MONTREAL PROTOCOL ON SUBSTANCES THAT DEPLETE THE OZONE LAYER

REPORT OF THE TECHNOLOGY AND ECONOMIC ASSESSMENT PANEL

DECISION XXXV/11 TASK FORCE REPORT

ON

LIFE CYCLE REFRIGERANT MANAGEMENT

MAY 2024

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Montreal Protocol on Substances that Deplete the Ozone Layer

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Report of the Technology and Economic Assessment Panel

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DECISION XXXV/11
TEAP TASK FORCE REPORT
ON
LIFE CYCLE REFRIGERANT MANAGEMENT

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DISCLAIMER

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The names of the Task Force Co-chairs and member-authors are given in Chapter 1.

The opinions expressed are those of the Task Force and do not necessarily reflect the views of any sponsoring or supporting organisation.

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Foreword

The 2024 TEAP Report

The 2024 TEAP Report consists of three volumes:

Volume 1: *TEAP 2024 Progress Report covering the following:*

- ***Sector updates (Decisions IV/13 and XI/17)***
- ***TEAP procedures, organisational matters and matrix (Decisions XXXI/8)***
- ***Dec XXXV/6: Updated information on very short-lived substances***
- ***Dec XXXV/8: Feedstock uses***
- ***Dec XXXV/9: Abating emissions of carbon tetrachloride***
- ***Dec XXXV/10: Energy efficiency***
- ***Dec XXVIII/2, par. 5: Technical review of alternatives to hydrofluorocarbons***

Volume 2: *Evaluation of 2024 critical use nominations for methyl bromide and related issues - Interim Report – May 2024*

Volume 3: *Decision XXXV/11: Life-cycle refrigerant management*

This is Volume 3

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TEAP TASK FORCE REPORT

ON

LIFE CYCLE REFRIGERANT MANAGEMENT

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Definitions and Acronyms

Definitions from the Montreal Protocol Handbook

Recovery

The collection and storage of controlled substances from machinery, equipment, containment vessels, etc., during servicing or prior to disposal.

Recycling

The reuse of a recovered controlled substance following a basic cleaning process such as filtering and drying. For refrigerants, recycling normally involves recharge back into equipment, it often occurs "on-site".

Reclamation (Reclaim)

The re-processing and upgrading of a recovered controlled substance through such mechanisms as filtering, drying, distillation and chemical treatment in order to restore the substance to a specified standard of performance. It often involves processing "off-site" at a central facility.

Destruction

A destruction process is one which, when applied to controlled substances, results in the permanent transformation, or decomposition of all or a significant portion of such substances.

Definitions in the context of this report

Availability

The presence of technologies and products for Life cycle Refrigerant Management, such as leak prevention, leak detection, recovery, recycling, reclamation or destruction of refrigerants.

Accessibility

The ability of the user to acquire and/or use technology and products for Life cycle Refrigerant Management. It varies with location within a region, country or even district within a country (impacted by infrastructure, tools, affordability, supply chain, policies, knowledge, servicing capacity …).

Policies

Mandatory requirements from governments or authorities. Examples are legislation, regulations, treaties, decrees, building codes, ordinances, mandatory standards.

Reverse supply chain

The logistic process of returning recovered refrigerant for the purpose of recycling, reclamation or destruction. (the opposite to delivering refrigerant for a new RACHP installation or servicing of an installed RACHP equipment or system).

Acronyms

AC	Air Conditioning
A5	Article 5
AHRI	Air Conditioning, Heating and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
CAA	Clean Air Act
CFC	Chlorofluorocarbon
CO_2e	Equivalents to one unit CO_2
DRE	Destruction Removal Efficiency
EOL	End of Life
EPR	Extended Producer Responsibility
ESG	Environmental, Social and Governance
ETS	Emissions Trading Scheme
GEF	Global Environment Facility
Gt	Giga tonnes
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HCl	Hydrochloric Acid
HF	Hydrofluoric Acid
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HPMP	HCFC Phase-out Management Plan
HVAC	Heating, Ventilation and Air Conditioning
IEC	International Electrotechnical Commission
ISO	International Standards Organization
KIP	Kigali Implementation Plan
LRM	Life cycle Refrigerant Management
LVC	Low Volume Consuming (Country)
MAC	Mobile Air Conditioning
MLF	Multilateral Fund
MOP	Meeting of the Parties
MVAC	Motor Vehicle Air conditioner
non-A5	Non Article 5
ODP	Ozone Depletion Potential
ODS	Ozone Depleting Substance
PCB	Polychlorinated Biphenyl
PFC	Perfluorocarbon
POP	Persistent Organic Pollutant
RACHP	Refrigeration, Air Conditioning and Heat Pumps
RRRD	Recovery, Recycle, Reclaim and Destruction
SAE	Society of Automotive Engineers
TEAP	Technology and Economic Assessment Panel
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VRF	Variable Refrigerant Flow
WEEE	Waste from Electronical and Electric Equipment

Executive Summary

Decision XXXV/11 paragraph 1, requests the Technology and Economic Assessment Panel (TEAP) to prepare a report for discussion at the Forty-sixth Meeting of the Open-ended Working Group of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, on the following topics:

> *(a) Available technologies for the leakage prevention, recovery, recycling, reclamation and destruction of refrigerants, and their accessibility in parties operating under paragraph 1 of Article 5 of the Montreal Protocol, including regionally specific approaches;*
>
> *(b) The obstacles and challenges associated with the effective leakage prevention, recovery, recycling, reclamation and destruction of refrigerants;*
>
> *(c) The costs and climate and ozone benefits associated with the leakage prevention, recovery, recycling, reclamation and disposal of refrigerants, taking into account the experience under the Multilateral Fund for the Implementation of the Montreal Protocol;*
>
> *(d) Policies, incentive schemes, such as producer's responsibility schemes, good practices and lessons learned related to ensuring the effective leakage prevention, recovery, recycling, reclamation and disposal of refrigerants.*

This report aims to provide a comprehensive overview of Life cycle Refrigerant Management (LRM) challenges, opportunities, and strategies, and to equip stakeholders with the necessary knowledge to address refrigerant management complexities effectively. With this report, the TEAP LRM Task Force hopes to support the ongoing dialogue surrounding refrigerant management and establishes the critical importance of LRM to minimise emissions, alongside phasing down HFCs, aimed at a more sustainable refrigeration, air conditioning and heat pump (RACHP) sector.

LRM aims to minimise direct emissions of refrigerants from RACHP systems and can increase refrigerant supply, especially for servicing-only parties that have less flexibility in their approach to phasing out or phasing down refrigerant consumption. Effective leak reduction and refrigerant reuse provides an additional tool to reduce the production and consumption for parties, which can assist with Montreal Protocol compliance.

The Task Force considered four key stages of LRM as follows: (a) preventing refrigerant leakage during design, manufacturing, installation, and operation, (b) recovering refrigerant during servicing and at end-of-life (EOL) and (c) reusing (through either recycling or reclaiming) or (d) destroying recovered refrigerant. Recovery is an essential step prior to reuse or destruction.

Technical elements of good LRM are well understood and comprehensively described in this report. Individual steps necessary to ensure leak prevention, recovery and refrigerant reuse are technically feasible. Additionally, the report describes the significant challenges likely to be faced by all parties implementing LRM initiatives. In particular, the infrastructure needed for the return of used refrigerants ("reverse supply chain"), recovery, reuse and destruction are limited in several parties, particularly in Article 5 (A5) countries and in Low Volume Consuming (LVC) countries.

Key findings

Within the limited timeframe for developing this report, the Task Force was able to draw a number of key findings, which were condensed to emphasize the multifaceted nature of LRM challenges and opportunities, while at the same time highlighting current efforts and policy frameworks which have been put in place to address LRM effectively.

1. Leakage Prevention and Design Considerations

- Effective leakage prevention is integral to LRM and encompasses all stages of the equipment life cycle from equipment design to proper disposal: it requires early actions at the design stage, proper leakage testing during manufacturing and good practices during installation, operation, and maintenance.
- Avoiding venting and leakage of refrigerant during maintenance or at EOL will reduce ODS and GHG emissions from RACHP equipment.
- There are needs for (a) comprehensive training, (b) accessibility to equipment such as appropriate leakage detection methods and (c) regulatory regimes that promote regular RACHP equipment tightness inspection and repair.
- Leak prevention during the operational phase of RACHP equipment lifecycle can maintain performance and energy savings.

2. Refrigerant Recovery

- Effective refrigerant recovery is an essential aspect of ODS and GHG emission reduction from RACHP equipment, and a pre-requisite for reuse or destruction.
- Effective refrigerant recovery requires (a) comprehensive and ongoing technician training, (b) access to appropriate equipment, in particular specialized refrigerant recovery machines, (c) availability of sufficient technician time to ensure good recovery to take place (d) a “reverse supply chain infrastructure” providing technicians access to refrigerant recovery cylinders, and (e) appropriate economic incentives to encourage responsible recovery.
- Ensuring refrigerant recovery during servicing and at equipment EOL for either reuse or destruction, continues to be challenging in most A5 and non-A5 parties, even in parties where policy frameworks have been established and financial support has been made available.
- The drivers that would incentivise the increased recovery rates and leak prevention are highly sensitive to the regulatory environment and to refrigerant prices and availability of alternative technologies. If phasedown of HFCs creates a shortage of refrigerant and leads to price increases, then refrigerant recovery may increase. However, if supply of newly produced refrigerant remains plentiful, other policy and economic measures may be required to incentivise effective recovery.
- Financial support may increase access to recovery equipment and reverse supply chain infrastructure (e.g., cylinder fleets, storage facilities and safe shipping capability) to provide for additional refrigerant reuse or destruction.
- The cost effectiveness of refrigerant recovery has not been fully assessed, as the limited schedule for delivery of this report did not allow for a full evaluation of reverse supply chain costs, especially for LVCs. Additional data would help to develop an assessment of cost effectiveness.

3. Refrigerant Reuse and Destruction

- In order to maximise the ODS and GHG emission reductions from refrigerant recovery, it is essential that recovered refrigerants in cylinders are either reused or destroyed and not emitted to the atmosphere.
- Recovered refrigerant can be reused as either (a) recycled or (b) reclaimed. The Montreal Protocol definition relates to the degree of purification, with recycled refrigerant undergoing simple cleaning whereas reclaimed is processed to a specified purity standard.
- Reused refrigerant does not count towards consumption targets under the Montreal Protocol; hence reuse can be used as a tool to achieve compliance.
- The market for reused refrigerant under a phasedown or phaseout scenario depends on several factors, including (a) the size and accessibility to the bank of refrigerant in installed RACHP systems, (b) the historical success of technical, economic and policy drivers towards recovery and reuse (c) the cost and availability of lower global warming potential (GWP) or zero ODP alternative technologies and (d) the difference between allowable virgin refrigerant supply relative to demand, which impacts refrigerant price.
- Appropriate testing and identification of recovered refrigerants are essential to ensure safe handling, including for destruction.
- Refrigerant recycling equipment is accessible and is used in many parties, especially for single component refrigerants, with technicians able to perform recycling locally.
- Infrastructure needed for refrigerant reclaim can be capital intensive (i.e., requiring sophisticated separation and testing technologies) and is limited in many A5 parties.
- Recovery, and subsequent reuse is highest in markets that allow for direct recycling with little change of ownership (e.g., auto industry recycling in maintenance garages and commercial refrigeration end-users with multiple pieces of equipment), likely because recycling allows for the simplest processing and lowest cost.
- To minimise emissions, refrigerants that are deemed too contaminated to reuse or for which there is low or nil market demand should be destroyed. For destroyed refrigerants to be accounted for under the definition of consumption, they must be destroyed using Montreal Protocol approved technologies. These are not always accessible in A5 parties. LVCs may have least access to destruction technologies. Some parties mandate that Montreal Protocol approved technologies be used for any refrigerant destruction, regardless of consumption accounting.
- The development of a market for end-of-life management of refrigerants is a driver for incremental improvements in destruction technologies. This opportunity will be dependent on the timely acceleration and effectiveness of LRM, HCFC phaseout and HFC phasedown generally as well as the availability of funding mechanisms to support the management of these legacy waste streams.

4. Disparity in infrastructure and accessibility

- The installed bank of controlled substances is currently dominant in non-A5 parties. In the future, however, there is a high probability that these banks become dominant in A5 parties due to RACHP growth. Fostering LRM capacity development in A5 parties, especially in larger industrialised ones, could represent substantial and sustained environmental benefits beyond 2030.
- In some parties, LRM practices have so far achieved modest success. In addition, most A5 parties and especially LVCs have inadequate access to the reverse supply chains, tools and equipment required for LRM.

- The lack of accessibility of recovery and recycling equipment and tools is more pronounced in A5 parties, especially in LVCs, which rely heavily on ongoing external funding, mainly from the MLF. It should be noted that in addition, there are also gaps in accessibility in non-A5 parties.
- Refrigerant reclamation and destruction are especially limited in LVCs and servicing-only regions with insufficient infrastructure or expertise to manage used refrigerants, as a lack of economy of scale make both the capital and running costs uneconomic.
- There is a technology accessibility gap between smaller and larger A5 parties. Smaller A5 parties still need to establish fundamental servicing infrastructure, and also may require access to more advanced LRM technologies. In contrast, larger industrialised A5 parties tend to have more developed infrastructure, but often require upgrades or replacements for their existing tools and equipment to maximise LRM.
- Significant benefits could arise from A5 parties working together in regional groups to set up reclaim and destruction infrastructure. It should be noted that recovered refrigerants subject to a transboundary movement for the purpose of disposal may be classified by some Parties to the Basel Convention as hazardous wastes controlled by that Convention

5. Policy Framework and Capacity Building

- LRM policy enforcement is challenging due to the sheer number of end-users, distributors, and independent contractors that are responsible for leak prevention, refrigerant recovery, recycling and reverse supply chains for destruction and reclamation.
- Various mandatory and voluntary LRM policies and programmes are currently implemented in many parties. Effective LRM necessitates stakeholder support and sufficient capacity, particularly when developing reverse supply chain infrastructure and technician training to manage refrigerants effectively throughout their lifecycle. This is less available in A5 parties.
- The greatest impact on effective LRM is the ease of availability and price of newly produced (virgin) refrigerant. Higher prices for refrigerants create economic incentives for leak prevention and refrigerant recovery and reuse. However high prices may also increase the risk of illegal refrigerant production and trade.
- Additional factors to consider in policies and programmes include complementary policies related to safety and the safe handling/transportation of refrigerants.

6. Barriers, Incentives and Financing Mechanisms

- Lack of consistent policy mandates and enforcement and fluctuating refrigerant pricing of newly produced (virgin) refrigerants make it difficult for reclamation and destruction companies to justify capital investment to support recovery, recycling reclamation and destruction, as well as to fund reverse supply chain infrastructure (e.g., cylinder fleets), even in non-A5 parties.
- Effective implementation of LRM requires comprehensive assessment of the overall costs associated with purchasing, operating, maintaining, and disposing of refrigerants throughout their life cycle. LRM costs could represent a significant economic investment for contractors, end-users, destruction, and reclaim facilities in both A5 and non-A5 parties.
- Expanding current financing mechanisms, including utilising carbon markets and creating innovative ones plus enacting policy changes, may reduce cost challenges linked to implementing LRM, especially in A5 parties.

7. Data Collection and Decision-Making

- Establishing a data collection system could inform decision-making for HFC phasedown initiatives and optimal LRM strategies. Tracking HFC usage by country, sector, and substance provides crucial insights for cost-effective policy development and operational implementation.

8. Ozone and Climate Benefits and Future Outlook

- Ozone benefits:

  Implementing effective LRM practices during the use and end-of-life of RACHP equipment is projected to cut HCFC emissions by about 5 kt ODP between 2025 and 2040.

- Climate benefits:

  Implementing effective LRM practices during the use and end-of-life of RACHP equipment is projected to cut HFC and HCFC emissions by about 39 Gt CO_2e between 2025 and 2050. This would achieve substantial additional climate benefits beyond those currently anticipated from the HFC phasedown agreed under the Kigali Amendment to the Montreal Protocol.

Overall conclusions

LRM minimises refrigerant emissions from RACHP equipment and systems. This report aims to provide a comprehensive overview of challenges, opportunities, and strategies for effective LRM, to provide stakeholders with the necessary knowledge to minimise refrigerant emissions as far as possible. In many parts of the world this will require a technical, policy and behavioural shift away from venting refrigerants.

- This first TEAP LRM Task Force Report emphasizes the critical importance of responsible refrigerant management to minimise emissions, alongside phasing out ODS and phasing down HFCs in increasingly energy efficient RACHP equipment.
- LRM can increase available refrigerant supply, especially for servicing-only parties that have less flexibility in their approach to phasing out or phasing down refrigerant consumption. Effective leakage prevention and refrigerant reuse provide additional tools to reduce the production and consumption for parties, which can assist with Montreal Protocol compliance.
- In the long term, the Kigali Amendment will facilitate a phasedown of high GWP HFC refrigerants. However, in the near- and medium-term there may be a build-up of HFCs in banks in A5 parties (both in RACHP equipment and HFCs for servicing) due to the overall rise in cooling demand in advance of technology transfer to lower GWP alternatives. The phasedown regimes in some A5 parties will ensure a continued market for HFC refrigerants for new RACHP equipment and for servicing. As a result, inexpensive new HFCs may be available in A5 parties, and HFC banks will inevitably build up.
- LRM strategies can help to minimise HFC emissions and make more refrigerant available through reuse, especially for A5 parties. LRM can include refrigerant venting prohibitions, leak prevention strategies, and establishing the reverse supply chain and infrastructure to maximise refrigerant recovery, prior to recycling, reclamation and destruction as appropriate.
- In non-A5 Parties, HFC consumption and production is rapidly phasing down in accordance with F-gas regulations and the Kigali phasedown schedule. In many A5 parties the HFC consumption and production phasedown schedules started from 2024, with some others starting in 2028.

- If phasedown of HFCs creates a shortage of refrigerant and leads to price increases, then refrigerant recovery may increase. However, if supply of newly produced refrigerant remains plentiful, other policy and economic measures may be required to incentivise effective recovery.

Chapter 1

Introduction

Chapter 1 Summary

- Refrigeration, Air Conditioning and Heat pumps (RACHP) are not a luxury, they are increasingly important in preserving life and for the replacement of fossil fuel-based heating.
- Everyone has a responsibility to minimise refrigerant emissions from RACHP into the environment to reduce their ozone and climate impact.
- Life cycle Refrigerant Management (LRM) refers to a comprehensive set of strategies to reduce emissions from the installed refrigerant bank.
- LRM includes leak prevention and recovery, through to recycling, reclamation, and destruction where appropriate.
- Parties to the Montreal Protocol have committed to ODS phaseout and in the case of the Kigali Amendment to HFC phasedown, which includes refrigerant consumption and production. Emissions reduction policies, such as leak prevention and end-of-life recovery and destruction policies are in effect in some parties and sub-national jurisdictions and are variably effective.
- Implementation of LRM measures at scale could reduce near- and long-term emissions from the installed refrigerant bank, protecting both the ozone layer and the climate

1 Introduction

1.1 Decision XXXV/11

With Decision XXXV/11 paragraph 1, parties requested the Technology and Economic Assessment Panel (TEAP) to prepare a report to be presented at the Forty-sixth Meeting of the Open-ended Working Group of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, on:

> (a) Available technologies for the leakage prevention, recovery, recycling, reclamation and destruction of refrigerants, and their accessibility in parties operating under paragraph 1 of Article 5 of the Montreal Protocol, including regionally specific approaches;
>
> (b) The obstacles and challenges associated with the effective leakage prevention, recovery, recycling, reclamation and destruction of refrigerants;
>
> (c) The costs and climate and ozone benefits associated with the leakage prevention, recovery, recycling, reclamation and disposal of refrigerants, taking into account the experience under the Multilateral Fund for the Implementation of the Montreal Protocol;
>
> (d) Policies, incentive schemes, such as producer's responsibility schemes, good practices and lessons learned related to ensuring the effective leakage prevention, recovery, recycling, reclamation and disposal of refrigerants.

1.2 Outline of the report

The report is structured in correlation to Decision XXXV/11 as follows:

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1.3 Life cycle Refrigerant Task Force membership

To respond to the decision, TEAP convened a Task Force consisting of experts from the TEAP, its relevant Technical Options Committees (TOCs) (Flexible and Rigid Foams TOC or FTOC; Fire Suppression TOC or FSTOC; Medical and Chemicals TOC or MCTOC; and Refrigeration, Air Conditioning and Heat Pumps TOC or RTOC), and external experts. Task Force Co-chairs are Roberto Peixoto, RTOC co-chair (Brazil), and Hilde Dhont, RTOC member (Belgium). The following persons are the members of the Task Force:

Jitendra BHAMBURE	RTOC member	India
Tilden CHAO	external	United States of America
Rick COOKE	MCTOC member	Canada
Hilde DHONT	RTOC member	Belgium
Bassam ELASSAAD	RTOC member	Lebanon
Kylie FARRELLEY	RTOC member	Australia
Laurent GUEGAN	external	France
Herlin HERLIANIKA	RTOC member	Indonesia
Ning JENG	external	United States of America
Richie KAUR	external	India
Mary NAJJUMA	RTOC member	Uganda
Elvira NIGIDO	FSTOC member	Australia
Tetsuji OKADA	RTOC member	Japan
Roberto PEIXOTO	RTOC co-chair	Brazil
Thiago PIETROBON	external	Brazil
Fabio POLONARA	RTOC co-chair	Italy
Pallav PUROHIT	RTOC member	India
Rajan RAJENDRAN	RTOC co-chair	United States of America
Madi SAKANDE	RTOC member	Burkina Faso
Helen WALTER-TERRINONI	FTOC co-chair	United States of America
Christian WISNIEWSKI	RTOC member	United States of America
Ashley WOODCOCK	TEAP	United Kingdom

The Task Force included 13 members from non-Article 5 (non-A5) and 9 members from Article 5 (A5) parties. TEAP is grateful for the significant contributions of the members of the Task Force on this report for parties.

This report has been developed through collaborative efforts during the period from January to April 2024, involving several Task Force online meetings and an in-person meeting held in London, United Kingdom, from February 28 to March 1, 2024, supported by the Ozone Secretariat.

1.4 The Importance of LRM and the Purpose of this Report

Refrigeration, Air Conditioning and Heat Pumps (RACHP) are becoming increasingly important as climate change progresses. In some parts of the world, they are essential for life whether through cooling and heating spaces or ensuring food and vaccine cold chains. Everyone has a responsibility to minimise refrigerant emissions from RACHP into the environment to reduce the ozone and climate impact.

This report discusses Life cycle Refrigerant Management (LRM), a comprehensive set of strategies to reduce emissions from the installed refrigerant bank. LRM starts with leak prevention in the design, manufacturing and assembly, servicing and use of RACHP equipment. Recovery is pivotal prior to reuse, recycling, reclamation or destruction as appropriate.

The need for LRM has come to the forefront of global climate discussions, including within the Paris Agreement and the Montreal Protocol. This report is a comprehensive examination of LRM including the challenges associated with it as well as the significant opportunity to mitigate emissions of hydrofluorocarbons (HFCs) and ozone-depleting substances (ODS) within the RACHP industry.

In terms of scope, this report addresses the refrigerant life cycle starting from leak prevention in the design, manufacturing and assembly of RACHP equipment, all the way through the use phase until refrigerant recovery and reuse or destruction. This report does not cover the production stage of the refrigerant itself.

Chapter 2

Technologies for refrigerant leakage prevention

Chapter 2 Summary

- Leak prevention for RACHP equipment is a fundamental component of LRM. Good leak prevention requires early actions at the design stage, proper leak testing during manufacturing, and good practices during transport, storage, installation, operation, and maintenance. It requires (a) comprehensive technician training, (b) accessibility to equipment such as appropriate leak detection technology and (c) a regulatory regime that promotes regular tightness inspection and repair.
- Leak prevention during the operational phase of the RACHP equipment lifecycle can provide significant energy savings.
- Various processes and technologies for leak prevention are well developed and available.
- Leak detection technologies are well developed and widely available for a wide range of applications. However, with changing safety needs for new refrigerants these technologies (such as sensors and software) are evolving and improving. New leak detection methods can be incorporated into equipment and installation design and monitoring strategies.

2 Technologies for refrigerant leakage prevention

Decision XXXV/11 requests information on available technologies for the leakage prevention, recovery, recycling, reclamation and destruction of refrigerants, and their accessibility in parties operating under paragraph 1 of A5 of the Montreal Protocol, including regionally specific approaches. This chapter provides information related to leakage prevention. Information on recovery, recycling, reclamation and destruction of refrigerants is provided in Chapter 3. Information on accessibility of technologies in A5 parties is provided in Chapter 4. Leak prevention is a fundamental component of LRM.

2.1 Definitions

Leak prevention refers to any measure taken to avoid a potential refrigerant loss during the RACHP equipment's life cycle, for example through proper design and installation practices, servicing with sufficient level of skills, regular tightness inspection, etc. The technologies available for preventing leaks are different depending on when, where and how during the equipment life cycle a refrigerant leak may occur. The equipment life cycle stages which are relevant in this context are:

- Design
- Manufacturing
- Transport & Storage
- Installation
- Use
- End-of-life

Tightness inspection refers to verifying whether the refrigerant may leak from the RACHP refrigerant circuit at the time of manufacturing, installation, commissioning or use. This inspection can be done with indirect or direct **leak detection methods** or a combination thereof (see paragraph 2.2). Tightness inspection may be part of a regular maintenance scheme.

Leak identification refers to locating where exactly on the refrigerant circuit the leak occurs, so that measures can be taken to repair it. This is done via direct leak detection methods.

2.2 Technologies for refrigerant leak detection

Technologies for detecting refrigerant leaks, including automatic leak detection systems, are used for assessing the potential presence of a refrigerant leak. These are briefly addressed in the following section to support the leak prevention discussion. The technologies are commonly available and are deployed at the stages of manufacturing, installation, commissioning, use and servicing. Refrigerant detection technologies can be broadly classified as indirect and direct methods.

Tightness inspections can be done via indirect or direct methods, whereas leak identification needs to be done with a direct leak detection method.

<u>Indirect methods</u> are based on identifying abnormal system performance, including analysis of relevant parameters over a period of time, such as pressure, temperature, compressor current, liquid levels etc. They are used for tightness inspection during the manufacturing, installation, commissioning and use phase. They are not suitable for leak identification: in case a leak is suspected, a direct method is used to identify the exact location of the leak.

Indirect methods are useful for complex installations or where the equipment is placed outdoors making it difficult to use leak detector devices. Indirect methods are typically more suited to detect slowly developing leakages compared to direct methods. Critically charged systems where the refrigerant charge is optimised for peak performance will show degradation of performance very quickly even for leaks that are less than 5 to 10%.

Direct methods use refrigerant gas detection devices to check parts of the refrigerant circuit representing a risk of leakage, or a detection fluid in the circuit or soaking methods. These methods are used for tightness inspection, as well as for identifying the exact location of the leak to be followed by repair.

Examples of direct methods are listed below:

- *Helium or nitrogen sensing* for leak detection during manufacturing is often used on compressors, heat exchangers and even on the complete unit.
- *Handheld sensors* or a *soaking test* are used to detect leaks in smaller manufacturing sites. *Hand-held sensors* are also used at the time of commissioning and servicing. Safety standards also recommend pressure and vacuum tests during commissioning in the field.
- *Remote automatic leak detectors* sample the air in the area around the equipment with an infrared sensor, and alert when refrigerant is detected.
- Other technologies for *sensors* include *corona discharge*, *heated diode* and *ultrasonic*.
- *Soapy water* and *pressurised air underwater* can help to localise the leak for repair and are widely used in the informal sector in some A5 parties and especially LVCs.
- *Ultra-violet dye additives* may be introduced into the RACHP system and are carried through the system by the refrigerant/oil. The leak is identified when it is exposed to an ultraviolet light detector used by the technician. This leak detection technique needs approval from the RACHP manufacturer. It is commonly used in the mobile air conditioning (MAC) sector.
- *Acoustic cameras* can detect and process an acoustic signature generated by escaping pressurized refrigerant propagating through pipeline walls, even when surrounded by noisy machinery.

2.3 Technologies for refrigerant leakage prevention

Below are some examples of technologies that may be used to prevent refrigerant leaks during the equipment life cycle, including the stages of design, manufacturing, transport and warehousing, installation, and use. The list is not intended to be exhaustive, and does not include technologies related to refrigerant recovery, recycling, reclamation, and destruction (These are covered in Chapter 3).

2.3.1 Design stage

The design stage is an important stage to reduce and prevent leaks during the equipment life cycle. This can be done by selecting suitable components to minimise any vibrations or friction during the transport and operation of the equipment which could lead to potential leaks. Corrosion protection coating in applications such as saline seashore environment should be given due consideration.

International and national standards provide guidance and recommendations in this regard. Examples of international standards are ISO5149 (Refrigerating systems and heat pumps: safety and environmental requirements) and ISO14903 (qualification of tightness of components and joints). Product specific standards also provide recommendations on how to design leak tight systems. Examples of these standards are IEC60335-2-40, IEC60335-2-89, and IEC60335-2-24.

Examples of specific considerations for components

- The type of compressor chosen is important as some may have more vibration than others.

- Specific consideration must be given to joints and brazed joints (ASHRAE, 2018) and selection of brazing alloy, brazed joint clearances, vibration during the equipment's starting, running and stopping.
- The end plate design of heat exchangers is critical in terms of clearances to avoid relative movement between components.
- Due consideration should be given to the use of copper tubes and brazed joints, as they can corrode when installed in the vicinity of sewage treatment plants, open drains, certain industrial environments, and polluting vehicles. Formicary corrosion usually happens in the indoor unit heat exchanger where copper is used, and the selection of appropriate materials and coating of exposed copper surface is important (ISHRAE, 2023).
- In small equipment, flare connections are often used. The design dimensions of flare nuts are critical as stress can potentially lead to micro cracks and leaks.
- The system pipework needs to be designed to avoid fatigue failure, because the unit system pipework (connecting compressor and heat exchanger and to valves) are subject to strain under different ambient conditions and need to be tested against potential rupture. The copper pipes connecting to compressor are more susceptible as the compressor vibrates during operation and start/stop. Industry has developed standards wherein the product is subjected to 10,000 start stop cycles under different conditions. Strain gauges are put on the pipes and calculations based on material properties are made to verify on safe limits.

The MAC sector has historically been the target for policies and programmes incentivizing better system designs that reduce leaks. Over the last two decades, vehicle OEMs have redesigned O-rings, fittings, gaskets, and seals that have significantly reduced expected leakage from MAC systems. Regulators typically quantify MAC refrigerant leakage using industry standards such as SAE International Standard J2727.

Conducting a Failure Modes and Effects Analysis (FMEA) to identify leak potential is a highly recommended step for the end of the design stage. Numerous references and resources are available for conducting these FMEA studies before releasing a product into manufacturing.

2.3.2 Manufacturing

During the manufacturing of RACHP equipment several technologies can be used to prevent leakages in the equipment life cycle. It is particularly important to assure that the refrigerant circuit is clean, dry and tight before refrigerant is charged into the system, to assure that the charging process is done accurately, and to check the equipment again after charging. Automatic brazing machines help with consistency. On a manufacturing assembly line, brazing is a specialized skill, and careful consideration must be given to brazing torch, flux, preheating and cooling.

A typical manufacturing process could include the following stages:

Piping / Heat exchanger line	Material selection
	Processing
	Brazing
	Airtight test
	Completion
Assembly line	Piping assembly
	Airtight test
	Vacuum drying
	Refrigerant charging
	Electric voltage test
	Operation test
	Leakage test
	Fitting out to completion

Several best practices can be used during the manufacturing process, here are just a few examples:

Tightness test before charging	Pressurize (higher than product design pressure) with a high-pressure gas mixture (helium, air or nitrogen) and confirm tightness with a gas leak detector. Helium leak detection is more effective than pressurized air or nitrogen.
Refrigerant charging	With a refrigerant charging device that can achieve high accuracy levels
Refrigerant leak test	After completion of an operation test, confirm no leakage is present from connecting parts with a gas leak detector sensitivity of 3 g/year

Below is an example of a factory layout for manufacturing (assembling) of RACHP equipment including the manufacturing of the heat exchangers, showing where leak tests can be implemented throughout the process.

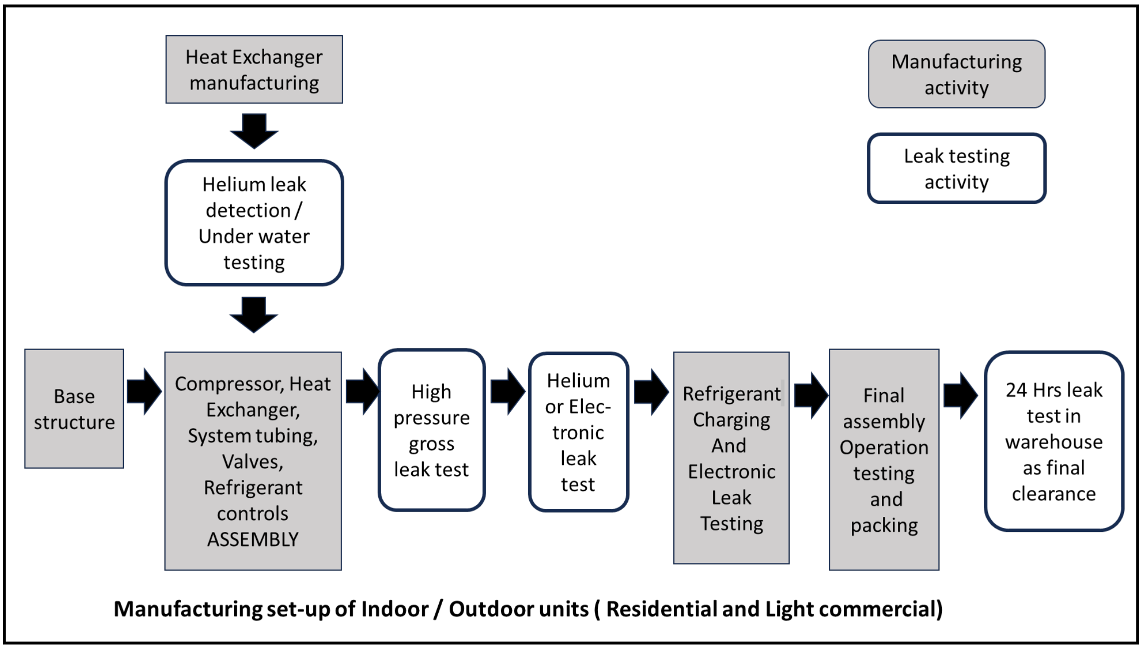

Figure 2.1 Example of factory layout

2.3.3 Transport & warehousing

Equipment may be subject to harsh conditions during transport by road, air and sea. The resiliency of the equipment during transportation must be considered during the equipment design stage. In addition, suitable packaging needs to be provided to avoid damage during both transport and storage. Standards and instruments can be used to test how the equipment behaves during simulated conditions, such as vibration and drop tests.

Inadequately designed packing can potentially lead to leakage of refrigerant during transportation and handling. As a part of design validation, the duly packed product is subjected to vibration and bump tests which reflect the conditions on the road. The units are handled in the various stages of transportation and delivery and in the process the product may get damaged leading to leakage. The popular standards used as reference are:

- The International Organization for Standardization (ISO) standard 2248 outlines procedures for drop tests on packages and their contents, with a focus on assessing the overall package's performance.
- IEC 60068-2-27 requires the specimen to always be mounted to the fixture or the table of the shock testing machine during testing. The testing consists of subjecting a unit either to non-repetitive or repetitive shocks of standard pulse shapes with specified peak acceleration and duration.
- The IEC 60068-2-64 package testing standard addresses structural integrity. The scope of this transit testing standard demonstrates the adequacy of equipment to resist dynamic loads under random vibration. Units that meet the test requirement have no or acceptable degradation of function or structural integrity.

2.3.4 Installation

Installation and commissioning are important, and trained service technicians play a crucial role in leak prevention. In some cases, training may be provided by equipment manufacturers at little to no cost to the installer or user. Selection of the location of the unit is the first important step to ensure adequate air circulation and approachability for servicing. The quality and range of available tools used such as torque wrenches, pressure gauges, leak detectors also play a role in leak prevention. The technicians should be trained to consider the environmental impact and the potential for leakage, mainly due to corrosion.

2.3.5 Use phase

During the use phase of equipment, it is recommended to regularly check if the refrigerant circuit is still "tight". Tightness inspection starts with a visual inspection, followed by direct or indirect leak detection methods, or a combination thereof. Indirect and direct leak detection methods are explained in section 2.2.

Visual inspection focuses on the presence or absence of frost on the heat exchanger, oil bleeding, abnormal vibrations and noise, corrosion or physical damage.

When the tightness inspection concludes that a leak is likely to be present, then the location of the leak needs to be identified using a direct method, followed by a repair.

Standards such as ISO5149 and national policies or legislation may define frequency of tightness inspection, typically depending on the refrigerant charge volume per circuit. Many publications are available from trade and other organisations that provide guidelines for technicians to properly detect, diagnose and resolve refrigerant leak issues (EPA, 2009; JARAC, 2021; JRA GL-17:2021; EU, 2015). The flowchart below illustrates an example of the requirements stipulated in EU Commission Regulation 1516/2007 (EU, 2015).

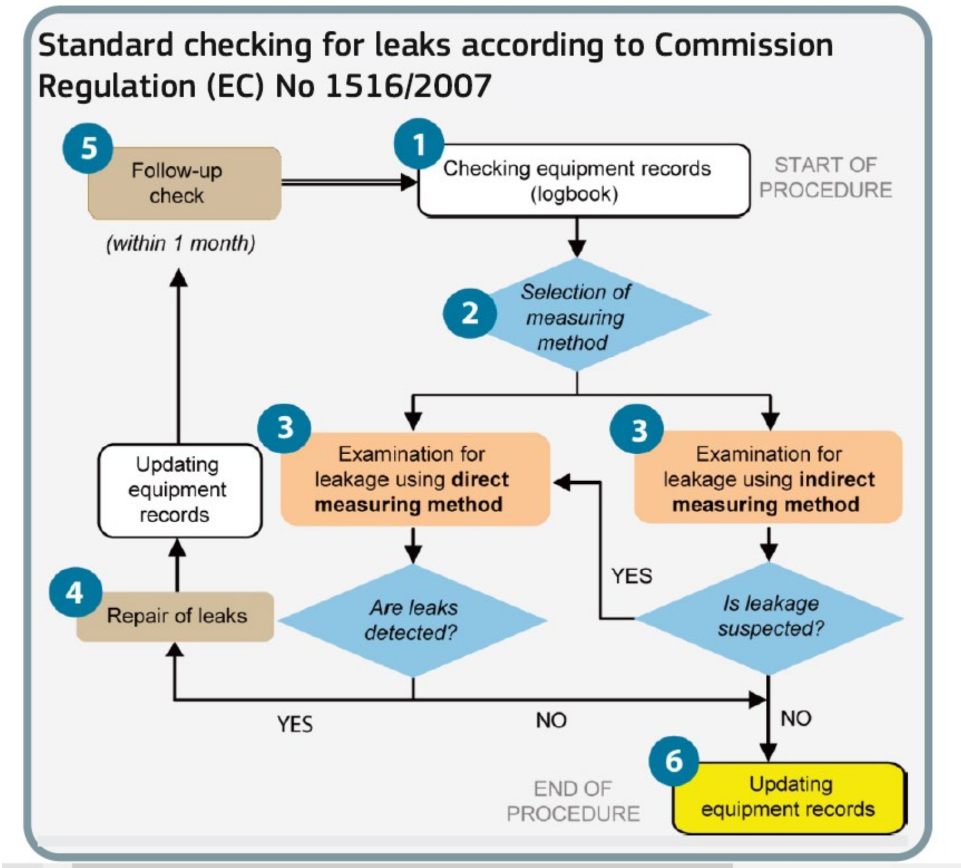

Figure 2.2 Standard checking for leaks according to Commission Regulation EC 1516/2007 (EU, 2015)

2.4 References

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Chapter 3

Technologies for Recovery, Recycling, Reclamation and Destruction

Chapter 3 Summary

- Proper refrigerant recovery utilizing fit-for-purpose recovery machines and cylinders prevents refrigerants from being emitted into the atmosphere. Recovery is pivotal before recycling, reclamation, or destruction can take place as appropriate.
- Recycling and reclamation support the circular economy by reducing the need to produce new (virgin) refrigerants and may create incentives to recover refrigerants during servicing and at equipment end-of-life. Some recovered refrigerants (e.g., highly contaminated) may not be feasibly, or cost effectively reused and need to be destroyed to prevent emissions.
- Refrigerant recovery and the reverse supply chain require fleets of recovery cylinders, storage tanks, and warehouses, as well as ancillary equipment such as vacuum pumps, scales, leak detectors, hoses, gauges, and fittings.
- Selective collection of recovered refrigerant enables efficient recycling, while heavily mixed cocktails of recovered refrigerant require advanced reclamation such as separation and fractional distillation technologies capable of separating each component before re-blending back to desired specifications. In some cases, recovered refrigerants are simply combined with new refrigerants to achieve desired quality levels.
- Chemical analysis plays an important role in controlling the quality of reclaimed refrigerant.
- The Montreal Protocol has established a list of approved destruction technologies. The mandatory use of destruction technologies approved on this list applies to controlled substances destroyed and accounted for within the Protocol's definition of 'production' under Article 7, as well as destruction of HFC-23 to the "extent practicable". Some parties and subnational jurisdictions also require use of Montreal Protocol approved destruction technologies even when controlled substances are not credited to production.
- The primary commercial constraint in destroying refrigerant at scale is recovering large enough volumes of recovered gas to support capital investment for destruction, unless refrigerants are destroyed at facilities that destroy other chemicals. Currently, most destruction capacity is in non-A5 parties and a few industrialized A5 parties.
- Destruction technologies continue to improve in terms of scale, cost, environmental performance, accessibility, and ability to be mobilized closer to sources as there is more emphasis on LRM. In some A5 parties, cement kilns offer a cost-effective method for destruction. LRM efforts, when combined with growing destruction capacity and deployment of financing mechanisms such as EPR and carbon markets, could create robust systems for ODS and HFC destruction.

3 Technologies for Recovery, Recycling, Reclamation and Destruction

3.1 Introduction

Decision XXXV/11 requests information on “available technologies for the leakage prevention, recovery, recycling, reclamation and destruction of refrigerants, and their accessibility in parties operating under paragraph 1 of A5 of the Montreal Protocol, including regionally specific approaches”. This chapter describes technologies associated with recovery, recycling, reclamation, and destruction (RRRD) as well as the supporting infrastructure and ancillary equipment necessary for effective use of those technologies.

Accessibility of these technologies may vary based on a variety of factors, which are discussed in later chapters. The obstacles and challenges pertaining to effective LRM are discussed in Chapter 6 and accessibility of LRM technologies in A5 parties is discussed in Chapter 4.

To fully understand the recovery and ancillary equipment that is required, the following factors needs to be considered.

- Refrigerant properties – high or low pressure, liquid or gas, flammability, toxicity.
- Size of the installation and safest means to access the refrigerant in the equipment itself.
- Volume of refrigerant to be recovered.
- Objective of the recovery - Reuse, recycling, reclamation or destruction.
- Location and safety aspects of the equipment and site - operator and technician safety, safety warnings, accessibility.
- Access to power and fuel sources to enable recovery equipment operation.
- Inventory management record keeping requirements.

3.2 Supporting Infrastructure

3.2.1 Recovery cylinders and storage tanks

Recovery cylinders are designed to contain pressurized and liquefied refrigerants. They are usually refillable and are subject to either national or international design, manufacture, and operational standards and regulations in most parties.

Non-refillable cylinders, known as disposable cylinders, are generally made of thinner metal than refillable cylinders, which makes them more vulnerable to rust and mechanical damage over time. Residual high purity refrigerant in disposable cylinders, known as the “heel”, can be recovered prior to puncturing an empty cylinder. The use of non-refillable cylinders is not recommended for recovered refrigerant.

Cylinders, including their valves need to be suitably sized, labelled and pressure rated for the intended refrigerant they are designed to contain.

A sufficient cylinder fleet will ensure that recovery technicians have enough filling capacity. Having access to sufficient and suitably sized, labelled and pressure rated storage tanks that will then be used to consolidate the recovered refrigerant from the recovery cylinders also underpins recovery. Inadequate storage capacity (cylinders and tanks) would inevitably result in venting practices.

Maintaining an adequate cylinder fleet requires access to facilities that are capable of refurbishing and retesting cylinders (hydrostatically[1]). Depending on the type of cylinder and the type of service of the cylinder, cylinders require testing periodically as prescribed by specific cylinder standards and regulations (which can vary from country to country). The frequency of testing is usually governed by a national agency and needs to be carried out by appropriately qualified personnel.

Managing and tracking a high-quality cylinder fleet creates the opportunity to establish a network for increased recovery. Some large reclamation companies use custom-made and proprietary cylinder tracking and management systems. Labelling assets with a barcode enables the traceability of the cylinder from the day of ownership, visibility on the current location of the cylinder, to tracking the range of refrigerant products it contains, including traceability on the quality of the refrigerants, and ensuring the cylinders are within their test dates.

Refillable recovery cylinders can be offered for use in different ways:

- Recovery cylinders for destruction are emptied and put under vacuum after each use but are not cleaned. Refrigerant recovered into these cylinders can be easily contaminated with other refrigerants, moisture, acid, oil and other impurities such as flammable refrigerants, and must be handled with care for technician, equipment owner and general public safety. Refrigerant recovered into these cylinders is unlikely to be reusable and should be labelled for destruction only.
- Recovery cylinders for the purpose of reuse, recycling and reclaiming (sometimes known as pump down cylinders), are emptied, cleaned, dried and put under vacuum after each use. They are provided to promote selective collection, to avoid cross contamination and to optimize the best yield for treatment.

3.2.3.1 Selective Collection

Selective collection is the practice of identifying high quality used refrigerant earmarked for recycling or reclamation for the purpose of optimised efficiency and yield during the recycling or reclamation process. When recovering such refrigerant, it is necessary to ensure that a recovery cylinder is used for collection to avoid cross contamination and to avoid the creation of bi, tri or quaternary azeotropic mixtures.

Service technicians may need to use multiple recovery cylinders to avoid mixing recovered refrigerants.

3.2.2 Cylinder exchange programmes

In some markets, commercial entities offer mobile recovery services to increase refrigerant recovery rates and provide cylinder exchange programmes to end users and wholesalers.

These include having an adequately sized cylinder fleet and logistics mechanisms to offer an on-site empty refrigerant recovery cylinder exchange service that helps the end user manage their used and unwanted refrigerant. The supplier delivers empty recovery cylinders and once filled, exchanges them with another cohort of certified cylinders, which are empty and under vacuum. In some cases, the supplier pays for the refrigerant that has been returned.

A slight variation to the cylinder exchange programme includes working with participating wholesalers in the market. End users fill recovery cylinders and return the filled cylinder to the participating wholesaler. The wholesaler collects the full cylinder and exchanges it with

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[1] Hydrostatic testing is a method to assess the structural integrity of the cylinder, by filling it with a liquid which is pressurised to a specific test pressure. The cylinder is then examined for leaks or changes in shape.

an empty one. The full cylinder is then collected by the reclaimer or destruction company, which again, in some cases, pays for the refrigerant.

3.2.3 Scales

Scales are an important tool in safely aggregating and storing refrigerant by preventing overfilling. Cylinders and any form of storage containment needs to be safely filled as per the relevant design and operating standards and regulations. Overfilling can be avoided by using fit-for-purpose calibrated scales (weighing devices). Scales and weighing devices need to be a suitable size and accurately measure the weight of the refrigerant in the cylinders of various sizes, storage tanks or bulk vessels (tank farm, ISO tanks).

3.2.4 Tools and fittings

Servicing tools, fittings, adaptors, pressure gauges, hoses, piping, vacuum pumps and leak detectors that are appropriately rated for refrigerants need to be available, be in a serviceable condition, maintained and used in accordance with the manufacturer's instructions, to avoid the potential for emissions from incorrect installation, use or selection.

3.3 Quality control

To determine whether a recovered refrigerant could be reused and where (in the RACHP system from which it was extracted, or in a similar system, or in a different system), it may be necessary to know its composition by conducting a chemical analysis.

Chemical identification /analysis of the refrigerant can be done on site using portable refrigerant identifiers or offsite at established laboratories that have the capability to perform full analysis, for example to Air-conditioning, Heating, and Refrigeration Institute (AHRI) Standard 700.

3.3.1 Analysis kits

Analysis kits and refrigerant identifiers are commercially available, but they do not identify the full range of ODS, HFC or HFO refrigerant substances. Many have limited ability to identify the presence of contaminants such as CO2, hydrocarbons, non-condensable, acids or oils. To the best knowledge of the Task Force, kits for analysis of new HFC/HFO refrigerant blends are not yet commercially available.

3.3.2 Full chemical analysis

Chemical analysis of refrigerants prior to any treatment determines the subsequent processing (recycling, reclamation or destruction). After processing, further full chemical analysis establishes whether the processed refrigerant meets the required product specifications.

Gas chromatography is the most accurate method for identifying refrigerant composition but is expensive and often not readily accessible. It uses complex equipment operated by qualified professionals. Laboratory quality reference samples for calibration can be difficult to obtain in some parties. Commercial reclamation companies have this capability in house or may offer this service for a fee. In some parties, reclamation companies that supply AHRI 700 standard reclaimed product must provide laboratory certificates showing the product has been certified to that standard prior to resale.

3.3.3 Warehousing and logistics

Recovered refrigerant in cylinders needs to be safely handled, transported, and stored pending consolidation in appropriate warehouses or facilities. Suitable transport, inventory management and storage (in accordance with local dangerous goods / hazardous chemicals regulations), and specific control and emergency planning measures (especially for large volumes of product), are necessary to mitigate not only emissions, but also health and safety risks.

3.4 Technologies available for recovery

Proper refrigerant recovery utilising appropriate and serviceable recovery equipment prevents refrigerants from being emitted into the atmosphere.

Refrigerant recovery equipment is used to remove the refrigerant from equipment before repairing, performing maintenance, or decommissioning systems. Refrigerant recovery machines are devices that recover the refrigerant into a cylinder for subsequent recycling, reclamation, or destruction. AHRI Standard 740 (2016) outlines performance rating of Refrigerant Recovery Equipment and Recovery/Recycling Equipment, however this standard has not been universally adopted.

Some jurisdictions impose evacuation performance standards on recycling and recovery machines.

3.4.1 Recovery equipment

The two most common recovery methods are:

1. *Gas recovery*: Not a very fast recovery method, but easy to do.
2. *Overpressure recovery* (Push-Pull): More sophisticated, but quicker due to significant higher flow rate.

In both cases, recovery of the vapour phase takes the longest and requires a machine equipped with a condensing system. With both techniques, refrigerant, oil and inadvertently other contaminants are recovered.

Compact, easy-to-transport recovery machines are available on the market that offer different capacities and efficiencies. However, these machines do not separate the oil and other contaminants contained in the refrigerant. Some recovery equipment can add additional impurities to the recovered refrigerant. For example, if the recovery equipment uses a lubricated compressor, additional oil from the compressor may be introduced to the recovered refrigerant. The use of equipment operating with a dry oilless compressor is necessary to avoid adding oil to the recovered refrigerant for reuse, recycling or reclaiming process.

Some recovery equipment on the market does not provide a sufficient vacuum to meet national and international standards and guidelines that define performance and operation standards.

All in one or RRR (Recover, Recycle and Recharging) machines are commonly used in the MAC sector where single component refrigerants such as CFC-12, HFC-134a or HFO-1234yf are used. This equipment recovers refrigerant, some types recycle with filtering and drying to remove moisture and other contaminants, and then recharges the system using either new or recycled refrigerant. Quality testing is required to avoid cross contamination.

3.4.2 Custom made recovery equipment and services

Depending on the scale, nature, and time requirements for the recovery, custom-made equipment can help facilitate the recovery process. To date, custom-made mobile and portable high-speed recovery equipment has been manufactured and deployed to some remote or restricted areas. This equipment has allowed refrigerant recovery at rates up to 10 times faster than traditional off-the-shelf recovery equipment.

Custom made equipment is not commercially available for purchase, however in some regions is used in conjunction with mobile recovery services and cylinder exchange programmes. A financial incentive for the recovered product may be provided in some cases. The recovered refrigerant is returned for further processing (recycling, reclamation or destruction). Examples of such policies and programmes are given in chapter 5.

3.5 Reuse

Recovered refrigerant can be reused as either (a) recycled or (b) reclaimed. The Montreal Protocol definition of these terms relates to the degree of purification, with recycled refrigerant undergoing simple cleaning whereas reclaimed refrigerant is processed to a quality standard. In practice the reuse of refrigerants can also occur immediately and without treatment on site when servicing or repairing a system.

3.6 Technologies available for recycling

Recycling is the filtration and drying process of recovered refrigerants to remove particulate, oil, moisture, and acidity and non-condensable. Recycling is most suitable for single component refrigerants. The recycling of multiple component blends of refrigerants often requires addition of new refrigerant or distillation and re-blending to achieve the original refrigerant composition. Recycling normally, but not always, involves re-charging back into the systems in which the refrigerant was originally recovered and often occurs on-site. ISO5149 standard provides recommendations for the use of recycled and reclaimed refrigerants, although national policies may deviate from it, and commercial contracts may have more or less stringent requirements regarding quality of recycled and reclaimed refrigerants (This is explained in chapter 6).

An example method to remove non-condensable gases is separation by a two-chamber membrane vent and separator system with different pressure and temperature. The high-pressure chamber contains non-condensable gases mixed with the refrigerant, and refrigerant is filtered through a selective membrane into the low-pressure chamber.

Some recovery machines on the market have a built-in filter, oil separator and dryers, whereas other require an additional external system.

Depending on the equipment used or the quantity of oil or moisture in the system, recycling machines may not adequately remove all impurities.

To avoid cross-contamination, it is recommended that recycled refrigerant only be used in the equipment from which it came or in similar types of equipment. Using new or recovered refrigerants or refrigerant blends in systems for which they are not designed can result in different system performance (e.g. more energy use). (Reference: DCCEEW Bench Testing Study).

3.7 Technologies available for Reclamation

Reclamation is the re-processing and upgrading of a recovered refrigerants in order to restore the substance to a specified standard of performance. This may include filtering, drying, distillation and chemical treatment. It usually involves processing “off-site” at a central facility. The performance level may be specified by standards such as AHRI-700, country policies or commercial agreements.

Where possible different types of recovered refrigerants should not be mixed in recovery cylinders however this can be challenging if the supply of available empty cylinders and storage tanks is limited.

Heavily mixed blends of recovered refrigerant require advanced reclamation equipment such as separation and fractional distillation technologies capable of separating each component before re-blending back to new specifications.

The reclamation of blends presents particular challenges as in some cases composition changes can occur if the different components have different evaporation temperatures. It may occur at several stages: in use in the event of a system leak, during recovery, and during the reclamation process itself. Often reclaimed blends need to be re-mixed with new (virgin) refrigerant or reclaimed single component refrigerants to meet the required specification.

3.7.1 Distillation

Distillation is a process to separate chemical mixtures and remove impurities (e.g. oils, water) by heating and cooling and removing streams at various temperatures in the distillation column. Impurities and even mixtures can be removed because different chemicals have different boiling points.

Distillation is a very effective purification process for single component refrigerants such as HCFC-22, HFC-32 or HFC-134a. The simple distillation separates contaminants such as oil, moisture, and non-condensable components (e.g. nitrogen) at a temperature of around 25°C.

For multi component refrigerants distillation is more complex and often less effective, especially when the components have similar boiling point temperatures.

3.7.2 Adsorption

Adsorption technologies use different materials (including membranes and activated carbon) to remove impurities such as moisture, oils and particulates. It is a relatively simple method that does not require multiple devices to extract pure refrigerant from a contaminated waste stream. In these methods the refrigerant enters a chamber where a specific component is captured by absorbent beds/materials that are exclusively designed to trap a specific refrigerant. Oils and particles are cleaned from the chamber and the refrigerant is desorbed through heat application, vacuuming, or purged using other gases such as nitrogen or helium as removal agents (Status Consulting 2010). These materials do lose their adsorption capacity overtime and the activated carbon will need to be reactivated. (Ana Belén Pereiro Estévez, NOVA University, Interview, February 27, 2023).

Membranes, activated carbon or any other absorbent materials are designed for a specific refrigerant. This requires a laboratory and advanced technology to be able to adjust or create a material with a specific value for porosity, surface area, elasticity, thermal and chemical stability among other physical and chemical properties (Status Consulting 2010).

The most common materials used in the adsorption of refrigerants are:

- *Activated carbon*: Adsorption with activated carbon is one of the most effective methods for reclamation. Activated carbon is accessible and has lower costs than the other materials. Different pore sizes are used to capture different refrigerants.
- *Membranes*: Membranes have specific physical and chemical properties that allow them to capture refrigerants and serve as a permeable barrier for some compounds. They have the advantage of being effective without the application of temperature or pressure. Also, they can be combined with solvents and nanotechnology to improve their properties including the adsorbent potential and the type of refrigerant that they can capture (Ana Belén Pereiro Estévez, NOVA University, Interview, February 27, 2023). http://www.ket4f-gas.eu/.
- *Metal-organic frameworks (MOFs)*: MOFs are highly complex and advanced three-dimensional structures formed by an array of metal ions with very high thermal and chemical stability. They use metals like zirconium to create highly porous structures with specific chemical properties that allow the capture of specific refrigerants. However, these materials require advanced technology and have high costs (Wanigarathna, Gao, and Liu 2018).
- *Advanced Solvents*: There are many solvents with the ability to capture and clean refrigerants and other fluorinated gases. They can be used, for example, to remove a

refrigerant from activated carbon. Ionic liquids are the most ideal solvents for reclamation processes. They have the advantages of being non-flammable, stable and non-volatile. Moreover, they can be immobilised with a supporting structure allowing the refrigerant to pass through, while separating non-desirable molecules and pollutants (Valkenberg, deCastro, and Hölderich 2002).

3.7.3 Sub cooling

Sub cooling and purification is another method used to reclaim refrigerants. Unlike distillation, this method can operate in low volume applications and is adaptable to different refrigerant species without significant changes to setup of the equipment. Additionally, since the refrigerants are mostly in a liquid state, the risk of a leakage is significantly lower than in other reclamation methods.

This process is carried out in three stages: Firstly, the refrigerant is condensed and kept in a liquid state by maintaining temperatures below its boiling point. The refrigerant is cryogenically filtered using coalescent filters and other types of microfilters to remove impurities and unwanted particles. Finally, a micro compressor equipped with a purge is used to capture the non-condensable impurities.

Whilst this method can achieve very good results in terms of the removal of particles and non-condensable gases, high establishment costs due to high-end tailormade technology means that it is rarely used for the reclamation of refrigerants. The energy consumption of the sub cooling method is also up to three times higher than that of distillation. (Stratospheric Protection Division and US EPA 2020).

3.7.4 Custom-made refrigerant separation equipment

Significant capital is required to build custom made reclamation equipment capable of separating and purifying complex refrigerant mixtures. Off -the-shelf units have limited sizes and reduced capacity to effectively separate the complex mixtures. Custom-made equipment also brings with it higher costs to maintain and operate at scale, given the nature of the equipment involved, for example distillation/fractionation towers, large storage tanks, valves, piping, inventory management systems etc.

Investment in sophisticated custom-made fractional distillation equipment by commercial entities is dependent on the increasing demand for reclaimed refrigerant supply in the market, the ongoing volume of refrigerant feedstock available and the composition/levels of refrigerant species impurities like CFCs, HCFCs and HFCs commingled in the same cylinder or bulk tank.

Some small enterprises remove contaminants and blend in new refrigerants to achieve the necessary composition of refrigerant blends. This is a lower cost alternative, but it does not allow for separation of multi-component blends or mixed refrigerants.

3.8 Destruction

To minimise emissions, refrigerants that are deemed too contaminated to reuse or that are no longer needed in the market should be destroyed. This section addresses destruction technologies and their application to environmentally sound destruction of refrigerants at end-of-life (EOL). This encompasses the application of the list of destruction technologies approved by Montreal Protocol parties as applied to parties' obligations. It also addresses other technology application options and associated trends that may be more broadly applicable in managing EOL ODS/HFCs outside the specific obligations of the Montreal Protocol.

The Montreal Protocol has established a list of approved destruction technologies that are required to be used for the destruction of controlled substances for the purposes of Montreal

Protocol production data reporting requirements. These are updated periodically on TEAP's recommendation by Decisions of the parties. The most recent list of approved destruction processes is contained in the Montreal Protocol Handbook as amended under MOP decision XXXV/5 in relation to application of cement kilns for dilute waste streams and assignment of portable plasma arc as a sub-set of nitrogen plasma arc.

The mandatory use of destruction technologies approved by Parties applies to the amounts of controlled substances destroyed and accounted for within the Protocol's definition of 'production' under Article 7, as well as destruction of HFC-23. This listing of technologies and the associated destruction removal efficiency (DRE), environmental emission standards and good practice guidance can also serve as a reference and guidance for destruction undertaken outside the Parties obligations under the Montreal Protocol. However, Parties may choose other technologies meeting national regulatory requirements where destruction is being undertaken outside their obligations under the Montreal Protocol.

The comprehensive list of destruction technologies approved by parties has been updated, with the most recent list of approved destruction processes contained in Annex II to the 30th MOP under decision XXX/6, as amended by decision XXXV/6:

Destruction procedures | Ozone Secretariat (unep.org)

The approved technologies can be grouped into three general categories:

- thermal oxidation,
- plasma technologies,
- chemical transformation technologies which are generally applicable to processes intended to recover chemicals that are not controlled substances for reuse within a production or manufacturing process.

For practical purposes the technologies that are available and realistically accessible for the destruction of EOL refrigerants generated will be within the categories of thermal oxidation, plasma arc and cement kiln.

Overall, there is adequate global capability and capacity for the destruction of halogenated chemicals including ODS/HFC refrigerants, with high levels of DRE and environmental performance. However, this is unevenly distributed between non-A5 versus A5 parties, and between industrialised A5 parties versus non-industrialised A5 parties (Chapter 4). Additionally, DRE and environmental performance may vary significantly between individual facilities utilising the same type of technology. Therefore, facility specific qualification of both types of performance is recommended.

Looking forward, it can be anticipated that destruction technology may improve in cost, scalability, mobility and efficiency, to respond to the growing market need for EOL management of refrigerants. This will depend on the timely acceleration and effectiveness of LRM and HFC phasedown generally as well as the availability of finance to support the management of these legacy waste streams (see Chapter 7). The emphasis on large facilities based on economies of scale to justify destruction may evolve to scaled down technologies such as plasma arc or new smaller scale technologies. These will be more economically viable for use close to the sources of EOL materials. Another expected trend may be the use of existing thermal industrial processes such as cement kilns, particularly in A5 parties. These require modest incremental investment to handle ODS and HFC refrigerants in addition to related waste streams such as foams.

3.8.1 Thermal oxidation

Thermal oxidation or incineration is the use of controlled flame combustion to destroy substances in an engineered device. The technologies have been developed for the dedicated incineration of ODS/HFCs, co-incineration of ODS/HFCs along with other waste or ODS incineration in a manufacturing process. For example, liquid injection incineration, gaseous flume oxidation, porous thermal reactor, and reactor cracking are integrated into process plants for halogenated by-product destruction, including for ODS and in most cases for HFCs, such as HFC-23. Equipment used in thermal oxidation facilities need to be constructed with materials compatible with acids, particularly HCl and HF especially due to HF formation in exhaust gases due to HFC destruction to avoid excessive downtime for maintenance.

3.8.2 Argon and nitrogen plasma arc

The use of plasma arc technology for destruction is long established and has been used in Australia since the 1990s to effectively destroy ODS and HFC refrigerants. Both argon and nitrogen plasma arc technology operate by way of pyrolysis.

As described in the TEAP Decision XXIX4 Task Force Report from April 2018 the pyrolysis process mixes liquid or gaseous waste directly with an argon plasma jet (“in flight”) generated by an electric plasma torch. Argon prevents reactions with the torch components. Waste is rapidly heated in the reaction chamber (a flight tube) to about 3,000ºC where pyrolysis occurs. Pyrolysis is followed by rapid alkaline quenching to less than 100ºC, which limits the formation of dioxins/furans, followed by exhaust gas passing through a caustic scrubber prior to release. A recently introduced refinement of the technology includes additional off-gas treatment.

Argon plasma arc is a well-established technology with more than 25 years of experimental and commercial experience in the destruction of CFCs, HCFCs, halons and HFCs. Worldwide it is understood that 12 units are operated commercially, largely for ODS and HFC destruction, including in Australia (4 units), Japan (4 units), Mexico (2 units), and the United States of America (2 units), with reported development projects in Canada.

The technology was specifically identified in the submission from Australia for application to HFCs, with supporting information provided by two operators/technology suppliers. Additional data applicable to HFC destruction in the United States of America uses the same technology. It was also identified in Mexico’s submission as being applied to HFCs with limited supporting performance data. Canada identified a refrigeration servicing company that is in the process of developing a plant for ODS and HFC refrigerant destruction.

3.8.3 Cement kilns

Cement kilns are identified as one of the most common methods of refrigerant destruction in A5 parties due to their accessibility and affordability. It is estimated that more than 2500 cement plants (GIZ 2020) could potentially be used for managing waste, including the destruction of refrigerants.

To date, despite its high potential, the destruction of refrigerants in cement kilns is limited (refer to Chapter 5 for the known list of installations worldwide).

Cement kilns have fundamental characteristics that make them ideal for the disposal of refrigerants, amongst other things. High temperatures reaching 1000°C – 1600°C combined with long resistance time of up to 10 seconds, good turbulence and mixing conditions, and oxygen supply, thermal inertia and dry scrubbing of the exit gas and not producing by-products from the waste.

Cement kilns are large rotating cylinders of varying sizes. The raw material for cement production is fed into the elevated, cool end of the kiln. As the kiln rotates the raw material for cement tumbles down towards the hotter, lower end of the kiln, forming clinker. The unwanted refrigerant is injected into the hottest end of the kiln and flows upward passing over the raw material, ensuring destruction, and the products of decomposition are absorbed by the clinker and leave the kiln at the higher end. The gas then passes through pollution control devices before entering the atmosphere.

Small amounts of fluorine can be beneficial to the cement making process because it allows the cement clinker formation to occur at lower temperatures, thus offering the opportunity for reduced fuel consumption. However, fluorine and chlorine levels need to be carefully monitored as higher levels of fluorine have negative effects on cement quality. Chlorine is considered an unwanted constituent which can create problems for pre-heater/pre-calciner dry process kilns which have the lowest tolerance for chlorine.

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Chapter 4

Accessibility of Life cycle Refrigerant Management technologies in A5 parties

Chapter 4 Summary

- Accessibility to LRM is impacted by commercial infrastructure, regulatory frameworks, economic considerations, and capacity building initiatives. Accessible tools and infrastructure are two critical pillars for an effective LRM system.
- Insufficient LRM infrastructure access impedes effective refrigerant management. This includes capital intensive processes like reclamation and destruction, and the necessary infrastructure or expertise to effectively manage used refrigerants.
- LRM technology is not consistently accessible in A5 parties. There may be more infrastructure in A5 parties that have larger consumption. Lower consumption, servicing only A5 parties may have less access to reverse supply chains or regional infrastructure to support refrigerant reuse and destruction.
- Sufficient replacement or upgraded tools and equipment (e.g. recovery machines and cylinders) are needed in many, if not most, A5 parties, including those with larger refrigerant consumption.
- Effective implementation of LRM options relies on a multifaceted interplay of factors, including awareness of options, robust policy framework, cost-effectiveness, incentives, and recovered refrigerant value versus new (virgin) refrigerant.
- The lack of availability of recovery and recycling equipment and tools is more pronounced in LVC A5 parties, which rely heavily on ongoing external funding from sources, mainly the Multilateral Fund (MLF).

4 Accessibility of Life cycle Refrigerant Management technologies in A5 parties

4.1 Introduction

Decision XXXV/11 requests information on "available technologies for the leakage prevention, recovery, recycling, reclamation and destruction of refrigerants, and their accessibility in parties operating under paragraph 1 of A5 of the Montreal Protocol, including regionally specific approaches". Chapters 2 and 3 listed many examples of technologies which are available for LRM. "Availability" refers to the presence of technologies and products for LRM, such as leak prevention, leak detection, recovery, recycling, reclamation or destruction of refrigerants. This chapter focuses on the "accessibility in A5 parties", where accessibility refers to the ability of the user to acquire and/or use technology and products for LRM. It varies with location within a region, party or even district within a party (impacted by infrastructure, tools, affordability, supply chain, policies, knowledge, servicing capacity, etc.)

Access to the LRM technologies is necessary for various stakeholders including manufacturers, installers, technicians, maintenance contractors, reclaimers, and end users, to work together effectively in preventing refrigerant emissions.

LRM accessibility is linked to several factors, including access to knowledge, training, and regulatory frameworks, which are covered in chapters 5 and 6. In this chapter, the focus is on accessibility to the infrastructure, tools and equipment necessary for implementing the five key processes of leak prevention, recovery and recycling, reclamation (of single substances, blends, and complex recovered mixtures of recovered refrigerants), as well as destruction. The discussion is limited to A5 parties. Chapter 5 provides examples of policies that facilitate accessibility, while Chapter 6 examines the obstacles and challenges that act as barriers to this accessibility. Chapter 5 and 6 cover both A5 and non-A5 parties.

This Chapter aims to examine accessibility in groups of parties based on the classification of party categories outlined by the TEAP 2023 Replenishment Task Force (RTF) (TEAP, 2023) and to draw conclusions regarding general accessibility trends, potentially providing a pathway forward. Since equipment and chemical usage varies between parties of different sizes and manufacturing capabilities, the RTF allocated the 144 A5 parties into "brackets" based on their baseline HCFC consumption in metric tonnes. The party category classification into five different brackets (A through E) is provided in Annex I.

- Bracket A is based on baseline HCFC consumption over 25,000 mt.
- Bracket B is based on baseline HCFC consumption from 10,001 to 25,000 mt.
- Bracket C is based on baseline HCFC consumption from 2,001 to 10,000 mt.
- Bracket D is based on baseline HCFC consumption from 360 to 2,000 mt.
- Bracket E is based on the list of HCFC low volume consuming parties (LVCs) (see Annex 3, TEAP 2023).

4.2 Background

Parties encounter challenges in accessibility to LRM which may be due in part to lack of, or insufficiency of the following factors:

- Tools and equipment
- Infrastructure
- Supporting policies
- Enforcement mechanisms

- Training
- Labour and employment
- Economic viability
- Environmental awareness
- Cost effectiveness

Capacity for LRM varies with i) the type of application or product, ii) the size and level of industrialisation of the country, and iii) the regions within the same country, with greater accessibility in urban areas.

Accessibility to LRM capacity varies across different regions:

- There is an uneven accessibility in A5 parties to LRM technologies, particularly to advanced reclaim and destruction capabilities. The implementation of Kigali Implementation Plans (KIPs) might contribute to enhancing access to leak prevention, recovery, recycling, and reclamation and destruction technologies.
- Smaller A5 parties are still developing basic servicing infrastructure and capabilities while increasing their access to advanced technologies. Larger industrialized A5 parties have better accessibility to the technologies but the tools and equipment are often in need of upgrade and/or replacement. The level of infrastructure accessibility tends to correlate with the level of consumption and economies of scale in the country.
- Other factors that may impact accessibility include a) awareness of the options, b) application of the relevant policy, c) cost (please refer to Chapter 7), d) incentives or disincentives put in place, e) the relative price of recovered (buy-back) versus new (virgin) refrigerants (see chapter 6).
- RRRD operates in reverse to the supply chain for equipment and new (virgin) refrigerant, i.e. it starts from the end-user point where the RACHP equipment is installed. Both logistic processes need accessibility to their corresponding technologies for proper functioning and can be operated in a complementary fashion.
- In the absence of a profitable business model, the capital investment for LRM in LVC[2] parties is unlikely without alternative mechanisms (Chapter 7).

The primary focus of this report is on accessibility for LRM for ODS and HFCs. However, in the future, accessibility needs to extend to low GWP replacements for HFCs, some of which are toxic or flammable (i.e., hydrocarbons, ammonia).

4.3 Accessibility landscape across the globe

The LRM Task Force has collected available information on the status of accessibility in terms of infrastructure, training and tools in the party categories as mentioned earlier. Additional information is available from the Climate and Ozone Protection Alliance (COPA, 2023) and US EPA (EPA, 2021) reports. The information is by no means exhaustive and not intended to pre-judge whether certain parties have sufficient infrastructure or tools for a proper LRM. Surveys made under Executive Committee Decision 91/66 on banks will contribute to better characterisation of the parties' status and proposed action plans on waste refrigerants. The information below does not replace the need for these surveys, nor does it intend to offer a solution for the needs of the parties.

[2] LVC: Low Volume Consuming (party)

A survey of parties on the African continent collected information on the status of accessibility to the infrastructure and tools needed for a working LRM. Please refer to Annex II for the survey outcome on accessibility in Africa.

4.3.1 Accessibility: Leak detection and prevention

Leak prevention is a best practice that largely depends on the availability of tools and appropriately trained technicians. Appropriate training includes a qualification or certification programme to demonstrate the application of good practices, including leak detection. Chapter 2 described technologies for leak prevention and detection.

The emerging inverter variable speed technology for air conditioning includes a microprocessor controller that may have the capability of a built-in predictive leak detection technology. The accessibility to this technology depends on the availability of the inverter equipment.

In A5 parties in **Brackets A & B**[3], which generally include larger equipment manufacturing A5 parties, leak prevention testing is conducted at various stages of equipment life cycle, including research and development, manufacturing, installation, and maintenance, with tailored approaches for each stage. Manufacturers of RACHP systems are increasingly using electronic and helium leak detection systems. Additionally, leak detection and prevention are commonly practiced during the maintenance of large commercial facilities. Utilization of a fault diagnostic model and a prediction model, applied for refrigerant leak, based on system data and low-cost sensor is documented in Lei *et al*. (2022).

In A5 parties in **Brackets C & D,** which generally include other manufacturing parties, the adoption of helium leak detection has been relatively low, but it is steadily growing in manufacturing. Electronic leak detectors are widely utilised by service technicians employed in formal medium to large enterprises. However, a challenge persists among technicians working individually, who reportedly often rely solely on traditional leak detection methods like soap solutions due to their affordability.

In A5 parties in **Category Bracket E**, which are LVCs with a primary focus on the servicing sector, leak detection technologies are infrequently used in the residential sector, but more prevalent in the commercial sector. There are reportedly insufficient leak detectors for the number of technicians in some parties. Maintaining, calibrating, and ensuring the upkeep of leak detection technologies has been reported as posing challenges in Category Bracket E parties. Much equipment is serviced by technicians in the informal sector using simple leak detection techniques, such as inspection and soapy water.

4.3.2 Accessibility: Recovery and Recycling

Accessibility to recovery and recycling is increasing in all A5 parties due to their adoption in HCFC Phaseout Management Plan (HPMP) programmes. However, capacity remains inadequate, particularly in LVCs, and recovery rates remain low. Accessibility to recovery and recycling is expected to increase under the KIP programmes especially in the years up to 2030 when the harmonization between HPMP & KIP activities will be taking place.

Access to recovery equipment alone will not contribute to improved LRM without access to a reliable, safe and well managed multi-use recovery cylinder stock, and the physical capacity to return refrigerants to a central storage location equipped with bulk storage cylinders. Without this storage hub and network, technicians will revert to venting or even stop recovering altogether (please refer to Chapter 6).

[3] Party classification is provided in Annex I and based on the classification of party categories outlined by the TEAP 2023 Replenishment Task Force (TEAP, 2023)

To increase accessibility to recovery and recycling, parties and stakeholders must recognise the benefits to refrigerant recovery and take ownership of the issues preventing it. End users also need to be educated on the harmful environmental impacts of venting and request the proper application of good refrigerant handling.

Brackets A & B: Refrigerant recovery from domestic refrigerators and air conditioners at their end-of-life is practiced in some parties where regulation exists. The low charge inside these appliances is a challenge for recovery during servicing which often leads to leaks and emissions. Recovery is more prevalent in larger equipment, with recycling typically occurring during maintenance of large-scale refrigeration systems, where refrigerants are purified for reuse. When recovery does happen from household appliances or scrapped vehicles, the refrigerants are stored and sent to reclamation companies. China hosts over ten companies specializing in refrigerant reclamation. Despite the easy availability of recovery equipment, challenges persist due to a lack of awareness about recovery processes, the affordability of recovery equipment, sufficient cylinders for storage, and lack of regulatory measures and its enforcement against venting. Although equipment is not scarce, in most cases the financial burden of purchasing it falls on technicians, presenting a significant obstacle.

- Refrigerant recovery is more common in the commercial and industrial sectors, often performed by large enterprises. This may be due to the economy of scale and application of regulation in those sectors. Some companies report recovery data due to environmental, social, and governance (ESG) programmes. In some parties, annual CO_2 emission reporting is mandatory for enterprises exceeding a designated turnover amount.
- Recovery is more common in MAC and large equipment (e.g. commercial refrigeration and air conditioning and industrial process refrigeration). For MAC, on-site recycling is prevalent for the recovered refrigerants. The recovered refrigerant from large equipment and industrial sources is more likely to be sent for reclamation or destruction. The availability of these tools is concentrated in major urban centres.

Brackets C & D: There is a mix of recovery and recycling accessibility with varying infrastructure levels with an increasing number of trained technicians and moderate regulatory frameworks.

Some parties have enterprises that provide accessibility to recovery equipment and incentives to enable technicians recover refrigerants and deliver them back for further processing. Equipment accessibility is reviewed for some parties in a CEEW report "*Global Best Practices on Life cycle Refrigerant Management*" (CEEW, 2023)

Bracket E: In LVCs, there is a trend for the establishment of recovery and recycling centres, also referred to as centres of excellence, focused on the collection of ODS. In some cases, tools have been made accessible to the parties through MLF-funded projects, but access and maintenance of those tools for technicians may be limited. Many of these parties have recovery and recycling machines kept in training centres for training purposes, but without the infrastructure and equipment being available more broadly, recovery and recycling in practice remains limited.

4.3.3 Reclamation, separation, and testing

The factors affecting accessibility to recovery and recycling also apply to reclamation; however, accessibility to reclamation and substance separation (beyond simple blending) is more complex. Parties might have access to the reclamation equipment, but this will be ineffective without appropriate logistics, and a business model that allows for the refrigerants to be collected and delivered to the reclamation centres. The economies of scale play a part in the success of the reclamation process, as well as the price of refrigerant and the supporting policies.

The Ozone Secretariat website lists under its Country Data page the reclamation facilities that were reported by the parties. The latest reporting dates back to 2000 while the rest date back to the 1990s (Ozone, 2024). Accessibility is improving through the proliferation of multinational refrigerant management companies that possess the technology and are operating across borders.

Reclamation centres for single component refrigerants are widely established, but those for the separation of blends or commingled refrigerants are mainly limited to larger industrial parties (Brackets A & B). Because of the complexity of the reclamation process, some parties shy away from establishing such centres.

Without a reclamation centre in an individual party, there is the option to export refrigerant to another party with reclamation, separation or testing capabilities. However, all relevant export protocols need to be met, and the Basel Convention could act as an obstacle to export (Chapter 6).

Some parties and end-users require that AHRI-certified testing of refrigerant be completed. This barrier limits the use of reclaimed refrigerant by adding costs and there are only seven AHRI certified laboratories[4][5], four in the United States of America, two in Malaysia, and one in Singapore. Several other laboratories can test reclaimed refrigerants and follow AHRI-700 in their analysis. Note that certification to the AHRI-700 specification is not mandatory in most parties, where commercial agreements regarding refrigerant quality are made independent of the standard. Non-AHRI certified laboratories may be used to validate quality, if agreed to by both entities.

Brackets A, B & C: Some parties have access to reclamation centres and lab testing capabilities; however, the labs are often lacking appropriate certifications. Where in-country reclamation is not possible, multinational refrigerant management companies are sending the refrigerants to larger regionally accessible reclamation facilities. An example is Australia for A5 parties in Southeast Asia.

Brackets D & E: Several parties, that have no accessibility presently, are in the process of establishing reclamation centres. Other parties with accessibility to reclamation centres have not put those to use due to economies of scale and low-cost new (virgin) refrigerant, which is further elaborated in Chapter 6. There is also insufficient volume of the reclaimed refrigerant to keep the equipment running. In some cases when parties have reclamation centres, they don't have the means to test the quality of the reclaimed refrigerants. Parties in these two brackets have very limited capabilities to separate comingled components or gas mixtures.

There is a deficit of facilities for reclamation, separation, and testing in some parties who have an accelerating use of refrigerants and blends. Some of these parties may be a desire refrigerant reuse to add to the supply of refrigerants. They also may seek to implement strategies to avoid the environmental impact of venting to the atmosphere. This may require investment in:

- Local facilities for single component refrigerants in most/all parties
- Blending to reclaim multi-component refrigerants
- Advanced equipment for separation and purification of complex mixtures, especially as the trend for using more refrigerant blends increases. (Theodoridi *et al.* 2022)
- Coordination and planning at national and regional levels for the most cost-effective logistics and provision.
- Review/coordination with the Basel Convention to allow trans-national movement of refrigerants where needed for reclamation, separation, and testing.

[4] Reference: Quick Search (ahridirectory.org)

[5] https://www.ahrinet.org/search-standards/ahri-700-700c-and-700d-specifications-refrigerants

4.3.4 Accessibility: Destruction

Destruction capacity is mainly concentrated in some non-A5 parties with mature high-quality chemical hazardous waste destruction capability, operating commercially or as part of the chemicals production facilities. Such facilities are also becoming increasingly available in larger A5 parties.

Existing industrial facilities, particularly cement kilns, have been used for destruction in both non-A5 and A5 parties and have the potential to be utilised with modest investment in qualification, reception, and feed infrastructure. In practice, parties where most of the refrigerants require destruction at EOL would usually have access to such capability either in the country of origin or in the region where capacity exists. There is growing advocacy for the use of cement kilns to increase cost-effective destruction accessibility closer to the source (COPA 2023), (IGSD 2023). A significant obstacle, as noted in Chapter 6, to allowing this global capacity to be most efficiently used is the complexity and variability of national and international regulatory regimes that may apply to doing so.

Some parties classify used or EOL refrigerants in a different way from newly produced (virgin) refrigerants, suggesting the need for a consistent approach to Basel classification. This is further discussed in Chapter 6. The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, usually known as the Basel Convention[6], is an international treaty that was designed to reduce the movements of hazardous waste between nations, and specifically to prevent transfer of hazardous waste from developed to less developed countries. The convention states that illegal hazardous waste traffic is criminal but contains no enforcement provisions. The control of transboundary movement of listed hazardous waste requires substantial administrative, time, and transactional cost challenges, in particular in cases where volumes are relatively small. In many A5 parties, there is limited institutional capacity within governments to administer the process of export.

Some parties classify used or EOL refrigerants in a different way from newly produced (virgin) refrigerants, suggesting the need for a consistent approach to Basel classification. Transboundary movement could then be done more efficiently and cost-effectively, while potentially reducing emissions. This is further discussed in Chapter 6.

In 2021, a U.S. Environmental Protection Agency (EPA) report (EPA, 2021) identified 166 destruction facilities globally, of which 14 were in A5 parties.

Globally there are many facilities with the capability and capacity to provide high destruction efficiency/high environmental performance at EOL. There are no technological limitations – the capacity is large in that it serves a large halogenated hazardous waste market within which the EOL of ODS/HFC is a small component.

The primary issue lies in the unequal distribution of destruction facilities between non-A5 and A5 parties (Brackets A and B), as compared to other A5 parties (Brackets C, D and E). Cement kilns, now increasingly considered for the EOL of ODS/HFC destruction, offer opportunities to expand this accessibility across A5 parties.

Refrigerant destruction today mainly uses commercial facilities with large rotary kiln incinerators, plasma arcs, and cement kilns. In the future, the anticipated development of effective and efficient LRM (capturing larger markets of refrigerants) may drive the

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[6] Basel Convention > The Convention > Overview > Text of the Convention

commercial development of facilities regionally and nationally. Additionally, smaller scale destruction technologies closer to the source could be financed in LVCs such as through carbon offsetting. This would address the logistical and economic barriers detailed in Chapter 6.

The examples listed below are not exhaustive of what exists in A5 parties; they are listed here for demonstration of the capabilities that exist in some regions. The parties are listed alphabetically.

Africa: Only three parties are reported to have access to destruction infrastructure. Ghana has a rotary kiln with limited access and Benin has a cement kiln. Tunisia is in the process of establishing a rotary kiln as part of a demonstration project. See also survey information in Annex II.

Brazil: One demonstration Project for Waste Management and Final Disposal of Substances that Deplete Ozone (ODS), was implemented in Brazil between 2014 and 2022. The incineration equipment, located at Caieiras-SP, underwent adaptations for the burning process of ODS with high chlorine and fluorine content. Reclaim and storage centres were involved in supplying refrigerants for the burn tests and analysis of the collection cylinders. Work undertaken by the implementing agency in preparation for the above MLF demonstration project (MLF, 2014) identified and undertook a preliminary evaluation of seven incineration facilities of various technologies operating as commercial hazardous waste enterprises or located in chemical or pharmaceutical production facilities that had the capability to destroy halogenated wastes and could potentially be qualified for destruction of MP controlled substances.

Colombia: During an MLF demonstration programme, a medium-sized commercial hazardous waste rotary kiln facility (two units) was fully qualified in accordance with Montreal Protocol requirements for the destruction of CFC-11, CFC-12, and HCFC-22.

Costa Rica: Consideration is being given to qualifying a cement kiln for destruction of halogenated chemicals including persistent, organic pollutants (POPs) (PCBs, pesticides) under a Global Environment Facility (GEF) project, which if successful would offer qualified capacity for ODS/HFC destruction. This could also offer a regional option for ODS/HFC destruction in Central America and the Caribbean subject to local regulations and trans border arrangements.

Indonesia: possesses at least two facilities that are technically capable of destroying ODS and HFCs. These facilities are incinerators designed for primary purposes other than fluorocarbon destruction.

Mexico: An MLF demonstration programme qualified a cement kiln and a commercial scale plasma arc facility for the destruction of CFC-12 and HCFC-22 and the latter is currently being considered for destruction of HFC-23 by product from HCFC-22 production**.** Mexico could potentially offer access to its facilities to parties in Central and South America with no domestic access to ODS/HFC destruction of their own.

Pacific Island parties do not possess destruction capacity and often face significant barriers in exporting recovered refrigerant for reclamation or destruction due to the Basel Convention. Fiji has a cement kiln in country, but it has not yet had a proper assessment to destroy fluorocarbons at TEAP-required levels. Neighbouring parties, including New Zealand and Australia possess argon plasma arc destruction technology and might be a resource for EOL ODS/HFCs from neighbouring small island states.

Thailand: There are two facilities that perform fluorocarbon destruction (E&E Solutions Inc., 2015) for disposing of hazardous waste in Thailand. One facility is licensed to commercially destroy fluorocarbons that are brought in from outside sources. An in-house disposal facility of a Japanese manufacturer mainly destroys fluorocarbons that are discharged in repairing off-spec products produced on the plant line and fluorocarbons that are discharged every morning in the inspection of refrigerant filling machine. With the current licence, it is allowed to perform destruction of fluorocarbon it generates in-house, but it is not permitted to accept fluorocarbons from external companies or plants.

Trinidad, Cuba, and Jamaica have cement kilns that could potentially destroy ODS. However, other parties within the Caribbean region with no local destruction capacity usually cannot logistically or cost-effectively export refrigerant for destruction.

Türkiye: has a high-volume commercial rotary kiln hazardous waste facility fully qualified for a wide range of halogenated hazardous waste including all major annexed Stockholm Convention chemicals (PCB, DTT, HCD, etc.) which serve as reference chemicals for ODS and HFC destruction qualification. Several other smaller commercial rotary kiln facilities handling non-halogenated hazardous waste exist but are not licenced for halogenated chemicals. Additionally, Türkiye has a large modern cement industry that would potentially have an interest in waste streams serving to offset current carbon emissions.

Vietnam has at least one qualified cement kiln operated by a major multi-national company that was formally qualified for destruction of POPs (PCBs and POPs pesticides) under a World Bank-GEF project in accordance with the destruction and environmental performance standards applied under the Basel and Stockholm Conventions. These are more stringent than those applied under the Montreal Protocol for controlled substances. This facility has undertaken additional destruction for POPs and obsolete pesticides on a commercial basis. By applying relatively minor infrastructure modifications, it could be considered as a qualified, available, and accessible facility for the destruction of EOL ODS and HFCs on a national basis and, potentially, for the region. This is subject to local regulatory requirements and trans border transaction arrangements.

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Annex I

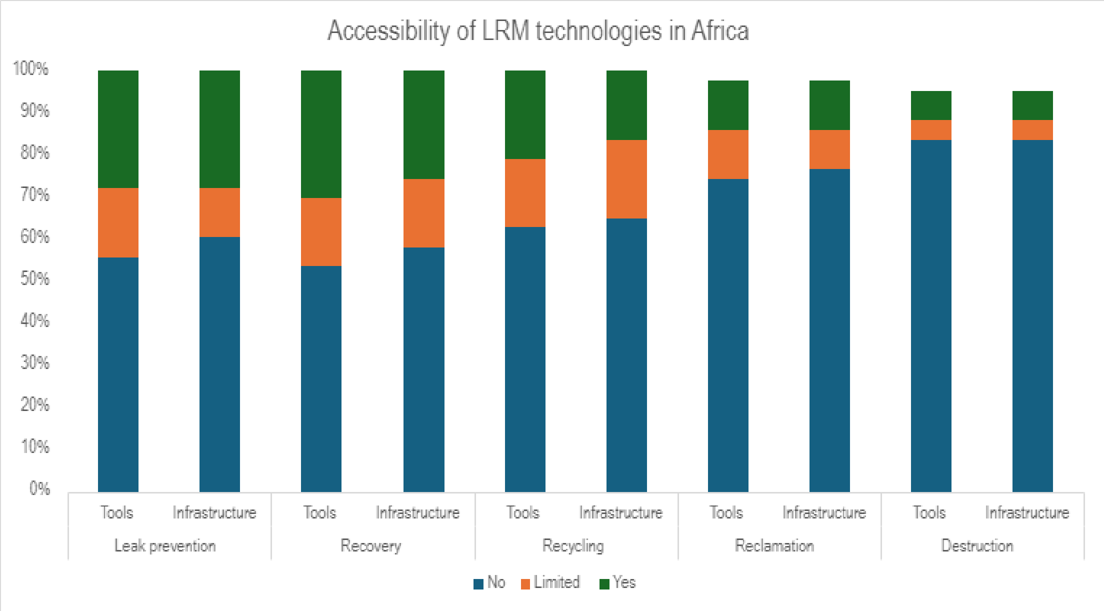
Categorization of parties according to the TEAP RTF (TEAP, 2023).

Bracket (mt HCFCs)	Parties
A: Over 25,000	***Group 1:*** China
B: 10,001 to 25,000	***Group 1:*** Brazil, Mexico, Thailand ***Group 2:*** India, Saudi Arabia
C: 2,001 to 10,000	***Group 1:*** Argentina, Colombia, Egypt, Indonesia, Malaysia, Nigeria, Philippines, South Africa, Türkiye, Venezuela (Bolivian Republic of), Viet Nam, Yemen ***Group 2:*** Iran (Islamic Republic of), Kuwait, Pakistan
D: 360 to 2,000*	***Group 1:*** Afghanistan, Algeria, Bangladesh, Cameroon, Chile, Côte d'Ivoire, Democratic People's Republic of Korea, Dominican Republic, Ghana, Guinea, Jordan, Kenya, Lebanon, Libya, Mauritania, Morocco, Panama, Peru, Senegal, Somalia, Sudan, Syrian Arab Republic, Trinidad and Tobago, Tunisia, Uruguay ***Group 2:*** Bahrain, Iraq, Oman, Qatar
E: HCFC LVCs	***Group 1:*** Albania, Angola, Antigua and Barbuda, Armenia, Bahamas, Barbados, Belize, Benin, Bhutan, Bolivia (Plurinational State of), Bosnia and Herzegovina, Botswana, Brunei Darussalam, Burkina Faso, Burundi, Cambodia, Cabo Verde, Central African Republic, Chad, Comoros, Congo, Cook Islands, Costa Rica, Cuba, Democratic Republic of the Congo, Djibouti, Dominica, Ecuador, El Salvador, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Fiji, Gabon, Gambia, Georgia, Grenada, Guatemala, Guinea Bissau, Guyana, Haiti, Honduras, Jamaica, Kiribati, Kyrgyzstan, Lao People's Democratic Republic, Lesotho, Liberia, Madagascar, Malawi, Maldives, Mali, Marshall Islands, Mauritius, Micronesia (Federated States of), Mongolia, Montenegro, Mozambique, Myanmar, Namibia, Nauru, Nepal, Nicaragua, Niger, Niue, North Macedonia, Palau, Papua New Guinea, Paraguay, Republic of Moldova, Rwanda, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Samoa, Sao Tome and Principe, Serbia, Seychelles, Sierra Leone, Solomon Islands, South Sudan, Sri Lanka, Suriname, Timor-Leste, Togo, Tonga, Turkmenistan, Tuvalu, Uganda, United Republic of Tanzania, Vanuatu, Zambia, Zimbabwe

* NOTE: Benin, Gabon, Niger, and Togo received funding for HPMPs as being LVCs. They are classified in this report under Bracket E. Madagascar had its baseline changed and is an LVC.

Annex II

Fig. AII.1 Accessibility of LRM technologies in Africa



	Leak prevention		Recovery		Recycling		Reclamation		Destruction	
	Tools	Infrastructure	Tools	Infrastructure	Tools	Infrastructure	Tools	Infrastructure	Tools	Infrastructure
No	56%	60%	53%	58%	63%	65%	74%	77%	84%	84%
Limited	16%	12%	16%	16%	16%	19%	12%	9%	5%	5%
Yes	28%	28%	30%	26%	21%	16%	12%	12%	7%	7%

A survey on the accessibility of LRM technologies in Africa sent to 54 parties in Africa, received 43 responses that have been considered for this analysis.

Leak prevention: Though the tools have been made available in most of the parties through different programmes such as the HPMPs and the Green Cooling Initiative, only 28% of the parties have access to leak prevention tools and infrastructure, whereas 56% and 16% have no and limited access respectively. Some of the equipment is reported to be obsolete since it was acquired over 20 years ago.

Recovery & Recycling: Access to tools and infrastructure is still limited in Africa with a range of 16% to 19%. Though the infrastructure is available in mainly training centres, local technicians/end users have limited access to the tools outside the training. The technicians may receive free hands-on training with the tools; however, a high percentage cannot afford them for their workshops.

Reclamation: 12% of the parties reported to have received reclamation equipment through the HPMP but are not in use due to the challenges mentioned in chapter 6 involving business models for the operation of reclamation centres.

Destruction: Only three parties are reported to have access to destruction infrastructure.

Chapter 5

Overview of policies, regulations, and projects related to Life cycle Refrigerant Management

Chapter 5 Summary

- While no LRM policy or programme can achieve full end-of-life recovery or eradicated refrigerant emissions, parties with strong consensus and high stakeholder awareness have developed more successful LRM policies.
- LRM policies and programmes vary in level of development, and include aspects of leak prevention; recovery, recycling, reclamation and destruction.
- Many parties' policies and programmes implementation provide important lessons learned, including their varying degrees of success.
- Technician training programmes are elements included in more in particular with a change in culture from venting refrigerants, is a key component of an effective LRM programmes.
- Programmes include voluntary action, compliance offset generation, incentive-based programmes, and corporate citizenship programmes, among others.
- There are complementary policies and programmes which support LRM, such as those related to safety and energy efficiency.

5 Overview of policies and programmes related to Life cycle Refrigerant Management

5.1 Introduction

Decision XXXV/11 requests information on "policies, incentive schemes, such as producer's responsibility schemes, good practices and lessons learned related to ensuring the effective leakage prevention, recovery, recycling, reclamation and disposal of refrigerants". This chapter provides an overview of different policies and programmes, including successes and opportunities for improvement for effective and efficient implementation of LRM.

Policies in the context of this report refers to mandatory requirements from governments or authorities. Examples are legislation, regulations, treaties, decrees, building codes, ordinances, mandatory standards. Programmes include various types of voluntary initiatives such as guidance documents, demonstration projects, stakeholder initiatives, and voluntary standards.

Several policies and programmes include aspects related to refrigerant management for leak prevention, recovery, recycling, reclamation, and destruction.

- Leak prevention policies and programmes are focused on reducing releases of refrigerant from equipment to ensure that equipment is operated efficiently and as intended. Within leak prevention, policies related to tightness checks and leak detection may be included.
- Policies and programmes related to refrigerant recovery, recycling, and reclamation focus on the proper handling of refrigerant, generally when such equipment is repaired, undergoes a refrigerant retrofit or reaches the end-of-life and the refrigerant can be recovered. Subsequent reuse of recovered refrigerants after recycling or reclamation can ensure continued supply of those refrigerants for servicing legacy equipment and may provide the benefit of avoiding additional production of new (virgin) refrigerants. It should be noted that policies and programmes that encourage high refrigerant reuse can extend the life of equipment for decades, which can provide benefit when there are no technical alternatives (e.g., halons for airplanes), but it may also extend the life of antiquated, leaky inefficient equipment. Such policies can be complemented by effective leak prevention to manage releases of refrigerants.
- Destruction policies and programmes focus on the management of refrigerants that are deemed to be unwanted or not recyclable or reclaimable. For example, refrigerant may be destroyed if it is too contaminated to be effectively reclaimed, if there is deemed to be excess refrigerant in the market, if there is a desire to sunset some types of equipment or if there is no infrastructure or market to reclaim refrigerants.

In general, these policies and programmes seem to be more effective when implemented in combination with measures associated with ODS phaseout and HFC phasedown, and with stakeholder support.

In addition, the most successful LRM policies and programmes have been implemented by parties where there is a high level of awareness, understanding and consensus across stakeholders, particularly industries and refrigerant end-users. This leads to stakeholders' active participation in policy and programme development and being fully engaged in LRM implementation.

In addition to the policies and programmes directly related to LRM aspects, Parties may have complementary policies and programmes that support good LRM practices. Examples are those related to transport, storage, handling, data collection and reporting. In some cases, such additional policies or programmes could also create obstacles and challenges, this is discussed in Chapter 6.

An integrated plan within a country and region is synergistic in LRM. Leak minimisation, together with cost-effective recycling and reclamation conserves the amount of refrigerant in use and reduces the need for newly produced (virgin) refrigerants. Good servicing practice together with effective destruction programmes all contribute to further reduce emissions and environmental harm.

5.2 Overview of types of policies and programmes

As defined in this report, policies refer to mandatory requirements from governments or authorities. Examples may include legislation, regulations, treaties, decrees, building codes, ordinances and mandatory standards. Other types of refrigerant management initiatives may include voluntary programmes, partnerships, incentive-based programmes, carbon markets, and corporate-level actions. Such policies and programmes have been in place at different levels and for varying lengths of time at the national and subnational levels in many parties. Policies and programmes related to LRM generally focus on management of refrigerants in RACHP equipment. However, some programmes extend beyond recovery and handling of refrigerants from these types of equipment, such as the recovery of foam blowing agents from foams within the equipment or appliances and fire suppressants. While some policies and programmes exist governing non-refrigerant end-uses of ODS and HFCs, this report is limited to refrigerant-related policies and programmes.

5.3 Policies and programmes related to leak prevention

5.3.1 Overview

As explained in Chapter 2, leak prevention occurs at several stages of the RACHP equipment life cycle, including during the design process, charging equipment during manufacture, transport and storage, installation (including charging), use phase, and at the end-of-life of the equipment.

This chapter section 5.3 provides examples of policies and programmes that address leakage prevention.

Leak prevention policies and programmes include a wide array of requirements (e.g., equipment design and maintenance, qualification, certification and licensing, repair and reporting requirements, venting prohibitions etc.). Some of the requirements are listed separately highlighting the broad array of these policies and programmes.

5.3.2 Equipment design, including international and national standards

Several international standards detail requirements to reduce leaks from RACHP equipment. Examples are generic and specific equipment (product and system) standards such as ISO5149, IEC60335-2-40, IEC60335-3-89, as well as component and joint standards such as ISO14903. The standards have been reflected into policies in several parties (e.g., through building codes and other policies) and reduce emissions from equipment by design.

For example, the European Union (EU) mandates RACHP equipment design through product safety regulations, the Low Voltage Directive (for household equipment), the Machinery Directive (for non-household equipment) and the Pressure Equipment Directive (for both commercial and household equipment). These policies require manufacturers and importers to complete risk assessments and determine ways to mitigate or reduce those potential risks to ensure that only safe products are placed on the market, including safety risks associated with refrigerant leaks. Harmonised European standards may be used by manufacturers to demonstrate compliance with these directives, but they are not mandatory.

5.3.3 Manufacturing safety policies that reduce emissions

There are also policies and programmes designed to prevent emissions during manufacturing to protect the safety and health of the workers and/or surrounding community (especially while charging equipment or from storage locations). Some examples include the EU ATEX Workplace Directive (EU)[7], the EU SEVESO[8] Directive and the EU REACH regulation[9]. ISO45001:2018 is an example of an international standard for occupational health and safety management systems.

5.3.4 Transportation safety policies that reduce emissions

There are also safety-related transportation policies that are designed to reduce emissions during equipment transport to minimize human exposure and safety risks.

Due to the trans-border nature of transport, international agreements may have an impact on local policies. Examples of international agreements are ADR[10] (UNECE) related to road transport and the Dangerous Goods Regulation (IATA)[11] related to air transport. These agreements may require specific measures for leak prevention depending on the type and weight or volume of refrigerant contained in the equipment. In some cases, transport may not be allowed, as is the case for air transport of RACHP equipment containing flammable refrigerants.

An example of a national policy is the Pipeline and Hazardous Materials Safety Administration (PHMSA) in the United States which mandates pressure testing and design requirements for shipping of equipment containing refrigerants.

In the EU, various types of legislation apply when the RACHP equipment is transported by road/rail/sea/other waterways. Road tunnels may have additional restrictions.

5.3.5 Refrigerant release prohibitions and repair mandates

Many parties have policies that prohibit intentional release of refrigerants from RACHP equipment or mandate repair when a leakage is detected. Below are some examples.

In Eritrea, the Environmental Protection and Management Regulation “Legal Notice 127/2017” prohibits any project or activity which is likely to discharge emission to the environment in excess of the amount declared. The National Waste Management Directive 01/2023 gives responsibility and guidance to the generator of waste to manage its waste (where possible) through the 3 Rs (Reuse, Recycling and Reprocessing) mechanisms.

The South Korean Act on Control of Manufacture of Specific Substances for the Protection of the Ozone Layer prohibits unauthorized release of refrigerants into the atmosphere from equipment used to cool and heat buildings, freeze and refrigerate foods, and for commercial and industrial cooling, and mobile air conditioning. The Act also requires annual inspection for refrigerant leakage.

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[7] ATEX workplace Directive : Directive 1999/92/EC of the European Parliament and of the Council on minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres.

[8] SEVESO Directive : Directive 2012/18/EU of the European Parliament and of the Council on the control of major-accident hazards involving dangerous substances.

[9] REACH Regulation : Regulation 1907/2006 of the European Parliament and the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals.

[10] ADR (UNECE) Agreement concerning the International Carriage of Dangerous Goods by Road

[11] DGR : Dangerous Goods Regulation, by IATA (International Air Transport Association)

Section 608 of the U.S. Clean Air Act (CAA) prohibits the knowing release of refrigerant during the maintenance, service, repair, or decommissioning of refrigeration and AC equipment.[12] The updated U.S. EPA 2020 rule maintains provisions on the venting prohibition, sales restriction and technician certification requirement, safe disposal requirements, evacuation requirements, reclamation standards, and requirement to use certified recovery equipment for substitute refrigerants (e.g., HFCs).

Leak repair requirements for ODS-containing equipment under section 608 of the CAA include various provisions to ensure leaks that are detected are properly repaired. The requirements include certain provisions for verification that leaks have been repaired and recordkeeping and reporting. In general, U.S. EPA requires that owners or operators of equipment containing 50 or more pounds of ODS refrigerants must take corrective action is leak rates exceed certain thresholds that vary by end-use. If leaks cannot be repaired within the specified timeframe, owners or operators may be required to develop equipment retrofit or retirement plans and carry those plans out within a year (U.S. EPA, 2023a).

Similar policy measures exist in European parties, Türkiye and many other parties.

5.3.6 Policies and programmes designed to reduce emissions by best practices in maintenance.

Predictive and preventive maintenance (including inspection) can be very effective in reducing and preventing equipment and piping leaks.

The EU ODS regulation and the EU Fluorinated (F)-gas regulation mandate regular tightness inspections of RACHP equipment depending on the refrigerant charge contents.[13] Separately, the European Energy Performance of Buildings Directive mandates regular energy efficiency inspections of cooling and heating systems above 70kW capacity which also implies tightness inspections.

In China, leak prevention for equipment that use ODS are regulated under "Regulations on the Management of Ozone Depleting Substances"[14] amended in effect on March 1, 2024 (MEE, 2024). The regulations require that units that produce or use ODS shall take the necessary measures to prevent or reduce the leakage and discharge of ODS. Those engaged in activities as maintenance, repair, or scrapping treatment of refrigeration equipment or a refrigeration system that contains ODS shall apply for a record with the competent environmental protection department of the people's government at the county level. The regulations also include relevant recordkeeping requirements and submission of relevant data.

Where a unit that produces or uses ODS does not take the necessary measures to prevent or reduce the leakage and discharge of ODS as required, corrections must be made on a specified timeline and a fine is incurred, as prescribed by the relevant environmental authority. If the corrections are not done as prescribed, an additional fine will be incurred, and the unit may have its quota reduced. The amendments to the regulations adopted stricter fines.

The amendments also include that units that produce and use a large amount of ODS, as well as incidentally produce a large amount of ODS during the production process, should install automatic monitoring equipment and network with the monitoring equipment of the

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[12] In 2016, the U.S. EPA updated the existing leak repair provisions related to ODS refrigerants and extended them to include HFCs (US EPA, 2016). In February 2020, the U.S. EPA issued the final rule Protection of Stratospheric Ozone: Revisions to the Refrigerant Management Program's Extension to Substitutes that rescinds the 2016 extension of the leak repair provisions to appliances using ODS substitute refrigerants (e.g., HFCs).

[13] The 2024 F-gas regulation expanded this requirement to HFO refrigerants.

[14] Regulations on the Management of Ozone Depleting Substances, available: http://en.moj.gov.cn/pdf/RegulationsonAdministrationofOzoneDepletingSubstances.pdf

Ecological Environment Department. The monitoring equipment must be ensured to be in normal operation and to have authentic and accurate data. Where the monitoring equipment is not kept under normal operating conditions or connected to report, corrections must be made, and entities required to use the monitoring equipment would be subject to fines.

In China, refrigerant leakage from the mobile air conditioning (MAC) sector has been addressed through the development of standards such as GB/T 21361-2017 and GB/T 327123-2018. As of 2022, China was also developing test methods and limits for leakage of HFC-134a from MAC systems.

The United States of America has also offered credits toward light duty passenger vehicle emissions standards for reducing refrigerant leaks, as early as model year 2009. Leak reduction credits are quantified using SAE Standard J2727, which estimates refrigerant leakage from MAC systems with specific components. Standard J2763 quantifies true refrigerant leakage from assembled systems. These credits have been immensely successful in incentivizing design changes to make MAC systems less prone to leaks, with all major vehicle manufacturers having taken steps to reduce refrigerant leaks as of 2021 (Taddonio *et al.*, 2023).

The United States of America also has a voluntary partnership called the Green Chill Program between the U.S. EPA and the food retail industry. The program, which was launched in 2007, is aimed at reducing refrigerant emissions and their impact on the ozone layer and climate. As of 2022, Green Chill Partners cover one-third of food retail locations in the United States (U.S. EPA 2023b). Through a store certification program and corporate partnerships, Green Chill rewards transitions to zero ODP and low GWP refrigerants, lower refrigerant charge sizes, and lower leak rates. The Green Chill program highlights the performance of Green Chill Partner stores, which have an annual average leak rate of 13% as compared to the industry average annual leak rate of 25%.

5.3.7 Qualification, Certification and licensing policies and programmes

Technician skills in installation and maintenance of joints and fittings, proper commissioning (leak detection, vacuum checks, and pressure checks), maintenance and EOL refrigerant recovery ensure best practices in LRM, safety, equipment operability and energy consumption.

Standards may provide guidance regarding the necessary competencies for technicians and can be adopted by national and subnational governments. These standards may have a voluntary or mandatory status depending on how the local mandates address standards. International standard ISO22712 (2023) provides an overview of competences for persons related to the refrigerant circuit of RACHP equipment, from the original design to the final dismantling and disposal, including an assessment of tools on which training, qualification or certification programmes can be based. ISO/IEC17024 contains requirements a certification body needs to comply with in case competences are assessed by a certification body.

Australian refrigerant management is an exemplar of excellence in EOL refrigerant recovery globally. It has been in place since 2004 and when the Ozone Protection and Synthetic Greenhouse Gas Management Act (1989) was expanded to include HFC refrigerants and make refrigerant recovery mandatory. All participants in the value chain (e.g., businesses and individuals, including technicians etc.) assume responsibility for refrigerant management through a comprehensive licensing/permit structure. The permit requirements ensure that Australian technicians and businesses have the qualifications, skills and tools to prevent the release of ODS and synthetic greenhouse gas refrigerants into the atmosphere and contain such refrigerants in cylinders and RACHP equipment.

In Australia, businesses and individuals must have a Refrigerant Trading Authorisation to acquire, store, or dispose of refrigerants under the Ozone Protection and Synthetic Greenhouse Gas Management Regulations of 1995, restricting refrigerant access to only qualified entities. Authorisation is subject to conditions and processes designed to minimise the risk of emissions while the refrigerant is in the business or individual's possession. Refrigerant handling licenses are only granted under specified conditions, such as holding a registered qualification or a certificate from a registered training organization.

A refrigerant handling license is required for any work related to the refrigerant or a component of the equipment that involves risk of the refrigerant being emitted, including: releasing the refrigerant (e.g., manufacturing, installation, commissioning, servicing and maintaining equipment, whether or not refrigerant is present; and decommissioning RACHP equipment in which refrigerant is present). Licenses are granted by equipment type (e.g. stationary air conditioning and refrigeration, automotive air conditioning, restricted heat pump installation and decommissioning, and restricted domestic refrigeration and air conditioning appliances etc.).

Management of ODS in the Philippines is regulated under the revised Regulations on the Chemical Control Order for Ozone Depleting Substances (DENR Administrative Order No. 25 of 2013). The regulations cover the control, restriction or prohibition on the importation, manufacture, processing, sale, export, distribution, use, disposal, storage, possession, and destruction of ODS. Service providers of ODS-using equipment must register with the Department of Environment and Natural Resources (DENR) to determine capability in handling and working on these substances. A certification of registration is provided under the condition that the service provider has been certified by the Technical Education and Skills Development Authority in the case of individual mechanics or those accredited by the Department of Trade and Industry, in the case of service/repair shops. Service providers should have the capability to take effective measures, including the necessary equipment, technology, training and infrastructure, for the purpose of effectively handling ODS, including responsible reuse of refrigerants and minimizing their emissions. Service providers shall also participate in a system to recover, reclaim, and reuse refrigerants that will be led by DENR. A certificate of registration issued by DENR is valid for three years before it must be renewed.

The EU F-gas regulation requires technicians[15], and in some cases also companies, to be certified, depending on the type of activity and product. The 2024 revision of the EU Regulation on fluorinated greenhouse gases extends the scope of qualification and/ or certification to HFOs and for some activities also to non-fluorinated refrigerants.

U.S. EPA regulations under Section 608 of the CAA also requires certifications for technicians who maintain, service, repair, or dispose of equipment that could release refrigerants into the atmosphere, to ensure that persons working on refrigerant-containing appliances are doing so in a proper manner. Section 608 defines a "technician" as an individual who performs any of the following activities: attaches or detaches hoses and gauges to and from an appliance to measure pressure within the appliance, adds or removes refrigerant from an appliance, or performs any other activity that would require opening the refrigerant circuit of a motor vehicle air conditioner (MVAC)-like appliance or small appliance (other than disposal). Apprentices are exempt from certification requirements provided they are closely and continually supervised by a certified technician.

Technicians must pass a test, administered by an EPA-approved certifying organization, specific to equipment type. There are four types of certifications available for technicians under section 608 of the CAA:

- Type I: for servicing small appliances.
- Type II: for servicing or disposing of high- or very-high pressure appliances, except small appliances and MVACs.

[15] Technicians are referred to as "Persons working on a refrigerant circuit"

- Type III: for servicing or disposing of low-pressure appliances.
- Universal: for servicing all types of equipment.

Technicians who service MVACs for consideration (e.g., payment) have a similar but separate certification under Section 609 of the CAA. The Section 609 certification program trains technicians in how to use refrigerant recovery, recycling, and recharging machines required to responsibly service MVACs (U.S. EPA, 2023c).

5.3.8 Reporting policies and programmes

Some national and subnational policies and programmes also require more stringent reporting requirements based on a certain refrigerant or equipment type threshold. For example, some policies are established based on a GWP threshold[16]. Many of these policies include a charge size (in kg or CO2e charge) or equipment type threshold (e.g., Japan's Home Appliance Recycling Law does not have any special regulations in place, partly because the amount of leakage during use in home appliances is extremely small).

Under Japan's Act on Rational Use and Proper Management of Fluorocarbons, Managers[17], maintainers, and disposal personnel of Class I specified products[18] are required to use a registered fluorocarbon filling and recovery maintenance operator. Equipment must be sited appropriately to prevent damage and properly maintained. At least quarterly, simple inspections are required, unless remote monitoring systems are available. Expert inspection is required at a frequency determined by equipment category and output level. The policy also mandates that recharging equipment is prohibited until the leak is repaired.

Under the Act, equipment owners must also record and save a history of equipment (e.g., inspection, repair, refrigerant charging, refrigerant recovery) and disclose records upon request, including records for maintenance companies. Equipment owners must report an estimate of any leak greater than the equivalent of 1,000 tCO_2e from their commercial refrigeration and air conditioning equipment to the government. The estimate is calculated based on charging and recovery certificates issued by a Class I fluorocarbon filling and recovery operator. The government publishes the calculated amount of the leak and additional information (e.g., the name of business operators) annually.

The California (U.S. subnational) Refrigerant Management Program regulation has been in effect since 2011 and applies to stationary refrigeration equipment containing more than 50 pounds of refrigerant, and requires periodic leak inspections, leak repairs within reasonable timeframe, and retrofit and retirement plans for chronically leaking systems. It also requires reporting on the amount of refrigerant purchased by owners and operators annually, which is then used to estimate equipment leak rates (CARB, 2024a). In addition to a state-wide rule, California also has a regional refrigerant management program regulation in the southern part of the state that covers both refrigeration and AC equipment (SCAQMD, 2024).

Washington State and New Jersey (U.S. subnational) enacted a similar mandate for both stationary refrigeration and AC systems with more than 50 pounds of refrigerant. The new regulation also requires owners/operators to estimate their equipment leak rates and requires reporting of leaks above certain thresholds.

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[16] California requires reporting for any Registration Requirements for Companies with Retail Food Facilities. On or before January 1, 2022, retail food facilities shall register the following information in the R3 database: *A) Refrigeration systems containing more than 50 pounds of refrigerant with a GWP less than 150*

[17] As a general rule, the term "manager" refers to the business or corporation that owns the equipment.

[18] Commercial refrigeration and air conditioning equipment that is subject to Act on Rational Use and Proper Management of Fluorocarbons is called a "Class 1 specified product".

The EU, UK and Türkiye have similar types of logbook and record keeping requirements for ODS and HFCs and some EU member states implemented electronic reporting requirements, which facilitate to compare leakage rate data trends of various types of RACHP equipment.

5.4 Policies and programmes related to Recovery, Recycling, and Reclamation

5.4.1 Overview

Chapter 3 provided an overview of the technologies available related to recovery, recycling, and reclamation of refrigerants.

There are several examples of policies that mandate that refrigerants be recovered at the end-of-life. Some of these are described as "venting or release prohibitions" as explained in section 5.3.6. Others are designed to generally improve end-of-life refrigerant management and encourage recycling or destruction.

Section 5.4 describes examples of policies that address recovery, recycling, and reclamation.

5.4.2 International and national standards

ISO5149 includes recommendations on refrigerant recovery, recycling, reclamation, reuse and destruction.

AHRI 700 specifies acceptable levels of contaminants (purity requirements) for fluorocarbon, hydrocarbon, and carbon dioxide refrigerants regardless of source and lists acceptable test methods (AHRI, 2024).

AHRI 740 applies to equipment for recovering and/or recycling non-flammable, single component refrigerants, azeotropes, zeotropic blends, and their normal contaminants from refrigerant systems. It defines the test apparatus, test refrigerant mixtures, sampling procedures, and analytical techniques that will be used to determine the performance of refrigerant recovery equipment and recovery/recycling equipment.

UL Standard 1963-2011 (Fourth Edition) covers refrigerant recovery and recycling equipment to be employed in accordance with other relevant standards and also covers recovery/recycling equipment intended for use with a flammable refrigerant.

5.4.3 Australia

All importers of refrigerant, both in bulk and pre-charged in equipment, must have an import licence issued by the Department of Climate Change, Energy, the Environment and Water. Importers take responsibility for refrigerant by mandatory participation in a product stewardship scheme. Thus far all importers have chosen to enter into an agreement with Refrigerant Reclaim Australia to participate in the industry-wide product stewardship program and to contribute the levy that ultimately funds the collection and destruction of EOL refrigerant.

In Australia, Refrigerant Reclaim Australia (RRA) is an industry-run not-for-profit organization that manages a refrigerant product stewardship program supported through a government-backed co-regulatory approach. Under Australian Government requirements, technicians are legally obligated to recover and return refrigerant for safe disposal; and licensed importers of bulk refrigerant and pre-charged equipment above a certain threshold are required to participate in a product stewardship program as a condition of their import licenses. RRA is established as the only approved product stewardship organization for the Australian refrigerants industry that provides destruction services. The industry stewardship program is funded through an industry levy charged per kg on all HCFC, HFC and HFO/HFC blends, both in bulk and equipment, that is imported into Australia. The levy on imported refrigerant is collected and administered by a trust on behalf of RRA.

5.4.4 United States of America

Title VI of the Clean Air Act (CAA) includes requirements for recovery, recycling, and reclamation of refrigerants. As noted in section 5.3, regulations under section 608 of the CAA prohibit the venting of refrigerants. Section 608 covers the safe disposal of appliances and required evacuation and recovery of the refrigerant from the appliances. For small appliances and motor vehicle air conditioners (MVACs)[19], the recovery of the refrigerant must be performed prior to the disposal of the appliance, or the refrigerant must be recovered by the final processor (e.g., landfill operator, scrap metal recycler).

Section 608 also includes provisions related to the certification of equipment used to recover and/or recycle refrigerant from refrigeration and air conditioning appliances. Certification involves meeting the specified requirements in the regulation, which are based on AHRI 740 and UL 1963. Refrigerant removed from an appliance may be returned to the same appliance or another appliance owned by the same person without being recycled or reclaimed, unless the appliance is an MVAC. Recovered used refrigerant may only be resold if the refrigerant has been reclaimed by a reclaimer who has been certified by the U.S. EPA, unless the refrigerant was only used in an MVAC.

Regulations under section 609 of the Clean Air Act covers servicing of MVACs and the recovery and recycle of refrigerant used only in MVAC. A person who repairs or services MVACs for consideration (e.g. payment) must properly use equipment meeting requirements under the regulation, be trained and certified by an approved technician training program. The Section 609 certification program trains technicians in how to use refrigerant recovery, recycling, and recharging machines required to responsibly service MVACs. Refrigerant recycling equipment must be certified by the U.S. EPA or an independent testing organization approved by the U.S. EPA to meet the applicable standards (40 CFR subpart B[20]).

The American Manufacturing and Innovation (AIM) Act, among other things, directs the U.S. EPA to establish certain regulations for the purposes of maximizing the reclamation of HFCs and minimizing the release of HFCs from equipment (US EPA, 2023b). The AIM Act also authorizes the U.S. EPA to consider its authority in increasing opportunities for reclamation of HFCs used as refrigerants. The AIM Act defines reclaim/reclamation as (42 USC 7675):

> *"The terms "reclaim" and "reclamation" mean-*
>
> *(A) the reprocessing of a recovered regulated substance to at least the purity described in standard 700–2016 of the Air-Conditioning, Heating, and Refrigeration Institute (or an appropriate successor standard adopted by the Administrator); and*
>
> *(B) the verification of the purity of that regulated substance using, at a minimum, the analytical methodology described in the standard referred to in subparagraph (A)".*

As described earlier in this chapter, states (subnational) can set additional or more stringent policies when it comes to refrigerant management. For encouraging the use of reclaimed refrigerants, California has promulgated a regulation and enacted a law.

- California's 2020 HFC regulation contains a section called the "Refrigerant Recovery, Reclaim, and Reuse Requirement" or the R4 Program. Under this program, AC and VRF manufacturers are required to use reclaimed refrigerants for a time-limited period. This

[19] Mobile air conditioning is abbreviated as MAC in other parts of the world. U.S. regulations use the abbreviation MVAC (motor vehicle air conditioner).

[20] Subpart B – Servicing of Motor Vehicle Air Conditioners, available: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-82/subpart-B

was the first example of a U.S. policy where the use of reclaimed refrigerants was mandated. The same regulation also developed the first standard that limits the amount of newly produced (virgin) HFCs contained in HFC refrigerants to 15% (CARB, 2024b).

- In 2022, California legislature enacted SB 1206. Under this state law, starting 2025, sale of newly produced (virgin) HFCs will be prohibited if the HFCs or blends thereof have a GWP greater than 2,200. The GWP limit for virgin HFCs will be ratcheted down over time. After 2033, all virgin HFCs and their blends with a GWP greater than 750 will be prohibited in the state. While this law does not mandate the use of reclaimed HFCs, the only viable option to service existing high-GWP equipment is to use reclaimed refrigerants until the legacy equipment can transition to lower-GWP alternatives.

5.4.5 European Union

Examples of EU legislation related to servicing and end of life of equipment are the EU ODS regulation (for CFCs and HCFCs), the EU F-gas regulation (HFCs and in the 2024 F-gas regulation this is extended to HFOs) and the WEEE directive (CFC/HCFC/HFC and hydrocarbons). Refrigerant recovery from RACHP equipment is basically mandatory in these legislations.

The WEEE directive further stipulates that recovery shall be applied "*in such a way that environmentally sound preparation for reuse and recycling is not hindered*". Note that in the WEEE directive "recycling" is a general term equivalent to both "recycling or reclamation" in the context of this report.

The EU ODS and F-gas regulations include some limitations on the reuse of certain refrigerants by specifying an end date after which even some types of recycled or reclaimed refrigerants can no longer be reused. The EU Regulation on Ozone Depleting Substances (Regulation 2037/2000 and updated Regulation 1005/2009) determined that service and maintenance of refrigeration and air conditioning equipment with virgin HCFC was not allowed from 1st January 2010, while the use of recycled or reclaimed HCFCs for service and maintenance was prohibited from 1st January 2015. The intention of limiting the use of virgin HCFC was to comply with the EU and Montreal Protocol HCFC consumption phaseout schedules, while the limit on using recycled or reclaimed HCFC was done with the intention to further reduce the HCFC emissions. The remaining challenge is to make sure that HCFC is effectively recovered because there is no market anymore for recycling or reclamation as a refrigerant.

The 2014 EU Regulation on Fluorinated Greenhouse gases (Regulation 517/2014) prohibited the use of virgin refrigerant with a GWP of 2500 or more to service or maintain refrigeration equipment with a charge size of 40 tonnes of CO_2 equivalent or more from 1st January 2020, while the use of recycled or reclaimed HFCs with a GWP of 2500 or more remains possible until 1st January 2030. This creates a 10- year market opportunity for the recycling and reclamation of refrigerants such as R-404A, while it contributes to the phasedown of virgin HFCs consumption. In the 2024 EU F-gas regulation, additional limits are included on the use of virgin HFCs for servicing. The EU price trend of R-404A for service companies (virgin and reclaimed) is illustrated in the figure 5.1 below. The 100% baseline is the R-404A virgin price in 2014, which is the year before the start of the EU HFC phasedown schedule.

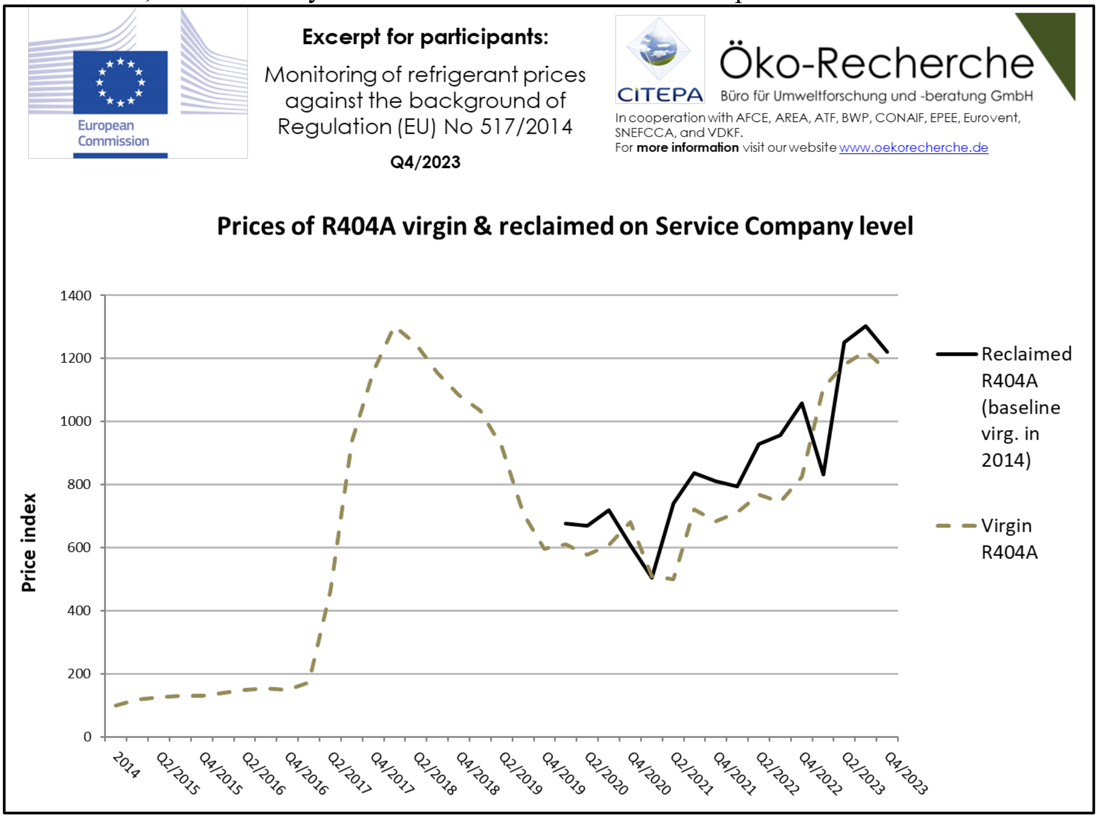

Figure 5.1 The EU price trend of R404A for service companies (virgin and reclaimed) (Source: Oeko-Recherche on behalf of European Commission, 2024)

Some equipment manufacturers in the EU are implementing programmes to use reclaimed refrigerants in the manufacture of certain types of new equipment.

5.4.6 Japan

Japan has extensive legislation governing refrigerant management across various sectors, including residential, commercial, industrial cooling, refrigeration, and mobile air conditioning. These laws address different stages of the refrigerant life cycle, from production and appliance manufacturing or import to maintenance and end-of-life collection, recycling, or destruction (Garg *et al*., 2023). The "*Law Concerning the Protection of the Ozone Layer through the Control of Specified Substances* and *Other Measures*" regulates the production and import of controlled substances under the Montreal Protocol, enforcing limits through a permit system (METI, 2000). Refrigerant manufacturers, licensed by the Ministry of Economy Trade and Industry, are encouraged to promote low-GWP refrigerants.

Japan enacted the Act on Ensuring Recovery and Destruction of Fluorocarbons Related to Specified Products (Fluorocarbon Recovery and Destruction Act) in 2001. This law obligated equipment users to recover fluorocarbon refrigerants from commercial refrigeration and air conditioning equipment during acts of maintenance and disposal, as well as to destroy the recovered refrigerants. The law was amended in June 2013 to include comprehensive measures encompassing the life cycle of fluorocarbons, from manufacturing to disposal. Since this expanded on the initial scope of the law – fluorocarbon recovery and destruction – the legislation was renamed the Act on Rational Use and Proper Management of Fluorocarbons (Fluorocarbon Emissions Control Act). The revised act became effective on April 1, 2015. In June 2019, the Fluorocarbon Emissions Control Act was amended in order to increase the recovery rate of fluorocarbon refrigerants during disposal, which had remained low at less than 40% for over 10 years. Major changes were made, including the addition of direct penalties for users who violate the law by failing to recover fluorocarbons at the time of equipment disposal. The amendment became effective on April 1, 2020.

The law enforces comprehensive measures for the entire life cycle of fluorocarbons in commercial systems (MoE, 2015), specifying reporting requirements and establishing a system for refrigerant treatment reporting. Manufacturers and retailers must reclaim used products, manage waste, including recovered refrigerants, in accordance with legal requirements.

The "*Law for the Recycling of Specified Kinds of Home Appliances*" aims to promote waste reduction and maximize the utilization of recyclable resources to establish a circular economy (MoE, 2010), encompassing air conditioners and refrigerators among specified appliances. The law outlines responsibilities, including retailers collecting from users, recycling by producers/importers, and consumers paying for transportation and recycling. It mandates recovery and processing of cooling equipment fluorocarbons, with record-keeping required. E-waste handlers recover refrigerants from decommissioned appliances for reuse or destruction. Improper disposal can result in imprisonment or fines for producers/importers.

The "*Act on Recycling End-of-Life Vehicles*" mandates automobile manufacturers and importers to collect and dispose of fluorocarbons recovered during the treatment of end-of-life vehicles (EOL) under the extended producer responsibility principle (MoE, 2010). This statute includes a provision where recycling fees for EOL treatment, including refrigerants, are charged to the car owner at the time of purchasing a new vehicle. This approach has notably improved compliance, with recycling fees typically set by automobile manufacturers and recommended or corrected by the national government.

As mentioned above, in Japan, domestic equipment and commercial equipment are regulated by different laws, but recovering, recycling, and reclamation or destruction are all required by law. For domestic air conditioners and refrigerators, the Home Appliance Recycling Law covers that, in most cases, when refrigerant is recovered from domestic appliances, it is transported to a recycling factory while still being sealed inside the appliance itself. It is then destroyed or recycled at a recycling factory. Commercial air conditioners and refrigerators are covered under the Act on Rational Use and Proper Management of Fluorocarbons. The requirements for different entities are described here.

Sales, installation, or maintenance operators who collect a used Class I[21] specified product containing a fluorocarbon refrigerant for disposal or trade-in from a person undertaking the disposal of Class I specified product are considered a "person entrusted with the delivery of Class I fluorocarbons". When such an operator collects commercial refrigeration and air conditioning equipment containing fluorocarbon refrigerants, they will receive a written confirmation of entrustment issued by the contracting party (the person undertaking the disposal of Class I specified products). The contracting party must provide this written confirmation of entrustment to the Class I fluorocarbon filling and recovery operator and retain a copy for three years.

[21] Class I products refer to certain types of commercial air conditioning and refrigeration products filled with CFC/HCFC or HFC refrigerants. This does not include residential air conditioners or car air conditioners which are classified as Class II.

Waste and recycling operators who dispose of products collected from a person undertaking the disposal of Class I specified products or who recycle parts from such products, are considered a “person undertaking collection of Class I specified products”. It is illegal to collect such equipment that contains fluorocarbon refrigerants without a collection certificate provided by the person undertaking the disposal. Violators are subject to direct punishment, and there are cases where enforcement has led to arresting a person.

Building demolition operators who undertake contracts for demolition work directly from a party that orders building demolition work (other than a contractor) are considered a “primary contractor for specific demolition work” unless there is no commercial refrigeration or air conditioning equipment present in the building to be demolished. A primary contractor for specific demolition work must confirm in advance whether any Class I specified products are present and issue documentation (advance confirmation) to explain the results of the confirmation to the party ordering the specific demolition work. A copy of the advance confirmation must be retained for three years.

Fluorocarbon filling and recovery operators must register with the prefectural governor having jurisdiction over the area where he/she intends to conduct business. The operator must comply with the filling and recovery standards when filling or recovering fluorocarbons. When undertaking filling or recovering fluorocarbons, a person must be present who has adequate knowledge of fluorocarbon filling or recovery. A technical guidebook published by the government is available for filling and recovery operators to increase the amounts of recovered fluorocarbons. Industrial organizations are engaging in activities to enhance the skills of technicians by holding seminars, issuing certificates, publishing guidelines, etc.

Under the Act on Rational Use and Proper Management of Fluorocarbons, a fluorocarbon recycling operator must obtain a license from the Minister of the Environment and the Minister of Economy, Trade and Industry for each place of business where he/she will operate. An operator must comply with the recycling standards when recycling fluorocarbons. There have been 37 recycling operators licensed as of the end of 2023.

Releasing fluorocarbons without good reason is subject to a penalty of imprisonment of up to one year or a fine of up to ¥500,000 ($3,400 USD).

5.4.7 Republic of Korea

The *Clean Air Conservation Act* discusses in Articles 9 and 14 the establishment of a management strategy for the proper disposal of substances contributing to global warming (Republic of Korea, 2017). Additionally, according to the law, owners or managers of cooling units are obligated to either recover the refrigerant themselves or arrange for its recovery and proper disposal. Additional information related to proper disposal is in chapter section 5.5.9.

5.4.8 Canada

In 2017, Canada issued its Regulations Amending the Ozone-depleting Substances and Halocarbon Alternatives Regulations, which requires the proper destruction or recovery for recycling and reclamation of HFCs that are no longer in use, as well as outlines the schedule for HFC phasedown (Government of Canada 2017).

5.4.9 Brazil

IBAMA IN 05/2018 prohibits the intentional release of controlled substances into the atmosphere during activities involving its commercialization, packaging, collection, reclamation, recycling, final disposal or use, as well as during the installation, maintenance, repair and operation of the equipment that use these substances. During the process of removing controlled substances from equipment or systems, it is required that the controlled substances are collected and sent to a reclamation of destruction facility. Further, under the regulations it is required to remove all residual controlled substances from their packaging before their final destination or disposal.

5.4.10 Norway

Norway has introduced domestic incentives through a tax and refund system for HFCs. This scheme imposes taxes on all imports of HFCs, whether in bulk or in products. The tax also extends to production, although since Norway lacks domestic production of HFCs and PFCs (or any other F-gas), it essentially applies to imports. The tax rate is determined by the Global Warming Potential (GWP) of the refrigerant and is linked to the CO_2e tax for mineral oils, amounting to NOK 766 per GWP-weighted tonne in 2022. However, the tax is reimbursed to those who dispose of HFCs or PFCs for destruction, without requiring documentation of tax payment. Instead, detailed documentation of the quantity and composition of the refrigerant destroyed is mandated. Regulations concerning the handling of waste refrigerants post-recovery from products and equipment are outlined in the national waste regulation directive, which addresses collection, recycling, destruction, export, and other aspects related to all types of waste. This directive is primarily based on the EU Waste Framework Directive and its implementing acts (EU Directive 2008).

5.4.11 Southeast Asia region

In Malaysia, the production, consumption, import, export, sale, and disposal of cooling devices containing ODS substances are all governed by Environmental Quality (Refrigerant Management) Regulations 2020 (MoEW, 2020). The supporting tools to control the EOL management of refrigerants include penalties, reporting mechanisms, and manufacturers responsible for providing the technicians with the necessary training (MoEW, 2020). The law does not yet regulate HFCs; it only applies to HCFCs and CFCs. This law forbids the production and assembling of air conditioners or refrigeration devices using particular refrigerants and encourages the disposal of specified refrigerants (MoEW, 2020).

The Environmental Quality (Refrigerant Management) Regulations 2020 (PU(A) 79) in Malaysia govern the handling of refrigerants in both existing and new installations. These regulations cover training requirements for reclamation, recycling, and retrofitting. Prohibitions include the use of refrigerants in new building chillers and refrigeration systems and the export of refrigerants outside of Malaysia. Malaysia has regulated CFCs since 1999, with HCFCs included in 2020. Disposal of refrigerants must occur in designated facilities as per the Environmental Quality (Prescribed Premises) Regulations PU(A) 140/1989. Failure to comply may result in a penalty of 100,000 Ringgit ($22,935 USD), imprisonment for up to two years, or both (Kelpsaite *et al*., 2023).

Singapore enforced regulations requiring the recovery and proper disposal of used refrigerants from dismantled air conditioners. Subsequently, in 2022, the country introduced the Environmental Public Health (Toxic Industrial Waste) (Amendment) Regulations, categorizing "spent refrigerants" as toxic industrial wastes and imposing specific requirements for their proper management (Kelpsaite *et al*., 2022).

In Viet Nam, Decree No. 06/2022/ND-CP regulates the collection, recycling, reuse, and disposal of controlled substances, including HCFCs and HFCs (Kenji, 2022). Effective January 1, 2024, it encourages the recycling and reusing of the collected substances. If recycling or reuse is impractical, proper disposal is mandated in adherence to hazardous waste management regulations. Circular No. 36/2015 specifically addresses the management of HCFCs and HFCs in toxic and hazardous waste management.

5.4.12 China

The recovery and disposal of ODS is regulated under the "Regulations on the Management of Ozone Depleting Substances", and amendments to the regulations were adopted on December

18, 2023, and came into effect on March 1, 2024 (MEE, 2024). Units engaged in activities related to maintenance, repair, or scrapping of refrigeration equipment or a refrigeration system that contains ODS shall recover or recycle the ODS or send the equipment to a unit engaged in activities such as recovery, reclamation, or destruction of ODS for environmentally sound disposal. A unit specifically engaged in activities such as recovery, reclamation, or destruction of ODS shall apply for a record with the competent environmental protection department of the people's government of the province, autonomous region or municipality directly under the Central Government where it is located. The regulations also include relevant record keeping requirements and submission of relevant data.

Where a unit engaged in activities such as maintenance, repair, or scrapping treatment of refrigeration equipment or a refrigeration system that contains an ODS fails to recover or recycle ODS or send the equipment to units engaged in activities such as recovery, reclamation, or destruction of ODS for environmentally sound disposal, as required, fines will be incurred. Entities engaged in activities for recovery, reclamation, or destruction of ODS who do not conduct environmentally sound disposal and instead vent to the air are subject to fines.

5.5 Policies and programmes related to destruction

5.5.1 Overview

Chapter 3 provided an overview of the technologies available related to the destruction of refrigerants. Destruction, when applied to refrigerants, refers to the permanent transformation or decomposition of the substances. Under the Montreal Protocol, there are approved destruction technologies for controlled substances. Some parties have policies mandating refrigerant destruction, while others do not.

Some programmes destroying refrigerants involve the generation of carbon credits for international, national, and sub-national cap-and-trade policies and programmes. Credits from refrigerant destruction are typically one project type in a larger emissions trading scheme. When used for regulatory compliance, credit generation from destruction is regulated through established protocols and standard methodologies. Credits can also be generated in the voluntary carbon market. Although participation in the voluntary carbon market is not mandated, there are carbon market registries and verifiers that have a list of acceptable methodologies and project activities.

This chapter section 5.5 describes example of policies and programmes that address destruction.

5.5.2 Australia

Under Australian Government requirements, technicians are legally obligated to recover and return refrigerant for safe disposal. Licensed importers of bulk refrigerant and pre-charged equipment above a certain threshold are required to participate in a product stewardship program as a condition of their import licenses. Refrigerant Reclaim Australia (RRA) is established as the only approved product stewardship organization for the Australian refrigerants industry that provides destruction services. The industry stewardship program is funded through an industry levy charged per kg on all HCFC, HFC and HFO/HFC blends, both in bulk and equipment, that is imported into Australia. The levy on imported refrigerant is collected and administered by a trust on behalf of RRA.

5.5.3 United States of America

Under Title 40, Part 82 of the Code of Federal Regulations (CFR) the U.S. EPA requires that any person who destroys a Class I or Class II ODS controlled substance reports the name and quantity of the substance destroyed in quarterly and annual reports. The data are evaluated, aggregated, and are included as part of the United States' annual reporting consistent with Article 7 of the Montreal Protocol (U.S. EPA 2021).

In addition, under Title 40, Part 372 of the CFR, the U.S. EPA tracks the management of toxic chemicals, including ODS from certain sources, and requires facilities in certain industry sectors to report annually on the volume of toxic chemicals managed as waste. The volume of ODS destroyed falls under the TRI categories of "energy recovery", which can include combustion of chemicals in an industrial furnace or boiler, and "treatment" which includes methods such as incineration and chemical oxidation (EPA 2018a). These methods result in varying degrees of destruction of the chemicals.

ODS may also be imported for destruction, especially in cases where a country may not have the proper destruction capabilities or if seeking to earn offset credits on voluntary carbon exchanges. Current EPA regulation cover the import of used and new (virgin) ODS that is sent for the sole purpose of destruction based on a shipment-by-shipment process called Certification of Intent to Import ODS for Destruction (40 CFR Part 82), while also considering the Basel Convention (discussed more in Chapter 6). Requirements related to the destruction of HFCs are regulated under Title 40, Part 84 subpart A.

Subnational: California and Washington State have enacted cap-and-trade and cap-and-invest programmes, respectively, capping carbon emissions state-wide which are ratcheted down with time. Under both programmes, companies in the state must lower their emissions per the cap or purchase offset credits for compliance. For both state programmes, compliance offset credits are available for projects related to the destruction of ODS from certain eligible sources. Refrigerants are included in the listed of eligible sources but the type of refrigerants eligible for destruction credits is limited and periodically updated. Currently, in California, six CFC refrigerants are eligible for generating ODS destruction credits and only if the refrigerants originate from the U.S. and the destruction takes place within the U.S. (CARB, 2014). Destruction must be performed using technologies that can meet or exceed the standards on destruction and removal efficiency as well as other emissions limits recommended by TEAP and incorporated by U.S. EPA into national regulations for consistency with the Montreal Protocol (U.S. EPA, 2021). Protocols used for ODS destruction credits on the California and Washington compliance markets are modelled after existing methodologies on the voluntary carbon market but subject to strict scrutiny and oversight.

5.5.4 European Union

Next to the EU ODS and F-gas regulations, which include mandatory reporting on ODS and HFC destruction, some EU member states have national legislation concerning the handling of waste gases post-recovery from products and equipment, which addresses collection, recycling, destruction, export, and other aspects related to all types of waste. These national legislations are primarily based on the EU Waste Framework Directive[22] and its implementing acts.

Emissions prevention at destruction facilities are regulated by the EU Directive on industrial emissions[23] (integrated pollution prevention and control).

5.5.5 Japan

Japan's 2001 Fluorocarbon Recovery and Destruction Law, targeting commercial refrigeration and air conditioning emissions promoting the destruction of fluorocarbons, was

[22] Directive 2008/98/EC of the European Parliament and the Council on waste

[23] Directive 2010/75/EU of the European Parliament and of the Council on industrial emissions (integrated pollution prevention and control)

amended in 2013 as the Act on Rational Use and Proper Management of Fluorocarbons to take comprehensive measures across the entire life cycle of fluorocarbons, from manufacture to disposal. The extensive and drastic 2019 amendments introduced direct penalties for violations of these laws and regulations.

The *"Act on Rational Use and Proper Management of Fluorocarbons" regulates that "Managers"* must ensure specified substances are destroyed adhering to prescribed standards, and *products containing* provide details on quantity, operators, and facilities. *Product manufacturers* utilizing these substances in product manufacturing must cooperate in rationalization.

Under the Act on Rational Use and Proper Management of Fluorocarbons, a fluorocarbon destruction operator must obtain a license from the Minister of the Environment and the Minister of Economy, Trade and Industry for each place of business where he/she will operate. There have been 56 destruction operators licensed as of the end of 2023. An operator must comply with the destruction standards when destroying fluorocarbons.

5.5.6 Canada

In 2017, Canada issued its Regulations Amending the Ozone-depleting Substances and Halocarbon Alternatives Regulations, which requires the proper destruction or recovery for recycling and reclamation of HFCs that are no longer in use, as well as outlines the schedule for HFC phasedown (Government of Canada, 2017).

On a subnational level, Quebec has enacted a similar cap-and-trade program to California and linked programmes with California in 2014 to form the Western Climate Initiative (WCI). The programme in Quebec developed a protocol for ODS foam and refrigerant destruction for issuing carbon offset credits.

5.5.7 New Zealand

Since 2013, New Zealand's Emissions Trading System (ETS) has included HFCs and applies import taxes on new (virgin) refrigerant (by GWP) and on importers of goods that contain HFCs (motor vehicles and pre-charged equipment). The ETS does not apply to ODS, which is not considered a UNFCCC greenhouse gas. For 2024, New Zealand has set its carbon price at NZD $71.97 per metric ton CO_2e.

New Zealand's ETS is relevant for HFC destruction because it allows regulated entities to comply with emissions reductions mandates by using New Zealand Emissions Units (NZUs) to offset emissions. New Zealand's 2009 Climate Change Regulations allow regulated entities under the ETS to export and/or destroy HFCs in exchange for NZUs (Ministry for the Environment, 2022). Since New Zealand has historically not had in-country destruction capacity, collected HFCs have been exported to Australia for destruction in a plasma arc plant. Given the high price for carbon across the country, the ability to destroy HFCs for NZUs has created a large incentive for the recovery export of HFC refrigerant. New Zealand estimates refrigerant recovery rates from end-of-life equipment at 11 percent.

Historically, Cool-Safe, funded by the Trust for the Destruction of Synthetic Refrigerants, has managed the recovery and destruction of HFCs and ODS in New Zealand. Participation in Cool-Safe is voluntary as of 2024. Cool-Safe is funded from the levy on bulk imports of HFCs and from the liquidation of NZUs generated from their activities. Although Cool-Safe has historically had a functional monopoly on the generation of NZUs from HFC destruction, new regulations from 2023 allow any regulated entity under the ETS to generate HFC destruction NZUs. Cool-Safe pays incentives for recovered refrigerant at NZD $25/kg, with higher rates for volumes of refrigerant above 500 kg. Although product stewardship under Cool-Safe has been voluntary, it will transition into a mandatory model in 2024 (Cool-Safe, 2024).

5.5.8 Republic of Korea

As noted in section 5.4, The Clean Air Conservation Act discusses in Articles 9 and 14 the establishment of a management strategy for the proper disposal of substances contributing to global warming (Republic of Korea, 2017). The Act on Resource Recycling of Electrical and Electronic Equipment and Vehicles does not specifically address refrigerant-related substances (Republic of Korea, 2008). However, Article 27 of this legislation mandates waste management organizations to segregate and store substances originating from discarded equipment and vehicles that contribute to climate and ecosystem alteration.

The Waste Control Act mandates the appropriate handling, recovery, or disposal of equipment containing refrigerants within the South Korean regulatory framework (Republic of Korea, 2015). However, it does not specifically or directly regulate ODS or HFCs. The guidelines for the disposal of refrigerants are also outlined in this legislation.

In South Korea, e-waste management is primarily carried out through the Extended Producer Responsibility (EPR) scheme, placing the responsibility for safe disposal of end-of-life (EOL) products on manufacturers (Ohm *et al*., 2017). Manufacturers must meet recycling rates for specific materials, though refrigerants are not yet included. Failure to meet targets incurs penalties. Cooling appliances are collected by e-waste agencies and taken to Metropolitan Electronic Recycling Centres (MERC) for pre-treatment, including refrigerant recovery. Similarly, in the mobile air conditioning (MAC) sector, end-of-life vehicles undergo refrigerant recovery before dismantling. Manufacturers or importers are responsible for establishing end-of-life vehicle collection and recycling systems. Additionally, commercial cooling appliance owners must handle refrigerants responsibly under the Clean Air Conservation Act, commissioning recovery and disposal to authorized companies. Refrigerant management records must be maintained and submitted to the Refrigerant Information Management System (RIMS) managed by the Korea Environment Corporation (K-eco). Recovered refrigerants are either purified for reuse or sent to destruction facilities. The Ministry of Environment plans to issue a comprehensive pre-announcement regarding the revision of the Enforcement Rule of the Clean Air Conservation Act. This revision aims to specify the scope of additional refrigerant-using machines that necessitate management (MoE, 2023).

5.6 Policies and programmes related to logistics

5.6.1 Flammable refrigerant transportation and storage

The reverse supply chain for recovered flammable refrigerants may require updates to allow for shipping for recycling or destruction beyond hazardous waste requirements.

The United Nations (UN) Global Harmonized System (GHS) provides an internationally agreed-upon approach to hazard communication (e.g., labelling, safety data sheets, pictograms etc.). GHS creates harmonized definitions and classifications of physical, health and environmental hazards. The 7th version of *The Globally Harmonized System of Classification and Labelling of Chemicals* (GHS Purple Book v7) expanded the hazard classes for flammable gases, differentiated lower flammability (ASHRAE and ISO A2L refrigerants) from fluids with higher flame speeds (e.g., hydrocarbons). This differentiation has been adopted into building codes and transportation requirements in some parties, including allowing for the reverse supply chain to transport recovered refrigerants.

The United States Pipeline and Hazardous Materials Safety Administration (PHMSA) Department of Transportation has created special permits to allow for the shipping and return of equipment containing A2L refrigerants in recent months[24].

5.6.2 Disposable cylinder bans

As mentioned in 3.2.1, disposable cylinders are more vulnerable to rust and mechanical damage over time. The use of non-refillable cylinders is not recommended for recovered refrigerant.

A number of parties have banned the use of disposable cylinders for refrigerants, including, but not limited to, the following:

- Australia
- Canada
- EU
- UK
- India

In Australia, disposable cylinders were banned in 2007 after an amendment to the Ozone Protection and Synthetic Greenhouse Gas Regulations of 1995. The ban was put in place as a condition of the licencing system for those who are allowed to purchase or sell refrigerants. Licence holders are required to only use refillable containers for the storage of refrigerants (Australian Refrigeration Council, 2020). Further, this approach avoids placing any burden on determining if a container was placed on the market prior to the ban being put in place (EIA, 2019). The import of non-refillable containers containing HCFCs is prohibited, unless the substance is being imported for calibration or testing purposes, for laboratory or analytical purposes, or there is no practical alternative to importing the substance in a non-refillable container. Non-refillable containers are specifically manufactured single-use containers used for servicing or commissioning equipment. After use the containers are sent for disposal and deliberately punctured, in accordance with pressure vessel regulations, emitting the residual amount of refrigerant to the atmosphere.

In Canada, disposable cylinders were banned incrementally, by considering different refrigerants at different step of implementation by regulation. The ban was implemented through the Federal Halocarbon Regulations of 2003 and then by the Ozone-depleting Substances and Halocarbon Alternatives Regulation of 2016. The ban on disposable cylinders restricts the storage, transport, and purchase of halocarbons to be only in containers that are designed and manufactured to be refilled (Government of Canada, 2003). Additionally, imports of HFCs and HCFCs that would be used as refrigerants must be stored in a refillable cylinder and any HCFC that is manufactured to be used as a refrigerant must be stored in refillable cylinders (Government of Canada, 2016).

In the European Union, a ban of placing on the market ODS in disposable cylinders began in 2000 in the EU Ozone Depleting Substance Regulation and continued to apply in the 2009 updated ODS Regulation. The sale of disposable cylinders containing HFCs was banned under the F-gas regulation in 2006 and continued in the 2014 F-gas regulation. In the 2024 EU F-gas regulation a requirement was added for the refillable cylinders, where the placing on the market is subject to providing evidence that a binding arrangement is in place for the return of the cylinders for the purpose of refilling. The UK also has a disposable cylinder ban that is an extension of the EU F-gas regulation.

In India, disposable cylinders are banned for storage, transport, distribution and use within the country but are permitted for exporting domestically produced F-gases.

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[24] https://www.phmsa.dot.gov/hazmat/documents/authorization/2023125288_SP21379.pdf/2023125288/SP21379

5.6.3 Safety requirements that may reduce emissions

Many low-GWP refrigerants have different flammability and toxicity characteristics than those that replaced ODS. The safe use of these refrigerants depends on modified handling, storage, shipping, and refrigerant management. There is an added benefit to these new practices and requirements. There will be less leaks and emissions from systems and the supply chain when these practices are followed.

Updated safety standards for flammable refrigerants (e.g., IEC 60335-2-40, IEC 60335-2-89, and ASHRAE 15) require additional leak checks when commissioning systems (e.g., pressure check, leak check and vacuum check before operation). Depending on the refrigerant charge size, safety standards require that sensors be installed to detect leaks and may require closing valves or other mitigation measures to minimize leaks.

The safety standards and the transition to more flammable refrigerants has also provided an opportunity to retrain technicians about the importance of minimizing or eliminating leaks during installation, operation, maintenance, and at end-of-life.

Technicians and reverse supply chain managers (e.g., recyclers, reclaimers, destruction facilities) must also be aware and use measures to manage flammable refrigerants. Hydrocarbons, ammonia, and lower flammability fluorocarbons (ASHRAE class 2L) may be mixed in recovered refrigerant cylinders. Awareness needs to be raised for all stakeholders of the need to properly label and communicate with other reverse supply chain managers of cylinder contents for safe handling.

5.6.4 Corporate citizenship programmes

Many companies have established sustainability goals that can include refrigerant management. For example, more than 5,000 companies under the Science-based Targets Initiative[25] (SBTi) have approved near-term and long-term net-zero greenhouse gas (GHG) emissions goals for their supplies and facilities (Scope 1 and 2) and the use of their products (Scope 3 emissions).

Building and equipment owners may work with suppliers to maintain equipment during its use and ensure EOL refrigerant management when replacing equipment. This can include best predictive and preventive maintenance practices, automated leak detection, telematics and other programmes. Replacement of equipment represents an opportunity to increase recovery quantities and introduce best procurement practices, educating procurement personnel to purchase more efficient equipment with lower-GWP refrigerant, increasing demand for new products and subsequently its market uptake.

5.6.5 Conditional mandates for LRM practices

Some subnational governments or utilities providers offer incentives or funding to adopt lower-GWP and more efficient equipment. Many of these programmes mandate evidence that the refrigerant from the equipment to be replaced is properly recovered in order to gain access to funds.

For example, when setting up greenhouse gas (GHG) or fluorochemical reduction incentive programmes, some key requirements for robust Life cycle Refrigerant Management programmes have been included as part of the requirements. For example, California's F-Gas Reduction Incentive Program (FRIP) provides financial support to California's retail food facilities for adopting ultra-low GWP refrigerants (CARB, 2024c). As part of meeting the

[25] https://sciencebasedtargets.org/target-dashboard Some companies have aligned their targets with the 1.5 °C temperature rise goals for 2030 and net-zero emissions goals by 2050, while others have not.

program's criteria, funding recipients must conduct proper refrigerant recovery of the retiring systems.

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Chapter 6

Obstacles and challenges associated with effective leakage prevention, recovery, recycling, reclamation, and destruction of refrigerants

Chapter 6 Summary

- There are many obstacles and challenges which may discourage LRM effectiveness, including policy (e.g., waste stream mandates), technical capacity and skills, logistics, and economics. Understanding and overcoming these barriers will be critical in implementing LRM.
- LRM policies vary nationally and sub-nationally, impacting industries and end user behaviour. In some cases, policies may inadvertently create barriers to LRM.
- Classifying recovered refrigerants as hazardous waste may create regulatory and logistical hurdles that limit the capacity to be reused or destroyed. In some parties the application of the Basel Convention creates difficulties for recovered refrigerant to be transferred across national boundaries for reuse or destruction.
- Challenges in MLF-funded training include measuring the impact of training on LRM practices, addressing the informal technician sector, gender mainstreaming and providing enough tools for recovery and recycling, and maintaining training facilities.
- Enforcement of LRM policies is a universal challenge due to sheer number and diversity of affected regulated entities.
- Practical barriers can be at individual or company level. For example, end users may divide maintenance responsibility among different employees without linking the savings of leak reductions to the cost of maintenance, creating a disincentive for best leak reduction practices.
- Lack of quality control/compositional analysis may hinder decision making on refrigerant reuse and safe handling of refrigerants.
- Reclaiming refrigerant blends and removing contaminants from recovered refrigerants beyond blending require significant financial investment in specialized equipment and processes. Separation technology is complex and costly, which has limited its access to smaller A5 parties.
- Economic barriers to LRM efforts persist, including in non-A5 parties with readily available infrastructure. Economic barriers could include investment costs and variable costs such as labour, and opportunity costs (e.g., the opportunity to make more money installing equipment than by tightness controls or recovering refrigerant).
- A major challenge for the reverse supply chain regarding recovered refrigerants is providing sufficient supporting infrastructure, such as sufficient cylinder fleets, warehousing, transport, and inventory management.
- Historical volumes of recovered refrigerants may have been too low to justify sustained investment in reclamation and destruction.
- Lack of awareness can lead to incorrect and unsafe servicing practices and lead to topping up leaky systems and venting refrigerants at equipment end-of-life.

6 Obstacles and challenges associated with effective leakage prevention, recovery, recycling, reclamation, and destruction of refrigerants

Decision XXXV/11 requests information on the “obstacles and challenges associated with the effective leakage prevention, recovery, recycling, reclamation and destruction of refrigerants”.

Obstacles and challenges to effective LRM arise for various reasons. The growth of equipment usage is high in many parties, exacerbating the challenges of training enough technicians and developing a reverse supply chain infrastructure to properly manage and recover refrigerants. Obstacles and challenges can be related to policies, technical aspects, economic feasibility, logistics, skills and competences, awareness, knowledge, and behaviour.

Implementation of LRM policies require strong regulatory support and concrete measures to collect, store, destroy or reclaim ODS and HFC banks. Some Parties are facing barriers that result in insufficient recovery of these substances as large quantities enter the informal recycling market.

6.1 Policies

While Chapter 5 covers examples of policies which facilitate LRM, this first section of Chapter 6 discusses examples of policy (or lack of policies) which create obstacles and challenges for LRM. In the context of this report, “policies” refers to mandatory requirements from governments or authorities. Examples are legislation, regulations, treaties, decrees, building codes, ordinances, mandatory standards.

6.1.1 General observations

Appropriate LRM policies can help to reduce practical barriers and enhance investments in the infrastructure needed to support LRM. However, the combination of LRM policies currently in place has not yet led to the complete elimination of refrigerant emissions, even in Parties with advanced regulations. Historically, the most successful LRM policies have been implemented by Parties, when economic drivers are strongest, where there is a high level of awareness and consensus across stakeholders, particularly industries and refrigerant end users.

The absence of comprehensive and well-defined policy directives can present an obstacle to effective LRM, resulting in emissions throughout the product’s life cycle (manufacture, distribution, use, servicing, and EOL disposal).

Existing policies can inadvertently create challenges for LRM supply chains (e.g., shipping limits and export restrictions), especially if they are impractical or do not provide sufficient longevity to justify long-term investments (e.g., capital investment in distillation columns).

Policies may also create practical barriers to recovery. For example, some Parties prohibit the use of refrigerant recovery cylinders below a certain weight capacity (e.g., 60 kilograms minimum weight). Refrigerant cylinders with such weights are heavy and unwieldy, providing a practical and logistical challenge to technicians.

Another example of an impractical barrier can be the obligation to only recover refrigerant on site, thus not allowing the transport of EOL equipment including the recovered refrigerant. Under this restriction, recycling companies will not be able to access the refrigerant itself for recovery. An exception was recently made in the United States under a Special Permit created by the Department of Transportation[26].

6.1.2 National policies related to waste treatment

An important aspect of policy obstacles and challenges for LRM is related to the definition of "waste". Once the refrigerant is recovered from RACHP equipment, policies may have a different interpretation on when the recovered refrigerant is considered "waste". This "waste" classification typically leads to strict requirements for transport, storage, and handling.

Some refrigerants may even be classified as "hazardous" waste, and this creates further obstacles and challenges. Companies that are trying to access LRM technologies either within or outside their parties would face significant challenges when shipping recovered refrigerants classified as "hazardous". Even for Parties that allow recovered refrigerant shipping, policies may need to be modified to allow for shipping of flammable refrigerants in a category other than hazardous waste[27].

There are two main types of classification of "waste", as illustrated in Figure 6.1 below. Some parties may define the classifications differently as a combination of the two, or with exceptions.

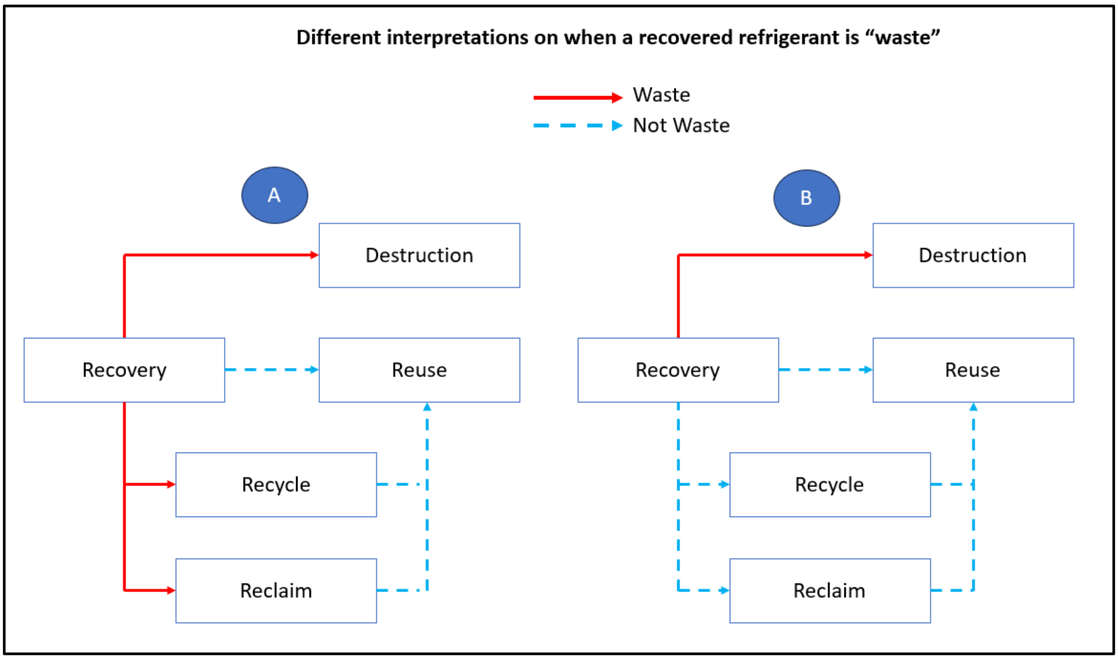

Figure 6.1 Interpretation of "waste" and "non-waste" of recovered refrigerant

As shown in Flowchart A in Figure 6.1, recovered refrigerant is always considered waste, unless it is directly reused. The refrigerant label changes back from waste to non-waste after a recycling or reclamation process has taken place. In this case, service technicians need to overcome several practical and economic obstacles after they have recovered the refrigerant, such as administration steps and permits for the transport and storage of recovered refrigerant.

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[26] 26 21379–M Trane U.S. Inc To modify the special permit to authorize reconditioned (used) refrigerator machines or components thereof.

[27] U.S. Environmental Protection Agency (EPA) is proposing alternative standards for spent ignitable refrigerants when recycled for reuse that do not belong to flammability Class 3 as classified by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 34–2022.[2]

In addition, recycling and reclamation facilities may face obstacles in obtaining environmental permits. In addition, classifying recovered refrigerants as waste may require traceability in logistics by increasing recordkeeping requirements along the reverse supply chain.

As shown in Flowchart B in Figure 6.1, recovered refrigerant is considered waste only when it is intended to be destroyed or otherwise disposed of. In other words, if the recovered refrigerant is designated to be reclaimed or recycled, it remains as non-waste. In this case, transport and storage become easier for service technicians, as well as setting up recycling and reclamation facilities in a country which facilitates LRM infrastructure development. Examples of countries that applied this principle are given in the Annex of this chapter.

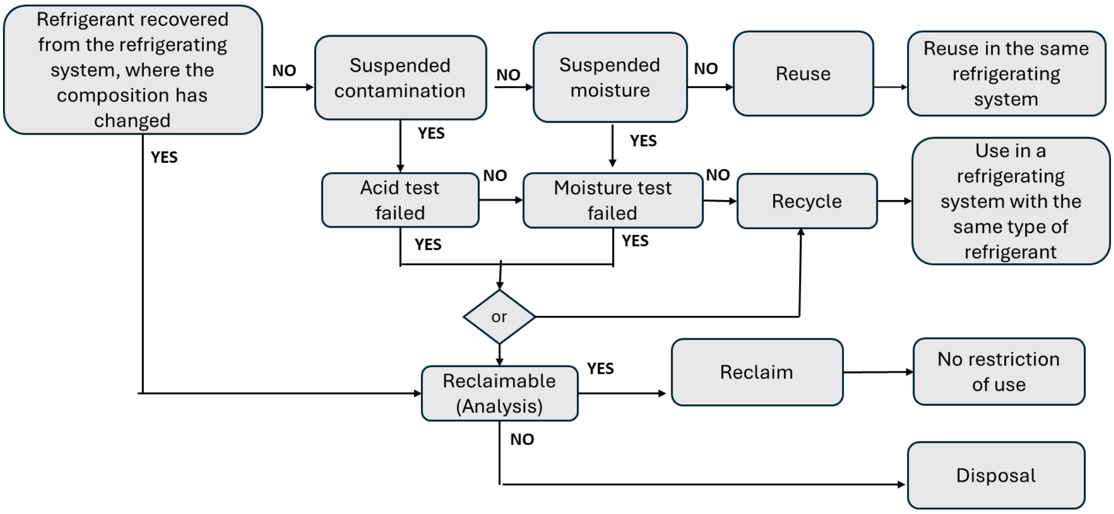
Regarding the classification of "hazardous" waste or "non-hazardous" waste, different policies may apply. The issue of "hazardous waste" is mentioned in this section regarding international policies, in particular the Basel Convention, and in section 6.4 on logistic obstacles and challenges.

Classification may be non-hazardous based on the interpretation that it has no different local environmental and human health impacts in comparison to the original product and has no differentiation in either content or manner of handling with respect to risk than the original product. Classification as a "dangerous good" may be applicable in both classifications due to use of pressurized containers.

6.1.3 Reuse of refrigerants

International standard ISO5149-4 (2022) provides recommendations on the handling of recovered refrigerants. Specifically, the ISO standard proposes conditions when a refrigerant can be directly reused without treatment and uses of recycled refrigerant versus reclaimed refrigerant. It suggests the timing of the end-of-life of recovered refrigerant[28]. A diagram outlining the recommendations is provided in Figure 6.2 below.

Please refer to Chapter 3 which describes various technologies for recycling, reclamation, and destruction.



[28] ISO 5149-4 (2022) recommends reuse without treatment is recommended when no contamination or moisture is suspected, and it may only be reused in the same RACHP system from which the refrigerant was recovered. Recycled refrigerant needs to pass an acid test and moisture test and can be used in a RACHP system with the same type of refrigerant, while there are no restrictions of use on reclaimed refrigerants.

Figure 6.2 Recommendations of recovered refrigerant handling, in line with ISO5149-4 (2022)

Some national policies include additional limitations on the use of recycled or reclaimed refrigerants. The use of recycled or reclaimed ODS refrigerants or HFC refrigerants with a high GWP may not be allowed in some cases to further reduce ODS or HFC emissions. In some cases, the use of recycled refrigerant is limited to systems belonging to the same owner. These regulations may also disincentivize the recovery of refrigerant since they limit possible uses for the recovered refrigerants.

Other national policies, on the other hand, promote the use of recycled or reclaimed refrigerants by prohibiting the use of new (virgin) refrigerants in specific applications. These policies are typically aimed to reduce the consumption of ODS or HFCs in view of their Montreal Protocol targets. Please refer to Chapter 5 for additional information and examples of policies related to reuse of recycled or reclaimed refrigerants.

6.1.4 Updating policies

Refrigerants may be a part of a general national policy on waste, or a separate dedicated policy for refrigerants, or part of a policy related to waste of RACHP equipment. All policies may be applicable at the same time and could conflict with one another in some cases. Aligning and updating such national policies may be challenging, especially if they fall under different authorities (e.g., waste management policy and separate ozone depleting substance policies).

Many LRM policy barriers have been addressed for refrigerants classified as low toxic and non-flammable under the Global Harmonized System (GHS) or ISO and ASHRAE classifications. Flammable and highly toxic refrigerants pose more complex policy challenges, requiring updates to manage safety aspects of various uses of both new (virgin) refrigerants and used refrigerants (e.g., handling, use, shipping, storage, disposal, and destruction)

The process to change policies can be time-consuming and challenging, requiring engagement from stakeholders that are unfamiliar with the intricacies of refrigerant supply chains and industry practices. The best outcomes removing barriers from policies appear to have been the result of significant interaction between policymakers and the regulated community, including manufacturers, contractors, and others.

6.1.5 International treaties

The ability to manage the transboundary movement of EOL ODS/HFCs is necessary to achieve complete global access to reclamation and destruction technologies. In many parties, EOL ODS/HFCs are considered as hazardous wastes, given their global ozone depleting and climate impacts, their potential for unsuitable disposal, and association of dumping of used and scrap RACHP equipment from developed to developing parties. As such their transboundary movement could be subject to the requirements of the Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal, as well as other related international shipping standards.

The Basel Convention aims to prevent the transfer of hazardous and other waste environmental legacies that originated in developed parties to developing parties, which might not have the capacity or resources to manage such legacies. Under the Basel Convention there must be informed consent by the governments of the exporting country, transit parties, and the importing country, as well as provision and enforcement of standards for environmentally sound management of environmentally sensitive waste streams. Although the framework is generally effective in preventing illegal trade of waste, the process of informed consent is inevitably bureaucratic, time consuming and costly given the approvals required by multiple jurisdictions sequentially, resulting in significant transaction costs.

The Basel Convention has inadvertently created issues for parties and companies without the capacity to adequately conduct LRM domestically who may want to access EOL ODS/HFC reclamation and destruction elsewhere. Barriers to transboundary movement of refrigerant is a major challenge for smaller A5 parties that lack national capability for destruction or the resources to undertake export transactions of relatively small quantities of EOL refrigerants.

6.1.6 Shortcomings in enforcement

Despite the establishment of comprehensive regulations designed to address environmental and regulatory concerns, there may be insufficient implementation and enforcement of these policies. This enforcement gap diminishes the potential impact of the policies. Weak application of regulatory control over leakage of refrigerants, end-of-life recovery, recycling, reclamation and destruction limits effective LRM.

Many Parties have adopted prohibitions on the intentional release (“venting”) of refrigerants to the atmosphere, as explained in chapter 5. These prohibitions often make the recovery of refrigerant mandatory. However, in practice, venting prohibitions are difficult to enforce because there is no clear responsibility for enforcement and it is difficult to detect refrigerant emissions. Thus, many parties find effective enforcement of venting prohibitions problematic, especially where reporting or auditing is not required.

Another significant challenge in enforcing policies effectively lies in the widespread participation of RACHP technicians in the informal sector, particularly evident in many A5 parties. These individuals often operate without the full certifications and qualifications mandated by law, existing outside the formal regulatory framework. This prevalent issue not only complicates enforcement efforts but also raises concerns regarding the adherence to and the overall efficacy of established policies. The informal sector's detachment from legal and regulatory standards means that policies designed to ensure safety, environmental protection, and professional competency are less likely to be observed.

Sustainable business models for LRM may aid in improving compliance with regulations. A solution that was implemented by some Parties to overcome this barrier is stricter enforcement of its HFC import and export licensing system, to align with the regulations covering controlled ODS which now encompass HFCs and to reflect enhanced oversight in accordance with the Montreal Protocol (UNEP, 2021).

A combination of sector-specific strategies and a collaborative multi-pronged approach may also be suitable in economies where most of the workforce handling refrigerants at different stages is informal. Even with the existing mandates in place, with most decommissioned products being handled by the informal sector, refrigerants may still be vented into the atmosphere. In such cases, finance and investment may be one of the key pillars in operationalizing LRM.

6.2 Technical and Procedural Elements

Although technology exists to implement LRM across the globe (Chapter 2 and 3), it is not always accessible in practice to parties due to widely varying economy size, market conditions, and geography (Chapter 4). Even in cases when the technologies are broadly available and accessible to Parties, technical improvements may still be needed to make LRM processes more efficient and cost effective. This section discusses technical obstacles and challenges that, if resolved, could help accelerate LRM deployment.

6.2.1 Refrigerant recovery

Efficient use of refrigerant recovery equipment requires that it be suitable for the refrigerating equipment containing the refrigerant. It must also be designed for the vapor pressure of the refrigerant to be removed. It may not be practically feasible to recover 100 percent of gas from the equipment, especially for larger equipment when using recovery equipment that is not designed for that specific equipment and refrigerant type.

Additional equipment challenges include the following:

- Inadequate supply of certified, empty vacuumed recovery cylinders available to contain product and store product pending further recycling, reclamation, or destruction.
- Inadequate supply of suitable recovery equipment and supporting reverse supply chain infrastructure.
- Some recovery equipment does not provide a sufficient vacuum.

Refrigerant recovery typically slows down as the remaining capacity of the recovery cylinder decreases. For example, recovering the second half of the refrigerant charge is generally much more time intensive compared with recovering the first half.

Some recovery equipment, such as machines with lubricated compressors, may introduce impurities to the recovery operation. The presence of oil in recovered refrigerant may compromise the performance of the equipment if the refrigerant is further recycled. The presence of impurities ultimately increases costs to reclaim the refrigerant.

Even though companies have developed their own refrigerant recovery machines that significantly speed up the process of recovering refrigerant from commercial RACHP systems, this technology is not available to technicians at large.

Some recovery cylinders are not properly cleaned, leading to contamination or mixing of the recovered refrigerants. Reusing cylinders without proper evacuation can contaminate the recovered refrigerant with oil, moisture, air, and other fluorocarbons and hydrocarbons. Furthermore, the refrigerant contained in equipment is itself a mix of several chemicals which may not always be listed on the equipment nameplate. Technicians may unknowingly mix refrigerants during the recovery process, lowering the likelihood that the refrigerant can be reused.

There are technical barriers to refrigerant recovery for disposable cylinders that typically contain newly produced (virgin) refrigerant. These cylinders commonly trap residual refrigerant (on average amounting to 5 percent of the cylinder's total charge size) which is known as the "heel". Refrigerant heels are generally released to the atmosphere when the cylinder is punctured or the valve is damaged.

6.2.2 Composition analysis

Recovered refrigerant composed of a single component (e.g., HFC-134a) is often recovered with impurities (e.g., water) that can be easily removed for reuse. However, it is helpful to know the refrigerant composition when recovered refrigerant is composed of multiple chemicals or when refrigerants are mixed together in a cylinder, potentially with other gases.

Composition analysis determines the best way to purify or re-blend recovered refrigerant for reuse in other equipment[29]. The most common form of analyses is the rapid use of a handheld portable analyser[30] and second, through laboratory analysis.

Handheld devices, although convenient in identifying broad contamination levels and common refrigerant species, cannot identify the full range of CFCs, HCFCs, and HFCs used

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[29] In the United States and in the voluntary carbon markets, this analysis becomes a requirement for projects that reclaim and destroy recovered refrigerants for carbon credits, to ascertain the eligibility of the components in the recovered refrigerant sent for destruction.

[30] One example is the use of a Neutronics analyser.

in equipment, nor all contaminants that could be present in recovered refrigerants. These devices often cannot identify CO_2, hydrocarbons, non-condensable, acids, and oils.

Laboratory analyses can provide a detailed purity and composition of recovered refrigerants. Laboratory analysis requires large capital investment and has higher operating costs than handheld identifiers (Chapter 7).

Without adequate training of personnel, good laboratory practices and access to calibrated and well-maintained equipment, the capacity and capability to determine the composition and purity of the refrigerant is compromised. Knowledge of composition and purity is ultimately critical in determining the appropriate end use for the recovered gas.

6.2.3 Recycling and reclamation

Refrigerant recycling and reclamation face several technical challenges, please refer to chapters 3.

6.2.4 Destruction

Availability of technologies in some parties or regions may be limited. Parties may wish to consider development of shared regional destruction assets and supporting infrastructure.

Potential advances in existing technology could be scaling down existing technologies to provide dedicated destruction capacity for refrigerants in EOL equipment in parties and regions with lower volumes of recovered refrigerants.

6.3 Economic feasibility

Economic barriers impede LRM, including in non-A5 parties where LRM infrastructure and tools are otherwise readily available and accessible. This section discusses economic challenges and barriers to implement LRM, with a specific focus on required capital expenditures and other fixed costs, variable costs including labour, and opportunity costs. Costs associated with LRM and potential financing mechanisms are discussed in more detail in Chapter 7.

6.3.1 Macroeconomic challenges

The economics for LRM activities are generally defined by country- or region-specific market dynamics around the price of new (virgin) refrigerant. These dynamics often depend on when and how stringently phasedown policies are implemented. For instance, prior to or early in a phasedown, new refrigerants may still be plentiful and available at low cost. Low prices for new refrigerants result in weaker incentives to detect leaks and to recover, reuse, and reclaim refrigerants. These low incentives occur mainly because the costs of undertaking those activities is higher than the cost of purchasing new refrigerants. Similarly, if there are significant number of excess allowances relative to demand ("headroom") or large stockpiles, prices for new refrigerants may also remain low well into the phasedown.

Stringent phasedown schedules may initially increase new refrigerant prices, to which the market responds by shifting to alternatives and enhancing LRM practices. In some cases, high prices may incentivise illegal trade, especially when the price gap relative to other countries is large. On the other hand, the market in turn may respond to higher prices with refrigerant transitions and improved LRM. These complex market dynamics may result into fluctuating refrigerant prices, which may make it difficult to justify capital investments in RRRD and reverse supply chain infrastructure.

Figure 6.3 shows the evolution of virgin refrigerant prices in the EU servicing sector between 2020 and 2023, compared to the price of R-410A in 2014. The EU HFC phasedown schedule started in 2015.

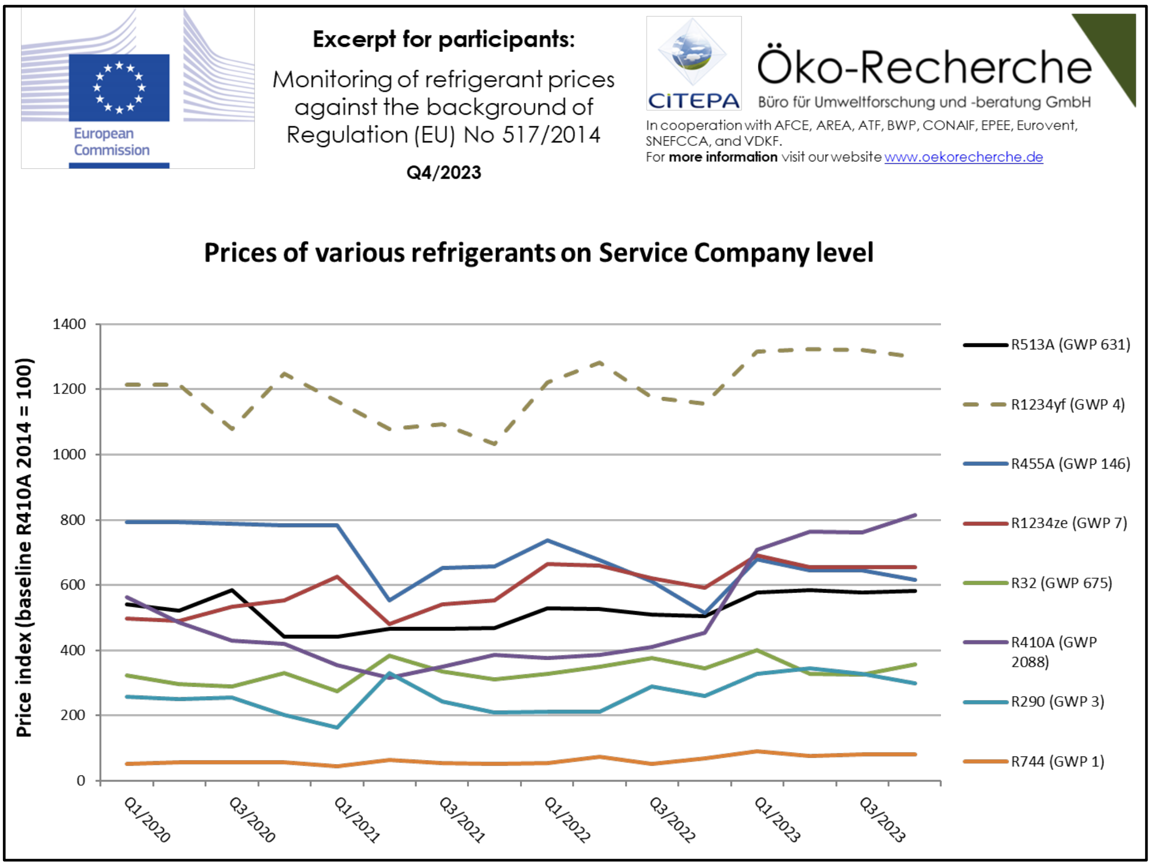

Figure 6.3 Evolution of new (virgin) refrigerant prices in the EU servicing sector between 2020 and 2023, compared to the price of R-410A in 2014 (Source : Oeko-Recherche on behalf of European Commission, 2024)

6.3.2 Leak detection and repair

Costs for leak detection and repair generally fall in four categories: capital investment for leak detection equipment, labour costs, costs of servicing and repairs, and product losses in the case of food retail. These costs are outlined in Chapter 7. As discussed above, the price for new (virgin) refrigerant is a major determinant in whether investments in leak detection and repair pay off for the end user. Some examples are provided here:

- In fisheries, which is one of the largest refrigerant end users in some A5 island parties, leak detection and repair is rare. Fishing boats typically top up leaky equipment, instead of responsibly repairing it because of the high opportunity costs of docking boats for repairs. Although many boat owners are aware that topping up leaky equipment is not environmentally sound, the inconvenience of docking a boat is too costly to simply repair leaky equipment.
- In food retail, store owners may opt to simply top up their refrigeration systems with refrigerants instead of fixing leaks, if repairs require temporary store closures.
- In the mobile air conditioning (MAC) sector, market prices for new (virgin) refrigerants also determine technicians' behaviour when servicing MAC systems in non-A5 and A5 parties. Currently, most MAC systems – especially systems manufactured before 2017 – use HFC-134a. However, some parties, including the United States and European Union, have begun to shift to using HFO-1234yf, a low-GWP alternative. Currently, HFO-1234yf is considerably more expensive than virgin HFC-134a (for example, in certain markets, the unit price per kilogram is 23 to 38 times more expensive in 2023), which has led technicians in the MAC sector to

recharge leaky systems designed for HFO-1234yf with HFC-134a (Taddonio *et al.*, 2023). HFO-1234yf and HFC-134a operate under similar pressure and temperatures, making them technically possible substitutes in MAC systems.

6.3.3 Recovery

Refrigerant recovery is pivotal for successful LRM, and a prerequisite for recycling, reclamation and/or destruction. Refrigerant recovery is not mandated by the Montreal Protocol but it is encouraged through economic drivers of the phaseout/phasedown plans. Moreover, recovery is a best practice to reduce refrigerant emissions and to enable the destruction or reuse of refrigerant through recycling or reclamation.

Refrigerant recovery rates, and the proportion of recovered gas then sent for reuse versus destruction is variable, and there are limited studies and data available. Refrigerant that is recovered and recycled (e.g., R-404A recovery and recycling by a retailer, R-134a recycled in an auto mechanic shop, or R-22 or R-410A recovered by a building owner from chillers and recycled etc.) is not generally reported to an external entity for data collection. Reporting is required related to destruction or reclamation in some parties (e.g., Australia, EU) and total reclaimed refrigerant produced in a single year is reported in others (e.g., United States, EU).

Anecdotally, refrigerant from equipment containing larger charge sizes of refrigerants (e.g., chillers and distributed systems if grocery stores) is generally recovered. Small charges in household appliances may be recovered in some locations where there are specific white goods return programmes or local refrigerant recovery programmes. Some parties have policies with strong compliance for white goods return programmes (e.g., EU) while others do not. Some parties have determined that white goods return programmes are unnecessary due to small charge sizes.

From a limited data perspective, reported reclamation rates of HCFC-22 and R-410A in some parties is significantly lower than new HCFC-22 and R-410A use[31]. Anecdotally, it is believed that recovery from equipment, containing less than 10 kg is minimal, with some exceptions (e.g., EU) as noted above.

Refrigerant recovery from non-white goods systems containing less than 10 kg would likely be serviced by a single contractor or technician, and there are very few, if any, formal studies regarding the challenges that may preclude recovery at end-of-life. There are also anecdotal reports of small stockpiles of recovered refrigerant that have not been returned for destruction or reclamation.

The Task Force is unaware of published studies of the root cause of low refrigerant return rates for reclamation in locations where there are national or subnational recovery mandates or venting prohibitions. An unpublished United States industry survey explored the challenges associated with recovery and return of refrigerant by asking stakeholders why some technicians did not recover refrigerant. Some respondents noted that some technicians were charged a destruction fee upon return of refrigerant or that some technicians might be more willing to recover refrigerant if they were financially incentivised to do so. More respondents noted that it took too long or that their recovery equipment was not functioning properly.

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[31] Reference to quantities of HCFC-22 and R-410 A reclaimed in United States as reported to EPA https://www.epa.gov/section608/summary-refrigerant-reclamation-trends#:~:text=EPA%2Dcertified%20reclaimers%20are%20required,discrepancies%20in%20the%20reported%20totals

Reference to reported consumption and production of the components or R-410A https://www.epa.gov/climate-hfcs-reduction/hfc-data-hub

The motivation for service technicians to recover refrigerants instead of venting to the atmosphere may be influenced by economic and logistical circumstances. Although venting refrigerant is illegal in many parties, it seems that there may be similar challenges with compliance of venting prohibitions even in parties with venting prohibitions and a large financial risk from non-compliance (e.g., fines, loss of license, or imprisonment). There are few reported enforcement actions related to illegal refrigerant venting.

With these factors considered, it is unclear what proportion of refrigerant is recovered and recycled compared to refrigerant vented at end-of-life equipment or recovery and stockpiling in cylinders. Even in parties with long-standing policies aimed at implementing LRM, reported recovery rates for refrigerant at equipment end-of-life reach only 40 percent (Japan, Australia). Policies aiming to incentivize refrigerant recovery are detailed in Chapter 5.

Costs for refrigerant recovery, as discussed in Chapter 7, include both capital expenditures on technology such as recovery machines, recovery cylinders, and manifolds, but also operating costs such as rent for storage warehouses and labour associated with refrigerant recovery and aggregation. Capital expenditures may vary slightly based on geography. Costs to procure recovery equipment tend to be higher in A5 parties where the market for recovery equipment is less mature compared with non-A5 parties.

Some governments explicitly mandate refrigerant recovery (or conversely, prohibit refrigerant venting). These mandates put the economic and/or technical onus on the refrigerant technician to recover refrigerants. As a result, technicians in some markets may be required to pay other actors in the value chain (e.g., aggregation warehouses, refrigerant reclaimers, and destruction facilities) for cylinder handling, refrigerant testing, and in some cases, destruction of mixed refrigerants. These fees add to the variable costs associated with refrigerant recovery.

A third type of cost is opportunity cost – i.e. the potential benefit that technicians forfeit by choosing to recover refrigerant rather than venting it. Opportunity cost is a significant barrier to refrigerant recovery, since recovering refrigerant is often a less valuable activity to the technician than moving on to the next job. The major determinant of opportunity cost is time. The longer refrigerant recovery takes relative to the value of the recovered refrigerant, the more potential revenue a technician is forfeiting by not moving on to other jobs. The previously mentioned unpublished industry survey has highlighted the opportunity cost as an important barrier to refrigerant recovery.

Examples of opportunity cost of refrigerant recovery

When considering opportunity cost, the true costs of refrigerant recovery are much higher than analysing the costs of labour and equipment alone.

- Offsetting Technician Wages: If the contractor believes that refrigerant recovery will require one hour for their technician, and the contractor pays the technician $20/hour, then the contractor would need to be paid more than $20 for the refrigerant recovery service (including the value of the recovered gas) to recoup the cost of paying the technician’s wage.
- Lost Opportunity: Hypothetically, a contractor may make $50/hour in profit from non-recovery jobs, such as installing equipment or repairing compressors. These activities are more valuable to the contractor than recovering refrigerant. Thus, to truly cover both the costs of technician labour and the opportunity cost of refrigerant recovery, the contractor would need to be paid at least $70 for the recovery service and the recovered refrigerant, to cover labour cost and foregone profit.

Across much of the world, recovered refrigerants are not valuable enough to fully cover a technician’s costs for the time to recover the refrigerant. Technicians may be paid incentive fees by reclaimers or even some governments. However, these incentive payments are limited when the price of virgin refrigerant is low, because the cost of recovery plus incentives makes the recycled or reclaimed refrigerant non-competitive with virgin refrigerants.

In many parties – particularly LVCs – there is an insufficient quantity of recovered refrigerant to justify investment in destruction or reclamation facilities. It may also take time to accumulate sufficient volume to make shipping recovered refrigerant to another location economical. There are known small stockpiles of recovered refrigerants in some parties and in many rural and remote locations awaiting collection for destruction or reclamation.

An important prerequisite for cost effective EOL management is to accumulate enough controlled substances to be reclaimed or destroyed to make land and/or sea transport viable and justify the individual shipment transaction costs. This requires collection, consolidation in appropriately sized and qualified tankage, and secure storage until such a viable quantity is available for shipping. This would typically be an amount that might fill a standard shipping container. For EOL refrigerant, this would involve investment in incremental infrastructure, developed and operated collectively by refrigeration servicing providers.

There may be opportunities for regional cooperation in developing an economically sustainable regional market for such destruction capacity that could serve several parties in reasonable proximity that were willing to cooperate efficiently on Basel Convention approvals. This approach may ease the challenges of EOL refrigerant management for LVCs, regions with limited destruction capability, and remote, albeit small stockpiles of refrigerant. Smaller scale EOL ODS/HFC destruction facilities and use of existing industrial based destruction capacity, such as cement kilns may also create an opportunity, for EOL management.

LRM companies, may also individually or collectively, develop business growth plans to facilitate the consolidation, handling, and export/import transactions of EOL ODS/HFCs for reclamation or destruction. Companies may also participate in such models in support of product stewardship or extended producer responsibility policies as well as facilitating access to carbon markets that financially incentivize the destruction of EOL ODS and unwanted HFCs.

6.3.4 Incentives for refrigerant recovery

In the last three decades, economic incentives for recovering HFCs have been weaker than for many ODS. Since ODS has been almost completely phased out across the globe, the value of recovered ODS – which can then be recovered for reuse or destroyed for carbon credits or other payment – has been significant enough in some parties to generate modest recovery volumes. The high prices of recovered and reclaimed ODS have also supported higher rates of refrigerant recovery when the market demand seems to be larger than supply.

Some value chains, especially commercial value chains (e.g., retailers or building owners with multiple pieces of RACHP equipment) consider refrigerant recovery to be part of the contractual obligation or condition of equipment procurement or installation or maintenance agreements. Other equipment owners maintain equipment with their own employees and recover refrigerant for reuse in their facilities. Some contractors consider the requirement to recover refrigerant a mandate for their technicians.

Refrigerant recycling data is generally not collected by most parties and subnational governments, so it is unclear how much recovery takes place for that purpose, including recycling where reclamation is required for a change of ownership. However, it is clear, even in parties with extensive end-of-life management programmes that less than expected quantities, especially of R-410A, are returned for either destruction or reclamation, as noted above. The following discussion postulates possible causes for the limited return of refrigerants including R-410A, especially from unitary split systems containing less than 10 kg of refrigerant, for destruction or reclamation.

Sales of recovered refrigerants can help to recover costs associated with recovering refrigerants. However, across much of the world, recovered refrigerants are not valuable enough to fully cover a technician’s costs for the time to recover the refrigerant. In some localities, where contractual obligations are not in place in some localities, technicians are paid additional fees beyond their normal income, to comply with venting prohibitions and recover refrigerant for reclamation or destruction by private companies (e.g., reclaimers and distributors) or even some governments. For some parties, these incentives exist in a regulated model, while for others, private companies voluntarily make payments to technicians to boost recovery volumes. However, these incentive payments have practical limitations in markets where the price of new refrigerant is lower than desired and close to the cost of reclaimed refrigerant. If the incentive payments are too high, refrigerant reclaimers or companies that sell reclaimed refrigerant must sell the reclaimed refrigerant at prices below the collective cost of fees for recovery and the cost of reclamation or leave them in inventory.

Refrigerant also tends to be a small percentage of total equipment scrap value, particularly in parties where the price for new (virgin) HFCs is still low. As seen in the tables below, refrigerant tends to be only 4 percent to 5 percent of a split air conditioner's total scrap value in markets that have not yet entered phasedown, compared with 20 to 23 percent of scrap value in the European Union.

Summaries of split AC system scrap values and recovered refrigerant weights and values for reversible splits in a hypothetical A5 party and EU (chosen as an example of a non-A5 party well into HFC phasedown) are provided in Tables 6.1 and 6.2, respectively. These tables are useful in showing how the economics of refrigerant recovery change as phasedowns progress and market conditions for HFCs change. In some cases, depending on the technician's opportunity cost, the value of the recovered refrigerant itself – in absence of additional incentives – may be adequate to drive higher recovery rates. However, even if the value of recovered refrigerant rises under phasedown, it may not entirely cover a technician's costs, including opportunity cost.

Table 6.1 Split system scrap value by material, refrigerant weights, and respective values for reversible splits at 0-6 kW & 6-12 kW capacity in A5 parties

Split System Estimated Scrap Value – A5 Party			Reversible split [0-6 kW]			Reversible split [6-12 kW]		
Material Group	Material	Approx. Scrap Value ($/kg)	Weight (kg)	Value ($)	% Total Value	Weight (kg)	Value ($)	% Total Value
Plastics	Polypropylene	$1.13	6.355	$7.18	7%	14.88	$16.81	6%
Plastics	Polyamide	$3.00	0.615	$1.85	2%	1.44	$4.32	2%
Ferrous metals	Cast iron	$1.30	18.45	$23.99	23%	43.2	$56.16	22%
Non-ferrous metals	Copper	$9.07	6.97	$63.22	61%	16.32	$148.02	57%
Non-ferrous metals	Aluminium	$2.27	2.87	$6.51	6%	6.72	$15.25	6%
Electronics	Printed circuit board	$3.50	1.23	$4.31	4%	2.88	$10.08	4%
Refrigerant	HFC-410A	$5.00*	0.98	$4.90	5%	2.01	$10.05	4%
Other	Misc.	N/A	3.53	N/A	N/A	8.55	N/A	N/A

Material values are approximate as of early 2024, from the London Metal Exchange and other price indices.

Adapted from Review of Regulation 206/2012 and 626/2011 Air Conditioners and Comfort Fans (European Commission, 2018).

*In markets deep into HFC phasedown, such as the European Union, the price for HFCs such as R-410A can be as high as $40/kg.

These prices, as discussed in the main text, could significantly change the economics for refrigerant recovery from small equipment.

Table 6.2. Split system scrap value by material, refrigerant weights, and respective values for reversible splits at 0-6 kW & 6-12 kW capacity in European Union

Split System Estimated Scrap Value – European Union			Reversible split [0-6 kW]			Reversible split [6-12 kW]		
Material Group	Material	Approx. Scrap Value ($/kg)	Weight (kg)	Value ($)	% Total Value	Weight (kg)	Value ($)	% Total Value
Plastics	Polypropylene	$1.13	6.355	$7.18	5%	14.88	$16.81	5%
Plastics	Polyamide	$3.00	0.615	$1.85	1%	1.44	$4.32	1%
Ferrous metals	Cast iron	$1.30	18.45	$23.99	17%	43.2	$56.16	18%
Non-ferrous metals	Copper	$9.07	6.97	$63.22	46%	16.32	$148.02	47%
Non-ferrous metals	Aluminium	$2.27	2.87	$6.51	5%	6.72	$15.25	5%
Electronics	Printed circuit board	$3.50	1.23	$4.31	3%	2.88	$10.08	3%
Refrigerant	HFC-410A	$32.00*	0.98	$31.36	23%	2.01	$64.32	20%
Other	Misc.	N/A	3.53	N/A	N/A	8.55	N/A	N/A
Material values are approximate as of early 2024, from the London Metal Exchange and other price indices. Adapted from Review of Regulation 206/2012 and 626/2011 Air Conditioners and Comfort Fans (European Commission, 2018). *In markets deep into HFC phasedown, such as the European Union, the price for HFCs such as R-410A can be as high as $40/kg. These prices, as discussed in the main text, could significantly change the economics for refrigerant recovery from small equipment.								

6.3.5 Reclamation

The refrigerant reclamation industry currently faces several economic barriers holding back scale, particularly in parties that do not have developed infrastructure for refrigerant recovery and have not yet entered HFC phasedown. Reclaimers must invest capital in reclamation infrastructure while also covering variable costs associated with labour and logistics. These costs often drive up the price for reclaimed refrigerant required to make sustainable profit margins, making reclaimed refrigerants uncompetitive with virgin refrigerants in the absence of regulation, procurement standards or financial incentives.

Refrigerant recycling for reuse or blending with new refrigerant to achieve desired composition and contaminant levels are considerably lower cost alternatives to reclamation. However, reclamation may be necessary for refrigerant blends or in cases where one component of a refrigerant is needed and another is not (e.g., R-410A is composed of HFC-32 and HFC-125. HFC-32 may be needed while the R-410A and HFC-125 may not be needed). Reclamation technology may also be needed when refrigerant mixtures are returned in cylinders.

First, although reclaiming refrigerant creates incentives for refrigerant recovery and some studies indicate it is substantially less emissive compared to destruction and virgin manufacturing, there is no "green premium" for reclaimed refrigerants on the market. Instead, end users largely perceive reclaimed refrigerants to be lower quality compared with virgin refrigerants. Some equipment manufacturers and other refrigerant end users avoid using reclaimed refrigerants in their products, over concerns with quality and potential liabilities associated with subpar quality refrigerants with respect to warrantees or equipment guarantees [32]. In contrast, others including some equipment manufacturers in the EU have added reclaimed refrigerants in new equipment. Some companies sell reclaimed refrigerant in stores or provide reclaimed refrigerant for long-term equipment maintenance.

Reluctance to purchase and use reclaimed refrigerants is more notable in parties without access to refrigerant testing infrastructure to provide assurance that reused refrigerant can meet high quality standards. Testing requirements for both new and used refrigerants are generally left to refrigerant purchasers and their contractual agreements, rather than mandated by governments, even in parties with infrastructure. The absence of a green premium means reused refrigerant must compete on price with virgin suppliers.

Although there is some reclamation of refrigerant from A5 parties, reclamation volumes are still low, with focus on CFCs and HCFCs rather than HFCs. Some reclaimers that are active in these regions, only recover refrigerants in the origin country and export the recovered refrigerant for reclamation and resale into other parties. The primary barrier to reclamation in A5 parties is the low prices for virgin HFCs, making large-scale HFC reclamation uncompetitive with virgin HFC import or production. Refrigerant reclamation may provide an additional compliance option for A5 parties with servicing only refrigerant needs longer-term during their HFC phasedowns.

Reclaiming refrigerant by distillation, rather than blending with new refrigerant alone, requires significant capital investment, especially for commingled or contaminated refrigerants and HFC blends if blends need to be separated into individual components. Without a strong market for reclaimed refrigerants and without a steady supply of recovered refrigerant as raw material, these investments are not economically attractive.

Some refrigerants are more complex mixtures than previous-generation ODS and in addition some are blends of HFCs and other fluorocarbons. Volumes of common high-GWP HFCs such as HFC-134a (a single component refrigerant) and R-404A (a blend) are expected to

[32] https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2020/hfc2020/frorevised.pdf

peak in the waste stream this decade, with some HFCs such as HFC-32 (a single component refrigerant) and R-407C (a blend) peaking in the mid-2030s (further discussions on bank sizes in Chapter 8).

The growing proportion of refrigerant blends poses a significant challenge to reclaimers.

- Recovered blends that are selectively separated to avoid mixing different species of refrigerants reduce costs and increase reclaimed refrigerant yield. This requires capital investment in larger fleets of refillable cylinders, and larger vehicles to transport them.
- Separation or reclamation technology capable of fractionally distilling a mixture of refrigerants requires a multi-million-dollar capital investment, trained technicians and operating systems to run the equipment. This technology reportedly has higher operating costs compared with reclamation for one or two component refrigerants (see Chapter 7).

Some companies have filed patents on novel inventions in the reclamation process, blends, and the use of blends containing reclaimed hydrofluoroolefins (HFOs). Patents may prevent the widespread use of reclamation, particularly if recovered refrigerants contain HFOs.

6.3.6 Destruction

Destruction is a critical component of LRM because it permanently eliminates potential emissions of recovered ODS or HFCs. Across the world, volumes of recovered refrigerant have not been of sufficient quantity to justify large scale or dedicated investment in destruction facilities closer to source, resulting in high destruction costs relative to the volume of refrigerants being destroyed.

In general, the most significant portion of these costs comes from actual destruction, with transportation and transaction costs accounting for 10 percent of total costs for in-country destruction, and 20 percent of total costs when export of refrigerants is required. Furthermore, destruction of ODS and HFCs, depending on geography, has not always been able to be monetized for carbon credits or incentivized from a regulatory regime. Generally, industry and the value chain (e.g., end-users, contractors and distributors) have paid for destruction.

As discussed in Chapter 7, capital expenditure to establish destruction capacity can vary significantly based on the technology used for destruction and applicable economies of scale. TEAP has previously established a list of approved technologies for the destruction of controlled substances[33]. Although the technology approval list was developed specifically for Article 7 of the Montreal Protocol, it has since been adopted by country programmes and carbon financing methodologies as an authority on which technologies can destroy ODS and HFCs outside of Article 7 compliance.

Costs can fluctuate based on technology accessibility in a country or a region, availability of competitive options, and most critically quantity of material presented.

Another challenge is the available amount of waste. The amount of EOL refrigerant available for destruction today is small relative to the amount of refrigerant that could be recovered from banks from retirement and replacement (MCTOC 2022 Assessment Report). Except in some economies where more advanced LRM systems have been implemented and growing amounts of refrigerant are being captured for reclamation and destruction, the default option is intentional release (“venting”) of the refrigerant to the atmosphere. Effectively, there is little market for destruction, notwithstanding destruction capacity being available. A significant challenge in lowering costs for destruction will be creating markets for end-of-life

[33] MP Handbook reflecting the latest MOP XXXV decisions on amendment to the list.

refrigerants, recovering higher volumes of refrigerant, and transporting the refrigerant to locations where it can be responsibly destroyed.

While availability of viable destruction capacity exists globally[34], destruction capacity is not evenly distributed geographically (see Chapter 4). Destruction facilities tend to be concentrated in non-A5 parties that have mature, high quality chemical hazardous waste destruction capability operating commercially or as part of chemicals production facilities. Such facilities are also increasingly available in larger industrialized A5 parties. Existing industrial facilities, particularly cement kilns have also demonstrated destruction in both non-A5 and A5 parties and can be retrofitted to safely destroy refrigerants at low cost. In practice, destruction capacity exists most commonly in regions where end-of-life refrigerant is the highest volume. A significant obstacle in maximizing the potential of global destruction capacity is streamlining national and international regulatory regimes governing the classification and movement of refrigerant. These obstacles are discussed in Section 6.1. Transboundary movement of refrigerant, and its accompanying regulatory complexities, pose an administrative, time, and transactional cost challenge in the absence of economies of scale.

While costs may fall along with economies of scale, destruction remains largely unfunded except for mechanisms such as carbon financing and extended producer responsibility (EPR). These financing mechanisms are discussed in Chapter 5 and 7.

6.4 Logistics

A significant hurdle in establishing LRM practices globally is developing a reverse supply chain for the collection, transportation, aggregation, testing, and ultimate reuse or destruction of recovered refrigerants. This section discusses logistic challenges in establishing this reverse supply chain.

It can be argued that material recovered and going through the reverse supply for purposes of recycling, reclamation and reuse is not a waste and simply reprocessing of the original substances with intent of reuse. However, at each stage, waste may be generated that could be destroyed to reduce emissions. However, it can be argued that its classification at that point should be non-hazardous based on the normal interpretation of hazardous waste if it has no direct local environmental and human health impacts in comparison to the original product and is no different in either content or manner of handling as compared to the original product. However, classification as a dangerous good is appropriate in both cases because both are packaged in pressurized containers.

Presenting a case for more universal treatment of material in the refrigerant reverse supply chain, consideration of recovered refrigerant classification may potentially address many of the primary logistics and regulatory barriers that now exist particularly related to transactional cost and efficiency issues associated with the Basel Convention compliance and more generally international and internal domestic border regulatory barriers (both to export and import). These barriers limit accessibility to available destruction capability and restrict reclaim activities.

6.4.1 Refrigerant recovery

To recover refrigerant, technicians must first travel to the location of the end-of-life equipment. Depending on the country, there may already be specific collection systems for end-of-life appliances containing refrigerants, such as mini-split air conditioners or home refrigerators. Aggregation of equipment lowers barriers to recoveries since technicians can

[34] ODS Destruction in the United States and Abroad, US EPA/ICF, Document 440-R-21-006, April 2021.

recover large volumes of refrigerant without moving to different job sites for each recovery. However, especially in A5 parties, there are few formal policies coordinating the collection of the equipment. Therefore, technicians must travel to new locations to complete each refrigerant recovery. Travel to individual pieces of equipment is also necessary for equipment with medium or large charge sizes that cannot be easily relocated to a central facility.

When the technician reaches the job site, ideally with the proper tools to perform recovery, there may be additional logistic barriers. One of the most common ways to ensure refrigerant recovery goes efficiently is to surround the recovery cylinder with ice to reduce the temperature (and thereby pressure). Many technicians are unaware of this strategy. Sometimes technicians stop recoveries and vent the remaining refrigerant if they see refrigerants hiss out of the cylinder safety valve. Even technicians who are aware of sub-cooling may not have the resources or time to procure and have ice available when they do want to perform recoveries. Additionally, if the cost of ice is not included in the project budget, technicians may be reluctant to incur personal expenses for ice, and technicians may choose not to recover refrigerant or partially recover.

Recovery operations require additional time on-site, often facing pressure from facility owners or building management for rapid project completion. For instance, with many office buildings or malls, projects frequently need to be finished during off-hours before commercial operations resume. Under such time constraints, refrigerant recovery may not be completed. Technicians inclined to perform refrigerants recoveries frequently lack leverage to negotiate and may need external assistance to persuade facility management of the importance of refrigerant recovery.

Once technicians successfully recover refrigerant, they also may not know what to do with it. In many A5 parties, there are no developed end markets for recovered refrigerant, with no facilities to accept recovered refrigerants. Technicians may stockpile refrigerants in cylinders or vent the refrigerants to the atmosphere. Venting has been anecdotally reported in both non-A5 and A5 parties, especially where there is no infrastructure to reuse or destroy refrigerants at scale, including perhaps due to policies preventing transboundary movement of refrigerant to other (see Chapter 4).

6.4.2 Transportation and return facilities

In some A5 parties, technicians may use motorbikes to travel to different job sites. Motorbikes are typically large enough to fit ladders and cylinders of new (virgin) refrigerant for reaching equipment but are often not large enough to hold recovery machines or recovery cylinders. Thus, prevailing methods of transportation can also create barriers in equipping technicians with the necessary tools to perform refrigerant recovery.

Aggregation warehouses (or facilities where technicians can return recovered refrigerants) may also not be located close to the recovery site. In these cases, technicians may need to travel long distances to offload recovered refrigerants and to pick up empty recovery cylinders. As we discuss in section 6.3, transportation costs – and the cost of time spent driving – may become economic barriers to refrigerant recovery.

In some cases, cylinders containing A2L (slightly flammable) and A3 (flammable) refrigerants must have special certification to be transported or stored in large volumes. Costs and effort associated with certifying cylinders and gaining approval to transport flammable refrigerants may be a barrier to responsible recovery.

6.4.3 Cylinder access, Refrigerant aggregation and testing

Sufficient certified and suitably sized and labelled refillable cylinder fleets are not always available for the transport, consolidation, and secure storage of refrigerants to support the reverse supply chain. These cylinders, including their valves, are designed to safely store refrigerant and be continuously refilled and evacuated without losing structural integrity.

Without sufficient supply of refillable cylinders, technicians may commingle or venting refrigerant to the atmosphere. Co-mingled refrigerants are more difficult to reclaim without the use of advanced reclamation technologies such as distillation. There also must be sufficient space to safely store recovered refrigerants and recovery cylinders. If cylinders are exposed to the weather, components may degrade over time, resulting in refrigerant emissions.

Once aggregated, refrigerant chemical composition is often analysed in a laboratory prior to being destroyed or reclaimed. Laboratory analysis is also used to verify the quality of reclaimed refrigerant. Although large companies typically possess in-house laboratory testing, smaller companies may outsource testing and sometimes export samples for testing abroad. Furthermore, to destroy refrigerants for carbon credits on the voluntary carbon market, testing must be conducted by a third party. Depending on the country, laboratory analysis may not be readily available or accessible, therefore the quality of the recycled /reclaimed refrigerant is not guaranteed, which could possibly impact the effective operation of the equipment it is used in.

6.4.4 Destruction

Recovered refrigerant to be destroyed is impacted by the same challenges as recovered refrigerant for reuse. Transboundary shipment under the Basel Convention which requires prior informed consent of all parties receiving the shipment, including the final destination. Although larger parties and waste management companies typically have experience navigating these requirements, smaller A5 parties may not have the institutional capacity to coordinate and execute these processes. Barriers from the Basel Convention and definitions of hazardous refrigerant waste are discussed in greater detail in section 6.1.

6.5 Awareness, knowledge, and behaviour

Any person who handles refrigerants needs the necessary knowledge and awareness about the environmental and safety impacts associated with their activities. Training can increase knowledge and awareness and is discussed in section 6.6.

Good servicing practices can be made habitual for technicians to incorporate them in their daily work. An obstacle to implementing good practices is time. Technicians who view leak prevention or recycling as an extra function for which they are not paid for may be less likely to perform these tasks.

Another obstacle is practicality. Some technicians need to carry a recovery machine and an empty cylinder on their motorcycle on top of their toolbox. In some cases, two technicians (one technician with one assistant) are traveling on a single motorbike while carrying all of their needed tools, leaving not much room to bring additional equipment needed for recovery.

The third obstacle is the ambient temperature. Servicing in a high ambient temperature country at 40°C is considerably taxing. Technicians try to minimize time spent performing tasks that they do not believe necessary.

In addition to these barriers, small and medium-sized enterprises (SMEs) may find it difficult to recover refrigerant because of the lack of technological know-how and training. They may be unaware of the advantages of leak prevention for their customers in reducing energy and refrigerant (Rizos *et al*., 2015).

Anecdotally, refrigerant is sometimes recovered for reasons other than environmental stewardship. A food and beverage company reportedly recovered refrigerants in fear that venting would alter the taste of their products. Showing indifference to the refrigerant's fate post-recovery, in this case, it was vented right outside the factory premises. Similarly, recoveries can occur due to water contamination from leaks in condenser pipes, where proper disposal post-recovery was not considered a priority.

Similar challenges are highlighted in Chapter 4, noting lack of awareness about recovery processes, accessibility of recovery equipment, sufficient cylinders for storage, and lack of regulatory measures against leakage as the main barriers in awareness, skills, and behaviour. For an individual technician, having all the necessary tools is a challenge. The end consumer rarely demands the recovery due to lack of knowledge. In addition to the cost of tools, the technician must also bear the cost of the extra time required for collection and disposal.

6.6 Skills and competencies

The Multilateral Fund has funded training as part of capacity-building in A5 parties including leak prevention, recovery, recycling and safe handling practices for flammable refrigerants where applicable. Training and tools are often provided together.

Some of the training challenges are listed below:

- In some parties, technicians have not received any form of formal education. Most RACHP technicians may be self-taught or may have joined repair shops as apprentices and learned from more senior technicians. This can lead to inconsistent and wide-ranging abilities among working technicians. Addressing the informal sector carries its own challenges due to either incomplete information about the sector, or in convincing the technicians to give up part of their time for training.
- Access to available training facilities and costs to attend could be a disincentive for technicians to undertake training.
- There may not be sufficient tools for technicians to perform recovery and recycling after they receive the training.
- Gender mainstreaming in training is still a challenge for women in some parties due to societal inhibitions.
- It is not easy to monitor if technicians continue to implement the good practices they learned. Generally, monitoring and secondary training are unfunded.
- Maintaining refrigeration training facilities or educational centres requires investment in laboratories and practical facilities, which may be idle most of the time and need constant updates, making this approach more expensive and viable only in places with higher demand, larger population, or when they receive subsidies to sustain themselves.
- Some formal programmes (e.g., vocational schools) may lack sufficient expertise to support up-to-date best practices and skills training. It has also been reported anecdotally that it can be challenging to attract and maintain qualified instructors.
- Anecdotes of injuries and fatalities due to tank explosions in the field, often resulting from technicians using disposable tanks for refrigerant recovery without adequate cooling, have been reported.

In the Annex to this chapter, an example is given on how India is aiming to overcome training challenges.

6.7 Annex

Examples of countries which changed the definition of refrigerant waste

- As part of the EU Life project Life3R, Hungary examined how the circular economy of refrigerants can be facilitated and concluded that their national legislation needed an update. In 2023, the legislation was revised to align with the interpretation explained in Flowchart B from the previous interpretation shown in Flowchart A. Additional conditions were applied, for instance, service technicians may only keep the recovered refrigerant for a maximum of two years after which it must be sold or handed over for reclaim or destruction (info Hungary National Climate Protection Authority[35])

- In France, HFC refrigerants that are recovered using equipment which will be removed from the site where recovery takes place, are classified as hazardous waste and must be traced on *Track déchets*[36] . An exemption applies when HFCs are recovered from a piece of equipment and reused without further treatment or simply reused after a recycling operation (through basic cleaning, such as filtration). The recovery process may be done on the same equipment, or on another equipment on the same site as that from which it was recovered, or on another equipment belonging to the same holder (in the case of a legal entity: same business identification number, referred as SIREN number) but located on another site, and the recovered refrigerant must not take on the status of waste based on national territory. Specific use example is the transfer of refrigerant for maintenance or repairs.

  For these cases of exemptions in France, the holder of the recovered refrigerant must be able to justify the effective possibility of reuse, without any prior treatment, or only after recycling (through basic cleaning, such as filtration), before reusing it on the same equipment or on other equipment on the same site as that from which it was recovered, or before transporting it to another site when the holder wishes to reuse it on other self-owned equipment located on a separate site based on national territory. The holder must keep the supporting documents and make them available on request to the approved bodies and the supervisory authorities (France Ministry of Ecology).

Example of how India aims to overcome training challenges

- In India, the growth of Room AC which forms 80 percent of refrigerant consumption is expected to reach 10 to 12 percent in 2037 (ICAP, 2022). This means that production will approximately double every 6 years. Penetration rate is growing in rural areas, while technicians' capacity increase is not keeping pace with the growth of the cooling devices. To address this, the country implements multiprong approach to train the technicians which includes first time training and follow-up training as well as learning.
- First, the technicians with education from the Industrial Training Institutes are shortlisted for further training. Then, industry may choose certain routes for training. Some manufacturers have established their own training centres facilities. Some joined hands with other companies (not necessarily from the industry) and foundations who have taken skill development programmes under CSR (Corporate Social Responsibility) activities. To note, CSR is mandatory by law wherein 2 percent of the profit is to be utilized for social activities including skill development.
- Some manufacturers conduct training on wheels with the use of a fully equipped van that moves from place to place to train the technicians. This concept of "training at your doorsteps" is an effective method in rural areas. Other manufacturers have developed videos, and access is given to dealers and technicians through smartphones. These videos cover dos and don'ts, case studies, properties of refrigerants, and installation practices. Another common practice is to form a team of trainee technicians and senior technicians where the senior technician is given the responsibility to train the trainees in a period of 12 to 18 months.

[35] Nemzeti Klímavédelmi Hatóság (kormany.hu)

[36] Trackdéchets | La traçabilité des déchets en toute sécurité (beta.gouv.fr)

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Chapter 7

Costs associated with Life cycle Refrigerant Management

Chapter 7 Summary

- High refrigerant prices have driven more leak prevention, refrigerant recovery and reuse in many parties and markets. However, high prices may increase the risk of illegal trade in some cases.
- Effective implementation of LRM requires an evaluation of the total costs associated with acquisition, operation, maintenance, and disposal of refrigerants throughout their life cycle. These costs can be an economic barrier to LRM in both non-A5 and A5 parties.
- Lack of consistent policy mandates and enforcement and fluctuating refrigerant pricing make it difficult for companies to justify capital investment to support destruction, reclamation, and recycling, as well as to fund reverse supply chain infrastructure (e.g., cylinder fleets), even in non-A5 parties.
- The costs related to the LRM activities vary depending on several factors, including the type of refrigerant, the scale of the operation, regional regulations, technology employed, the fate of the recovered refrigerant (whether reused or destroyed) and the robustness of and access to the reverse supply chain.
- Market supply and demand dynamics for new (virgin) refrigerant refrigerants strongly affect the economics for LRM activities. Rising prices for virgin refrigerants may provide refrigerant end-users (e.g., retailers and building owners) with financial incentives to take action to reduce refrigerant leaks from equipment to save on the cost of refrigerant and to recover refrigerant for reuse. However rising prices may also cause risks of illegal trade or inappropriate use of refrigerants.
- Extended producer responsibility (EPR) has had some success in increasing recovery in some parties. Carbon markets have also had some success in incentivising refrigerant recovery and destruction. The expansion of existing and new innovative financing mechanisms, in addition to Multilateral Fund, will be required to address the cost challenges associated with implementing LRM, particularly in A5 parties.

7 Costs Associated with Life cycle Refrigerant Management

7.1 Introduction

Decision XXXV/11 requests information on *"costs associated with the leakage prevention, recovery, recycling, reclamation and disposal of refrigerants, taking into account the experience under the Multilateral Fund for the Implementation of the Montreal Protocol*".

Effective implementation of LRM requires an evaluation of the total costs associated with acquisition, operation, maintenance, and disposal of refrigerants throughout their life cycle. As discussed in Chapter 6, these costs may be a major economic barrier to LRM in both non-A5 and A5 parties.

Implementing LRM at scale globally will require capital expenditure for technology and equipment as well as setting up or updating of facilities, and sustainable business models to cover both capital and operating costs. This chapter provides an overview of the types of capital and operational expenditures associated with LRM, and where available, includes indicative costs for LRM processes. Climate and ozone benefits of LRM will be discussed in Chapter 8.

Understanding capital and operating costs associated with LRM, possible financing mechanisms, and how costs may change over time may support more public and private investment in LRM activities.

Compliance with environmental regulations and industry standards would increase successful LRM practices. LRM value chain costs include the proper handling, recovery, storage, reuse, and disposal of refrigerants. Non-compliance with policies can also result in fines, penalties, or reparative actions.

Financial incentives, such as grants, subsidies, tax credits, and carbon credits can encourage organizations to adopt sustainable refrigerant management practices. However, these types of programmes must be implemented with guardrails to ensure effectiveness to achieve emission reductions. These incentives help offset initial investment costs and promote implementation of LRM. Additionally, refrigerant management best practices can reduce operational costs by maintaining equipment efficiency and lowering energy consumption, reducing refrigerant purchase to recharge equipment, and extending equipment lifespan.

Integrating financial considerations into refrigerant management strategies can further reduce refrigerant emissions. This chapter describes the capital expenditures and operating costs associated with different LRM activities, as well as a menu of possible financing mechanisms for LRM activities.

7.2 Life cycle Refrigerant Management: economic aspects

Costs for LRM activities arise from both macroeconomic conditions and from microeconomic conditions along the refrigerant supply chain.

7.2.1 Macroeconomic influences

The timing and stringency of a country's HFC phasedown, as well as market supply and demand dynamics, are important determinants of new (virgin) refrigerant price and LRM economics. Parties phase out/phase down the production and consumption (production plus import minus export) or supply of controlled substances under the Montreal Protocol. If there is a large excess between allowed consumption of substances compared to market demand, new (virgin) refrigerant prices may be too low to make LRM investments economically attractive. Stringent phaseout/phasedown schedules may drive higher prices of controlled substances but may also risk spurring illegal trade or use of inappropriate gases.

Rising prices for new (virgin) refrigerants may provide refrigerant end-users (e.g., retailers and building owners) with sufficient financial incentives to take action to reduce refrigerant leaks from equipment to save on the cost of refrigerant. As the price of virgin refrigerant increases, eventually exceeding the cost of recycled or reclaimed refrigerant, there can also be a financial incentive for the value chain (e.g., end-users, automotive servicing businesses, contractors) to recover refrigerant, recycle refrigerant, and purchase reclaimed refrigerant.

There are temporal macroeconomic issues created by the different staggered Kigali Amendment phasedown schedules for non-A5 and A5 parties. At the same time, demand for low GWP refrigerants/equipment will climb rapidly.

In A5 parties:

- Inexpensive regulated virgin refrigerants in the early phasedown years (e.g., 2024, 2029 etc.) may make LRM not commercially viable.
- The increased supply of virgin refrigerants and equipment may increase the size and longevity of the installed bank and servicing tail, especially in servicing-only parties.

In non-A5 parties:

- Unless the HFCs contained inside imported pre-charged HFC-based equipment are included in the receiving parties' phasedown schedules, or unless specific product bans apply, the import of HFC-based equipment will increase the size and longevity of banks and the servicing tail.

Drawing on the past experiences of the ODS phaseout and recent experiences from the early years of the HFC phasedown, dumping of low-cost, high-GWP refrigerants between parties may lead to disruptions in the market, depressing costs in both non-A5 and A5 parties.

7.2.2 Reuse of refrigerants - benefits and costs

The reuse of refrigerants in RACHP equipment can offer various benefits and costs, which are important to consider.

Refrigerant reuse increases when the price of new (virgin) refrigerant is higher than the price of used refrigerant. Refrigerant reuse also increases when new (virgin) refrigerant becomes unavailable, but equipment has not yet reached the end of its useful lifetime (e.g., CFC-11 in large chillers). Reusing refrigerant allows for new equipment to achieve its useful lifetime, and old equipment to operate far longer than designed, however it may be at higher leak rates. It may also enable the continued use of inefficient old equipment.

7.2.3 Microeconomics of refrigerant recovery

Refrigerant recovery requires functional recovery equipment and time. Equipment that is not well maintained or not designed for the vapor pressure of the refrigerant to be recovered slows the process. There are other considerations that can influence the decision to recover or the choice not to recover refrigerant. There are costs associated with the recovery, recycling and reclamation at the technician level and non-established reverse supply chains. Businesses may not be required to recover refrigerant at end-of-life or view the risk and penalty of not recovering refrigerant as low.

Some businesses have anecdotally reported that they compare cost to pay a technician for the time to recover refrigerant or the profit from sending the technician to another maintenance or installation to any payment that they may receive for selling used refrigerant. This "opportunity cost" analysis means that the payment for recovered refrigerant would need to exceed the value of competing opportunities for the technician.

7.2.4 Microeconomic impact of refrigerant reclaim compared to recycling

Reclamation adds cost to the reuse of refrigerants and can result in pricing that is equal to or higher than new (virgin) refrigerants. Used refrigerant is often sold without mandatory purification reducing costs of reuse. In some Parties to the Montreal Protocol, this recycling economy is reportedly extensive, especially for end-users that have multiple pieces of equipment and even multiple locations (e.g., by retail chains, by owners of multiple buildings, and for automobiles at maintenance shops). The volume of recycled refrigerant is not often documented and depends upon the internal company processes or internal company practices and business agreements between end-users and suppliers.

Some parties allow the resale of used refrigerants with no quality requirements relying on business agreements to determine agreed upon quality. Some other parties require that refrigerant be purified or blended to meet a specified purity before selling to another company for some uses, while allowing sales or reuse for certain markets or by the same owner without this mandate. The process used to achieve the required purity level (e.g., blending or distillation) is not mandated. These purity standards may de-risk the use of reused refrigerant for the end user but add costs to the reuse process – both from refrigerant testing and purification.

Recovered refrigerant can be returned with many different impurities or it can be returned mixed with other refrigerants. Recycling machines remove water and other impurities and have been used successfully in the automotive industry for CFC-12 and HFC-134a for decades, returning these single-component chemicals to sufficient purity for reuse.

In some jurisdictions, mandates to use reclaimed refrigerants are also accompanied by mandates that limit the amount of new (virgin) refrigerant allowed in reclaimed refrigerant have been put in place (e.g., California, and under consideration by U.S.EPA). The latter are a safeguard to ensure that reclaimed refrigerant contains mostly recovered refrigerant. This is because allowing unlimited quantities of virgin refrigerant to be blended with reclaimed refrigerant may lead to "counterfeiting" or greenwashing of reclaimed refrigerant. However, it is noted that mixing virgin refrigerants is the lowest cost approach to "diluting out" the impurities from recovered blended refrigerants and a mandate to limit the virgin content does increase costs related to reclamation. However, those safeguards ensure that use of reclaimed refrigerant results in greater recovery and the emission benefits associated with recovery and reuse.

Other reclaimers use distillation columns to separate contaminants from refrigerants and even separate blends into components to be recombined to create new refrigerant blends, including low GWP blends. This separation technology typically requires more significant capital investments than for technology reclaiming chemically simpler or purer recovered refrigerants.

7.2.5 Opportunity for LRM for RACHP applications

The feasibility and opportunity to implement recovery, recycling, and reclamation actions across various RACHP applications are influenced by the economics of LRM. Table 7.1 below offers an assessment of the potential of LRM actions, primarily based on the quantity of refrigerant charged in the equipment.

The type and volume of refrigerant used in RACHP equipment significantly impacts the feasibility and cost-effectiveness of LRM actions. Equipment with higher refrigerant charges may present greater opportunities for recovery and recycling, whereas systems with lower charges may pose challenges due to cost constraints.

As noted in Chapter 4 and shown in the table below, refrigerant recovery from domestic refrigerators and air conditioners at their end-of-life is practiced in some parties where regulation exists. The low charge inside these appliances is a challenge for recovery during servicing which often leads to leaks and emissions. Recovery is more prevalent in larger equipment, with recycling typically occurring during maintenance of large-scale refrigeration systems, where refrigerants are purified for reuse. European Union policy recovery mandates shifted this trend in 2002 with requirements to recover controlled substances at the EOL from appliances and small air conditioners and extended it later to larger appliances.

Table 7.1 LRM considering equipment type and refrigerant charge

EU view Equipment type	Charge size	Leak rates during use	High reuse (recycle or reclaim)	Recovery at EOL?
MAC	<1 kg	high[37]	yes	Low
White goods	<1 kg	Almost none	no	Yes
Distributed refrigeration	>25kgs	High	Yes	Yes
Chillers	>100kgs	Low	Yes	Yes
US view Equipment type	**Charge size**	**Leak rates during use**	**High reuse (recycle or reclaim)**	**Recovery at EOL?**
MAC	<1 kg	high	yes	No
White goods	<1 kg	Almost none	no	No
Unitary residential	5 -15 kgs.	Medium	no	No
Distributed refrigeration	>25kgs	High	Yes	Yes
Chillers	>100kgs	Low	Yes	Yes

7.3 Cost analysis for Life cycle Refrigerant Management

The costs related to the refrigerant leak prevention RRRD can vary depending on several factors, including the type of refrigerant, the scale of the operation, regional regulations, technology employed, and the end use for the refrigerant (whether reused or destroyed). A description of the main cost components for LRM, along with cost estimates is presented below.

7.3.1 Capital expenditure (CAPEX)

Capital expenditures are the costs associated with acquiring and maintaining fixed assets such as equipment, tools, and infrastructure. In the case of LRM, capital expenditures may be required for leak detection and repair equipment, refrigerant recovery equipment, and technologies to reuse (recycling and reclamation) and destroy refrigerants. There may also be required capital expenditure for supporting tools, such as refrigerant recovery cylinders and equipment for refrigerant purity testing, and quality control laboratory costs (chromatography, etc.).

7.3.2 Operational expenditure (OPEX)

Operational expenditures are the costs associated with equipment maintenance, labour, energy consumption, quality control, and administrative costs (such as reporting and regulatory compliance). It should be noted that responsibility for operating and capital costs are often held by different people.

In the case of refrigerant recovery, OPEX items such as labour and transportation occur from the source of the gas through the first point of storage and consolidation. Thus, when considering OPEX associated with refrigerant recovery, reuse and destruction, technician labour costs (and opportunity cost) must be considered and potentially offset using a financial incentive.

Leaking refrigerant also adds operating costs from the new refrigerant required to recharge equipment.

7.3.3 Centralized handling, storage, and other logistical costs

Transporting recovered refrigerants from the point of extraction to designated facilities is a vital aspect of the recycling/reclamation process. There are several expenses associated with transportation, including the cost of fuel, coordination and logistics, and secure handling/storage infrastructure.

The ability to reuse or destroy recovered refrigerant depends on the ability to move recovered gases from their source to a location where they can be tested, aggregated, and stored. Costs of interim handling, storage, consolidation, and analysis are all important considerations in developing a reverse supply chain for refrigerants.

The classification of refrigerant as to whether it is a waste or a product to be regenerated or recycled can also impact costs if waste transportation and storage requires more licenses, transportation documents, and reporting.

7.3.4 Training and education costs

Technician training for refrigerant life cycle management involves comprehensive education on various aspects of handling refrigerants throughout their life cycle, focusing on leakage prevention, recovery, recycling, and reclamation.

In addition, training should include safety protocols, environmental regulations, and ethical considerations related to refrigerant management.

Maintaining a refrigeration school requires investment in laboratories and practical facilities, can have low utilization if not integrated with robust programmes within trade educational institutions, and need constant updates, making the practice more expensive and viable only in places with higher demand, larger population, or when they receive subsidies to sustain themselves.

7.3.5 Compliance costs

Compliance costs for LRM arise from adherence to regulatory requirements and standards. These costs can include training materials, instructor fees, certification programmes, compliance for reporting requirements, documentation for refrigerant transaction fees, licenses, and consulting for regulatory compliance.

7.3.6 Destruction costs

The three most common technologies used for destruction of EOL ODS/HFCs are rotary kiln incineration, plasma arc, and cement kilns. Costs can fluctuate based on technology accessibility in a country or a region, availability of competitive options, and most critically quantity of materials to be destroyed as follows:

- Commercial rotary kilns applied to moderate/large volumes can be similar to market halogenated HW destruction (US$2-3/kg), but on smaller demonstration quantities are in the range of US$5-8/kg.
- Commercial scale plasma arc destruction is estimated to be US$8/kg, with smaller units over US$20/kg.
- Cement kilns are estimated to cost ~ US$8/kg, (COPA, 2023).

Of all the LRM component activities, destruction cost will generally be the highest in terms of unit cost, it is estimated to range from US$2 to greater than US$20/kg. However, ultimately these costs will have to be assumed to avoid the default option of release to atmosphere with consequential of forgoing additional negative ozone impacts and major climate impacts. This is illustrated in Chapter 8 and documented in the TEAP MCTOC 2022 Assessment Report in its estimation of the cumulative bank and its annual availability of EOL ODS/HFC available for destruction. This translates into significant legacy cost for destruction if the ozone and climate benefits of completing the LRM process are to be obtained. Based on an average estimated annual accessible EOL ODS/HFC available between 2024 and 2030 (225 ktonnes) the global annual cost would be approximately US$675 million at a low unit cost of US$3/kg, primarily in non-A5 parties. After 2030 through 2050, destruction costs shift increasing to A5 parties and with an increase in annual availability increasing to a 350 k/tonne the legacy costs associated with destruction would be in the range of US$1 billion again at US$3/kg. Except perhaps in smaller low volume/low income A5 parties, it is likely that these costs will either have to be accommodated within the cost recovery generated commercially for LRM, or by the introduction of external circular economy-based financing mechanisms such as carbon finance and EPR as discussed in the next section.

Table 7.2 presents a summary of RRRD and estimate costs

Table 7.2 Scoping framework for indicative costs for Life cycle Refrigerant Management of ODS and HFC Refrigerants[38]

Process	**Capital Expenditure (CAPEX)**	**Operational Expenditure (OPEX)**			
	Equipment, Infrastructure, and Installation costs	**Laboratory Testing and Operational costs**	**Centralized Handling, Storage and other Logistics costs**	**Training costs**	**Compliance costs**
Leak prevention	- Hand-held leak detectors (US$ 400/unit) Automatic leak detectors (not hand-held) (depends on size of coverage required, not possible to provide indicative price)	- -		- Continuous technician training on leak prevention and detection, recovery, and recycling can be combined. Indicative cost, US $250 – 400 per technician. - Awareness campaigns can be consolidated for LRM activities. Programmes vary in cost starting at US $10,000	- Putting policies in place. Indicative cost start at US $15,000 - Recordkeeping by operators. Cost borne by end users. Cost of awareness campaigns and workshops start at US $15,000/Workshop - Monitoring & tracking. Capacity building cost of NOUs. Indicative cost starts at US $25,000
Leak Detection	- Hand-held leak detectors (US$ 400/unit) - Automatic leak detectors (not hand-held) (depends on size of coverage required, not possible to provide indicative price)	-	-	-	- Reporting and recordkeeping
Recovery	- Recovery cylinders and or bulk containers (below US$100 for the smallest cylinder, prices depend on sources, volume, presence of valves, transport and registering costs.) - Recovery equipment (US$ 300-1000/unit for very basic	- Cost for contracting out GC analysis (US$500) - Incremental technician time - Technician financial incentive	- Incremental handling equipment - Storage for economies of scale for onward return/treatment/ destruction - Incremental costs associate with handling mildly	-Technician training/awareness -Training for new operations/staff	- Emission ban enforcement - Tracking/ recordkeeping - Reporting and recordkeeping

[38] Prices presented in this table were not obtained from a detailed market survey; they are estimates based on expert information.

	recovery equipment, US$ 30K-40K for more complex equipment that can do faster recoveries) - Refrigerant identifiers (US$ 5,000/unit)		flammable or flammable refrigerants - Transport for treatment or destruction - Indicative costs vary from US $5 – 15/kg		
Recycling	- Recovery and recycling machine (US$ from 1200 onward, prices depending on capacity) - Bespoke[39] recycling equipment	- Moisture, high boiling residue, and other impurities removal and testing[40]	- If applicable, operation and maintenance costs for the testing facility or laboratories	-	- Reporting and recordkeeping
Reclamation **(single component refrigerants)**	- Refrigerant identifiers (US$ 5,000/unit) - Gas Chromatography (GC) equipment (US$ 45K to 50K) - Additional lab infrastructure (e.g., fume cupboards, lab balances) - Reclamation equipment to remove moisture, high boiling residue and other impurities	- Cost per GC analysis (US$ 500) - Incremental staffing costs - Incremental laboratory operational costs (e.g., sample and reagent bottles, calibration standards etc.)	- Operation and maintenance costs for the testing facility or laboratories - Incremental handling equipment (e.g., forklifts, trolleys etc.) – will vary by facility size - Storage for recovered refrigerants pending reclamation - Appropriate cylinder fleet for returning reclaimed refrigerant to the market - Where applicable, costs associated with providing third party certification (e.g., AHRI-700, ISO 90001, ISO 17025) - Storage of non-reclaimable/contaminated refrigerants for destruction	- Employment and training of operators of reclamation equipment (which is more extensive than typical technician training) Indicative cost US $500 – 750/operator	- Inventory management (paper or electronic) - Where applicable, facility permitting and individual licensing/certification - Reporting and recordkeeping
Reclamation **(multi-component refrigerants)**	- Refrigerant identifiers (US$ 5,000/unit, may not yet available to identify the composition for all types of blends)	- Cost per GC analysis (US$ 500) - Incremental staffing costs - Incremental laboratory operational costs (e.g., sample and reagent	- Operation and maintenance costs for the testing facility or laboratories - Incremental handling equipment (e.g., forklifts,	- Employment and training of operators of reclamation equipment (which is more extensive than typical technician training)	- Inventory management (paper or electronic) - Where applicable, facility permitting and individual licensing/certification

[39] Bespoke equipment refers to custom-made equipment that is not commercially available.

[40] Producing larger volumes of recycled refrigerants will need access to moisture and oil removal and testing equipment

	- Gas Chromatography (GC) equipment (US$ 45K to 50K) - Additional lab infrastructure (e.g., fume cupboards, lab balances) - Reclamation equipment to remove moisture, high boiling residue and other impurities	bottles, calibration standards etc.)	trolleys etc.) – will vary by facility size - Storage for recovered refrigerants pending reclamation - Appropriate cylinder fleet for returning reclaimed refrigerant to the market - Where applicable, costs associated with providing third party certification (e.g., AHRI-700, ISO 90001, ISO 17025) - Storage of non-reclaimable/contaminated refrigerants for destruction	Indicative cost US $500 – 750/operator	- Reporting and recordkeeping
Destruction	- Existing facility: Retrofitting existing hazardous waste facilities i.e. rotary kilns, cement kilns) with approved refrigerant destruction technologies co-disposing EOL ODS/HFCs (US$50,000 – 100,000) - New dedicated facility: Design, fabrication, installation, commissioning costs for approved destruction technologies (e.g., plasma arc etc.) – costs will vary depending on location, scale, and technology type. References costs: >3 million US$ for a small rotary kiln and >.4.2 US$ for a commercial scale plasma arc facility (COPA (2023)	- Commercial hazardous waste chemical destruction using lowest-cost incineration technology US $2-3/kg, assuming economies of scale are potentially achievable if contracted with established qualified facility - Low volume costs in commercial rotary kilns may be US$6-8/kg. - Cement kiln destruction estimated at US$ 8/kg. - Commercial scale plasma arc estimated at US$8/kg while small scale plasma arc at US$20+/kg References (COPA (2023), UNEP (2019)	- Operation and maintenance costs for destruction facilities in accordance with the Montreal Protocol handbook - Costs associated with achieving optimal operating efficiencies (may include quality testing of material prior to destruction) - Storage of non-reclaimable/contaminated refrigerants pending destruction	-Employment and training for new operations/staff (new facility) -Training of operators on lower cost destruction technologies has a similar indicative cost to RRR operators at US $500 – 750/operator	- Permitting, and if applicable, periodic recertification[41] - Inventory management - Facility performance qualification - Testing of waste streams, air/effluent discharge etc. to meet local environmental regulations - Reporting and recordkeeping

[41] Depending on local jurisdiction requirements, there may be ongoing needs to prove compliance with local environmental laws governing hazardous waste facilities. Additionally, if destruction is being used to generate carbon credits, proof may be required that the destruction plant performance conforms to requirements. Methodologies for the destruction of refrigerants may require ODS to be destroyed at approved destruction facilities that meet Montreal Protocol performance requirements.

7.4 Overview of potential financial mechanisms for LRM

Given the financial and economic barriers to LRM discussed in Chapter 6 and the costs outlined above, stakeholders have identified an urgent need for financing for LRM projects. Several possible financing mechanisms, including the Multilateral Fund, extended producer responsibility (EPR), and carbon markets, are discussed below. This section covers major financing mechanisms for LRM activities but may not in itself be exhaustive.

7.4.1 Multilateral Fund (MLF)

The MLF has funded projects that lie squarely in the LRM domain, including technical assistance for the recovery and reclamation of refrigerants, demonstration pilot projects covering ODS disposal and destruction, and most recently inventories of used or unwanted controlled substances and plans for their collection and disposal (ExCom Decision 91/66). The latter group of projects has an open submission window from 2024 to 2025, with project completion expected between 2025 and 2027. The scope of the current replenishment for 2024 to 2026, however, is expected to cover at most inventories and plans for ODS and HFC management, but not the implementation of these plans. The 35th Meeting of the Parties requested the Executive Committee to consider providing funding to parties that have completed bank inventories and management of these plans to implement these plans (decision XXXV/11). In the meantime, however, the MLF does not possess funding to support large-scale implementation of LRM activities.

7.4.2 Extended Producer Responsibility (EPR) and product stewardship

Extended Producer Responsibility (EPR) and product stewardship are policy models that assign the technical and/or financial responsibility for end-of-life equipment handling to fluorocarbon suppliers or equipment manufacturers. Typically, these programmes generate revenues to support downstream handling of refrigerants by attracting voluntary assumption of certain LRM costs by industry stakeholders individually or collectively, or mandatory schemes imposed by authorities that charge fees upon equipment purchase or apply levies to imported fluorocarbons. Some existing EPR and product stewardship programmes are discussed in detail in Chapter 5.

7.4.3 Carbon financing

Carbon credits are tradeable certificates that represent 1 metric ton of CO_2e removed, reduced, or avoided. Carbon financing uses the creation, sale, and retirement of carbon credits to finance projects that reduce, avoid, or remove greenhouse gas emissions. Historically, carbon financing projects have generated credits from a wide range of LRM activities, including leak detection and repair, HFC reclamation, and ODS and HFC destruction. These credits can then be sold on the carbon compliance or voluntary market, providing revenue for the project developer and opportunities in some cases, for further investment in LRM capacity. Carbon finance can also be blended with other sources of finance, such as grants or loans, or transition into policies such as mandatory RRRD measures, EPR and mandatory product stewardship.

7.4.3.1 Voluntary carbon market

The voluntary carbon market is currently the largest platform for buying and selling carbon credits, both by credit volume and value. The voluntary market primarily consists of companies and institutions that purchase carbon credits to meet voluntary emissions reduction commitments. In 2023, the voluntary carbon market was valued at USD $2 billion, with the expectation of growing to USD $10 to $40 billion by 2030. The voluntary market currently supports a wide range of LRM activities, including infrared leak detection, HFC reclamation, and ODS destruction. Crediting for these activities, however, is sometimes limited based on the geography of the activity. Despite its rapid growth, the voluntary market is still a nascent space and has recently experienced market-wide challenges with credit integrity and price stability. Resolving these challenges - including by improving methodological integrity, mechanisms for ensuring transparency, governance, and oversight - is critical in enhancing consumer confidence in their efficacy and achieving large-scale and stable financing from the voluntary market.

In the absence of regulation prohibiting the venting of refrigerants, carbon crediting methodologies and ensuing LRM projects could fill the gap to increase recovery of refrigerant at end of life. Additionality can be demonstrated.

Carbon crediting methodologies for Life cycle Refrigerant Management activities in the voluntary carbon market Adapted from Yale Carbon Containment Lab, 2023.			
Registry	Methodology name	Eligible parties	Eligible activities
American Carbon Registry	Certified Reclaimed HFC Refrigerants, Propellants, and Fire Suppressants v2.0	United States, Canada, Mexico	Reclamation and sale of certified HFCs to charge existing or newly manufactured refrigeration, air conditioning, aerosol, or fire suppression equipment.
American Carbon Registry	Destruction of Ozone Depleting Substances and High-GWP Foam v2.0	United States, Canada, Mexico	Destruction of ODS refrigerants from equipment or stockpiles, or destruction of foam blowing agents from appliances or buildings.
American Carbon Registry[42]	Destruction of Ozone Depleting Substances from International Sources v1.0	For sourcing material: outside the United States For destruction: anywhere	Destruction of ODS refrigerants from equipment or stockpiles.
Climate Action Reserve	U.S. Ozone Depleting Substances Project Protocol	United States	Destruction of ODS refrigerants from equipment or stockpiles, or destruction of foam blowing agents from appliances or buildings.
Climate Action Reserve	A5 Ozone Depleting Substances	For sourcing material: A5 parties For destruction: United States	Destruction of select ODS refrigerants, either recovered from equipment or acquired from stockpiled that cannot legally be resold (or can be legally resold but are held by an A5 government).
Climate Action Reserve	Mexico Halocarbon Protocol	Mexico	Destruction of select halocarbon refrigerants from stockpiles, equipment, or

[42] This ACR standard is one case where TEAP destruction requirements (referred to as a standard) is adopted externally as a destruction qualification requirement more broadly than in the narrow context of the MP. See Section 2.1 of the ACR (document) 2021.

			used servicing cylinders. Eligibility varies by species.
Verra	Infrared Automatic Refrigerant Leak Detection Efficiency v1.1	Anywhere	Installation of infrared automatic leak detection systems in commercial refrigeration systems using HFCs.
Verra	Recovery and Destruction of Ozone Depleting Substances v1.1	Parties to the Montreal Protocol	Destruction of ODS refrigerants and blowing agents (both CFCs and HCFCs). Refrigerants may be recovered from end-of-life appliances.

7.4.3.2 Compliance carbon market

Compliance carbon markets are platforms for the trading of carbon credits that can be retired for regulatory compliance. These compliance markets now exist in many parties and in several U.S. states, including California and Washington. These markets typically have more stringent rules about which emissions reduction or removal activities are eligible to generate credits, often with a bent toward more measurable and higher quality projects.

The State of California, under the Western Climate Initiative, has been one of the longest-standing compliance carbon markets that allow the trading of credits generated from destruction of ODS. A similar mechanism is currently being adopted in Washington State.

New Zealand uses carbon credits from the export or destruction of HFCs on its Emissions Trading Scheme (NZ ETS). As discussed in Chapter 5, New Zealand applies a national carbon tax to imported bulk HFCs and HFCs contained in products. Regulated entities under the NZ ETS can generate/purchase and retire carbon credits toward NZ ETS compliance.

7.4.3.3 International carbon markets

Beyond the voluntary and compliance carbon markets, international carbon markets have financed LRM projects such as the Clean Development Mechanism (CDM) under the Kyoto Protocol, and the Joint Crediting Mechanism (JCM) under article 6.2 of the Paris Agreement. These international markets are distinctive because they rely on multi-national cooperation, often with a buyer country providing carbon financing to a host country to develop an emissions reduction project.

7.4.3.3.1 Clean Development Mechanism

The Clean Development Mechanism (CDM) was one of the world’s earliest carbon financing schemes. The CDM was established under the Kyoto Protocol to facilitate climate financing for projects in developing parties, which then could compensate for emissions from developed parties. One of the most popular CDM projects was for the capture and destruction of HFC-23 from HCFC-22 production. It is expected to transition over to the Sustainable Development Mechanism (SDM) established under Article 6.4 of the Paris Agreement. As of early 2024, Article 6.4 has yet to be operationalized.

For CDM projects to reduce HFC-23 emissions by thermal oxidation at chemical plant sites, there was evidence that carbon credit revenues created perverse incentives to produce more HCFC-22, which could hinder global efforts to phaseout from HCFC (the plants were so called “swing plants”). For these reasons, the CDM Executive Board ruled limiting the sites of HFC23 destruction under the CDM to limit the perverse incentives. These kinds of perverse incentives can be problematic, specifically in HCFC-22/HFC-23 production sites, but are not relevant with the end-of-life of RACHP equipment whose emissions are already regarded as “consumed” under the Montreal Protocol Inventory and “emitted” as most methodologies of the IPCC guidelines, applied in National GHG Inventory. Furthermore, the situation is distinctive in that the CDM projects were conducted without the Enhanced Transparency Framework (ETF) under the Paris Agreement which obliges Parties to report all carbon credits (ITMOS) generation and transfer in the Biannual Transparency Report (BTR). Currently, there are systems such as ETF and BTR to ensure transparency of CDM projects, with low risk of perverse incentives.

The CDM has developed approaches to reduce transaction costs while maintaining environmental integrity. Such programmes of activities (PoAs) and standardized baselines should be built into Article 6 pilot activities for HFC reduction to ensure environmental integrity through robust accounting and credible additionality tests. CDM methodologies can also ensure that interventions supported by public climate finance deliver results.

7.4.3.2.2 Joint Crediting Mechanism

The Joint Crediting Mechanism (JCM) is one of mechanisms in cooperative approach under Article 6. 2 of the Paris Agreement, which involve the use of internationally transferred mitigation outcomes towards nationally determined contributions (NDCs), promote sustainable development and ensure environmental integrity and transparency. The mechanism has been initiated by Japan and 29 partner parties (as of 1 April, 2024). Since its commencement in 2013, Japan supported approximately 250 projects in the partner parties.

Through the JCM, Japan has also been a leader in developing projects destroying HFCs in A5 parties. Currently, HFC destruction projects under the JCM are being developed in Thailand, Vietnam, and the Philippines.

7.4.3.3.3 Other mechanisms under Article 6 of the Paris Agreement

Due to historical fund replenishment levels, it seems unlikely that the Multilateral Fund (MLF) for the implementation of the Montreal Protocol will possess adequate financial resources to fund initiatives such as leak prevention, recovery, recycling, reclamation, and particularly ensuring the proper disposal of refrigerants at the equipment end-of-life. Therefore, other financial incentives need to be harnessed.

Article 6 of the Paris Agreement outlines a framework for parties to engage in voluntary cooperation to achieve their climate objectives. Specifically, Article 6 creates three platforms to facilitate international climate finance, with the goal of streamlining investment from developed parties in climate change mitigation projects in developing parties.

It facilitates international collaboration to address climate change and provide financial assistance to developing nations. This platform allows parties to transfer carbon credits (formerly known as Internationally Transferred Mitigation Outcomes, ITMOs) obtained through GHG emission reductions to support other parties in meeting their climate goals. Among the tools available under Article 6 is the Article 6.4 mechanism, which is the UN's newly established high-integrity carbon crediting mechanism.

The market mechanisms under Article 6 of the Paris Agreement - cooperative approaches (Art.6.2) and a multilaterally governed Sustainable Development Mechanism (Art.6.4) could provide such incentives by generating revenues from the sale of carbon credits generated by HFC abatement. As these revenues depend on the credit price level, a “division of labour” could be envisaged: market mechanisms would drive the options with low marginal abatement costs while public climate finance could harness the higher cost options. This could lead to the emergence of a landscape of ‘integrated climate finance’ for HFC reduction exceeding by far the limited funding resources of the MLF (Michaelowa *et al*., 2019). So far, one HFC project activity on “Green AC market transformation programme” from Ghana is submitted to Article 6 activities of the Paris Agreement.

Many CDM initiatives, including those associated with HFC destruction, are eligible for transition to the Sustainable Development Mechanism (SDM) under Article 6, enabling them to persist in generating carbon credits within the updated framework. Article 6 mechanisms facilitate funding for HFC destruction or transition endeavours by issuing carbon credits. Existing CDM projects concentrating on HFCs can sustain their credit generation within the SDM, fostering ongoing engagement. Under the CDM, project types eligible included Project Activities (PAs) and Programmes of Activities (PoAs). PAs represented individual projects, while PoAs served as overarching frameworks encompassing multiple smaller projects. These project types could be utilized to organize HFC reduction initiatives within the SDM, offering adaptability.

Three HFC project activities previously under the Clean Development Mechanism (CDM) can transition to the Article 6.4 Mechanism. These include the HFC Decomposition Project in Ulsan from South Korea, the Quimobásicos HFC Recovery and Decomposition Project from Mexico, and the Avoidance of HFC-134a emissions in rigid Poly Urethane Foam (PUF) from India. However, only one of these HFC activity types, specifically the Quimobásicos HFC Recovery and Decomposition Project from Mexico, with a potential reduction of 3.43 Mt CO_2eq, has requested a transition to the Article 6.4 Mechanism and intends to continue applying CDM methodologies.

Currently, activities under the CDM are phasing out and transitioning to the United Nations' Supervisory Body for Article 6.4 of the Paris Agreement. The Supervisory Body will fill a similar role to CDM in acting as a registry for projects and determining the scope of available methodologies. As of 2024, the Supervisory Body has not been operationalized.

7.4.4 Other measures

Some policies, although not taking the form of EPR or carbon financing, have created end markets for recovered and reclaimed refrigerants. These policies are described in greater depth in Chapter 5.

7.4.4.1 Tax measures

Various tax mechanisms should be noted, such as tax measures by local/national jurisdictions, import taxes on controlled substances, license fees for end-users/servicing sector".

As noted in Chapter 5, some subnational governments or utilities providers offer incentives or funding (e.g., to encourage adoption of more efficient equipment). Many of these programmes mandate evidence that the refrigerant from the equipment to be replaced is properly recovered in order to gain access to funds.

For example, when setting up greenhouse gas (GHG) or fluorochemical reduction incentive programmes, some key requirements for robust Life cycle Refrigerant Management programmes have been included as part of the requirements. For example, California's F-Gas Reduction Incentive Program (FRIP) provides financial support to California's retail food facilities for adopting ultra-low GWP refrigerants (CARB, 2024c). As part of meeting the program's criteria, funding recipients must conduct proper refrigerant recovery of the retiring systems.

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Chapter 8

Climate and ozone benefits associated with Life cycle Refrigerant Management

Chapter 8 Summary

- Ozone benefits: Implementing effective LRM practices during the use and end-of-life of RACHP equipment is projected to cut HCFC emissions by about 5 kt ODP between 2025 and 2040.
- Climate benefits: Implementing effective LRM practices during the use and end-of-life of RACHP equipment is projected to cut HFC and HCFC emissions by about 39 Gt CO_2e between 2025 and 2050. This would achieve substantial additional climate benefits beyond those currently anticipated from the HFC phasedown agreed under the Kigali Amendment to the Montreal Protocol.
- The dominant location of the installed refrigerant bank is shifting rapidly from non-A5 parties to A5 parties. Fostering capacity development in A5 parties, especially larger industrialized ones, could achieve substantial and sustained benefits beyond 2030.
- Low Volume Consuming A5 Parties (LVCs) can potentially maintain or even surpass compliance with the Kigali Amendment through effective LRM, at the same time as reducing refrigerant emissions and climate impact.
- The responsible use of refrigerant includes the adoption of a robust system to accurately track refrigerant use, accounting for refrigerant recovered, recycled, reclaimed, and destroyed.
- Recently, LRM has received special interest as a climate solution for its ability to make outsized reductions in near-term atmospheric warming by mitigating HCFC and HFC emissions (short-lived climate pollutants).

8 Climate and ozone benefits associated with Life cycle Refrigerant Management

8.1 Introduction

Decision XXXV/11 requests information on the "climate and ozone benefits associated with the leakage prevention, recovery, recycling, reclamation and disposal of refrigerants, taking into account the experience under the Multilateral Fund for the Implementation of the Montreal Protocol".

This chapter addresses the substantial incremental climate and ozone benefits associated with LRM, highlighting its importance as an effective ODS and HFC emission mitigation measure.

Although the Kigali Amendment takes significant strides in controlling the amount of HFCs entering the global market, much of the forward-looking climate and ozone protection opportunities arise from reducing emissions from the current and future installed bank of HFCs and ODS. The 2005 IPCC/TEAP Report on Safeguarding the Ozone Layer and the Global Climate System (SROC) defines banks (in the context of ODS) as the total amount of substances contained in existing equipment, chemical stockpiles, foams, and other products not yet released to the atmosphere (IPCC/TEAP, 2005). Currently, estimates for ODS and HFC banks (inclusive of foams and other non-refrigerant uses) range from 16 Gt CO_2e (UNEP, 2022a) to 24 Gt CO_2e (Theodoridi *et al*., 2022). On top of the installed bank today, Theodoridi *et al*., (2022) projected that approximately 67 Gt CO_2e in ODS and HFCs are expected to enter the global market by 2100, even with full compliance with the Montreal Protocol, across all applications.

Implementing LRM at scale can maximize the climate benefits expected from the Kigali Amendment by reducing emissions from equipment operations and decommissioning, and may create conditions under which Parties may consider an accelerated HFC phasedown.

8.2 Modelling description

The chapter employs the Greenhouse gas-Air pollution Interactions and Synergies (GAINS) model framework (Purohit and Höglund-Isaksson, 2017) to assess the technically feasible emissions mitigation potential of LRM strategies. Purohit et al. (2020) used the GAINS model (Höglund-Isaksson *et al*., 2017; Purohit and Höglund-Isaksson, 2017) to produce detailed future scenarios for HFC emissions, which have fed into climate models to assess potential impacts on global warming (e.g., IPCC, 2021; IPCC, 2018; UNEP, 2017; Gambhir *et al*., 2017). The baseline HFC emissions, prior to the Kigali Amendment to the Montreal Protocol, were projected to increase from around 0.5 to 4.3 Gt CO_2e between 2005 and 2050 (Figure 8.2). The estimated 2050 emissions align with the range (4.0–5.3 Gt CO_2e) from Velders et al. (2015). It is important to note that current policies have lowered the anticipated 2050 emissions from the initial estimate of 4.0–5.3 Gt CO_2e by Velders *et al*. (2015) to a reduced range of 1.9–3.6 Gt CO_2e (Velders *et al*., 2022). In this report, we utilized the GAINS pre-Kigali baseline scenario to evaluate the ozone and climate benefits of LRM across the subsequent subsections.

The GAINS model considers "good practices" as a control or abatement option that encompasses a comprehensive set of measures: leakage prevention during use and recovery of the refrigerant after end-of-life of the equipment. The removal efficiency[43] of good practices

[43] It's important to note that removal efficiency plays a crucial role in evaluating the effectiveness of pollution control measures and ensuring compliance with environmental regulations. As an illustration, in refrigerant management, removal efficiency monitors the effectiveness of processes in capturing and eliminating refrigerants during their use and at the end of their lifespan, aiming to prevent them from leaking into the atmosphere.

(i.e., leakage reduction), such as leakage prevention during equipment use, is estimated at 20 to 50%, meaning that if robust leak prevention practices are adopted, average leak rates can be reduced by 20 to 50%, depending on the type of equipment (Tohka, 2005). In contrast, the removal efficiency of end-of-life recovery measures is considered to be higher, ranging from 70 to 90% for RACHP technologies (Höglund-Isaksson et al., 2012; Schwarz *et al*., 2011; Tohka, 2005; Devotta *et al*., 2004; Harnisch and Schwarz, 2003; Harnisch and Hendriks, 2000; Heijnes *et al*., 1999). To evaluate the technical potential for ozone and climate benefits from leakage prevention and end-of-life recovery, we assume that both A5 and non-A5 parties will adopt good practice measures throughout the use and end-of-life phases of RACHP equipment.

Figure 8.1 shows projected HFC and HCFC emissions, using the GAINS model, for major cooling sectors. The GAINS model also shows expected emissions under Kigali Amendment compliance, as well as emissions under a "maximum technically feasible reduction" (MTFR) scenario. The Kigali Amendment scenario assumes refrigerant transition to low-GWP alternatives alongside the implementation of LRM strategies (i.e., leakage prevention and end of life recovery of refrigerants) in regions with established regulations (i.e., EU). In contrast, the MTFR scenario investigates the potential for further emission reduction by utilizing all existing best available technologies (BAT), in addition to current regulatory measures including LRM, and a rapid transition to low-GWP refrigerants. It is a hypothetical scenario, where emissions are reduced to the lowest possible level using existing BAT, irrespective of the cost constraints.

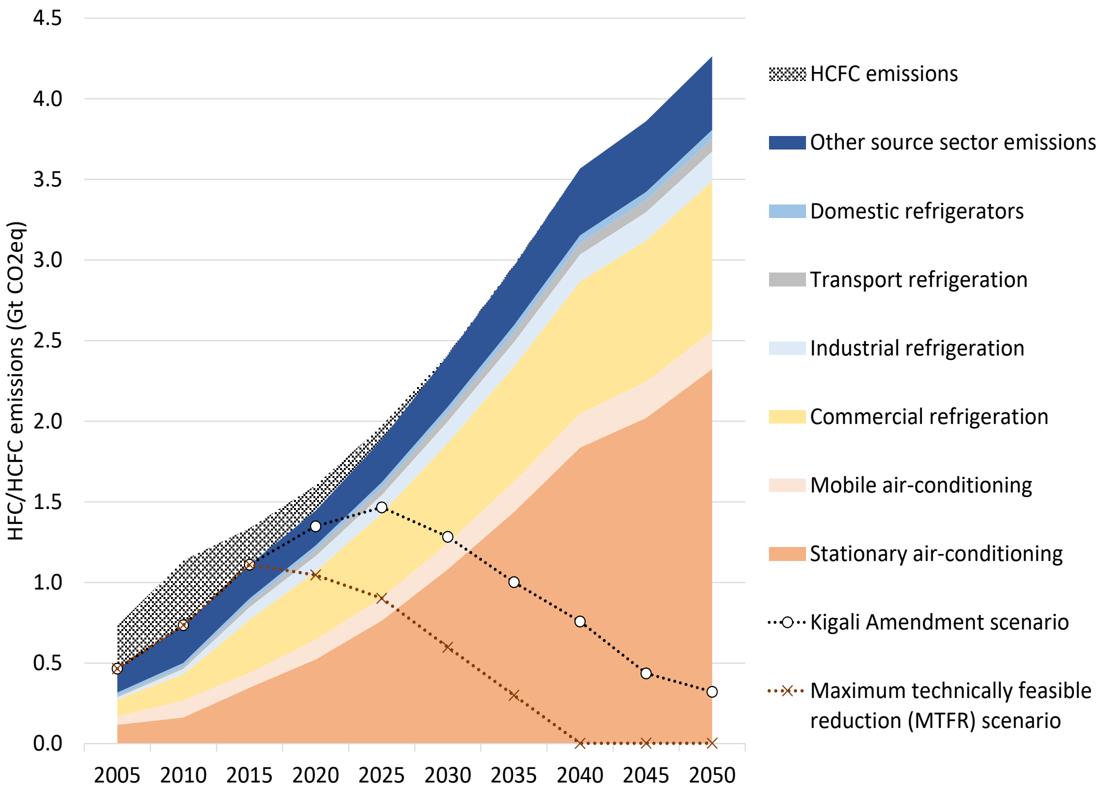

Figure 8.1 HFC/HCFC emissions in the pre-Kigali baseline and alternative Kigali Amendment and Maximum Technically Feasible Reduction (MTFR) scenarios. Source: Purohit et al. (2020)

8.3 Ozone protection benefits of LRM

LRM can help to reduce ozone depletion by preventing the release of ODS into the atmosphere. Even though the phaseout of most ODS under the Montreal Protocol are in advanced stages, ODS refrigerants are still being used in legacy equipment around the world and every effort must be made to prevent their emissions into the atmosphere. This can be achieved through leak prevention, recovery, recycling, and reclamation and destruction.

The assessment and analysis of the "banks" of controlled substances in use have been conducted by TEAP since 2002, collaboratively with IPCC/TEAP in 2005 (see IPCC/TEAP, 2005), and Scientific Advisory Panel (SAP) in 2022 (WMO, 2022). The 2022 Assessment Report of the Medical and Chemical Technical Options Committee (MCTOC) of TEAP (UNEP, 2022a) documents ongoing efforts to maintain ODS/HFC bank data and estimates by GIZ Proklima, providing valuable insights into past and future opportunities for climate and ozone benefits through LRM management. In 2022, around 6 million tonnes of ODS and HFCs were estimated to be contained in the active bank, which is equal to the 16 Gt CO_2e (UNEP, 2022a). Active global ODS banks of the five most common ODS (CFC-11, CFC-12, HCFC-22, HCFC-141b, HCFC-142b) amount to 3.2 million tonnes, equivalent to 9.9 Gt CO_2e in 2022 (UNEP, 2022a). Moreover, active HFC banks in the RACHP sector, which is the predominant usage of HFCs, are estimated at 2.8 million tonnes (5.5 Gt CO_2e) in 2022 and 3.9 million tonnes in 2030 (UNEP, 2022a). While ODS banks have been more concentrated in non-Article 5 parties, HFC banks are currently more evenly distributed between non-Article 5 and Article 5 parties and are expected to become concentrated in Article 5 parties. Banks of ODS refrigerants will diminish to relatively low levels by the early 2030s, particularly for HCFC-22 (UNEP, 2022a). However, it is important to acknowledge the ongoing importance of responsible ODS management and explore alternative solutions for long-term sustainability.

Figure 8.2 (a) presents ozone benefits in terms of HCFC mitigation due to leakage prevention using the methodology outlined in Section 2 above. Taking an Ozone Depletion Potential (ODP) of 0.055 for HCFC-22 (IPCC/TEAP, 2005), effective leakage prevention is anticipated to yield cumulative reductions in HCFC emissions totalling 1.6 kt ODP from 2025 to 2040.

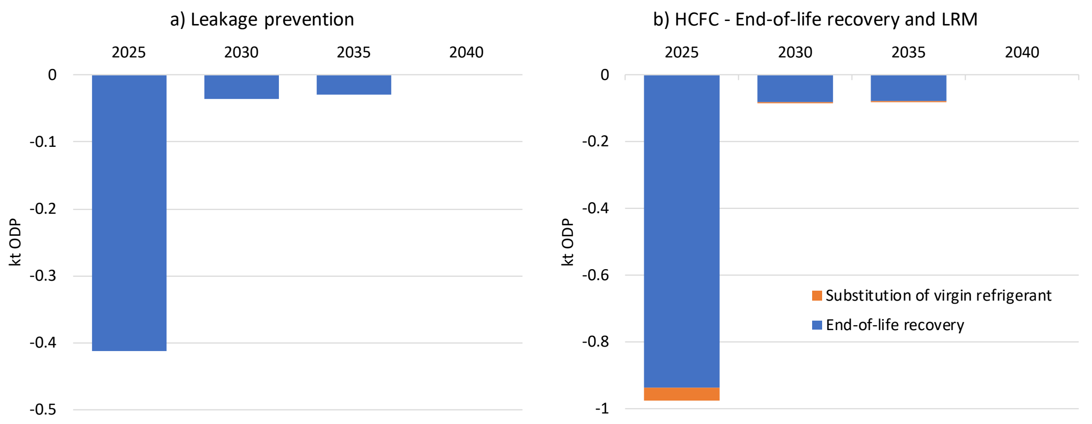

Figure 8.2 Ozone benefits in terms of HCFC mitigation (in terms of kt ODP) due to a) leakage prevention, and b) end-of-life recovery.

8.3.1 ODS Leakage prevention

Leakage of refrigerants is a major source of direct emissions and resulting in ozone depletion. Refrigerant leakage, stemming from factors like wear and tear, improper installation, and inadequate maintenance, is a significant contributor to ozone depletion. Even minor leaks accumulate over time, releasing substantial amounts of ozone-depleting chemicals into the atmosphere. Regular monitoring and prompt repair of any detected leaks are essential preventive measures. Mitigating refrigerant leaks not only protects the ozone layer but also aids in climate change mitigation, highlighting the interconnectedness of leakage prevention and environmental sustainability. Taking such measures not only ensures ozone protection but also enhances human health, preserves ecosystems, and contributes to climate change mitigation. These strategies are elaborated upon in greater detail in Chapter 2.

8.3.2 Recovery, Recycling, Reclaiming and Destruction (RRRD) of ODS refrigerants

Improving the EOL management of products containing ODS provides an opportunity to reduce the impact of remaining ODS banks on the ozone layer. Recovery, Recycling, Reclamation and Destruction (RRRD) are vital in mitigating ozone depletion by preventing harmful substance release, promoting resource efficiency, and offering economic advantages like job creation and revenue generation. Ensuring appropriate refrigerant disposal can further preserve the ozone layer, preventing the release of harmful substances, reducing UV radiation reaching Earth, and combating climate change.

The Montreal Protocol has historically encouraged the environmentally sound destruction of surplus or contaminated ODS and HFCs. However, it has mandated only the destruction of HFC-23[44] produced as a by-product of HCFC-22 production as a formal obligation and only then with the qualification "as practical". Mandating destruction of substances that are not under a phaseout can lead to perverse outcomes; however, it makes robust leak prevention and recovery practices that much more important to ensure those substances are not emitted. Technical destruction requirements and guidance on environmental performance applied to specific listed destruction technologies are mandatory only where destruction is included in the definition of production under Article 7 related to reporting. According to Global Article 7 reports, the destruction of ODS has ranged from 4.5 to 6.4 kt annually, with a possible downward trend or stable levels. In 2019, total reported destruction of ODS amounted to 5.3 kt. The non-A5 parties have been responsible for over 99% of overall reported ODS destruction since 1996, with a share of 94.4% in 2019. Among major non-A5 parties in 2019, Japan accounted for 31.6%, the European Union and the United Kingdom 36.6%, the United States 30.5%, and Australia 0.6% of the total reported ODS destruction (UNEP, 2022a).

Historically, RRRD of ODS has not occurred consistently at equipment EOL, especially for small residential equipment and in A5 parties. Annual quantities of controlled ODS substances in equipment and foams reaching end-of-life are estimated between 250 and 400 kt (about 0.5 to 0.8 Gt CO_2e) from 2020 to 2050 (UNEP, 2022a). This number is expected to peak in absolute amounts in the mid-2030s. The stockpile of HCFCs (and HFCs) available for LRM is expected to increase significantly until all parties stop using them. Small commercial and residential RACHP appliances tend to have very high end-of-life loss rates. One report states that 100% of the recoverable refrigerant at end of life for small RACHP equipment can be lost (Theodoridi *et al*., 2022), so it important to ensure that the barriers to refrigerant recovery from those appliances are minimized. Figure 8.3 (b) presents ozone benefits in terms of HCFC mitigation due to end-of-life recovery and substitution of virgin refrigerant due to LRM measures using the GAINS model (see Section 8.2 above). Effective end-of-life recovery of refrigerants is anticipated to yield cumulative reductions in HCFC emissions totalling 3.6 kt ODP from 2025 to 2040. Furthermore, implementing improved LRM practices through the replacement of new (virgin) refrigerant could result in approximately 4%[45] further reduction (UNEP, 2022a) if the recovered refrigerant displaces new refrigerant production and is not simply added to the supply of refrigerant. As a result, the technical mitigation potential of RRRD is projected to reach 3.7 kt ODP between 2025 and 2040.

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[44]HFC-23 is generated as a byproduct of HCFC-22 production used in refrigerants and as a chemical feedstock for manufacturing synthetic polymers (Andersen *et al*., 2021; Stanley *et al*., 2020)

[45] The Medical and Chemical Technical Options Committee (MC-TOC) and Technical and Economic Assessment Panel (TEAP) have estimated that virgin productions emissions range from 0.5 to 4% (UNEP, 2022a).

8.4 Climate change mitigation benefits of LRM

The Montreal Protocol has already generated significant climate benefits by phasing out ODS production and consumption, and by phasing down HFC production and consumption via the Kigali Amendment.

LRM has gained increasing attention in the last several years for its potential to mitigate global climate change, beyond what the ODS phaseout and HFC phasedown can accomplish alone. LRM focuses on reducing emissions from the installed refrigerant bank (controlled substances currently in operating equipment and products) and refrigerant that will enter the market in a Montreal Protocol-compliant scenario. The climate protection already achieved by the Montreal Protocol alone is far larger than the reduction target of the first commitment period of the Kyoto Protocol. New studies support previous Assessments in that the decline in ODS emissions due to compliance with the Montreal Protocol avoids global warming of approximately 0.5–1 °C by mid-century compared to an alternative scenario with an uncontrolled increase in ODSs of 3–3.5% per year (WMO, 2022). Additional environmental benefits could be achieved by actions under the Montreal Protocol, by managing the emissions of substitute fluorocarbon chemicals and/or implementing alternative low-GWP refrigerants.

Recent studies anticipate a substantial rise in atmospheric HFC levels in the coming decades, along with rising demand for RACHP and the ongoing HCFC phaseout (Purohit *et al*., 2020; Velders *et al*., 2015; Gschrey *et al*., 2011; Velders *et al*., 2009), portending negative repercussions for the global climate (Hurwitz *et al*., 2015). The Kigali Amendment phases down the consumption and production of high-GWP HFCs and constitutes perhaps the single most significant contribution to keeping warming to 1.5 °C to date (UNEP-IEA, 2020). Achieving complete adherence to the Kigali Amendment is projected to prevent a temperature rise of 0.3–0.5 ° C by 2100 (WMO, 2022). Notably, this estimation does not account for the impact of HFC-23 emissions.

Prior to this report, there has been at least one other attempt to estimate the climate benefits of LRM. In 2022, Theodoridi *et al*. (2022) estimated that the implementation of LRM measures could determine the fate of 91 Gt CO_2e by 2100, approximately equivalent to three years' worth of emissions from the global energy sector. In addition to ratifying and implementing the Kigali Amendment, parties can achieve more HFC mitigation through various methods: an accelerated phasedown schedule (Purohit *et al*, 2022); collecting and destroying HFCs from end-of-life equipment (Castro *et al*., 2021); reducing HFC refrigerant leaks through better design, manufacturing, and servicing; and replacing older inefficient equipment (WMO, 2018). According to the *Global Cooling Watch Report 2023*, additional policy measures, surpassing the objectives outlined in the Kigali Amendment, can expedite the phase-down of HFCs by adopting low-GWP technologies in new equipment and improving refrigerant life-cycle management to minimize leakages and end-of-life emissions. This could potentially halve HFC emissions by 2050 compared to the Kigali Amendment's schedule (UNEP, 2023a). Rapidly transitioning away from high-GWP HFCs together with improving refrigerant management and collection, and destruction of HCFCs and HFCs could avoid emissions on the order of 50 Gt CO_2e through 2060 (Sun *et al*., 2022; WMO, 2021; WMO, 2018).

Recently, LRM has received special interest as a climate solution for its ability to make outsized reductions in near-term atmospheric warming. Most HFCs are considered short-lived climate pollutants (SLCPs), chemicals with short atmospheric lifetimes and high GWP. The IPCC's Sixth Assessment Report (IPCC, 2021) highlights the importance of reducing SLCPs like HFCs by stating that, "*Over time scales of 10 to 20 years, the global temperature response to a year's worth of current emissions of short-lived climate forcers is at least as large as that due to a year's worth of CO_2 emissions (high confidence)*". Because of their short residence time in the atmosphere, reducing the rate of short-lived ODS and HFC emissions can create net reductions in near-term atmospheric warming, even if net emissions of these chemicals are positive (Benedetti, 2023). It is now well understood that pairing decarbonization with additional mitigation of SLCPs can slow the rate of warming a decade or two earlier than decarbonization alone (Dreyfus *et al*., 2022). Growth in ODS and HFC banks is fairly “front-loaded” in the next few decades, suggesting that mitigation potential – and possible mitigation of near-term temperature rise – are immediate and critical.

As per the MCTOC report by UNEP (2022a), it is projected that within the current decade, the predominant banks of ODS and HFCs will emerge from non-A5 parties, underscoring the necessity of immediate management strategies. Therefore, there is a pressing need to commence the development of LRM capacities and foster awareness now to address these forthcoming challenges effectively and efficiently.

LRM measures, even if implemented in only a handful of large parties, would still have large benefits for the climate. Improved end-of-life management for HFCs thus offers an opportunity to reduce ample emissions (Sovacool, *et al*., 2021), (Duan *et al*., 2018), Kumar *et al*. (2023) emphasizing the critical need to improve RRRD practices.

It is also worth noting that, in addition to boosting availability of refrigerants for servicing, recycled and reclaimed HFCs can also be used to fulfil some of the need for newly produced HFCs for filling new equipment, which could further drive down the need for new production and act as a lever for acceleration of the HFC phasedown. Currently, there are policy proposals under consideration in the U.S. that would mandate the use of reclaimed HFCs even in new equipment (more details are given in Chapter 5 of this report).

Globally, in 2012, 60% of newly produced HFCs were estimated to be used for servicing or “topping up” leaks in refrigeration, air-conditioning, and heat pump (RACHP) equipment, while the remaining 40% was used for filling new equipment (UNEP, 2015). Implementing LRM measures can reduce emissions from the installed bank and conserve the quantity of refrigerant in use, easing demand for virgin production. Below, we discuss outputs from the GAINS modelling framework for how LRM best practices could affect global HFC and HCFC emissions.

8.4.1 HFC and HCFC Leakage prevention

Minimizing refrigerant leakage from operational equipment not only results in significant climate benefits but also offers simultaneous cost savings. The implementation of leak reduction measures not only decreases emissions and conserves refrigerant but also improves equipment efficiency, leading to substantial energy savings as well as the preservation of vital cold chains for ensuring supply of food and medication. DECC (2014) observed that a refrigerant charge reduction of just 10% would lead to a COP reduction of about 3% in heating and 15% in cooling operation. Leaks leading to undercharging by 40%, however, would reduce the COP by a significant 45% in heating mode and 24% in cooling operation (DECC, 2014).

The financial impact becomes more pronounced for equipment owners, particularly if refrigerant prices rise during phasedowns. The financial impacts of leakage are further exacerbated in certain end-use sectors where a drop in the equipment’s cooling efficiency can lead to food and other product losses, e.g., in a supermarket or grocery store. Thus, focusing on leak prevention is crucial in mitigating climate change by reducing harmful refrigerant releases, contributing to global warming containment. The multifaceted benefits include direct reduction of GHG emissions, particularly HFCs, complementing broader climate change mitigation strategies. Addressing refrigerant leaks today ensures a climate-friendly future, promoting sustainable refrigeration practices and the adoption of low-GWP refrigerants while reducing reliance on high-impact HFCs.

Using the methodology outlined in Section 8.2 above, Figure 8.3 (a-b) illustrates the climate benefits resulting from HCFC and HFC mitigation through leakage prevention. This assumes the effective implementation of policies, measures, and regulations for leakage prevention by both A5 and non-A5 parties. Effective leakage prevention is projected to result in cumulative HFC/HCFC emissions reductions of 15.6 Gt CO_2e from 2025 to 2050 relative to the pre-Kigali baseline, as illustrated in Figure 8.1 above.

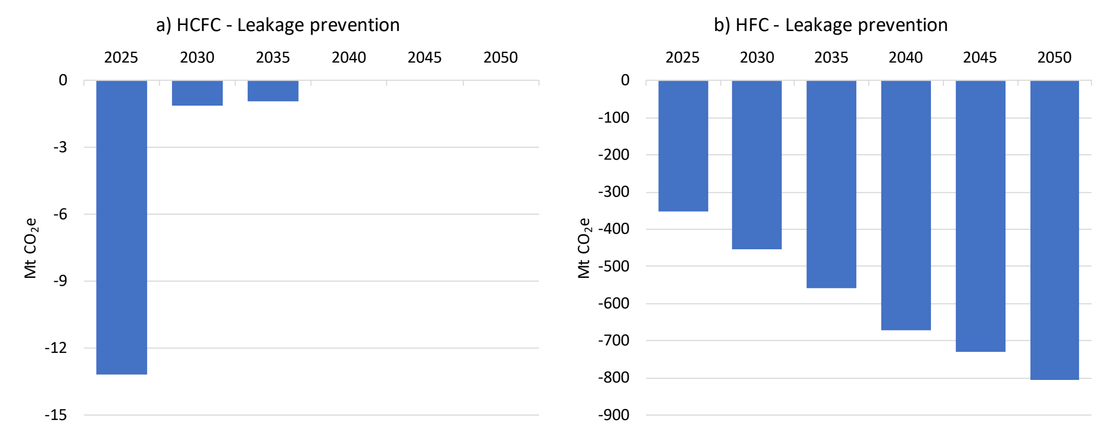

Figure 8.3 Climate benefits due to leakage prevention a) HCFC mitigation and b) HFC mitigation. (Please note the scale differences).

8.4.2 Recovering, Recycling, Reclaiming and Disposal (RRRD) of refrigerants

Many of the forward-looking climate change mitigation opportunities for controlled substances lie in improving the management of ODS and HFCs contained in equipment reaching end-of-life. Previously, TEAP has referred to this portion of the installed bank as the "reachable bank", acknowledging that controlled substances in end-of-life equipment can be captured and abated upon entering the waste stream. Historically, ODS and HFCs contained in end-of-life equipment have been largely emitted, representing a lost opportunity to mitigate climate change. The underlying technical, logistic, policy and economic barriers to refrigerant RRRD are discussed extensively in Chapter 6.

As mentioned in Section 3.2, refrigerant recovery, recycling, and reclamation are important strategies for climate change mitigation. However, it is worth noting that while reusing ODS and HFCs through recycling or reclamation prevents potential emissions, it may only postpone emissions. The benefits are largely negated if equipment has a high leakage rate because when emitted, reclaimed ODS and HFCs have the same deleterious impact on the ozone layer and climate as new (virgin) ODS and HFCs. Therefore, leak prevention, leak detection and repair are essential to complement refrigerant recycling and reclamation, ensuring climate benefits from recovery and reuse.

Moreover, recovered refrigerant can also be destroyed, permanently preventing its emission to the atmosphere. When there is a market for reused HFCs, recycling and reclaiming HFCs can be environmentally preferable to destroying them. Yasaka *et al.* (2023) conducted a life cycle assessment comparing the environmental impact of reclamation and destruction following refrigerant recovery. On the whole, the process of recycling or reclaiming refrigerant is less emissive than destroying refrigerant. Ultimately, the maximum emissions reductions will occur when equipment is properly maintained, reducing leaks, and refrigerants are recovered, reused and eventually destroyed rather than vented at the end of their use.

Annual quantities of ODS and HFCs in equipment and foams reaching end-of-life are estimated between 250 and 400 kt (about 0.5 to 0.8 Gt CO_2e) from 2020 to 2050. This number is expected to peak in absolute amounts in the mid-2030s (UNEP, 2022a). It is noteworthy that before this timeframe, non-A5 parties are the primary contributors, whereas afterward, the level is sustained at a relatively high level by A5 generation, particularly from larger industrialized A5 parties. Applying the methodology detailed in Section 8.2, Figure 8.4 (a-b) depicts the climate advantages arising from HCFC and HFC mitigation through end-of-life recovery. This assumes the successful implementation of policies, measures, and regulations for leakage prevention by both A5 and non-A5 parties. From 2025 to 2050, effective LRM practices of refrigerant management at the EOL of RACHP equipment are projected to result in cumulative reductions of approximately 23.4 Gt CO_2e in HFC/HCFC emissions.

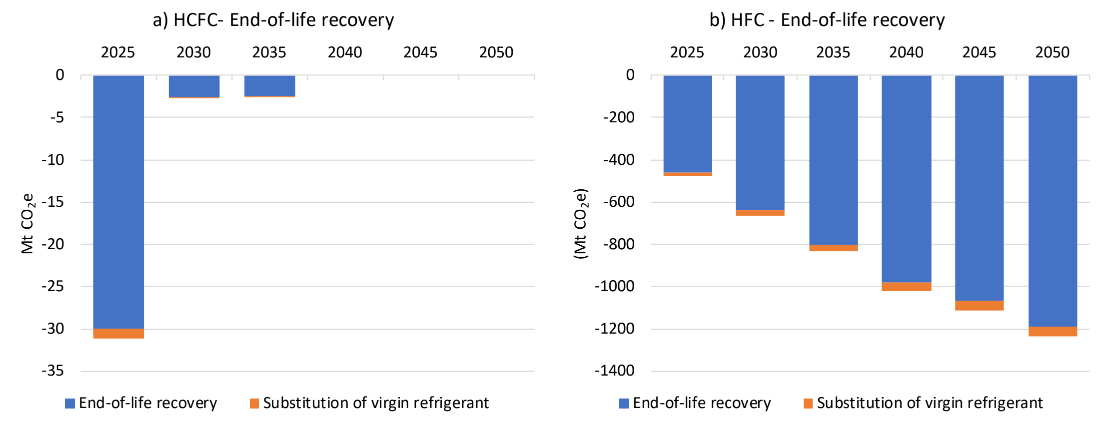

Figure 8.4 Climate benefits due to end-of-life recovery a) HCFC mitigation and b) HFC mitigation. (Please note the scale differences).

MLF Pilot Demonstration Disposal Project

The MLF Pilot Demonstration Disposal Project encompassed s initiatives led by the Multilateral Fund (MLF) aimed at testing and showcasing effective methods for disposing of Ozone Depleting Substances (ODS). These projects played a vital role in continuing interest in and by providing data and expertise necessary for the further development and implementation of end-of-life ODS management programmes particularly in A5 parties. The primary objectives of MLF Pilot Demonstration Disposal Projects include a) assessing the technical and economic viability of different ODS destruction technologies; b) establishing and demonstrating best practices for safe and environmentally friendly ODS EOL management; c) enhancing the capacity of developing parties in ODS collection and destruction techniques; and d) facilitating lesson's leaned and the replication of successful results. Various ODS disposal methods explored in these projects include high-temperature incineration (rotary kilns, cement kilns) and plasma arc technology.

The direct benefits resulting from the Pilot ODS Disposal Program's execution, in terms of reducing ODS releases and mitigating associated climate change impacts, are quantified at 392.15 tonnes of ODS destroyed (largely comprised of CFC-11 and CFC-12), leading to a reduction of 2.23 million tonnes CO_2e in greenhouse gas emissions (UNEP, 2018b; UNEP, 2019). These benefits, though modest as anticipated due to the program's scale, its focus mainly on existing stockpiled End-of-life (EOL) ODS, the diverse array of participating parties, and its primary emphasis on operational waste management and destruction, are inherent in the program's design. Nevertheless, the outcomes also demonstrate the potential to amplify these primary global benefits through broader initiatives aimed at integrating LRM and EOL management practices, while also offering valuable insights into the challenges and successes encountered, thus informing ongoing efforts in this domain within the framework of the Montreal Protocol and the MLF.

Key lessons learned from these experiences include: i) the need for reliable predictive tools to forecast EOL material generation from retiring equipment, vital for scaling up EOL management capabilities and business models; ii) challenges in procuring meaningful quantities of material for anticipated demonstration purposes were noted as a notable constraint; iii) validation and assessment of three commercially available destruction technologies (hazardous waste rotary kilns, plasma arc, and cement kilns); iv) the viability of exporting end-of-life ODS in compliance with the Basel Convention's requirements, especially when integrated with similar chemical waste disposal mandates, to enhance economic feasibility; v) regional strategies' effectiveness in executing disposal initiatives to improve economies of scale; vi) the importance of consistent national policies and regulatory frameworks supporting the capture, retention, reuse, reclamation, and environmentally sound destruction of ODS, integrated with broader national waste management and circular economy efforts; vii) initial demonstrations of the feasibility of external co-financing mechanisms to bolster LRM and EOL management, particularly through extended producer responsibility (EPR) and carbon finance; and viii) the significance of raising awareness among stakeholders, especially those at the end-user level, servicing operations, and within national chemical supply chains.

8.5 Other benefits

8.5.1 Energy Efficiency

Since refrigerant leakage compromises equipment energy efficiency, preventing leaks can save both energy and costs for equipment operators. Kim and Braun (2012) estimated that a 25% decrease in refrigerant charge below “full” operating charge can lead to a 16% increase in energy use. Thus, ensuring optimal charge and leak tightness can help significantly reduce both direct and indirect GHG emissions over the lifetime of the equipment. Optimal energy performance also results in environmental and economic benefits due to reduced cost burden on consumer for electricity. A study by the Natural Resources Defence Council (NRDC) found that leak reduction measures could save the United States $28 billion per year in energy costs.

Previous TEAP Energy Efficiency (EE) Task Force reports have also shown that combining HFC mitigation with energy efficiency would lead to substantial reductions in cumulative GHG emissions between now and 2050 (UNEP, 2023; UNEP, 2022b). These benefits arise because refrigerant leaks contribute to the poor energy performance of RACHP equipment. Increased energy demand due to refrigerant leaks can, in turn, lead to greater air pollutant emissions from power plants such as sulphur dioxide (SO_2), nitrogen oxides (NO_x) and particulate matter, all of which contribute to adverse health and ecological impacts associated with poor air quality.

8.5.2 Circular economy and sustainability

Circular economy attempts to eliminate waste and pollution and reuse products and materials in circulation. LRM can play a significant role in advancing the circular economy – especially in conserving the amount of refrigerant in use through leak prevention, refrigerant recovery, reuse and destruction. First, implementing best practices for equipment installation and leak detection and repair can reduce the amount of refrigerant necessary to keep equipment operational. Reducing leaks over the lifetime of equipment can also conserve the amount of refrigerant in end-of-life equipment that can be recovered. Second, refrigerant recovery, recycling, and reclamation extend the lifetime of refrigerants and enable their safe reuse in operating systems and new equipment. Refrigerant reuse (e.g., recycled and reclaimed refrigerants) can help increase supply for scarce controlled substances, when there are no other technical alternatives available. Contingent on supply and demand dynamics for refrigerants, the reuse of refrigerant has the potential to reduce demand, and consequently, the production of new (virgin) refrigerants as well. If no technical alternative is available refrigerant reuse can mitigate supply shortages for fluorocarbons, making equipment servicing less costly for equipment owners. This issue is especially noteworthy in servicing only A5 parties. Refrigerant recycling and reclamation may provide additional refrigerant supply, mitigating disruption in the market (Mayhew *et al*., 2023).

From a holistic life cycle emissions perspective, LRM practices such as reuse of reclaimed refrigerants have lower carbon footprint compared to new (virgin) production of fluorocarbons. This is because all the GHG emissions associated with the production of new (virgin) fluorocarbons are avoided when existing gases are recovered and reused. Even though there are GHG emissions related to recovery and reclamation, the magnitude of those GHG emissions may be lower compared to virgin production. Three recent studies estimated life cycle emissions of F-gas separation technologies and compared those with the life cycle emissions of virgin F-gas production. Their findings indicate that the overall environmental load (or carbon footprint) for the blending and separation technologies can be between 50% to 99% lower than virgin production (Gonzalez-Olmos *et al*., 2024; Jovell *et al*., 2021). Yasaka *et al*. (2023) conducted a lifecycle assessment using actual plant data and found that the GHG emissions associated with recovery and reclamation process were 80% lower than the GHG emissions from destruction and production of new (virgin) refrigerants. These preliminary results are encouraging, but there is a larger need for life cycle assessments to quantify the circular economy benefits of recovery, recycling and reclamation.

8.5.3 Air quality and health benefits

Apart from climate pollution or global warming, refrigerant releases can also contribute, either directly or indirectly, to air pollution. Direct increases in air pollution can occur when certain refrigerants that are classified as volatile organic compounds (VOCs) react with other chemicals in the atmosphere to form harmful pollutants. For example, some non-fluorinated refrigerants (e.g., hydrocarbons) can react with nitrogen oxides to form ground-level ozone, a major component of photochemical smog. While ODS and HFC refrigerants do not have a direct impact on air quality, RACHP equipment operating with sub-optimal refrigerant charge due to leaks results in inefficient operation and increased energy use. Increased energy demand due to refrigerant leaks can, in turn, lead to greater air pollutant emissions from power plants such as sulphur dioxide (SO2), nitrogen oxides (NOx) and particulate matter, all of which contribute to adverse health and ecological impacts associated with poor air quality. Thus, LRM plays a crucial supporting role in minimizing direct and indirect air quality impacts.

LRM is a critical approach for reducing ecosystem risks and protecting the environment from the harmful impacts of refrigerants. By minimizing leakage, improving efficiency, choosing low-GWP refrigerants, promoting alternative refrigerants, enhancing monitoring, and educating stakeholders, LRM can safeguard ecosystems and human health for future generations. An added consumer benefit of recovery and recycling is that they could also cause prices to fall for F-gas manufacturing, and they would displace some of the resources needed to make new refrigerants (Sovacool, *et al*., 2021).

8.5.4 Employment / Job opportunities

Managing refrigerants throughout their life cycle can generate substantial employment opportunities in both non-A5 and A5 parties. The LRM sector offers diverse job opportunities, including roles such as refrigeration technicians for system installation and maintenance, trained refrigerant reclaimers specializing in recovery and recycling, and refrigerant auditors evaluating and optimizing management practices. As businesses and governments increasingly recognize the importance of managing refrigerants responsibly, the demand for skilled LRM professionals is expected to grow significantly in the coming years. The adoption of lower GWP refrigerants, mandated by the Kigali Amendment, is also creating demand for professionals capable of handling these alternatives safely. A study led by the Alliance to Save Energy found that investing in LRM could create 500,000 new jobs in the United States alone.

In addition, when implemented with incentives or rebates for technicians, LRM can supplement incomes for technicians performing incentives could be especially meaningful in A5 parties in which technician wages are typically lower relative to the value recovered refrigerant. The success of LRM also relies on the upskilling of technicians across the world, many of whom currently do not possess the skills and/or training to implement LRM best practices. Training and certification, especially if financially sponsored by governments, multilateral agencies, or equipment manufacturers, can provide much-needed workforce development particularly in A5 parties.

8.6 Conclusions

Life cycle refrigerant management is an important strategy for safeguarding the ozone layer and addressing climate change. By preventing the release of ODS and HFCs, LRM helps control downstream emissions of controlled substances that are currently not covered under the Montreal Protocol. In addition to preventing emissions, LRM can also reduce costs for equipment operators and lead to equipment efficiency gains.

Implementing LRM at scale can also aid compliance with the Montreal Protocol, by increasing volumes of recovered refrigerant that can then be reused. Reusing refrigerant in large enough volumes could ease demand for new (virgin) refrigerant, helping to facilitate the HFC phasedown. A sufficient supply of recycled and reclaimed refrigerant can provide additional supply, especially for servicing-only A5 parties. Verified, environmentally sound destruction of refrigerants can attract climate finance, which does not currently fund transitions but could provide funding for comprehensive refrigerant management and expediting the transition to eco-friendly technologies. Ultimately, LRM aligns with the core objectives of the Montreal Protocol: protecting the ozone layer and combating climate change.

The cumulative technical mitigation potential of ODS emissions, driven largely by mitigating HCFC emissions, from 2025 to 2040 is projected to be 1.6 kt ODP through effective leakage prevention and 3.7 kt ODP through improved end-of-life recovery and substitution of virgin refrigerants. Effective leakage prevention is projected to result in a cumulative technical mitigation potential of 15.6 Gt CO_2e in HFC/HCFC emissions from 2019 to 2050. Additionally, recovering refrigerant from end-of-life cooling equipment is projected to contribute to cumulative reductions of around 23.4 Gt CO_2e in HFC/HCFC emissions from 2025 to 2050.

The distribution of refrigerant banks and availability trends at the end of their lifespan, especially for HFCs, is shifting from being concentrated in non-A5 parties toward a roughly even split between non-A5 and A5 parties by 2030. Subsequently, A5 parties are projected to increasingly emerge as the primary source of banks and opportunities for LRM in the future. Therefore, A5 parties face an urgent need to prioritize the implementation of comprehensive LRM to maximize the potential climate benefits. Likewise, it is crucial to ensure that capacity develops in A5 parties, especially larger industrialized ones, to obtain substantial and long-term climate benefits.

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Chapter 9

Conclusions

9 Conclusions

LRM minimises refrigerant emissions from RACHP equipment and systems. This report aims to provide a comprehensive overview of challenges, opportunities, and strategies for effective LRM, to provide stakeholders with the necessary knowledge to minimise refrigerant emissions as far as possible. In many parts of the world this will require a technical, policy and behavioural shift away from venting refrigerants.

- This first TEAP LRM Task Force Report emphasizes the critical importance of responsible refrigerant management to minimise emissions, alongside phasing out ODS and phasing down HFCs in increasingly energy efficient RACHP equipment.
- LRM can increase available refrigerant supply, especially for servicing-only parties that have less flexibility in their approach to phasing out or phasing down refrigerant consumption. Effective leakage prevention and refrigerant reuse provide additional tools to reduce the production and consumption for parties, which can assist with Montreal Protocol compliance.
- In the long term, the Kigali Amendment will facilitate a phasedown of high GWP HFC refrigerants. However, in the near- and medium-term there may be a build-up of HFCs in banks in A5 parties (both in RACHP equipment and HFCs for servicing) due to the overall rise in cooling demand in advance of technology transfer to lower GWP alternatives. The phasedown regimes in some A5 parties will ensure a continued market for HFC refrigerants for new RACHP equipment and for servicing. As a result, inexpensive new HFCs may be available in A5 parties, and HFC banks will inevitably build up.
- LRM strategies can help to minimise HFC emissions and make more refrigerant available through reuse, especially for A5 parties. LRM can include refrigerant venting prohibitions, leak prevention strategies, and establishing the reverse supply chain and infrastructure to maximise refrigerant recovery, prior to recycling, reclamation and destruction as appropriate.
- In non-A5 Parties, HFC consumption and production is rapidly phasing down in accordance with F-gas regulations and the Kigali phasedown schedule. In many A5 parties the HFC consumption and production phasedown schedules started from 2024, with some others starting in 2028.
- If phasedown of HFCs creates a shortage of refrigerant and leads to price increases, then refrigerant recovery may increase. However, if supply of newly produced refrigerant remains plentiful, other policy and economic measures may be required to incentivise effective recovery.