half (IEA, 2020).

Earlier implementation typically results in greater impact. For example, applying the most stringent MEPS on a global scale in 2015 would achieve 21% savings from the BAU scenario whereas delaying the implementation until 2030 would have only achieved 14% savings from a much higher BAU (Molenbroek et al, 2015). The Kigali Amendment offers an opportunity to simultaneously improve energy efficiency along with refrigerant transition thus reducing the scale of the challenge and increasing the speed of implementation. This solution offers significant co-benefits in energy security, climate mitigation, peak load reduction, along with monetary savings (Shah, 2022; Dreyfus et al, 2020).

The IPCC sixth assessment report (ipcc.ch/report, 2023) lists different opportunities for scaling up climate action and the corresponding mitigation options measuring them in $GtCO_2$-eq/yr. of net emission reduction. This IPCC report suggests that the cost of EE measures are in the order of 0 to 20 USD above reference cost whereas the cost of using emissions reduction based on low GWP refrigerant measures can be up to 100 to 200 USD above reference cost.

Based on the results presented in the IPCC reports, The EEWG concludes that a concerted effort of higher EE and conversion towards lower GWP equipment can result in lower implementation cost (please refer to chapter 7 for more details) and yield better results than if EE and HFC conversion where to proceed independently.

4.2 Update on availability of locally manufactured high EE units in A5 parties

The EETF report on Decision XXXIII/5 defined "availability" as the ability of the industry to manufacture products with new technologies of lower-GWP refrigerants and higher efficiency. Availability depends on the ability of the industry in a country to absorb new technologies and is affected by factors such as the technical capabilities needed to implement the technology, scalability of operations, and the ability to remove technological barriers such as intellectual property rights and patents.

Some A5 parties do not only produce for their own market needs but also export to many parts of the world including to non-A5 parties. China, India, Thailand, and Mexico are some examples. The manufacturing landscape includes indigenous companies as well as multi-nationals. The availability of high energy efficiency technology in such countries does not however automatically result in accessibility at the importing countries as this will be dependent on the situation and the market demand of the destination country. For example, manufacturing A5 parties with high EE standards run multiple production models to meet the

[15] The concept of Scale, Speed, and Solution was described in an interview with Mike Wirth by Fareed Zakaria on March 5th, 2023. Reference can also be made to a book by John Doerr (Author) and Ryan Panchadsaram (Contributor) "*Speed & Scale: An Action for Solving Our Climate Crisis Now*"

demands of their internal markets and those of countries which demand lower energy efficiency products due to absence of EE regulations thus losing the effect of the economies of scale to produce higher EE products on a global scale. Conversely, the absence of technical capability and safety standards in some importing countries might drive exporters to abstain from providing their available high-EE, low-GWP products to those countries.

4.3 Assembly sector

Small- and Medium-sized Enterprises (SMEs) play a pivotal role in the development of the commercial and small industrial refrigeration sector since most equipment is bespoke equipment designed for a specific application and assembled mainly on site or in small workshops. SMEs in the assembly/installer sub-sector were considered as part of the servicing sector and did not always benefit from adequate support under the different stages of the HCFC Phaseout Management Plan (HPMP) under the Multilateral Fund (MLF), where funding is measured by the weight of refrigerant phased out. As a result, the uptake of energy-efficient technologies in the assembly sector has been slow and irregular. SMEs may need more time to make the transitions cost-effective and minimise market disruption.

The assembly sector typically waits for new technology to evolve, and the economies of scale to be in place prior to adopting new technology. For a faster adoption of new technologies, the assembly sector could benefit from programs such as regional centres of excellence for the demonstration of higher energy-efficiency low-GWP technologies, the provision of robust and constant capacity building, and the harmonisation of technology offerings across regions or economic communities. The transition to these technologies can be enhanced by other support mechanisms like demonstration or end-user projects and awareness raising activities.

4.4 Factors affecting accessibility

4.4.1 Challenges with electrical compatibility

Electrical voltage and frequency are often overlooked as a barrier[16] to product availability and therefore, accessibility of products worldwide. While in residential and light commercial applications, there are typically two voltages and frequencies (110 or 220 V and 50 or 60 Hz), the number of voltages for larger commercial and industrial applications is significantly more (worldstandards.eu/electricity, 2020). Voltages in RACHP applications can range from 115 to 600 V depending on the country and region. This leads to manufacturers of equipment making decisions on new product development and production that prioritizes one voltage and frequency over another. Voltage differences lead to motor (and associated safety devices) differences which can impose cost and development time constraints. Power fluctuations can damage sensitive electronic controls and reduce equipment lifetime.

4.4.2 Pull process created by certified labels[17]

Product certification to stated performance and performance standards is one of the most important differentiators in a crowded market where consumers need to be able to make trusted choices on what they purchase. When countries have minimum performance standards for their equipment, the labelling of performance should be from an independent testing laboratory rather than the manufacturer of the equipment, as is often the case.

[16] More on barriers in Chapter 7

[17] Reference to Chapter 6 on Measurements Verification and Testing Tools

Independent certification can verify that the performance is indeed as stated by the manufacturer(see Chapter 5). Several countries already have introduced MEPS and labelling programmes and are regularly upgrading them. Mandatory and voluntary certification programmes may coexist in some cases. For example, in the European Union a mandatory energy label database coexists with voluntary commercial certification programmes. The customer can find data in an EU central database (called EPREL : Product database (europa.eu)) which is mandatory for all products put on the EU market that are subject to energy labelling requirements. In addition, manufactures may choose to be part of voluntary commercial certification programmes such as Eurovent, Keymark or others. Another example is the certification offered by AHRI[18], which is a voluntary program where the manufacturer's equipment is tested in an independent laboratory to confirm performance (ahrinet.org/certification, 2023). Guidance on international best practice which includes many further examples, are included in "Energy Labelling Guidance for Lighting and Appliances", (UNEP, 2021) available at (https://united4efficiency.org/resources/energy-labelling-guidance-for-lighting-and-appliances/)When minimum performance standards are backed up by independent certification, this improves consumer confidence and increases adoption.

4.4.3 Costs

Manufacturers are typically faced with the choice of either buying the EE technology/component or building the internal capacity to develop and manufacture it (make vs. buy). Scale, based on the production volume, and speed, based on the capital recovery period, plays a role in deciding the business strategy. Another point to consider is that the break-even point can be different for different designs of the same component. A case-in-point is microchannel heat exchanger versus small diameter fin-and-tube design.

Funding provided by the MLF for refrigerant transition has covered basic conversions, but not efficiency improvements. EE is a game changer where costs for efficiency enhancement are additional to the incremental costs already covered by funding (see Chapter 9 for potential approaches for estimating additional costs for EE funding). Decision 90/50 of the Executive Committee asks the MLF Secretariat to develop criteria for pilot projects to maintain and/or enhance energy efficiency of replacement technologies and equipment in the context of the HFC phase-down. Financial incentives, along with regulatory drivers, are two of the factors in speeding up the process of transition to higher efficiency products and equipment. Market assessments tools can play an important role in providing insights on the potential financial impacts and economic benefits (UNEP, 2021).

4.5 Energy efficiency in mobile air-conditioning and heat pump units

4.5.1 Current use of technologies and the changing trends

Mobile air-conditioning (MAC) is the system that creates a more comfortable and pleasant environment for the occupants in different vehicles such as cars, trucks, buses, and trains. Currently, the majority use of refrigerants in MAC is high GWP refrigerants, mainly HFC-134a (GWP 1430) used in cars and trucks, and R-407C (GWP 1774) used in buses and trains. Car manufacturers in different regions are now using HFO-1234yf to replace the HFC-134a in MAC. In the EU, passenger car air conditioning has had a mandatory GWP limit of 150 in all new cars since 2017 and manufacturers mainly use HFO-1234yf with some car manufacturers also adopting R-744 (CO_2) in particular for heat pump application in the

[18] Air Conditioning, Heating, and Refrigeration Institute www.ahrinet.org

electric car sector. In China, and consistent with its carbon neutral policy, the use of HFC-134a in MAC is gradually being phased-out.

The rapid development of electric vehicles has given us the opportunity to review the cooling technology and refrigerant gases. The thermal management system with heat pump technology has been accepted as an energy-efficient solution for electric vehicles. The mobile heat pump can provide space cooling/heating and battery cooling/heating with significantly high energy performance. Electric vehicles require an electrically driven compressor vs. a mechanically driven one in a conventional vehicle and car manufacturers are shifting towards refrigerants that are compatible and can provide heating and cooling capacity. At present, the most widely used refrigerant in mobile heat pumps in electric vehicles is HFC-134a but R-744 systems have been used in some high-end models of electric vehicles because of their powerful heating capacity.

4.5.2 Availability and accessibility to low GWP refrigerants in electric vehicles MAC

Cost of new technologies, supply chain issues, and lack of industry collaboration are existing barriers related to the availability and accessibility of low GWP refrigerants in MAC and mobile heat pumps in electric vehicles. Local car manufacturers have had to redesign the refrigeration system and reconstruct the supply chains to accommodate the use of R-744. Industrial collaboration between automakers, refrigerant manufacturers, and suppliers is a crucial factor in accelerating the development and adoption of new refrigerants and technologies. For the end user, the cost is the most significant barrier to accepting higher EE MAC and heat pumps in electric vehicles with low GWP refrigerants. In many A5 parties, the introduction of electric vehicles will be slow, with a lack of charging infrastructure, and lack of regulations. Providing appropriate subsidies may be effective for a faster adoption of low GWP refrigerant in MAC and mobile heat pumps. For example, in China, with governmental subsidies, the sale of electric vehicles has exceeded 5 million, and the proportion of thermal management systems with heat pump technology in electric vehicles has increased to 38% by 2022 (globenewswire.com/en/news-release, 2022) .

4.6 Role of Technicians in encouraging Energy Efficiency

One of the key parameters for the effective implementation of more stringent MEPS and labelling is to ensure that the best available technology grows in parallel with the technicians' readiness to adopt these technologies. Upgrading technicians' knowledge and training, as well as improving their awareness on the advantages of labelling that can be communicated to their customers, helps in achieving the energy efficiency benefits from the policy. In Indonesia, funding provided by the MLF covered the certification of more than 20% of technicians, mostly in the informal sector.

Natural Resources Canada has found that improving operational practices and implementing energy-efficient retrofits can reduce energy consumption in commercial and institutional buildings by up to 20% (Natural Resources Canada, 2016). Certification improves operational practices and facilitates the implementation of energy-efficiency retrofits.

4.7 An integrated approach to energy systems: using synergies between heating & cooling and waste heat recovery

Heating and cooling represent half of the world's total final energy consumption of which roughly 90% is still based on fossil fuels (REN21, 2022). To stay within the 1.5°C limit as set out by the Paris Agreement, decarbonising heating and cooling is therefore a top priority and requires going beyond a merely product-based approach. Rather, it needs to be seen in the context of an integrated energy system where financial challenges are systematically being considered.

Doubling the share of renewables in electricity production to reach net zero by 2030 (IEA, 2022) and catering for new demand requires enormous capital investments in energy production and distribution. This has to be matched by increased focus on the demand side to keep the financial burden and its implications for society as low as possible. The impact of increasing product efficiency has already been described in previous reports. However, focussing on product efficiency alone could eventually lead to a situation, where the large incremental cost of super-efficient products could prevent their broad uptake in the market.

Taking an integrated approach to the energy system offers massive opportunities to reduce the need for energy generation, cost and emissions and to increase the resilience of the energy system. In Europe alone waste heat amounts to 2,860 TWh/yr, almost corresponding to the EU's total energy demand for heat and hot water in residential and service sector buildings (Danfoss, 2023). Much of this excess heat could instead be captured and reused. Looking specifically at cooling, critical cooling facilities that require both cooling and heating, such as supermarkets, datacentres or hospitals, are a prime example where an integrated approach needs to be considered. Supermarkets, for example, typically consume 3 to 4% of the annual electricity consumption in industrialised countries (cordis.europa.eu , 2019). Cooling equipment in supermarkets generates excess heat that can be reused either on site (e.g., to heat water) or fed into a district energy grid. The same goes for datacentres. Conservative estimates from 2020 counted 1269 datacentres across EU27 + UK, producing a total of 95 TWh of accessible excess heat yearly (Persson, 2020).

Besides reducing the need to generate heat or cold, using waste heat – or waste cold will also help balance the grid by providing additional and stable sources of energy which is increasingly important as the share of renewable energies grows.

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5 Measurement Verification and Enforcement Tools

Key Messages

- Energy test methods are central to appliance standards and labelling programs to validate efficiency claims by manufacturers before products enter markets and to ensure that products continue to meet program requirements and identify non-compliant products once on the market.
- Energy test methods for cooling appliances have been developed by international standards organizations like the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO) and other regional and national standard bodies. Several international and national energy test methods are in use in different regions for the most common residential cooling equipment – domestic refrigerators and room air conditioners.
- Test method attributes can and should be evaluated on an ongoing basis as the products and technologies they are intended to evaluate continue to evolve.
- Appliance energy and performance testing requires qualified test facilities where the laboratory, test equipment, personnel training, and operating procedures are all appropriate for the product being tested. Testing is one of the most resource-intensive and time-consuming aspects of an energy efficiency program but there are approaches to conduct effective testing with limited resources.
- Certifying and enforcing compliance is critical to safeguard climate and cost savings from energy efficiency programs. Robust, cost-effective, and well-rounded compliance processes protect markets from inefficient and low-quality products. Common approaches for conformity assessment adopted by governments around the world include supplier's declaration of conformity and third-party testing and certification by independent parties or government agencies.
- Product Registration Systems are effective tools for tracking compliance. They document tested and certified products on the market and can support market surveillance and enforcement efforts.

This chapter is responding to the following: Decision XXXIV/3 requests the TEAP to provide "[information] on testing equipment and procedures for validation of energy efficiency claims to enforce minimum energy efficiency standards and labels, and information on voluntary labelling programmes."

5.1 Test methods and trends in performance testing

Test methods (sometimes referred to as a test procedure or test standard) describe a means of measuring the performance of a product. Energy test methods are central to appliance standards and labelling programs to validate efficiency claims by manufacturers before products enter markets (initial verification of policy compliance), and to ensure that products continue to meet programme requirements and identify non-compliant products once on the market. UNEP (2021), "Ensuring Compliance with MEPS and Energy Labels" available at https://united4efficiency.org/resources/ensuring-compliance-with-meps-and-energy-labels/". Salvador and Honduras are examples of A5 parties are making progress with air conditioning. https://united4efficiency.org/el-salvador-and-honduras-advance-energy-efficient-and-climate-friendly-air-conditioners/

Good test methods achieve a reasonable balance between accuracy (results are within an expected tolerance), precision (results are repeatable and reproducible), affordability (testing costs do not place unnecessary burden), coverage (test is applicable to a wide range of products), representativeness (test is representative of end-user experience) and resilience (test methods should be difficult to circumvent).

Energy test methods for cooling appliances have been developed by international standards organizations like the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO) and other regional and national standard bodies. Below is a summary of test methods for the most common residential cooling equipment – domestic refrigerators and room air conditioners.

Domestic refrigerators had at least five international or national energy test methods in use in different regions. The IEC test method released in 2015 has been adopted (or is in the process of being adopted) by several major economies such as Japan, China, Australia/NZ and Europe. The US test method also underwent a revision in 2012, to more closely align with the new IEC test method during its development. Table 5-1 illustrates some of the key differences among some of the major test methods for refrigerators and freezers.

Table 5-1. Comparison of international test methods for domestic refrigerators

Test Method	IEC	US DOE	AS/NZS	ISO/IEC	JIS
Reference	IEC 62552-1, 2, 3	10CFR430 Appendix A&B	AS/NZS 4474.1	ISO 15502:2005 IEC 62552:2007	JIS C 9801 (2006)
Date	2015	Updated in 2012	2007 (superseded)	2005/2007 (withdrawn)	Withdrawn in 2015
Adopted in (full or partially)	Japan, China, Australia/NZ and EU	USA	Australia/New Zealand, India (uses a variant)	Brazil, SE Asia, Middle East, South America, South Africa, and others	Japan
Ambient Air Temperature	32°C and 16°C for energy ± 0.5°C	90 °F (32.2°C)	32°C ± 0.5°C	25°C ± 0.5°C (temperate & sub-tropical) 32°C ± 0.5°C (tropical)	15°C & 30°C
Relative Humidity	Max 75%	Not specified	Not specified	Max 75%	30°C: 75 ± 5 % 15°C: 55 ± 5 %
Fresh Food Compartment Temperature	4°C	39°F (3.9°C)	3°C	5°C	4°C
Freezer Compartment Temperature	-18°C	0°F (-17.8°C)	-15°C	-18°C	-18°C
Loading	No freezer loading for energy test	No freezer loading for energy test	No freezer loading for energy test	Loaded freezers (touching the walls)	Natural Convection: Yes for freezers; Forced Circulation: Yes for fresh food and freezer compartment
Door Opening	No (single door opening to insert water load for load processing test)	No	No	No	Natural convection system: No; Frost-free systems: Yes (35-times/day at 8 min intervals for fresh food compartment and 8 times/day at 40 min intervals for freezer compartment)
Volume & Measurement Methodology	WYSIWIG volume using ANSI/AHAM methodology	WYSIWIG volume using ANSI/AHAM methodology	Gross volume, using adapted ISO methodology	Storage volume, using ISO methodology	Storage volume, using ISO methodology

Test Method	IEC	US DOE	AS/NZS	ISO/IEC	JIS
Notes	Separate storage test with loaded freezer compartments. Wide range of other performance tests.	Updated in 2012 to more closely align with many new IEC parameters	Will be fully replaced by new IEC by 2021 (transition from 2019). Separate storage test with loaded freezer compartments	ISO15502 was a merging of 4 separate refrigerator and freezer standards. This product was transferred from ISO to IEC in 2007 and ISO15502 was republished as IEC62552 (identical)	Replaced by new IEC in 2015

Room air conditioners cooling capacity and efficiency are tested under ISO 5151:2017.. In addition, ISO 16358:2013 has been adopted by many countries as it allows for fixed speed and inverter air conditioners to be rated over the course of the year, and under the same metric as the ISO 5151 test points. The ISO 16358:2013 calculation method is designed to estimate the energy performance of inverter air conditioners and has been crucial in creating a global market shift towards more efficient inverter air conditioners.

Table 5-2. Comparison of international test methods and metrics used for room air conditioners

ECONOMY	NATIONAL TESTING STANDARD	REFERENCE TEST STANDARD	METRIC USED
AUSTRALIA	AS/NZS: 3823-2013	ISO 5151	AEER*
CHINA	Fixed speed: GB/T 7725-2004 Variable speed: GB/T 7725-2004, GBT 17758-2010	ISO 5151	EER for fixed speed SEER** for variable speed
EU	EN 14825	ISO 5151	EU SEER
INDIA	Fixed speed: IS 1391-1992 with all amendments Variable speed: 16358-1:2013	ISO 5151	Indian SEER
JAPAN	JIS B 8616:2015 for commercial ACs JIS C 9612: 2013 for Room ACs	ISO 5151, ISO 16358	Annual Performance Factor (APF)
REPUBLIC OF KOREA	KS C 9306:2011	ISO 5151, ISO 16358	CSPF
US	10 CFR 430, Subpart B, Appendix F	Consistent with ASHRAE Standard 16/69	US SEER
VIET NAM	TCVN 7830:2015	ISO 5151, ISO 16358	CSPF

Improving test methods to reflect real-life efficiency

Test method attributes can and should be evaluated on an ongoing basis as the products and technologies they are intended to evaluate continue to evolve. In Europe, for example, the European Commission's Smart Testing of Energy Products (STEP) project identified necessary improvements to the test standards for freezers / refrigerator-freezers to help ensure the ongoing trust of consumers in the Ecodesign and Energy Labelling policy measures. The STEP project identified specific improvements to the test methods to pass along to CENELEC, the European standardization body responsible for European Harmonised Test Standards. The improvements were recommended to address the following four problems:

- A lack of representativeness of test standards – more relevant test methods could result in more accurate quantification of performance, more accurate labelling and, potentially, more accurate energy savings potential assessment;
- A lack of suitability of test standards – certain characteristics of product performance are not measured effectively or simply do not have a test method;
- An ambiguity of test standards – existing standards are not precise enough or less adequate given how product technologies have changed; and
- A lack of user information – product modes can vary and the impact on energy consumption is not properly or clearly communicated.

In Brazil, the Brazilian National Institute of Metrology, Quality, and Technology (Inmetro) documented a case study where some manufacturers achieved a higher cooling seasonal performance factor (CSPF) by substantially reducing their product's efficiency during one of the tests used in the calculation of that metric. This represents a loophole in the ISO 16358:2013 calculation method (which is under revision) as it allows some manufacturers to achieve a better CSPF with a less efficient product. The relevant ISO working group has been alerted of this circumvention. The case study documents how policymakers can address this issue in a cost-effective manner in order to ensure that their energy efficiency policies are indeed promoting the most efficient products.

5.2 Test laboratories

Appliance energy and performance testing requires qualified test facilities where the laboratory, test equipment, personnel training, and operating procedures are all appropriate for the product being tested. There are three types of test laboratories: independent, manufacturer-operated, and government-operated facilities. The choice of test laboratory is often dictated by the nature of the policy or program for which the testing is required (voluntary or mandatory), the resources available to the program (both time and money), and the availability of accredited test facilities in the countries sourcing the appliances and the country of their destination.

A list of test laboratories for room air conditioners and refrigerators can be found at: https://www.clasp.ngo/research/all/test-labs-database/

Testing costs can vary dramatically based upon the product type and test method, the number of products being tested (e.g., with volume discounts), the selected laboratory, and other factors. Testing is one of the most resource-intensive and time-consuming aspects of an energy efficiency program but there are approaches to conduct effective testing with limited resources. Indicative costs of setting up and operating a testing laboratory for air conditioners and refrigerators are shown in Figure 5-1.

Some options for low-cost, high-quality testing include:

- Pooling resources with neighbouring countries to establish a regionally funded and managed test laboratory;
- Relying on existing test facilities from the country of origin if most units of an appliance are imported;
- Cooperating with existing test laboratories in the private sector or at technical universities.

Figure 5-1. Costs of setting up and operating a testing laboratory by product type (Source: Super-Efficient Appliance Deployment (SEAD) Initiative, Global Appliance Testing Costs Catalogue.)

5.3 Certification of compliance

Certifying and enforcing compliance is critical to safeguard climate and cost savings from energy efficiency programs, by ensuring products meet standards and labelling requirements and that they live up to their energy efficiency claims. Robust, cost-effective, and well-rounded compliance processes protect markets from inefficient and low-quality products.

Conformity assessment serves to verify policy compliance. Before products are allowed onto the market, they should demonstrate that they comply with national or regional appliance standards and labelling policy requirements. After products are certified as compliant, they can then be registered in a national or regional product registration system.

Common approaches for conformity assessment adopted by governments around the world include: i) a supplier's declaration of conformity (where the burden of proof of compliance lies with the product supplier), and ii) third party testing and certification by independent parties or government agencies (where a product is tested at an independent and accredited test laboratory to obtain unbiased results).

The approach selected depends on market conditions. A robust and effective conformity assessment approach can significantly increase compliance levels among products entering the market, thereby reducing the need for market surveillance. A summary of the main characteristics of approaches for conformity assessment is shown in Figure 5-2.

	Supplier's Declaration of Conformity (SDoC)	Third Party Testing & Certification
Who	Manufacturer or importer	Independent or accredited body
What	Provides Supplier's Declaration of Conformity	Provides impartial test report and certification
How	Supplier declares products have been tested and meet program requirements	Products are tested by accredited laboratories and certified by accredited body
When	• Prerequisite for market entry • Risk of non-compliance is low • Well resourced market surveillance in place • Self-declaration is sufficient	• Prerequisite for market entry and/or certification programs • Risk associated with non-compliance is high • Limited market surveillance resources • Independent assessment is necessary
Benefit	• Quicker to place products on individual markets • More flexible for suppliers	• Provides greater confidence and trust • Quicker to place products on multiple markets • Cost and time savings for regulators

Figure 5-2. Approaches for conformity assessment Source: CLASP Compliance Toolkit/Conformity Assessment[19], Also see: United for Efficiency Compliance with MEPS and Energy Labels.[20]

5.4 Tools for tracking compliance

Product Registration Systems[21] or databases document tested and certified products on the market and can support cost-effective market surveillance and enforcement efforts. They can take a variety of forms, from basic lists of compliant or certified products used by regulators to comprehensive searchable databases that also accessible by consumers online or in smartphone applications. Mandatory or voluntary registration systems are in place for products with efficiency policies or energy labelling in Australia, Canada, China, India, New Zealand, Singapore, Thailand, and the US, among others.

[19] https://www.clasp.ngo/tools/clasp-compliance-toolkit/

[20] https://united4efficiency.org/resources/ensuring-compliance-with-meps-and-energy-labels/

[21] (https://united4efficiency.org/product-registration-systems/)

6 Barriers to Energy Efficiency

Key Message

- The dumping of low energy efficient products in low-income countries coupled with the lack of knowledge and higher cost of purchase of energy efficient products contribute greatly to their low uptake.
- Barriers to the introduction of EE RACHP equipment can be overcome by:
    - education and consumer awareness campaigns,
    - reducing the investment risk through incentive schemes such as rebates and innovative financial mechanisms for the consumer,
    - stringent regulations and enforcement such as bans on the import of used equipment and products; the development of regulatory frameworks including MEPS for new and used equipment; investment in testing to provide consistency and clarity for consumers and businesses,
    - upgrading/ developing of training materials/ programs for RACHP technicians in vocational institutions and national associations, to incorporate the specialised knowledge and skills needed to install and maintain EE refrigeration systems.

This chapter is responding to the following: Decision XXXIV/3, requests the TEAP to provide "[information] on barriers to consumer and business acceptance of the adoption of more energy-efficient products and equipment containing low- or zero global warming-potential refrigerants, including barriers related to electrical compatibility of such products and equipment, and possible solutions for sustainable transition to such products and equipment."

In its report responding to previous Decision XXXI/7, the TEAP Energy Efficiency Task Force 2021 reported on the accessibility to high-efficiency Room Air Conditioning (Room AC) and Self-Contained Commercial Refrigeration (SCCRE) with lower-GWP refrigerants as being influenced by multiple factors, including supply chain, regulatory environment, affordability and return on investment and servicing, incorporating the availability of spare parts and refrigerants, trained technicians, electricity quality and reliability. Additionally, it was stated that in countries with lower scale of manufacturing and low presence of multinationals, accessibility to new technology will be a challenge. The following sections provide additional insights to barriers related to energy efficiency in response to the current decision.

6.1 Lack of consumer awareness

There is a lack of knowledge on the benefits of energy efficient products, and the negative impact of high-GWP refrigerants on the environment. Consumers who understand those benefits, and how energy savings accrue over time, might be more likely to purchase more efficient equipment, in spite of higher upfront cost. In a survey conducted in Uganda in 2019 on the use of refrigeration equipment in the retail sector, 83% of the respondents saved energy by switching off the equipment intermittently, which could impact the operation and durability. End-users were also unaware of the refrigerant in use in their refrigeration equipment and this responsibility was left to the technicians. There is a lack of targeted information on energy efficient products, and although energy labels are being applied, some are incorrect, and most consumers do not know what they mean. This information gap could lead to reluctance to invest in new technologies.

This barrier may be overcome through education and consumer awareness campaigns. Education and awareness campaigns conducted in local dialect by governments, utilities, and manufactures have proven to be effective in some countries. For example, in Uganda, animations and short video and audio clips have been used to communicate about LED bulb energy savings even to the grassroots. In Ghana, fliers, jingles, and local drama series are used to educate the public about energy efficient products.

6.2 Higher cost of EE products

Energy-efficient products and equipment with low or zero GWP refrigerants are often more expensive to purchase compared to the conventional products. Businesses in low-income countries do not have enough capital and collateral to import energy efficient products and equipment with low- or zero global- warming potential refrigerants. For local manufacturers, there are higher capital and manufacturing costs due to safety measures for flammable refrigerants, higher component costs or R&D etc as described in previous EETF reports. For example, the incremental capital cost for refrigerant conversion and energy efficiency upgrades conducted in 5 different manufacturing companies ranged between USD 0.2 to 2.0 million and USD 0.15 to 4.3 million respectively, based on the production volume as shown in the table below. Although the MLF funds incremental cost for refrigerant conversion, it has been suggested by some implementing agencies and beneficiaries that the funds are inadequate to include necessary improvements in energy efficiency (for example conversion to variable speed compressors). Consequently, this incremental cost coupled with import taxes is then transferred to the final consumer, making the final higher efficiency product more expensive.

Table 6-1: Incremental capital and operating cost for refrigerant conversion and energy efficiency upgrade.[22]

MDI	0.814	0.776	0.566	0.534	0.52	0.212
Production volume	140k	90k	150k	30k	300k	8.5k
ICC_{RC}	$1,982k	$593k	$870k	$291k	$265k	$208k
ICC_{EE}	$4.3M	$101k	$1M to $2.7M + $500k per base model	<$50k per base model	$100k + <$50k per base model	
IOC_{RC}	$(339k)	NA	$266k	$195	$4,511k	$53k
IOC_{EE}	$2M	Up to $2M	Up to $4.6M	Up to $2M	Up to $6M	NA

MDI – Manufacturer Development Index, ICC_{RC} – Incremental capital cost for refrigerant conversion, ICC_{EE} – Incremental capital cost for energy efficiency upgrade, IOC_{RC} – Incremental operating cost for refrigerant conversion, IOC_{EE} – Incremental operating cost for energy efficiency upgrade

[22] Extract from UNIDO guidance report on net benefits and costs for different energy efficient refrigeration design options

This barrier may be overcome by reducing the investment risk by government policies on incentive schemes such as rebates and innovative financial mechanisms for the consumer.

Governments can provide tax incentives for EE equipment to lower their cost and impose higher taxes on the low efficiency equipment and products. In addition, government purchasing power can attract top performing products into the market at economies of scale through Green Public Procurement / Sustainable Public Procurement approaches. This will enable EE equipment to compete favourably on the market. Labelling schemes and product registries tracking equipment energy efficiency and refrigerant performance would enable the development of policies that incentivise higher-efficiency and lower-GWP products and impose a fee on the least efficient and highest-GWP products.

In Ghana, the government introduced a rebate scheme between 2012 and 2015 where end users would return used inefficient appliances for a coupon to purchase new appliances. The project improved ODS management, reduced household demand and expenditure on energy, and increased awareness of the energy efficiency benefits for the end-users.

Innovative financial mechanisms such as the ECOFRIDGES Green on-wage in Ghana[23] and on-bill financing Senegal[24], support consumers to purchase energy efficient refrigerators and ACs by a partner bank by paying the upfront cost, with the consumer paying back over 12 months at zero percent interest. The "Coolease"[25] financial mechanism in Rwanda involves a finance leasing agreement between the financial institution and client in which the cooling system is either owned by the financial institution or taken as collateral. These initiatives reduce the cost burden on the consumer and de-risks the investment for businesses.

6.3 Dumping of inefficient equipment

In developing countries, most consumers are driven by the purchase price of the appliances and not the lifetime cost. (see Section 5.2.8 "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") A "race to the bottom" takes place in some markets, where low-efficiency new equipment and second-hand equipment flood the markets, effectively crowds out affordable higher-efficiency equipment from being made available (see TEAP EETF 2022). As a result, many developing countries have become dumping grounds for low-efficiency equipment at lower prices. In Ghana from 2004 – 2014, about 75% of the refrigerators imported were second- hand and average refrigerator energy consumption was more than four times the average in Europe (see TEAP EETF 2020 Case Study 2.2). Although a ban on the import of second-hand appliances was imposed in 2008 with full enforcement in 2013, this equipment is still available on the market.[26] This applies for most low-income countries especially in Africa.

This barrier may be overcome through stringent regulations and enforcement such as bans on the import of used equipment and products; the development of regulatory frameworks including MEPS for new and used equipment; investment in testing as detailed

[23] https://energy-base.org/news/ecofridges-go-just-launched-in-ghana/

[24] https://energy-base.org/projects/ecofridges-initiative-in-west-africa/

[25] https://energy-base.org/projects/r-cool-with-coolease-in-rwanda/

[26] https://www.gbcghanaonline.com/general/ghana-not-a-dumping-ground-for-substandard-electrical-appliances-energy-commission/2023/

in sections 3.1 and 3.2 (consistent standardisation would provide clarity for consumers and businesses).

The prevention of the export of inefficient or obsolete new or second-hand equipment at end-of-life, by extended producer responsibility programmes that don't export recycling and waste burdens to vulnerable countries, is an important complement to address these practices that create market barriers to access and export environmental pollution and economic harm.

6.4 The mismatch of the interests of the electricity supply and demand side

The electricity supply industry is usually private sector and profit driven and has easier access to finance to build more power stations and sell more electricity. On the demand side, the consumers have limited disposable income and opt to purchase the cheapest and least efficient equipment with greatest energy consumption. This is a perverse incentive where inefficient RACHP equipment makes energy companies richer, consumers poorer, and which exacerbates climate impact. How can efficient RACHP equipment be made available to more people without making climate change worse?

This barrier can be overcome by maximising synergy through parallel regulation of the electricity supply industry to incentivise energy efficiency, for example through utility obligation schemes (see TEAP EETF 2022), alongside decarbonization of electricity generation through adoption of renewables rather than fossil fuelled power stations.

6.5 Specialised infrastructure and training to support energy efficient appliances

- EE RACHP equipment requires specialised qualified technicians for installation and maintenance.
- Flammable refrigerants require discipline and training for their safe handling
- Some energy efficient RACHP systems require specific voltage, frequency, or wiring configurations that are not compatible with the existing infrastructure.
- Achieving and maintaining the energy performance equipment requires proper training on installation and maintenance
- Finding qualified technicians to install and maintain the system could be a challenge for businesses.

The barriers can be overcome by:

Upgrading/ developing of training materials/ programs for RACHP technicians in vocational institutions and national associations to incorporate the specialised knowledge and skills needed to install and maintain EE refrigeration systems. There are excellent online resources including the refrigerants drivers license, and the energy efficiency literacy course.[27]

Financial incentives to businesses and upgrading/ developing of training materials/ programs for RACHP technicians in vocational institutions and national associations to incorporate the specialised knowledge and skills needed to install and maintain EE refrigeration systems

Financial incentives and subsidies to support the installation of new electrical infrastructure. Collaboration with RACHP contractors and consultants to determine the upgrades needed to

[27] https://www.ashrae.org/professional-development/ashrae-unep-portal/unep-login-energy-efficiency-literacy-for-air-conditioning-and-refrigeration-systems-si-3-5-pdhs.

support new EE equipment and products which will in turn help businesses plan for investment and minimise any disruptions in their operations.

An EU funded study has found that training employees in energy-saving methods significantly enhances workplace energy savings in the food and beverage industry. A pilot project in 15 companies provided training to employees to improve energy management and energy-saving behaviour. The project achieved some 490 measures of energy efficiency saving 554 gigawatts-hr (GWh) per hour a year in the pilot companies – almost five times higher than the project goal of 106 GWh per hour in primary energy savings. In addition, and according to project estimates, around 13,500 tonnes of carbon emissions a year would have been avoided by the pilot companies implementing the project training.[28]

[28] https://cordis.europa.eu/article/id/428638-training-employees-improves-workplace-energy-savings.

7 Potential Benefits of Energy-Efficient RACHP, Including Climate Benefits and Costs, while Phasing Down HFCs

Key Messages

- Modelling shows significant potential for energy savings and reductions in peak power. By 2050, the difference in electricity use between "No efficiency gain" and "High efficiency gain" scenarios could be nearly 10,000 TWh per year. The High efficiency gain scenario leads to capital investment savings of USD 2 to 3 trillion by reducing the need to build new power station between now and 2050.
- The residential and commercial sectors dominate the use of electricity for cooling, representing around 44% and 42% of total consumption, respectively.
- Comfort cooling represents around 60% of electricity use, with refrigeration representing the remaining 40%.
- Reduction in the indirect energy related CO2 emissions from RACHP systems will be driven by efforts to reduce cooling demand (e.g., through better building design), improved equipment efficiency and improved operation and maintenance. The decarbonisation of the electricity supply is also a crucial factor.
- In 2023, indirect emissions represent around 75% of RACHP GHG emissions, with direct HFC emissions representing the remaining 25%. Both direct and indirect emissions can be substantially reduced by 2050.
- The cost impact of energy saving measures need to be evaluated on a project-by-project basis as the cost effectiveness is influenced by a range of project-specific technical factors and also by the local conditions (e.g., cost of electricity and grid carbon factor).

This chapter is responding to the following: Decision XXXIV/3 requests the TEAP to provide an "[analysis] of the potential benefits of introducing more energy-efficient refrigeration, air-conditioning and heat pump equipment, including costs and related climate benefits while phasing down HFCs."

7.1 Modelling reviews in previous EE task force reports

Previous TEAP reports have included reviews of different modelling tools that can provide analysis of the environmental benefits of HFC phase-down and of improved RACHP energy efficiency. The 2022 TEAP EE Task Force Report provided a number of useful insights from the modelling:

a) Combining HFC mitigation with energy efficiency would lead to substantial reductions in cumulative GHG emissions between now and 2050. Further synergy between EE and electricity generation decarbonisation makes a vital contribution to reduced emissions. Countries with high electricity generation carbon emission factors should consider, reducing RACHP energy use as a key priority. For countries with low generation carbon factors, a greater focus on reducing HFC emissions is more beneficial.
b) The avoided fossil fuel emissions using electric 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).

c) 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.
d) Actions taken to conserve refrigerants through regular leak tests and improved maintenance, with recovery at end-of-life would significantly reduce direct emissions in the short and long term.
e) Venting HFC refrigerants to atmosphere during maintenance or at equipment end-of-life is highly undesirable. Technicians should be enabled to collect high GWP refrigerants from equipment at end of life, and suitable infrastructure has to be available for re-processing.

7.2 New modelling of cooling at regional and global levels

Since the 2022 TEAP EE Task Force report, UNEP has supported the further development of the HFC Outlook modelling tool, to create a Global Model of RACHP GHG emissions, including both direct refrigerant emissions and indirect energy emissions. UNEP also completed in 2022 an update to its Country Savings Assessments on the impacts of MEPS and labels for RAC for over 150 countries. This is a relatively simple review of the impact of completed projects for adopting MEPS for individual products such as refrigerators.[29]

In this section, some preliminary outputs from the Global HFC Outlook model are presented. It must be stressed that outputs from this model are still being peer reviewed, hence it is likely that the data presented here will be updated later in 2023. It should be noted that the analysis presented in this section only addresses the indirect energy-related impact of refrigeration and air-conditioning. The current analysis does not include the significant decarbonisation benefits of heat pumps. A heat pump analysis will be available later in 2023.

7.2.1 Regional structure of the HFC Outlook global model

The new model consists of 14 Regional sub-models that are aggregated to create the Global Model. The regional models keep the different Kigali Amendment groups separate. Figure 7-1 shows the structure of regional sub-models. There are 8 Article 5 Group 1 regions, 2 Article 5 Group 2 regions and 4 non-Article 5 regions. Outputs from the model are available for each of the 14 regions as well as for the global total.

[29] https://united4efficiency.org/countries/country-assessments/

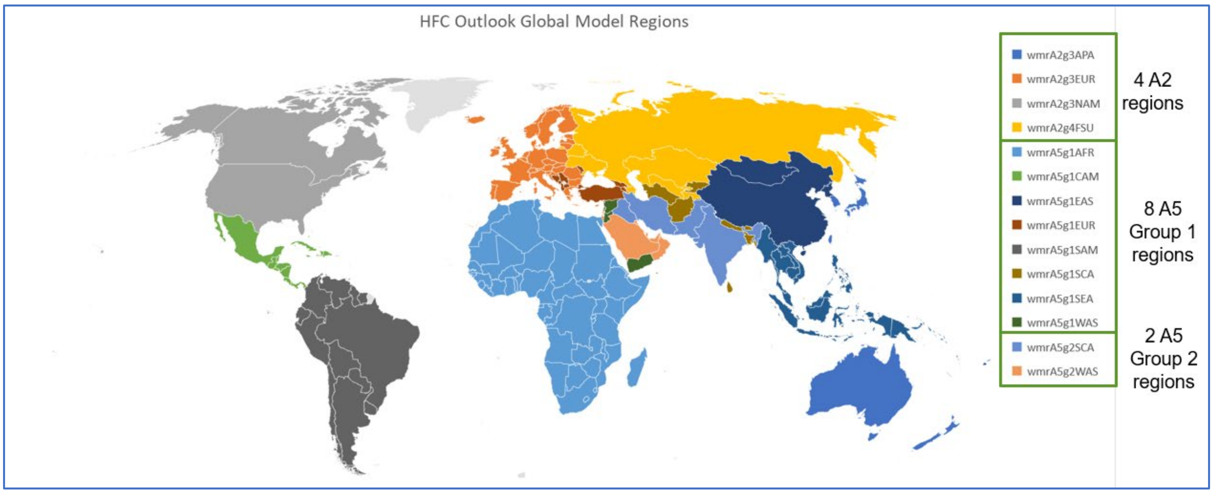


Figure 7-1. Regional Sub-Models in the HFC Outlook model

7.2.2 RACHP stock estimates show significant growth in all regions

The HFC Outlook model uses 40 technology types to represent the wide range of RACHP equipment used in domestic, commercial, industrial and transport applications. Equipment stock is calculated using algorithms that are applied at a country level. The algorithms account for population, GDP, climate and electricity usage to create an estimate of stock in each of the 40 technology types. The algorithms have been calibrated using numerous sources of published data to ensure that the stock estimates provide a reasonable basis for the modelling calculations.

The stock calculations show there will be significant growth between now and 2050. In A5 countries this is mainly driven by growing wealth. In non-A5 countries there is less growth in refrigeration and air-conditioning technologies, as these markets are already quite mature. However, massive growth in the use of heat pumps is forecast, to support the urgent need to decarbonise space and process heating. The warming climate is also expected to increase the demand for comfort cooling in all regions.

In terms of installed capacity, the Global model shows that under the mid-growth scenario, total cooling capacity grows by 300% between 2020 and 2050. This is illustrated in Figure 7-2, which also shows that the dominant cooling requirement is for comfort cooling. It is well recognised that without robust policies and actions that this increasing equipment stock could lead to significant increases in:

a) Direct refrigerant GHG emissions
b) Indirect RACHP energy-related emissions
c) Peak power requirements (requiring a significant investment in electricity generation).

An important consideration is whether the rate of RACHP growth can be reduced by taking a systems approach to the purchase of new RACHP equipment. Examples of load reduction opportunities include (a) improved building design, as discussed in Section 2.2, and (b)use of doors on food retail display cases. In some situations, it is possible to reduce cooling demand by over 50%.

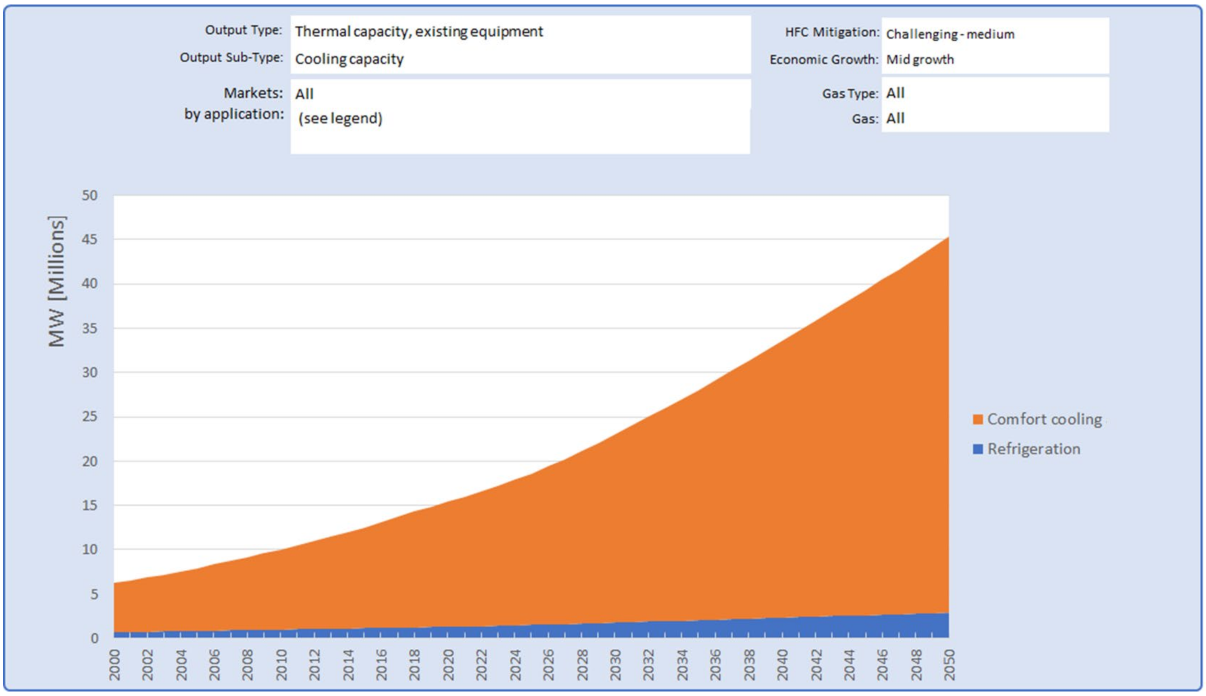


Figure 7-2. Global Growth of Installed Cooling Equipment, MW capacity, 2000 to 2050

7.2.3 Significant potential for energy savings and reductions in peak power

The Global Model illustrates the potential to limit the impact of the rapidly growing stock of RACHP equipment in terms of energy use and peak power requirements. Four different scenarios are analysed, representing increasing levels of ambition in terms of improving RACHP energy efficiency. The global forecast of future electricity use for RACHP is shown in Figure 7-3.

The “No efficiency gain” scenario assumes that the level of RACHP equipment efficiency modelled in 2022 remains unchanged to 2050. Under this scenario, the use electricity grows in direct proportion to the growth in stock, an increase of 300% between 2022 and 2050.

The other 3 scenarios represent increasing levels of efficiency improvement, reflecting increasing efficiency of new equipment (e.g., driven by MEPS and energy labels) and also improvements in operation and control (e.g., driven by improved training of RACHP technicians and end users). The “High efficiency gain” scenario represents a rapid introduction of equipment that is the most efficient available globally. Under this scenario the electricity consumed only rises by 8%, despite the 300% rise in equipment stock. The mid and low efficiency gain scenarios represent less ambitious efficiency initiatives which show a growth in electricity consumed of 150% and 220% respectively.

These figures show the enormous potential of maximising RACHP efficiency. The difference in peak power requirements between the No efficiency gain and High efficiency gain scenarios is estimated to be 1 to 1.5 TW in 2050. This would avoid the need to construct 1,000 to 1,500 power stations with a capacity of 1,000 MW each. Assuming it costs USD 2 million per MW to build new electric power stations, this represents a saving of USD 2 to 3 trillion by 2050. The financial saving related to reduced power station capacity is highly significant and is expected to be much greater than the cost of installing high efficiency RACHP equipment. As discussed in Section 6.4, the power generation sector finds it relatively easy to raise finance for large discrete power station projects and most have little or no incentive to invest in end-user efficiency improvements. Most end-users have limited resources and will often purchase the cheapest, and probably least efficient, RACHP option. This imbalance needs regulatory interventions to divert finance from electricity supply to end user efficiency.

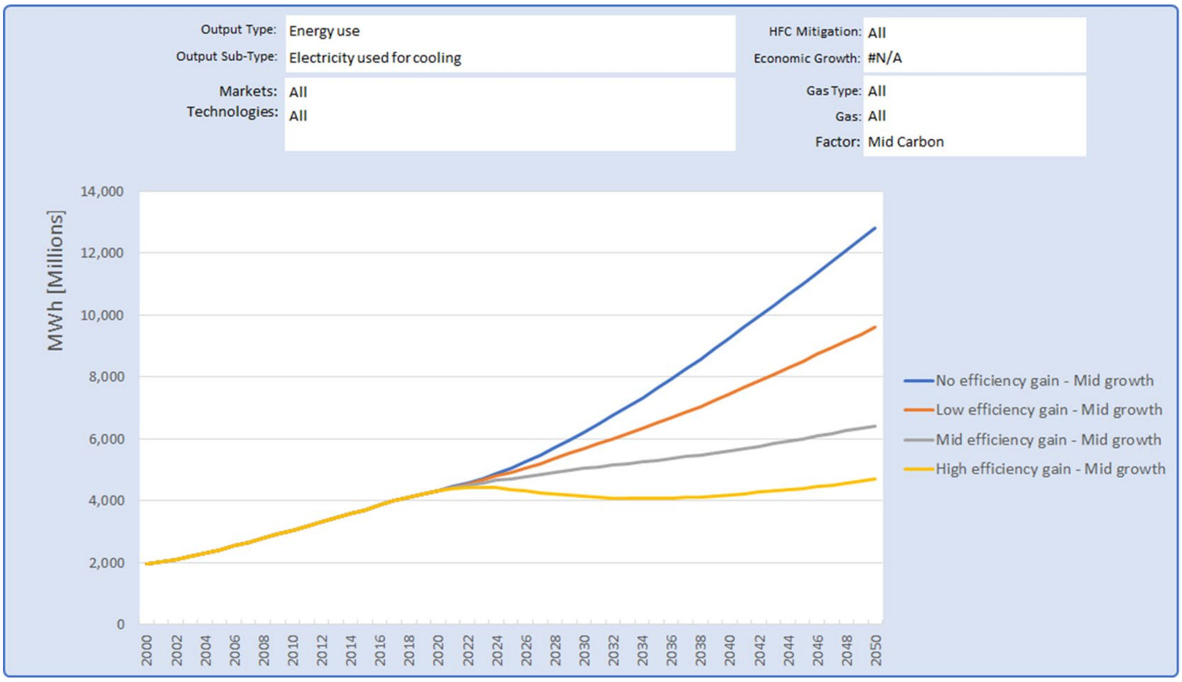


Figure 7-3. Global RACHP electricity for cooling forecast, 2000 to 2050, by EE scenario

7.2.4 Split of electricity use

Figure 7-4 shows a split of electricity used for cooling between market sectors. In 2023 it is estimated to be 44% residential, 42% commercial and 14% industrial. From around 2020 there is a growing use of electricity for transport cooling – mainly representing the air-conditioning of electric vehicles.

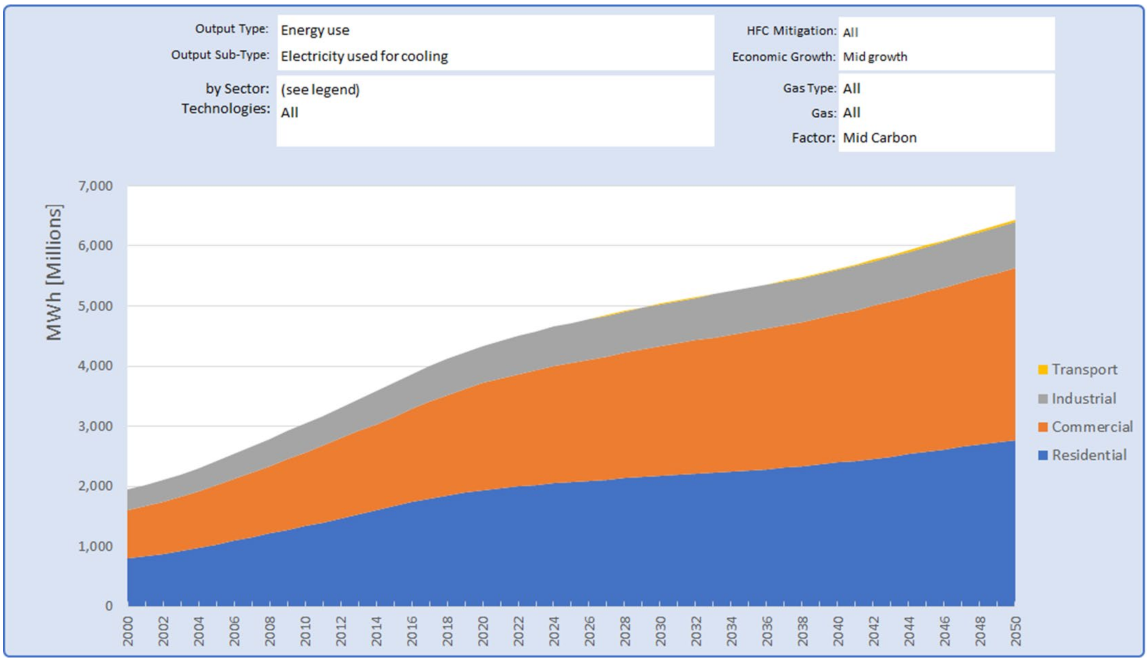


Figure 7-4. Global RACHP electricity for cooling forecast, 2000 to 2050, split by market

Figure 7-5 shows a split of electricity used for cooling between main applications. In 2023 the split is estimated to be around 60% air-conditioning and 40% refrigeration. It is interesting to compare this split with Figure 7-2 which shows that in 2023 air-conditioning represents 92% of installed cooling capacity. The reason for the reduced importance of air-conditioning in terms of electricity use is that refrigeration equipment is used for a much greater number of hours per year than air-conditioning equipment.

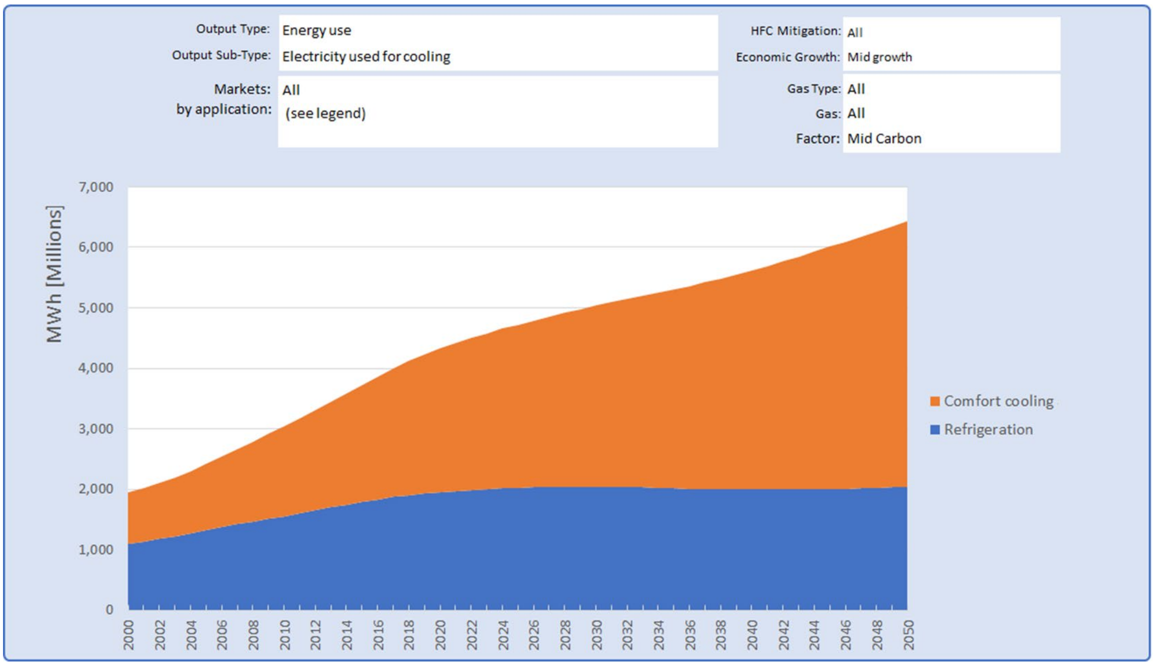


Figure 7-5. Global RACHP electricity for cooling forecast, 2000 to 2050, split by application

7.2.5 Indirect GHG emission saving potential

The level of emission reduction created by improving energy efficiency is dependent on the current and future electricity generation carbon emissions factors ("grid emissions factors", in kg CO_2 emitted per kWh generated). These factors are highly variable between different countries, depending on the current mix of generation technologies and the ambition to decarbonise electricity generation.

Currently, many countries use significant quantities of coal, oil and natural gas for electricity generation and have grid emission factors in the range 0.6 to 0.8 kg CO_2 per kWh. However, some countries with significant renewable generation (e.g., hydro-electric power, wind, solar etc.) or nuclear generation already have grid emission factors well below 0.1 kg CO_2 per kWh. In the last 8 years the global average has only fallen from 0.48 kg CO_2 per kWh in 2014 to 0.44 kg CO_2 per kWh in 2022[30]. Some A5 countries already have low grid factors (e.g., Brazil 0.16; Lesotho 0.02 kg CO_2 per kWh) usually because of significant levels of hydro-electric power.

Most countries are now setting targets for reducing their grid emission factors towards zero, using renewable or nuclear generation. In non-A5 countries the plans are often very ambitious, e.g., the UK is committed to reach a grid factor of 0 kg CO_2 per kWh by 2035. Figure 7-6 shows three possible global grid decarbonisation profiles. In 2022 the average global grid factor of 0.44 kg CO_2 per kWh is used and this value is reduced at different rates. The high carbon scenario is assumed to reach 0.29 kg CO_2 per kWh by 2050, on a pathway to

[30] Source: "Our World in Data" by Global Change Data Lab, hosted by Oxford University

zero by 2100. The low carbon scenario reaches zero in 2050. These grid scenarios have been used in the model results presented in Figure 7-7, but it must be noted that faster or slower decarbonisation rates than those shown below are possible.

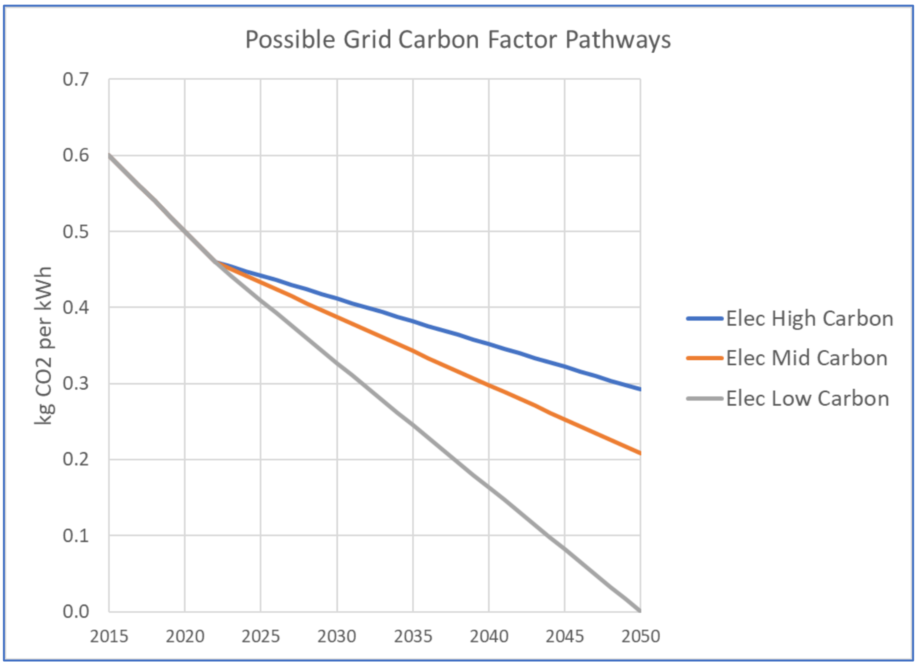


Figure 7-6. Modelled electricity generation carbon emission factors

Figure 7-7 shows a range of possible indirect emission pathways for global cooling applications. Four scenarios are shown. The worst case is no energy efficiency gain combined with a slow transition to lower grid carbon factors ("High CO2"). The best case is high energy efficiency gain combined with a rapid transition to lower grid carbon factors, reaching zero by 2050 ("Low CO2").

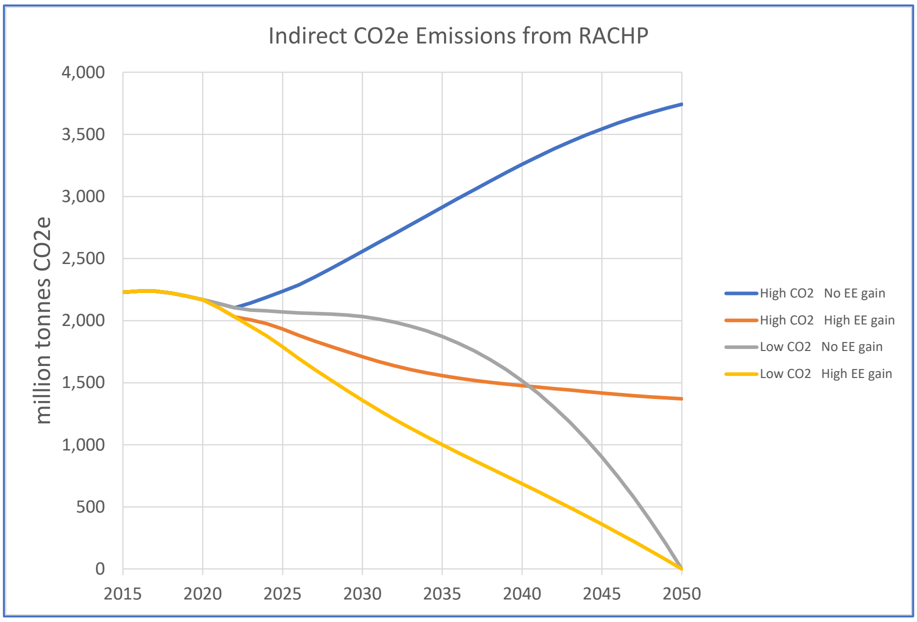


Figure 7-7. Global RACHP energy related CO_2 emission forecasts for cooling

7.2.6 Comparison of Direct and Indirect Emissions

The HFC Outlook model provides estimates of direct refrigerant emissions for a range of HFC mitigation scenarios. Figure 7-8 shows a global forecast of HFC emissions for 4 HFC mitigation scenarios. These scenarios take account of the various actions that can be used to mitigate HFC emissions including: (a) use of lower GWP refrigerants in new equipment, (b) reducing leakage rates from existing equipment and (c) recovering refrigerant at end-of-life.

The RACHP stock used in these forecasts is the same as that used for estimates of energy use – see Section 7.2.2. The Commercially Available scenario makes continuing use of the HFCs currently being used. It is non-compliant with the Kigali Amendment in A5 countries, although it is compliant for some non-A5 regions that already have switched to lower GWP technologies. This scenario can be considered as a base case. The other 3 scenarios show increasing levels of ambition to reduce HFC emissions. All are likely to be compliant with the Kigali Amendment. The high ambition mitigation scenarios indicate that HFC phase-down at a faster rate than in the Kigali Amendment is technically possible.

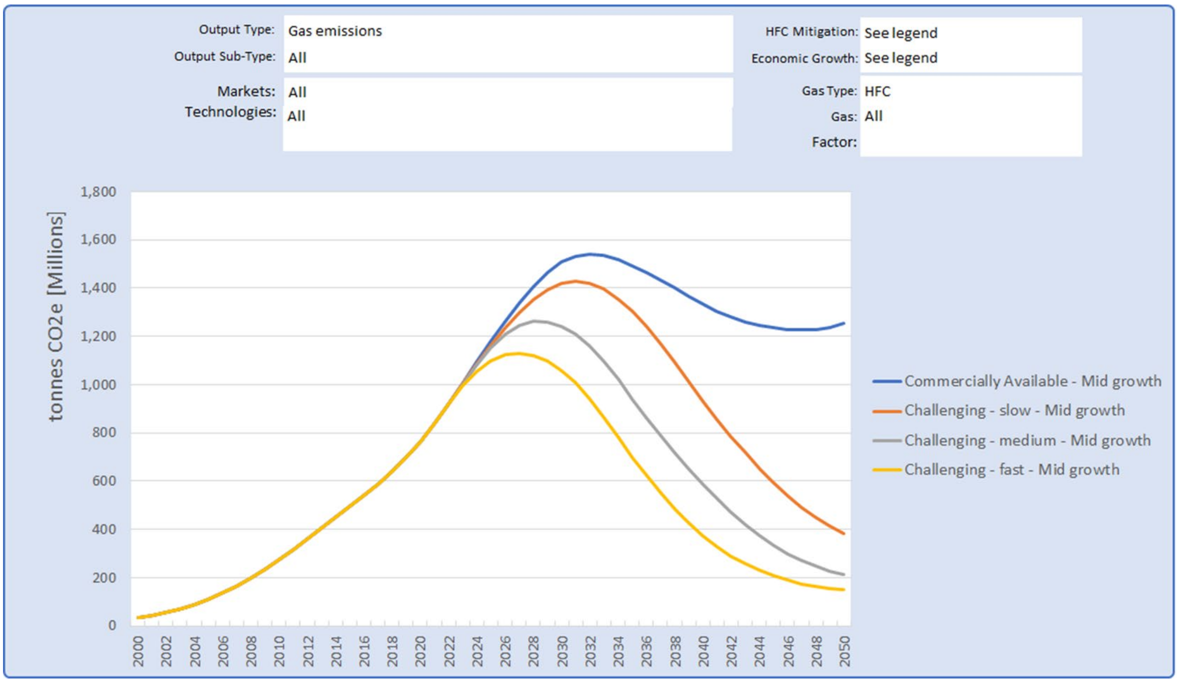


Figure 7-8. Global RACHP HFC emission forecasts, 2000 to 2050

Figure 7-7, clearly shows that a combination of maximising the ambition of energy efficiency improvements with a fast transition to zero CO_2 electricity generation can save a significant amount of GHG emission. Table 7-1 shows the cumulative indirect energy-related emissions between 2023 and 2050 for each of the 4 scenarios.

Table 7-2 shows the cumulative direct refrigerant emissions between 2023 and 2050 for each of the 4 scenarios. It is useful to compare the RACHP direct emission data in Figure 7-8 and Table 7-2 with the RACHP indirect emission data in Figure 7-7 and Table 7-1. It is clear that the indirect energy-related emissions are significantly higher than the direct HFC emissions. For example, base case cumulative indirect emissions between 2023 and 2050 are approximately 3 times higher that base case direct emissions.

Table 7-1. Cumulative RACHP energy related CO_2 emissions for cooling, 2023 to 2050

Scenario:	High carbon No EE gain	High carbon High EE gain	Low carbon No EE gain	Low carbon High EE gain
billion tonnes CO_{2e}	83.6	44.6	42.4	26.2
% reduction from high carbon, no EE gain	n/a	47%	406%	69%

Table 7-2. Cumulative RACHP HFC emissions, CO_2e, 2023 to 2050

Scenario:	Commercially Available	Challenging slow	Challenging medium	Challenging fast
billion tonnes CO_{2e}	37.4	28.2	21.9	17.5
% reduction from Commercially Available	n/a	25%	42%	53%

It is important to note that the HFC mitigation policies and EE policies are independent of each other. For example, it would be possible to achieve the “Challenging fast” HFC mitigation scenario at the same time as only going down the “No EE Gain, high carbon” pathway for energy efficiency.

The following charts show three extremes of the combined direct plus indirect emission pathways:

- Figure 7-9 shows fast action related to HFC emissions, but no action related to energy efficiency or grid decarbonisation.
- Figure 7-10 shows no action related to HFC emissions but high energy efficiency gain and rapid grid decarbonisation.
- Figure 7-11 shows coordination of fast action related to HFC emissions, high energy efficiency gain and rapid grid decarbonisation.

It is clear that combining both energy and refrigerant related policies gives the best environmental result. It is technically possible to achieve the "Challenging Fast" HFC mitigation scenario AND the "High EE, Low Carbon" pathway. However this will require a coordinated policy approach, targeting all three objectives: low direct GHG emissions, high energy efficiency and low-carbon electricity.

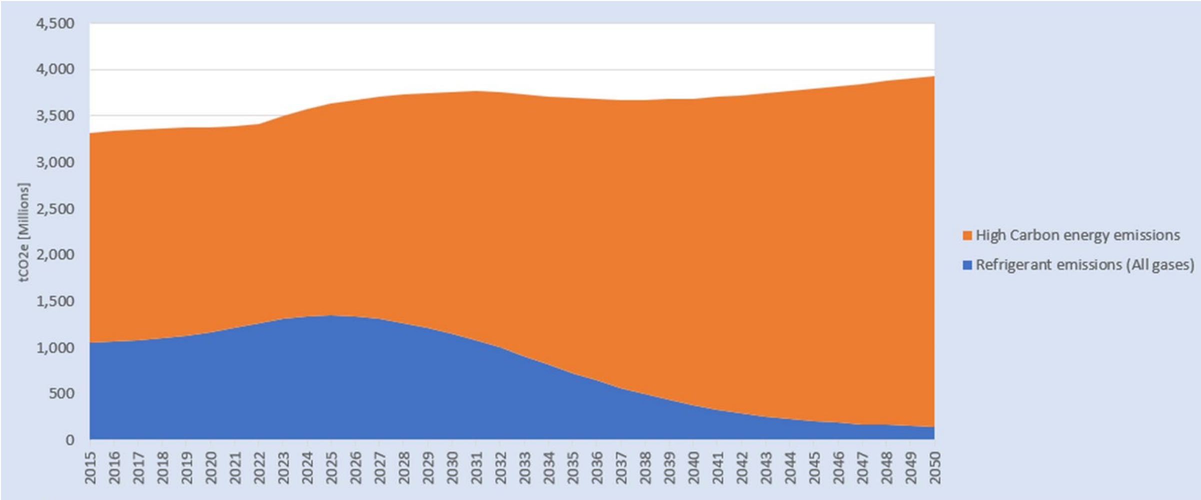


Figure 7-9. Fast HFC phase-down no EE gain slow grid decarbonisation

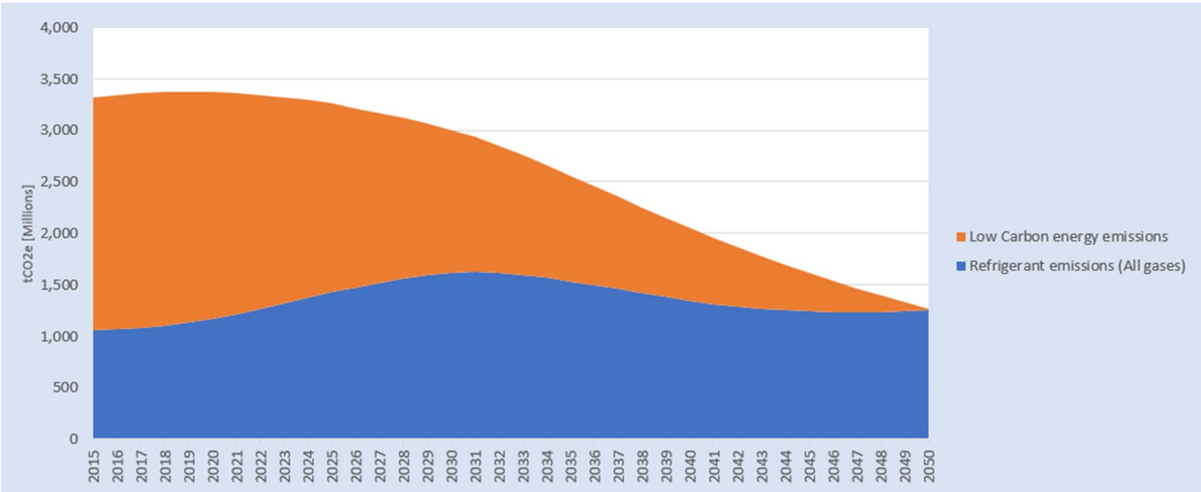


Figure 7-10. Little HFC phase-down high EE gain fast grid decarbonisation

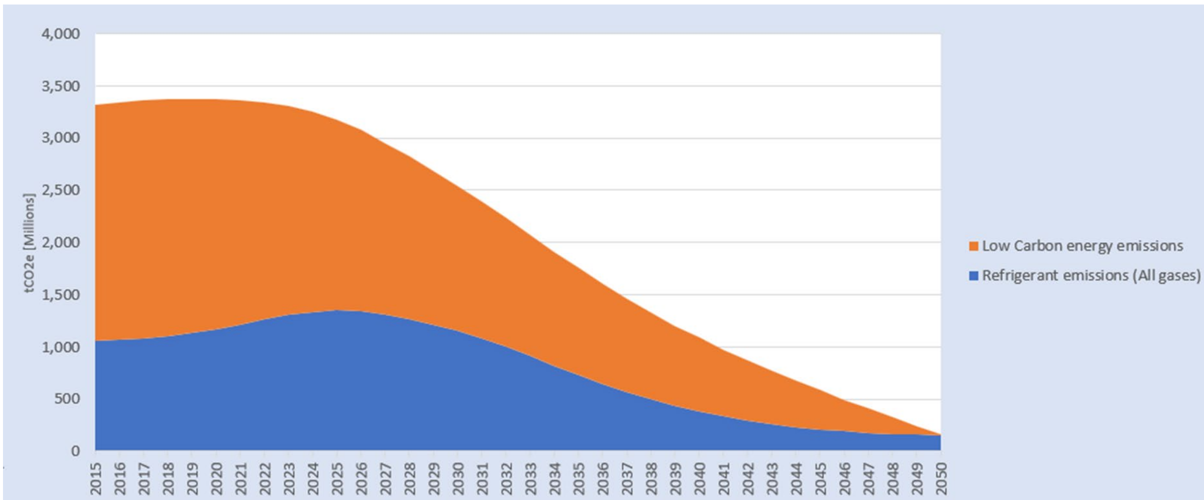


Figure 7-11. Fast HFC phase-down high EE gain fast grid decarbonisation

7.3 Modelling costs of energy efficiency improvement

Key Messages

- Modelling the costs of energy efficiency improvement can be difficult given that relevant data is proprietary and may involve design changes that manufacturers typically prefer not to disclose publicly.
- On a per-project basis, modelling such costs is crucial for understanding the value of energy efficiency investments that depend on factors such as climate, income, electricity prices, hours of use, CO_2 intensity of the grid and the costs of labour and capital.
- Standards setting bodies such as the US Department of Energy or EU Ecodesign conduct analyses of the costs to manufacturers and consumers of the revision of 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.
- Lawrence Berkeley National Laboratory has designed the Joint Investment Framework (JIF) tool for providing initial estimates of the costs and benefits of efficiency improvement in parallel with the phasedown of refrigerants under the Montreal Protocol on a per-project basis using publicly available data. Initially developed as a spreadsheet-based tool and currently implemented in Python for room AC projects, it is being further refined.

The previous section covered in detail the *benefits* of energy efficiency improvement. However, modelling the *costs* of energy efficiency improvement is somewhat difficult given that much of the relevant data is proprietary and may involve design changes that manufacturers typically prefer not to disclose publicly. However, on a per-project basis it is important from both a project design and project evaluation perspective to be able to estimate the costs of efficiency improvement. On an aggregate basis such estimates can guide Parties regarding project design with more precise budgetary allocations for energy efficiency improvements while phasing down HFCs under the Kigali Amendment to the Montreal Protocol.

Lawrence Berkeley National Laboratory has designed the Joint Investment Framework (JIF) tool for providing initial estimates of the costs and benefits of efficiency improvement in parallel with the phasedown of refrigerants under the Montreal Protocol on a per-project basis using publicly available data.[31] The workflow and overview of the JIF is shown in Figure 7-12.

Typically, standards setting bodies such as the US Department of Energy or the EU Ecodesign conduct analyses of the costs to manufacturers and consumers of the revision of MEPS or energy efficiency labels. Prior reports by the energy efficiency task forces of the TEAP have also shown examples from such studies. Similar studies have also supported energy efficiency standards improvements by various Parties including China, India, Mexico, Brazil, and others. These vary in their depth, analytical rigour, and cost from multi-year studies with detailed engineering analysis to short market studies. However, such studies are

[31] See here for a brief description of the Joint Investment Framework: https://ozone.unep.org/system/files/documents/JIF_final%20for%20publication.pdf

crucial for understanding the value of energy efficiency particularly in the context of considering investments that may have varying costs and benefits to consumers and manufacturers as well as varying environmental costs and benefits that depend on factors such as climate, income, electricity prices, hours of use, CO_2 intensity of the grid, and the costs of labour and capital.

There has been recent interest among various Parties in maximising energy efficiency improvements in parallel with the phasedown of HFC refrigerants under the Montreal Protocol.[32] To implement such action and coordinate investment in energy efficiency and refrigerant phasedown, a tool such as the JIF may be necessary to ensure the benefits of energy efficiency are maximised while the costs of energy efficiency improvement are minimised for specific energy efficiency improvement projects while phasing down HFC refrigerants under the Montreal Protocol.

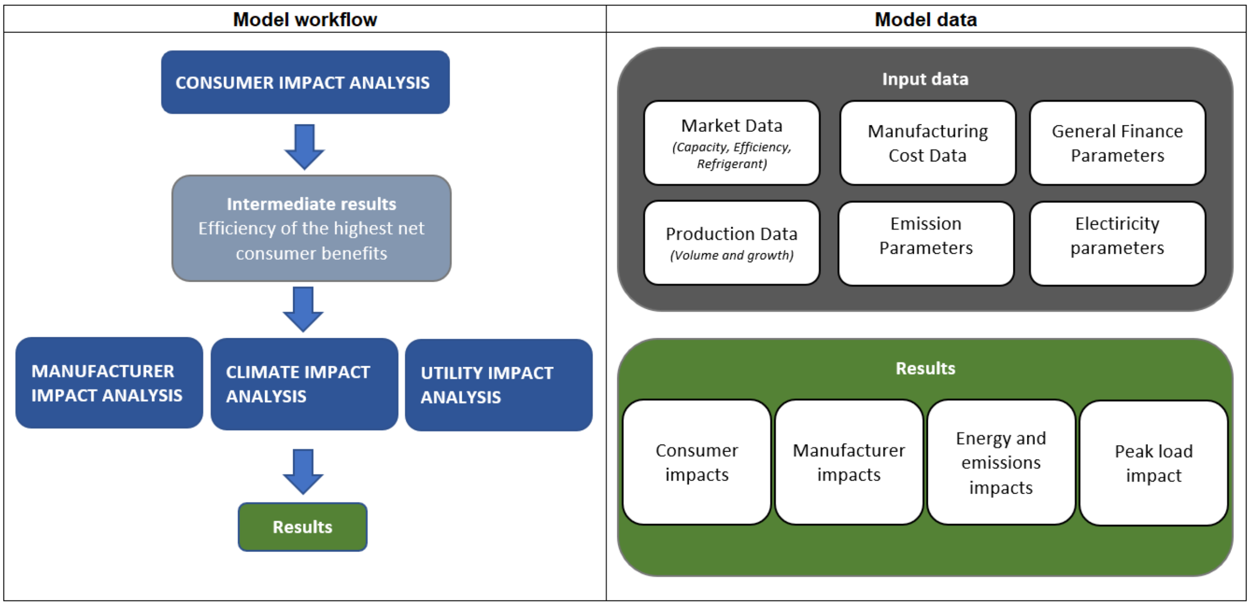


Figure 7-12. Workflow and overview of the JIF.

JIF is aimed at addressing needs among designers or evaluators of a particular project to:

Estimate the cost of refrigerant transition and energy efficiency improvement at different efficiency levels based on costs for more efficient components (Table 7-3 shows an example)

- Estimate the optimal level of energy efficiency improvement from a consumer perspective (Figure 7-13 shows an example)
- Estimate the level of investment needed at different efficiency improvement levels and for different alternative low-GWP refrigerants

[32] "Australia, Canada, the European Union, France, Germany, the United Kingdom, and the United States expressed support for a robust upcoming replenishment of the Montreal Protocol Multilateral Fund to incentivise early action on hydrofluorocarbon (HFC) reductions and to maximise parallel cooling efficiency improvements."(emphasis added) from: https://www.whitehouse.gov/briefing-room/statements-releases/2023/04/21/chairs-summary-of-the-major-economies-forum-on-energy-and-climate-held-by-president-joe-biden-2/

- Estimate the monetary, energy, and/or climate benefits of energy efficiency improvement and refrigerant transition.

JIF requires various inputs from the user including: equipment type, production volume, refrigerant, and the energy efficiency level of the baseline equipment. Based on the inputs, the JIF then outputs: (1) a recommended level of energy efficiency improvement that is cost-effective for the consumer, (2) the estimated cost of this efficiency improvement and estimated investment needed for the project, and (3) and the estimated energy and climate benefits. If the user does not have one or more of these inputs available, the tool assumes default values to provide reasonable estimates of the outputs.

The JIF tool relies upon publicly available data sources such as information on the cost of energy efficiency improvement for various types of equipment from the aforementioned USDOE Energy Efficiency Standard Rulemaking proceedings and test results from the AHRI low-GWP alternate refrigerant evaluation program. JIF was initially developed as a spreadsheet-based tool and currently has been implemented for room AC projects. It is now being implemented in Python and will be further refined with additional equipment types and countries going forward.

Table 7-3. JIF Estimated manufacturing cost increase for various efficient components for room air conditioner.

Modification	Component	Manufacturing cost increase	Energy savings
Compressor 1	3.0 EER compressor	1%	5%
Compressor 2	3.2 EER compressor	4%	10%
Compressor 3	3.4 EER compressor	9%	15%
Compressor 4	3.6 EER compressor	11%	20%
Inverter AC compressor	Alternating current compressor with variable speed drive	18%	23%
Inverter DC compressor	Direct current compressor with variable speed drive	22%	25%
Inverter DC compressor and fan	Direct current compressor and fan with variable speed drive	36%	28%
Heat eXchanger (HX) 1	UA of both HXs increased by 20%	1%	7%
HX 2	UA of both HXs increased by 40%	3%	13%
HX 3	UA of both HXs increased by 60%	8%	17%
HX 4	UA of both HXs increased by 80%	14%	20%
HX 5	UA of both HXs increased by 100%	16%	23%
Expansion valve	Electronic expansion valve	2%	5%

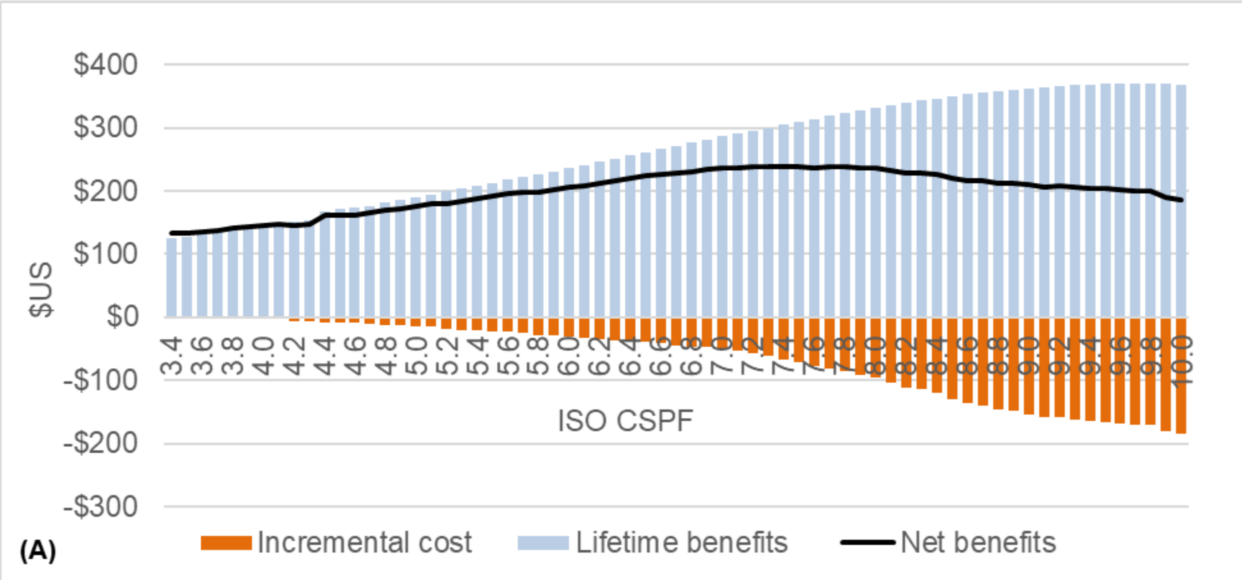


Figure 7-13. Lifetime net benefit of energy efficiency improvement of ACs with low GWP refrigerant

8 Range and Trends in GWP and EE of RACHP Equipment

Key Messages

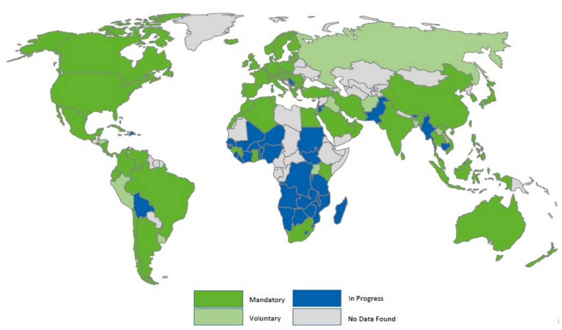
- There is a general trend toward increasing adoption of Minimum Energy Performance Standards (MEPS) and Labelling programs globally for RACHP equipment.
- Many Parties lack regulatory capacity and testing infrastructure to design, implement and enforce stringent MEPS programs, so there is an ongoing need for improvement and potentially technical assistance and/or financing in these areas.
- In all applications, there is a general trend of increasing efficiency e.g., through increased adoption of inverter drives that save energy when operating at part load conditions
- Similarly, there is a global trend towards lower GWP refrigerants, driven by the Kigali Amendment, with the weighted average GWP trending downward significantly with increasing deployment of lower GWP refrigerants globally.
- More efficient equipment on a market at any particular time will show more efficient models typically cost more than entry-level models due to multiple reasons including the bundling of non-energy related features in premium models. Hence retail prices may not actually the real cost of energy efficiency improvement.
- Costs of more efficient equipment and components tend to come down over time as a new technology becomes mainstream and due to economies of scale.

This chapter is responding to the following: Decision XXXIV/3 requests the TEAP to provide "[information] on the range of, and trends, in global warming potential and energy efficiency of refrigeration, air-conditioning and heat pump equipment, for which there are available data." Information on these trends is provided in this chapter.

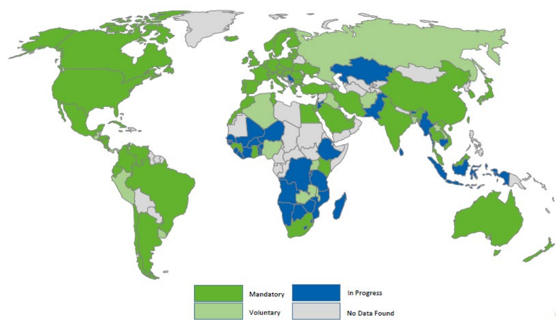
8.1 Status of standards and labelling programs globally

There is a general trend toward increasing the adoption of Minimum Energy Performance Standards (MEPS) and Labelling programs globally for room ACs, domestic refrigeration and commercial refrigeration equipment as shown in the maps shown in Figure 8-1. However, many countries lack regulatory capacity and testing infrastructure to design, implement and enforce stringent MEPS programs. These parties may require technical assistance and/or financing in these areas. A recent report by the IEA[33] showed that the proportion of final energy use by domestic refrigerators covered by MEPS increased from 49% in 2000 to 84% in 2021.

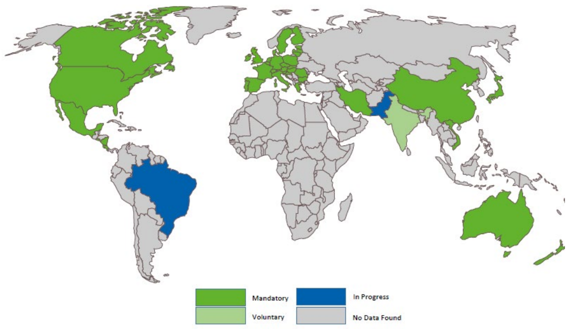
[33] https://www.iea.org/data-and-statistics/charts/proportion-of-final-energy-use-covered-by-meps-2000-2022



Room Air conditioner (RAC) MEPS programs



Domestic Refrigerator MEPS programs



Commercial Refrigeration MEPS

Figure 8-1. Mandatory (dark green), Voluntary (light green) and in progress (blue) MEPS programs for Room ACs, domestic refrigerators and freezers and commercial refrigeration equipment. Lack of data shown in grey. Source: UNEP United for Efficiency(U4E) Initiative

In all applications, there is a general trend of increasing efficiency e.g., through increased adoption of inverter drives that save energy when operating at part load conditions. Table 8-1 shows the increasing trend of inverter drive adoption across many room AC markets globally.

Table 8-1. Increase in adoption of inverter driven room ACs in various markets between 2017 and 2021 . Source: BSRIA and Park et al 2017

	Fixed-speed		Inverter	
	2017	2021	2017	2021
India	90%	52%	10%	48%
SE Asia	68%	59%	32%	41%
Indonesia	90%	87%	10%	13%
Thailand	73%	55%	27%	45%
Vietnam	47%	30%	53%	70%
Phillippines	57%	42%	43%	58%
Malaysia	100%	70%	0%	30%
Singapore	5%	4%	95%	96%
USA	100%	91%	0%	9%
Europe	26%	9%	74%	91%
Nigeria	97%	93%	3%	7%
Brazil	78%	31%	22%	69%
Japan	0%	0%	100%	100%
Saudi Arabia	93%	65%	7%	35%
UAE	88%	80%	12%	20%

It is important to note that in some markets, such as in the USA; the room AC market is largely composed by window and packaged through the wall units that are mostly fixed speed. This result in delayed adoption of inverter technology. As such, it is important to consider national and regional product registries (see TEAP EETF 2021 Case Study 2.3) provide additional level of granularity, where available.

More recent data shows very rapid growth in air-conditioning in India, over the period 2021-2022 with an increasing emphasis on inverter room ACs *(JARN (Japan Air Conditioning, Heating & Refrigeration News April 2023).* as shown in Table 8-2.

Table 8-2: Market scale and growth of Indian AC market

Category		2021 (Units)	2022 (Units)	Growth Rate (%)
Window		310,000	398,000	28
Wall-mounted	Non-inverter	1,162,000	1,512,000	30
	Inverter	2,711,000	3,721,000	37
RAC Sub-total		**4,183,000**	**5,631,000**	**35**
Cassette		82,000	109,000	33
Floor-standing (Tower)		7,000	8,100	16
PACs and Ducted Units*		65,000 (520,000 tons)	86,000 (687,000 tons)	32
Total		**4,337,000**	**5,834,100**	**35**

Notes: Primary sales
*Ducted units include ceiling-concealed types.

Similarly, there is a global trend towards lower GWP refrigerants, driven by the Kigali Amendment to the Montreal Protocol as shown in Figure 8-2. Globally around two thirds of the room AC units use HFC-32 refrigerant in 2021 increasing from just under 40% in 2019.

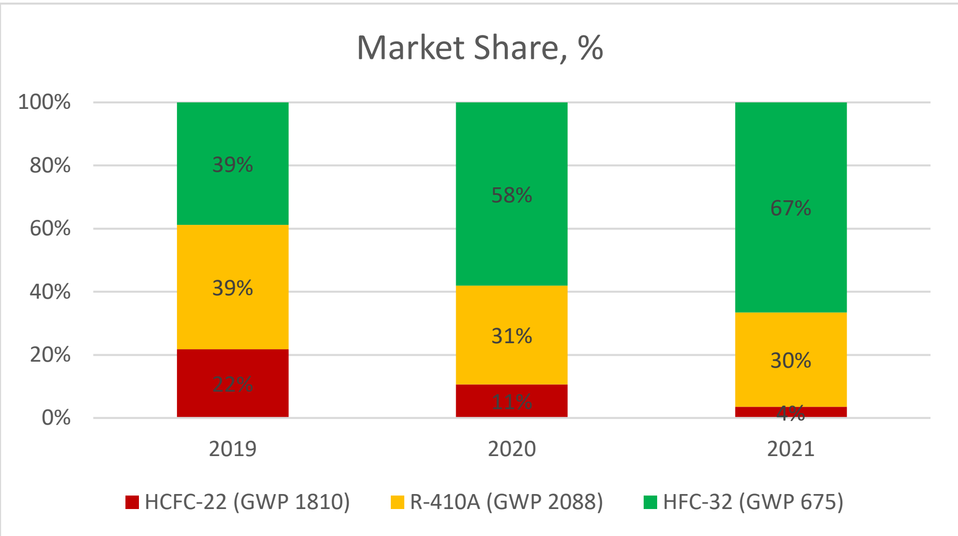


Figure 8-2. Trend in refrigerant GWP globally for room AC (Source, JARN - https://www.jraia.or.jp/english/statistics/file/World_AC_Demand_inverter.pdf)

Further, driven by industry innovation and regulation, there is an increasing trend for adoption of higher efficiency technologies in all applications. Table 8-3 and Table 8-4 below show the most efficient models for various types of commercial refrigeration equipment on a few markets in terms of their total energy consumption, total display area and annual energy consumption. More information is available in the U4E commercial refrigeration model regulation support document.[34]

Table 8-3: BAT energy consumption (most efficient in TEC/TDA) in Refrigerated Display Cabinets (RDC)

	Product Type[a]	TEC/TDA ($kWh/d/m^2$)	TDA (m^2)	TEC (kWh/d)[b]	AEC (kWh/y)	Market	Product Category in China[c]	$TECmax_{CN}$[d] (kwh/d)
Chiller (Refrigerator)	RDC-IHC	2.3 2.4	0.54 1.36	1.2 3.3	448 1,212	US EU	HC3, HC5-1, HC5-2	2.3 – 5.8 5.0 – 13.1
	RDC-IVC	2.1 2.1	1.45 3.91	3.0 8.2	1,113 3,006	AU EU	VC1, VC4	8.3 – 20.9 22.3 – 63.9
	RDC-RHC	0.6 1.2	4.58 0.62	2.9 0.7	1,052 271	US US	RS7, RS8, RS9	48.7 – 59.6 6.6 – 8.1
	RDC-RVC	1.9 2.2	2.87 6.72	5.6 14.9	2,036 5,454	US AU	RS3, RS4	37.5 104.2
	RDC-BC	0.9	0.34	0.3	110	EU		
Freezer	RDC-IHF	2.8 2.9	0.71 1.73	2.0 4.9	714 1,799	US EU	HF3 open wall site HF5-1 glass lid	5.1 – 16.8 12.4 – 40.7
	RDC-IVF	5.0 6.2	1.77 1.68	8.9 10.3	3,249 3,796	EU EU	VF4	43.2 41.1
	RDC-RHF	3.6 4.0	2.42 2.84	8.8 11.3	3,216 4,117	US US	RS13, RS14	33.3 – 37.9 39 – 44.5
	RDC-RVF	6.4 6.4	7.24 8.06	46.3 51.4	16,889 18,764	US US	RS12, RS19	209.4 – 384.2 233.1-427.7

a. IHC: integral horizontal chiller; IVC: integral vertical chiller; RHC: remote horizontal chiller; RVC: remote vertical chiller; BC: beverage cooler; IHF: integral horizontal freezer; IVF: integral vertical freezer; RHF: remote horizontal freezer; RVF: remote vertical freezer
b. Measured or estimated to values under ISO 22044 for RDC-BC and ISO 23953 for other RDCs at the conditions of CC3 and package temperature M2 or L1 (see Appendix 3 for temperature classes.)
c. Based on authors' assessment (see Appendix 4 for product categorization.)
d. Estimated EEI based on the China standard

[34] https://united4efficiency.org/wp-content/uploads/2021/11/U4E_CommercialRefrig_Supporting-Info_20211109.pdf

Table 8-4: Best Available Technology (BAT) energy consumption (most efficient TEC/100-L) in Refrigerated Storage Cabinets (RSC), Refrigerated Display Cabinets (RDC), Beverage Coolers (BC), Ice Cream Freezers (ICF)

	Product Type[a]	TEC/100-L (kWh/d/100-L)	Net Volume (L)	TEC (kWh/d)[b]	AEC (kWh/y)	Market	Product Category in China[c]	$TECmax_{CN}$[d] (kWh/d)
Chiller	RSC-IHC	0.16 0.17	750 1650	1.2 2.8	429 1,034	US US	HC9	2.1 4.0
	RSC-IVC	0.13 0.13	2300 2460	3.0 3.2	1,091 1,179	US US	VC5	6.6 – 9.3 7.0 – 9.9
	RDC-BC	0.16 0.19	190 790	0.3 1.5	125 540	EU EU		
Freezer	RSC-IHF	0.23 0.24	910 960	2.1 2.3	756 822	US US	HF9	7.3 7.6
	RSC-IVF	0.24 0.39	1380 560	3.3 2.2	1,208 786	US US	VF5	11.9 – 16.6 6.3 – 8.2
	RDC-ICF	0.30 0.41	300 300	0.9 1.2	329 438	EU EU		

a. ICF: ice-cream freezer
b. For RSCs, estimated to values under ISO 22041 at the conditions of CC4 and package temperature M2 or L1. For RDC-ICF, measured to values under ISO 22043 at the conditions of CC B and package temperature L1.
c. Based on authors' assessment
d. Estimated EEI based on the China standard

8.2 Trends in Price to the Consumer:

While a snapshot of more efficient equipment on a market at any particular time will show more efficient models typically cost more than entry-level models, this has many reasons including the bundling of non-energy related features in premium models. Hence retail prices may not actually the real cost of energy efficiency improvement.

Furthermore, costs tend to come down over time as a new technology becomes mainstream and due to economies of scale. For example, due to Japan's Top Runner program shown below, prices of more efficient models reduced, while efficiency simultaneously increased such that between 1995 and 2005, room AC efficiency in Japan improved by nearly 100% (from a COP of 2.55 to 5.10, a rate of 7.2% per year).

According to a report by a report by the IEA, the purchase price of appliances has fallen by an average of 2-3% per year while achieving huge efficiency gains. https://www.iea.org/reports/appliances-and-equipment

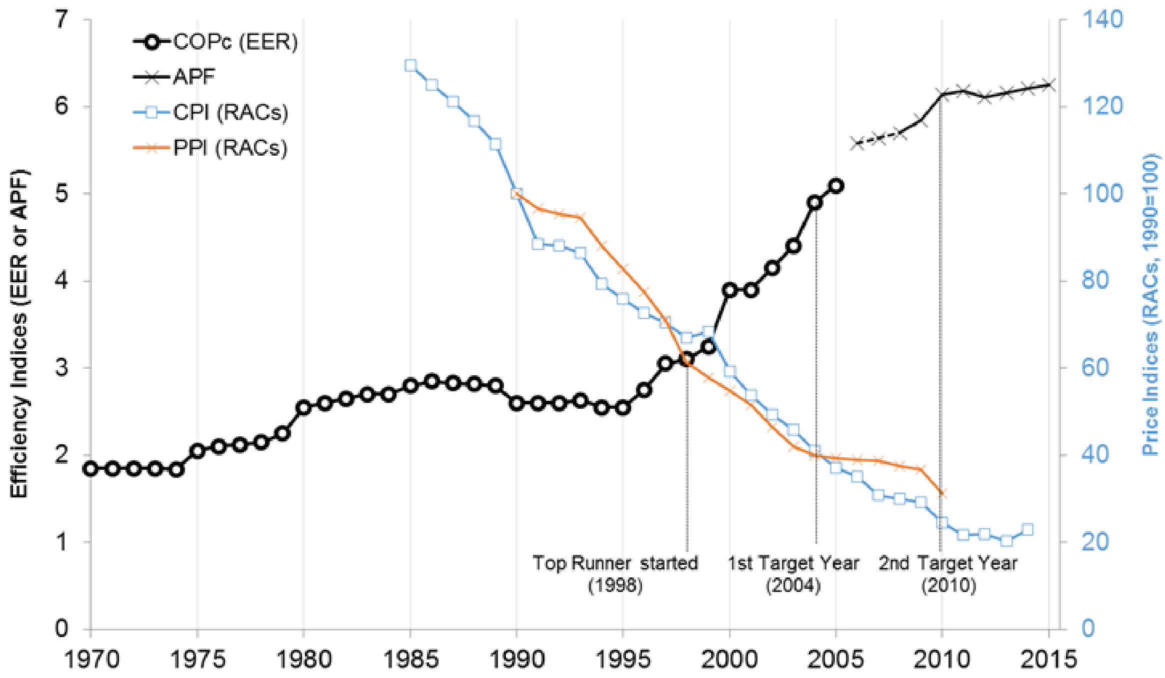


Figure 8-3: Efficiency cost trend. Source: Phadke et al., 2020.

8.3 References:

Khanna, Nina, Chao Ding, Won Young Park, Nihan Karali, and Nihar Shah. "International review of market trends, technologies and policies for commercial refrigeration equipment and implications for China." (2022) Lawrence Berkeley National Laboratory Report LBNL-2001489 https://escholarship.org/uc/item/7s05p8cp

Phadke, Amol, Nihar Shah, Jiang Lin, Won Young Park, Yongsheng Zhang, Durwood Zaelke, Chao Ding, and Nihan Karali. "Chinese policy leadership would cool global air conditioning impacts: looking east." Energy Research & Social Science 66 (2020): 101570. https://doi.org/10.1016/j.erss.2020.101570

Won Young Park, Nihar Shah, Kenji Shiraishi, Edward Vine "Improving energy performance metrics to maximize the benefits of disruptive technologies" Energy Research & Social Science, Volume 89, 2022, 102678, ISSN 2214-6296 https://doi.org/10.1016/j.erss.2022.102678

Won Young Park, Nihar Shah, Edward Vine, Patrick Blake, Brian Holuj, James Hyungkwan Kim, Dae Hoon Kim, "Ensuring the climate benefits of the Montreal Protocol: Global governance architecture for cooling efficiency and alternative refrigerants" Energy Research & Social Science, Volume 76, 2021, 102068 https://doi.org/10.1016/j.erss.2021.102068

9 Potential Approaches for Assessing Additional Costs for Improving EE while Phasing Down HFCs

Key messages

- Additional costs associated with improving the energy efficiency of equipment alongside conversion to HFC alternatives are summarised drawing on information presented in previous EETF reports and presented as Additional Capital Cost (ACC) and Additional Operating Cost (AOC) to differentiate from the Incremental Capital Cost and Incremental Operating Cost.
- The EEWG presents a novel approach for assessing additional costs using an efficiency improvement-linked incentive index. This approach is contrasted with a traditional incremental cost approach. A key feature of the incentive index is that it focuses resources on those enterprises with the greatest need for capacity building and access to knowledge for designing and integrating lower-cost components into their products to improve from minimum to medium and better energy performance. Such an approach focused on where manufacturing EE capacity is most needed, would address a key barrier to access to higher energy efficient equipment in manufacturing and importing countries.

This chapter is responding to the following: Decision XXXIV/3 requests the TEAP to provide "[updates] relating to the availability, accessibility, electrical compatibility, and cost of energy efficient products and equipment containing low- or zero global warming-potential refrigerants in the refrigeration, air-conditioning and heat pump sectors."

9.1 Introduction

Parties have recognised the importance and benefits of improving the energy efficiency of RACHP equipment during HFC phasedown, especially in the context of the climate emergency. Fully realising the potential energy efficiency improvements could double the global climate benefit at the same time as avoiding a substantial economic burden for individual A5 parties, especially those LVC/VLVCs who currently have limited access to efficient RACHP equipment.

The MFL and Secretariat have considered if//how to partner with climate funds to support the energy efficiency co-benefit during HFC phasedown. In 2022, an MLF Secretariat Report for the Executive Committee *(Decision 87/51)* identified a number of potential sources of climate co-funding, but concluded in para 47(d) that, "the compatibility of the procedures and conditions of non-MLF funding sources with MLF procedures and management processes seems to be limited."

Progress on funding guidelines for energy efficiency improvements during HFC phasedown in A5 parties has so far been tentative. In December 2022 Executive Committee Decision 91/65 established "a funding window for pilot projects in the amount of US $20 million with the possibility of augmenting that funding window at a future meeting to maintain and/or enhance energy efficiency in the context of HFC phase-down as specified in decision XXVIII/2," (*UNEP/OzL.Pro/ExCom/91/72**). Such a pilot funding window offers the opportunity for "the Executive Committee to gain experience in understanding the elements and costs associated with such projects." (*as recommended* in Para 48 of UNEP/OzL.Pro/ExCom/89/12)

In this Chapter, the EEWG presents a summary of information from previous EETF reports, other public information, and the authors' experience, on the costs associated with improving the energy efficiency of equipment alongside conversion to HFC alternatives. They are presented as Additional Capital Cost (ACC) and Additional Operating Cost (AOC) to differentiate from the Incremental Capital Cost and Incremental Operating Cost used by the MLF when assessing costs in typical refrigerant conversion projects.

In Section 9.5, the EEWG presents a novel approach for assessing additional costs using an efficiency improvement-linked incentive index. This approach is contrasted with a traditional incremental cost approach. A key feature of the incentive index is that it focuses resources on those enterprises with the greatest need for capacity building and access to knowledge for designing and integrating lower-cost components into their products to improve from minimum to medium and better energy performance. Specifically, the overall capacity of an enterprise based on the energy performance of its portfolio of products is considered in this approach. Previous TEAP EETF reports have identified MEPS as a major enabling policy for access to higher EE equipment. However, in manufacturing countries, the ability of small and medium domestic enterprises to access the capital, capacity and knowledge to improve the EE of their products can act as a limitation on the MEPS level for that country. When MEPS levels are low, there is no disincentive for higher capacity manufacturers to continue producing and exporting inefficient RACHP equipment into that market. The adage "a rising tide raises all boats" applies here, as "raising the floor" on manufacturing EE capacity would address a key barrier to access to higher energy efficient equipment in manufacturing and importing countries.

9.2 Summary of EE Indicative Costs

Previous reports from the TEAP EETF (in response to Decision XXXIII/5, Decision XXXI/7, Decision XXX/5, Decision XXIX/10, and Decision XXVIII/3) have provided indicative cost-efficiency data for different technologies that may be used to maintain or enhance the energy efficiency of RAC and SCCR. The most recent report was expanded to cover additional sectors but was not able to provide indicative data due to the large scope. In addition, the UNIDO green refrigeration program provided detailed data on cost and efficiency U.S. DOE technical support document for the development of the MEPS for the Commercial AC (CAC) along with best practice and current market information on the on-site assembly and installation technologies. Representative annual energy consumption for the different sectors were obtained from the U4E country assessment methodology report.[35] For CAC we assumed a typical 10 RT packaged unit with a yearly load varying from 3600 to 25200 TR.hr per year. Table 9-1 to Table 9.5 provide a summary for the ACC, AOC, and energy efficiency gains (as a percentage or a range in kWh/yr reduction) for domestic refrigerators, SCCR, RAC, CAC, and site-assembled refrigerators, respectively.

In these tables, the base model refers to basic equipment of a specific capacity that may be used by the manufacturer to offer different products on the market to the consumer. For example, a base-model for domestic refrigerators of a specific capacity would have the same internal and external dimensions. This base model may be sold under different brands and/or different model names by changing either:

- The external finishing
- The internal shelf configuration and style

[35] https://united4efficiency.org/resources/u4e-country-savings-assessments-methodology-and-assumptions/

- The controls and adding different displays options
- The sealed system components (e.g., compressor, heat exchangers, or all)

For a RAC, the base model will also offer the same outdoor unit design; but might have different indoor unit finishes and options, different compressors, and the option to operate as a heat pump.

Table 9-1. Cost and energy reduction for different technology options in the Domestic Refrigeration Sector

Technology	ACC, USD	AOC; USD/unit	Efficiency improvement, %	kWh/yr reduction -	
				min	max
Improved compressor	NA	1.05 to 6.5	6.5 to 25.5%	15	155
Improved Evaporator	NA	0 to 3.9	3 to 12.5%	7	76
Improved Condenser	NA	NA	up to 4%	9	24
High efficiency evaporator fan	NA	4 to 6	11 to 18.5%	25	112
High efficiency condenser fan	NA	0.71	11%	25	67
Optimise gasket (per gasket design)	3,000 to 9,000†	1 to 6	6.50%	15	39
Optimise defrost timer	NA	1 to 3	2.75%	6	17
Change insulation thickness (per base model)	50,000 to 500,000‡	2.5 to 17	4 to 9.5%	9	58
Inverter compressor (OEM solution; i.e., buy)	0 to 100,000††	16 to 45	up to 30%	68	182
Inverter compressor (develop own inverter and controller)	200,000 to 300,000 ‡‡	up to 5	12.5 to 15%	29	91

† Refers to the cost of design and purchase of one gasket welding jig. The number of jigs required per manufacturing line depend on the layout and production volume.
‡ Refers to the cost associated with the injection moulds. If the inner volume is not changing the cost will be on the low end (50,000 USD), if the refrigerator design needs to be changed to
†† Refers to the cost associated with new electrical wiring termination if needed
‡ Refers to the cost of internal capacity building to include embedded systems engineer(s) as part of the product development team to design and procure custom made control boards with an integrated inverter.

Table 9-2. Cost and energy reduction for different technology options in the SCCR Sector

Technology	ACC, kUSD	AOC; USD/unit	Efficiency improvement, %	kWh/yr reduction -	
				min	max
Improved compressor	NA	up to 20	8 to 30%	108	1350
Inverter compressor	NA	up to 50	up to 40%	538	1800
Improved cabinet airflow	0 to 100,000 †	0 to 100	4 to 15%	54	675
ECM fan with improved design for evaporator	NA	2 to 33.53	4 to 26.5%	54	1193
Heat exchanger optimization (same envelope)	NA	NA	up to 15%	202	675
Heat exchanger optimization (allow size to change) per base model	25,000 to 50,000‡	up to 10	up to 40%	538	1800
MCHX (buy)	25,000 ††	up to 5	2%	27	90
Increase insulation thickness	50,000 ‡‡	1 to 6	up to 5%	67	225
Optimise gasket (per gasket design)	3,000 †††	1 to 4	1.50%	20	68
High performance insulated glazing unit for doors	50,000 ‡‡‡	20 to 22	23 to 33%	310	1485
VIP	NA	5 to 400	4% to 15%	54	675
Smart Controller	NA	6 to 22.5	5 to 12.5%	67	563
Digital Controller with Internet of Things (IOT)	NA	40 to 55	30%	404	1350

† Refers to the cost of design of air flow using CFD simulations, experimental evaluation, retooling, new sheet metal dies and jigs, and adjustment to the assembly line for each base model.
‡ Refers to the cabinet assembly adjustment, retooling, and new sheet metal jigs to allow for optimization that impact the different heat exchanger size to be used.
†† Refers to new sheet metal jigs and retooling for assembly on the same production line.
‡‡ Refers to the new sheet metal jigs and retooling that account for the increased insulation thickness for each base model.
††† Refers to the cost of design and purchase of one gasket welding jig. The number of jigs required per manufacturing line depend on the layout and production volume.
‡‡‡ Refers to the cost of new door design, hinge design, and change in cabinet structure to handle the insulated glazing units.

Table 9-3. Cost and energy reduction for different technology options in the RAC Sector

Technology	ACC, USD	AOC; USD/unit	Efficiency improvement, %	kWh/yr reduction	
				min	max
Improved compressor	NA	0 to 5	up to 10%	10	303
Two-stage compression	NA	0 to 40	up to 10%	10	303
Inverter compressor (OEM solution; i.e., buy)	NA	0 to 75	20 to 30%	20	908
Inverter compressor (develop own inverter and controller)	200,000 to 300,000	0 to 25	up to 20%	20	606
ECM for indoor/outdoor fans	NA	10 to 50	5 to 15%	5	454
Heat exchanger optimization (same envelope)	NA	0 to 10	up to 10%	10	303
Heat exchanger optimization (allow size to change) – per base model	100,000 to 150,000	0 to 20	up to 15%	15	454
Electronic expansion valve	NA	18 to 30	6.5 to 20%	7	606
Microchannel condenser (buy)	0 to 25,000	0 to 5	up to 15%	15	454
Microchannel (make)	300,000 to 350,000	NA	up to 15%	15	454
Adiabatic condensers (buy)	20,000 to 25,000	40 to 70	25 to 30%	26	908
Adiabatic condensers (make)	100,000	Up to 25	Up to 25%	26	757

Table 9-4. Cost and energy reduction for different technology options in the CAC Sector

Technology	ACC, USD	AOC; USD/unit	Efficiency improvement, %	kWh/yr reduction -	
				min	max
Optimised heat exchangers (buy vs. make)	25,000 to 350,000	155 to 280	8 to 15%	116	419
Dual compressors with separate refrigerant circuit	NA	250 to 625	6 to 10%	467	374
Variable speed indoor blower + 2 stage outdoor fan	NA	180 to 430	6 to 8%	321	444
All variable speed and advanced control (buy)	NA	210 to 650	15 to 35%	488	317

Table 9-5. Cost and energy reduction for different technology options in the on-site assembly Sector

Technology	Installation Cost, USD		Component Cost, USD	EE improvement
	New	Retrofit		
On-site assembled commercial refrigeration				
Reduce leakage (caulking and gaskets)	Low	Medium	Low	Up to 5%
Reduce heat load (larger insulation thickness, better door gasket, and improved caulking)	Low	NA	Medium	10 to 20%
Optimised evaporating unit (better evaporator and fan)	NA	Low	Medium	Up to 5%
Optimised condensing unit (better compressor and condenser)	NA	Low	Medium	Up to 5%
Advanced controls	NA	Medium	Medium	5 to 20%
Advanced controls with inverter for compressor	NA	Medium	High	25 to 40%
Advanced controls with inverter compressor and ECM fans (replace indoor evaporating and condensing units)	NA	High	High	30 to 50%
Optimised compressor	NA	Low	Low	5%
On-site assembled commercial AC and chillers				
advanced controls	Low	High	Low	Up to 20%
advanced controls with inverter for compressor	Low	High	Medium	Up to 40%

The concept of learning curves is important when considering the additional costs in tables 9-1 through 9-5. In the examples discussed in this chapter, the additional costs are considered fixed. However, these costs are expected to decrease as the enterprise "learns by doing" and increases production scale (see Figure 9-1). As an illustration of the concept, consider an enterprise is building a new manufacturing line for AC units or for domestic refrigeration. There is an initial capital investment in the new line and production increases slowly to a commercially viable scale while R&D is completed, and components are optimised. The initial capital and operating costs of the new line requires upfront financial and staffing capacity that may not "pay back" in terms of sales revenue for several years and may prevent some enterprises from undertaking investments to improve energy efficiency. Figure 9-1 shows that the unit price for new designs decreases down a steep learning curve in the first several years. The knowledge development and testing covered in the ACC is an investment that enables the business to develop, with a progressive reduction in AOC through access to lower cost components due to design optimization or increased scale of production. Figure 9-1 suggests that price per unit comes down quickly in the first year by 18% for commercial AC units and 40% for domestic refrigeration and room air conditioners.

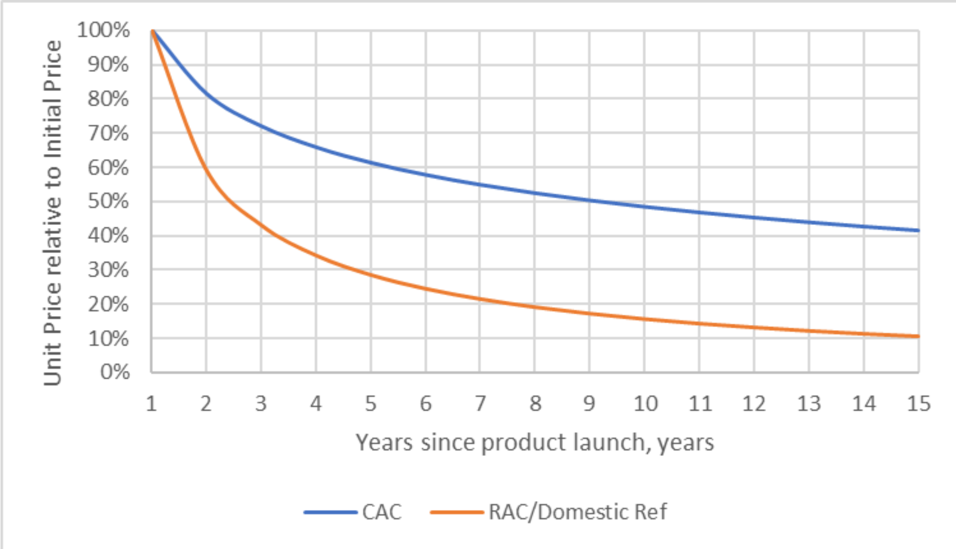


Figure 9-1. Learning curve for typical RACHP. The typical learning rate for commercial AC (CAC) is 18% and for domestic refrigeration and RAC is 40% in the first year.[36]

Taking into consideration the learning rates and the importance of knowledge development and capacity building, the EEWG proposes the use of an efficiency improvement-linked incentive approach for assessing potential additional EE costs (see section 9.5). Such an approach would encourage enterprises to build capacity to access energy efficient technologies by taking into consideration the existing capabilities of enterprises together with knowledge of typical incremental costs based on experience with previous projects.

9.3 Examples of non-MLF EE finance alongside with MLF funded projects

The Clean Cooling Collaborative (formerly K-CEP) provided support for enhancing energy efficiency alongside several MLF-supported manufacturing conversions at a time when there had been no MLF progress on HFC cost guidelines or decision on MLF finance of EE improvements. This includes two domestic refrigeration projects implemented in collaboration with UNDP and alongside MLF-funded projects as below:

9.3.1 Domestic refrigeration (Mabe, Mexico)

In addition to 8,564,008 USD in total project co-financing by Mabe-Mexico, K-CEP provided 400,000 USD in support for industrial conversion (design, manufacture, and testing protocols) for new energy-efficient compressors. This support enabled Mabe to upgrade the efficiency of its refrigerator compressors by 15–25% in parallel with a conversion from HFC-134a to R-600a.

[36] According to: https://www.osti.gov/servlets/purl/1047753 the LR for Refrigeration and RAC is ~ 40% for CAC is ~ 18%.

Table 9-6. IOC for domestic refrigerator manufacturing in Mabe-Mexico[37]

Models	HC-600a – Refrigerant Conversion (USD)	Energy Efficiency (USD)	Total (USD)
One Door (A210)	46,428	30,952	77,380
No Frost (230 to 300 L)	1,973,400	1,315,600	3,289,000
No Frost 360 L	777,240	518,160	1,295,400
No Frost (400 to 520 L)	853,440	568,960	1,422,400
BF Pangea	435,960	290,640	726,600
SXS	560,520	373,680	934,200
Total	4,646,988	3,097,992	7,744,980

9.3.2 Domestic refrigeration (Walton, Bangladesh)[38]

K-CEP provided 200,000 USD in support for industrial conversion to Walton Hi-Tech Industries Ltd. to improve the energy efficiency of its refrigerator compressors by 10 – 43% (depending on the model) in parallel with a conversion from HFC-134a to HC-600a.

9.3.3 Servicing Sector and MEPs

In the context of enhancing the servicing sector, the TEAP EETF report 2018 (in response to Decision XXIX) provides in Table 2.10 examples of costs for capacity building and training (average 212,500 USD per country).

In the context of ExCom Decision 91/65(b)(vi), Table 2.10 provides example costs for activities related to establishing MEPS in the range of 50,000 to 222,500 USD per country.

9.4 Cost effectiveness of EE Measures: Buying from Original Equipment Manufacturers (OEMs) vs. Making at own facility

SMEs trying to access essential energy efficient components often face higher costs, because they do not have the know-how, or volumes needed for economy of scale. Manufacturers are faced with the option to buy from OEMs, or to make the required components themselves, including those for both refrigerant conversion and EE upgrades. This decision depends greatly on the company size and experience, production volumes and the business strategy related to capital recovery period.

One major decision for RAC manufacturers is the use of variable capacity compressors. Compressor development and manufacturing require substantial capital investment and can only be warranted if a large production volume is guaranteed. Therefore, compressors are typically a “bought” technology. However, some RAC manufacturers are beginning to invest in their own compressor production to gain a competitive edge and reduce their dependence on OEMs. GMCC (a Midea subsidiary) has received international support to develop low GWP and energy efficient compressors for use by multiple RAC manufacturers – and not limited to Midea.

[37] http://www.multilateralfund.org/80/Document%20Library1/1/8045.pdf
[38] http://www.multilateralfund.org/80/Document%20Library1/1/8045.pdf

Large manufacturers typically develop their own integral controllers for inverter compressors at an ACC of ~200.000 in order to reduce the AOC. This investment can be easily recovered with large production volumes and result in cost-neutral or minimal cost increase to achieve significant efficiency improvement. In contrast an would rely on “buying in” a complete variable speed compressor solution with controller and inverter from the compressor OEM. This would result in minimal ACC; however, this would come at a significant AOC.

EE improvement can also be achieved through design optimization of the heat exchanger. The “buy versus make” decision for this component is more complex due to the supply chain issues and local regulations. Manufacturers in A5 parties typically make their own condensing units and pair them with more expensive indoor units from OEMs. Fin-tube heat exchangers are typically cheaper to manufacture than to buy when the volume is greater than 100,000 units per year and microchannel heat exchanger are typically cheaper to manufacture than to buy when the volume is greater than 200,000 units per year. When governments levy custom duty and provide incentives for local manufacturing, these values can change dramatically.

SMEs in A5s have a small production volume that limits the potential for absorbing the ACC. Generally, they use OEM technologies and/or solutions, limiting the ACC but with high AOC. With ACC support from external funding agencies to reduce the product cost, SMEs can remain competitive. Nevertheless, SMEs would be advised to understand the trade-off between ACC and AOC for the selected technologies and the “buy vs. make” impact on product cost.

9.5 Efficiency Improvement-Linked Incentives

The EEWG proposes to link the EE funding to the level of efficiency improvement, compared with the best-available technology (BAT). The EE funding should also consider the **beneficiary’s current portfolio of products and ability to produce high EE products**; e.g., their product development capacity, testing facilities, and intellectual properties. The EE funding would be divided into ACC, AOC, and Capacity Building. The level of funding will then be dependent on the proposed EE level compared with the lowest EE and BAT. The EE level will first be normalised and compared to the lowest EE level with a value of 1.0 and the BAT with a value of 10.0. The EE level is calculated using ISO methodology for comparability across countries. BAT level for incentive can evolve with technology innovation. The proposed EE will then be normalised as follows:

$$EE_{normalized} = 10 - \frac{(EE_{BAT} - EE)(10 - 1)}{(EE_{BAT} - EE_{Min})}$$

Figure 9-2 shows a sample incentive index as a function of the normalised energy efficiency. In this figure, if a beneficiary is starting with the lowest EE (level 1); then, he is eligible of up to 100% of the indicative EE conversion costs. However, if the beneficiary’s baseline efficiency is at level 4, he is only eligible of up to 21% of the indicative EE conversion costs.

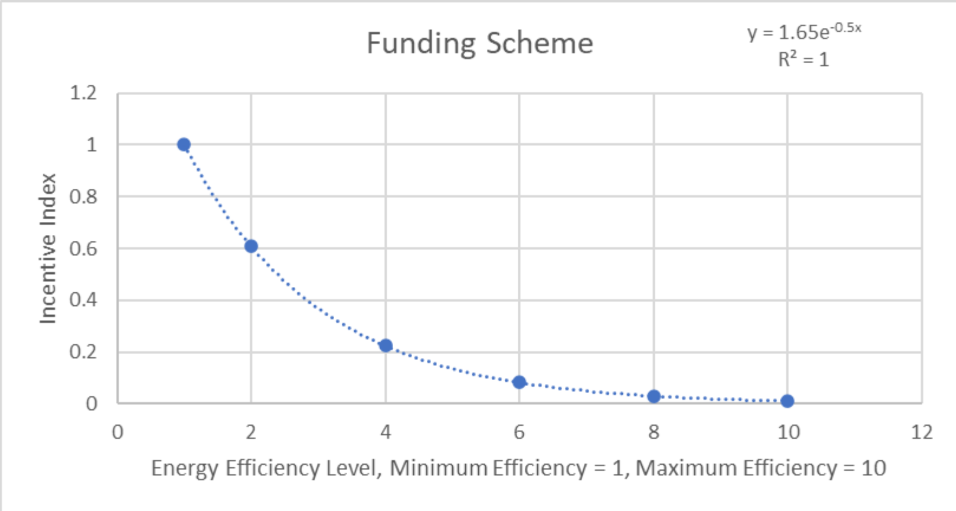


Figure 9-2. Incentive index as a function of normalised energy efficiency level.

Using the assumed distribution in Figure 9-2, the level of funding would be normalised according to the available funding based on an exponential function as follows:

$$Incentive\ Index\ =\ 1.65 \times \left(e^{-0.5EE_{BL,\,normalize}} - e^{-0.5EE_{proposed,\,normalized}}\right)$$

The Incentive index can be scaled to specific sub-sector manufacturing context to account for training needs, accessibility of components, etc.

The efficiency improvement-linked incentive could be scaled to the level of efficiency improvement and need for capacity building. In this example, improvements from lowest efficiency to medium efficiency would receive a greater incentive than improvements from medium to high efficiency. This indexing combined with the assessment of the enterprise’s portfolio of products would align funding with greater need for capacity building to access energy efficient designs and components in addition to greater opportunity for energy savings by improving the lowest energy performing product lines

The following examples provide an indication on how the different approaches would result on funding requirements to the MLF.

In the first example, an eligible compressor manufacturer is converting from HFC-134a to HC-600a. The MLF would typically provide ICC for refrigerant conversion. Improving the energy efficiency of the compressors in parallel to the refrigerant conversion would require additional investments, and potential funding from the MLF could be calculated based on the additional costs to create a suite of higher efficiency compressors including variable speed drive (VSD) compressors.

Under approach A [indicative incremental cost] the funding for AOC and ACC would be the same regardless of the beneficiary’s starting capacity and product efficiency level.

Under approach B [efficiency improvement-linked incentive], the AOC and ACC would be reduced according to the efficiency improvement-linked incentive index. If the compressor manufacturer already has the capacity to develop VSD compressors or compressors with higher efficiencies, they would receive less funding for ACC according to the improvement-linked incentive index based on the highest efficiency unit claimed in their catalogue compared with best available technology on the market.

The compressor manufacturer, based on their product development capacity and production volume may elect one of the following strategies:

- **Directly buy** the IP including schematics, controls, power electronics and VSD;
- Develop the capacity internally to design systems based on **open-source** tools[39]; or
- **Build** the capacity independently.

Table 9-7 and Table 9-8 below summarise the costs for a medium manufacturer (production volume of 100,000 units per year) adopting one of the three strategies (direct buy, open-source, vs build) and the theoretical additional funding by the MLF under Approach A (incremental cost) or Approach B (improvement-linked incentive) for two levels of improvement in EE during HFC conversion.

Case 1: The improvement-linked incentive index calculation would cover 80% of the additional cost for an improvement from **lowest efficiency (level 1) to medium efficiency (level 4)** and an assessment of the enterprise's current portfolio showing a need for capacity building (i.e., lack of existing product development capacity, testing facilities, and intellectual properties).

*Table 9-7. Potential additional funding by the MLF under Approach A (incremental cost) or Approach B (efficiency improvement-linked incentive). - Case 1**

OEM options	**Cost to Manufacturer**	**ACC/AOC by MLF (Approach A)**	**Incentive Based by MLF (Approach B)**
Directly Buy	0 capital cost 6.5 USD/unit	0 ACC 650,000 AOC	0.8 × 650,000 = 520,000 USD
Open Source	150,000 capital cost (capacity building) 1.5 USD/unit	150,000 ACC 150,000 AOC	0.8 × (150,000 + 150,000) = 240,000 USD
Build	450,000 capital cost (capacity building + proprietary models development) 1.5 USD/unit	450,000 ACC 150,000 AOC	240,000 USD {same as Open Source}

*Case 1: From level 1 to level 4 (lowest compressor to high efficiency compressor – not variable speed). Incentive index = 1.65 * (e^-0.5 - e^-2) = 0.78 (~ 0.8).

[39] K-CEP supported the World Bank in developing open-sourced tools and training materials for using the tools to design higher-efficiency systems and develop specifications for components.

Case 2: In this case, the incentive index calculation would cover 20% of the additional cost for an improvement from **medium efficiency (level 4) to high efficiency (level 7)** and an assessment of the beneficiary's current portfolio and capacity.

*Table 9-8. Potential additional funding by the MLF under Approach A (incremental cost) or Approach B (improvement-linked incentive index)- Case 2***

OEM options	**Cost to Manufacturer**	**ACC/AOC by MLF (Approach A)**	**Incentive Based by MLF (Approach B)**
Directly Buy	0 capital cost 45 USD/unit	0 ACC 4,500,000 AOC	0.2 × 4,500,000 = 900,000 USD
Open Source	400,000 capital cost (capacity building + new wiring and harness designs) 5 USD/unit	400,000 ACC 500,000 AOC	0.2 × (400,000 + 500,000) = 180,000 USD
Build	700,000 capital cost (capacity building + proprietary models development + new capital equipment) 5 USD/unit	700,000 ACC 500,000 AOC	180,000 USD {same as Open Source}

** Case 2: From level 4 to level 7 (good compressor to high efficiency variable speed compressor – not best available technology). Incentive index = 1.65 * (e^-2 – e^-3.5) = 0.173 (~ 0.2).

This financial model describes how industry could be differentially supported to establish production of energy efficient RACHP equipment. It has the benefit of providing most funding for those enterprises whose equipment currently has the lowest energy efficiency, and who can make the largest improvement. Support for both ACC and AOC would give time for SMEs to develop until they can have sufficient volume of production to become viable.

10 Conclusions

- It is important to consider energy efficiency from a system approach and consider cooling/heating load, equipment, and energy resource quality. Recent developments in the Foams sector and in the buildings envelope has significantly reduced the cooling/heating loads, which enables further reduction in equipment sizes and the corresponding refrigerant charge.
- In many non-A5 and some large A5 parties, where regional and national environmental gas regulations are driving down HFCs on or ahead of the Kigali schedule, high EE RACHP equipment is widely available.
- The dumping of low energy efficient products in low-income countries coupled with the lack of knowledge and higher cost of purchase of energy efficient products contribute greatly to their low uptake.
- Barriers to the introduction of EE RACHP equipment can be overcome by:
    - education and consumer awareness campaigns,
    - reducing the investment risk through incentive schemes such as rebates and innovative financial mechanisms for the consumer,
    - stringent regulations and enforcement such as bans on the import of used equipment and products; the development of regulatory frameworks including MEPS for new and used equipment; investment in testing to provide consistency and clarity for consumers and businesses,
    - upgrading/ developing of training materials/ programs for RACHP technicians in vocational institutions and national associations, to incorporate the specialised knowledge and skills needed to install and maintain EE refrigeration systems.
- There is a global effort towards improving equipment and system energy efficiency. The Montreal Protocol has the potential to maximise the co-benefits through concurrent implementation of HFC conversion while improving energy efficiency. Updated information on one model, the Global HFC Outlook Model, supports that synergised HFC phasedown and EE would give the greatest benefit at least cost. It shows that preventing the continued accumulation of low efficiency HFC equipment is projected to save trillions of dollars by avoiding building power stations.
- The EE co-benefit is not being achieved where the major growth in RACHP is taking place in HAT low-income countries. Building Cooling and Cold Chains demand is increasing rapidly in parties with increasing temperatures and income. At the same time, the RACHP equipment that is accessible to them continues to have low energy efficiency and contain HCFCs/HFCs. This will have a long-term economic impact for individual countries and have adverse impacts on global environment.
- Information is provided on an innovative funding model for A5 parties with low levels of industrialisation to enable manufacturing/ assembly SMEs to compete with large Original Equipment Manufacturers (OEMs) until they can achieve the necessary economies of scale.