White paper for immediate steps
for a sustainable future

Accelerating the transition to climate and environmentally friendly reefers

CLIMATE CENTER

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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Appendixes

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List of abbreviations

ADI	Acceptable Daily Intake
ANSI	American National Standards Institute
API	Active Pharmaceutical Ingredients
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ATO	ATO Certification of reefer containers, Wageningen University & Research
BAU	Business As Usual (scenario)
BMUV	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (by their German acronym)
BTU/h	British thermal unit per hour, used as an alternative to kW (1 kW = 3412.12 BTU/h)
CFC	chlorofluorocarbons
COP	Coefficient of performance
COP 28	Conference of the Parties to the United Nations Framework Convention on Climate Change 28 in Dubai, United Arab Emirates
ECHA	European Chemicals Agency
EE	Energy Efficiency
EER	Energy Efficiency Radius
EU	European Union
FMEA	failure mode and effects analysis
FTA	fault tree analysis
GCF	Green Climate Fund
GHG	Greenhouse Gases
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
GLEC	Global Logistics Emissions Council
GWP	Global Warming Potential
HAZOP	Hazard and Operability Analysis
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HPMP	HCFC Phase-out Management Plan
HVAC	Heating, Ventilation, and Air Conditioning
IIR	International Institute of Refrigeration
IKI	International Climate Initiative (of BMU)
IMO	International Maritime Organization
INTECO	Instituto Nacional de Tecnología Industrial (National Institute of Industrial Technology)
ISO	International Organization for Standardization
KCC	Kuehne Climate Center
LNG	Liquefied Natural Gas
MAC	Mobile Air Conditioning
MARPOL	International Convention for the Prevention of Pollution from Ships under the International Maritime Organization
MEPS	minimum energy performance standards
MINAE	Ministry of Environment and Energy of Costa Rica
MLF	Multilateral Fund of the Montreal Protocol
MOPT	Ministry of Public Works and Transportation of Costa Rica
MUR	mechanical refrigeration units
NDC	Nationally Determined Contributions
ODS	Ozone Depleting Substance
OMRA	Operating Mode Risk Assessment
PFAS	Per- and Polyfluoroalkyl Substances
PFBA	Perfluorobutanoic Acid
PFPrA	Perfluoropropanoic Acid
PTI	Pre-trip Inspection
RAC	Refrigeration and Air Conditioning
RACHP	Refrigeration, Air Conditioning, and Heat Pump
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
R & D	Research and development
SDG	Sustainable Development Goal
SEER	Seasonal Energy Efficiency Ratio
SOLAS	International Convention for the Safety of Life at Sea
TEU	Twenty-Foot Equivalent Units
TEWI	Total Equivalent Warming Impact
TFA	Trifluoroacetic Acid
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
WUR	Wageningen University & Research

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1 Wageningen Food & Biobased Research, ATO Certification of reefer containers, Wageningen University & Research, Retrieved May 2, 2024, from *Reefertransport - Home*

Foreword

The global shipping industry is at a pivotal juncture. As the lifeblood of international trade, it faces growing demands to decarbonise while maintaining the integrity of supply chains. Within this landscape, refrigerated maritime containers – or reefers – play a critical role. These containers are indispensable for transporting temperature-sensitive goods, but their reliance on high global warming potential refrigerants and energy-intensive operations presents a significant challenge to our collective climate goals.

During my tenure as Head of Global Seafreight at Kuehne+Nagel, I had the privilege of leading transformative initiatives that prioritised sustainability in maritime logistics. Together with our partners, we developed pioneering climate policies aimed at reducing CO_2 emissions and advancing green transportation solutions. These efforts not only aligned with emerging regulations but also anticipated the demands of our customers for sustainable logistics options.

At COP28, alongside GIZ, I was honoured to introduce the project that culminated in this white paper. It reflects a shared vision for addressing the dual challenges of operational efficiency and environmental stewardship. The insights presented here showcase the immense potential of transitioning to climate- and environment-friendly reefer technologies. From adopting natural refrigerants like propane (R290) and carbon dioxide (R744) to enhancing energy efficiency, these innovations represent tangible steps towards decarbonising the maritime cold chain.

This paper is a testament to the power of collaboration. It brings together research, industry expertise, and policy insights to provide a comprehensive roadmap for reducing greenhouse gas emissions in the reefer sector. It also highlights the critical role of public–private partnerships, capacity building, and regulatory alignment in achieving meaningful progress.

As a former industry leader, I recognise the challenges of driving change within a sector as complex and global as shipping. However, I also know that bold action is not just necessary – it is possible. This white paper is both a call to action and a source of inspiration for stakeholders across the maritime ecosystem.

I urge you to join us in embracing the opportunities outlined here. Together, we can make the reefer industry not only a cornerstone of global trade but also a leader in the fight against climate change.

Otto Schacht
Advisor to the Kühne Foundation /
Former Head of Global Seafreight, Kuehne+Nagel

Executive summary

This white paper delivers an urgent call to action: the reefer industry must transition to climate-friendly refrigeration technologies – immediately. The environmental impact of outdated refrigerants is alarming, with direct emissions from refrigerant leakage and indirect emissions from energy consumption driving the sector's carbon footprint to dangerous levels. Without swift and decisive action, the industry will fail to meet critical global climate targets, including the Paris Agreement and the International Maritime Organization's (IMO) 2023 Strategy for GHG Reduction.

Refrigerated maritime containers, or reefers, are indispensable to global trade, ensuring the safe transport of temperature-sensitive goods like food, pharmaceuticals, and electronics. With reefer demand soaring – projected to grow at 8% annually to 2030 [2] – the industry is at a tipping point. Yet, the current fleet overwhelmingly relies on hydrofluorocarbon (HFC) refrigerants such as R134a and R404A, which contain per- and polyfluoroalkyl substances (PFAS) – harmful 'forever chemicals' – and have sky-high global warming potentials (GWPs) of 1,530 and 4,728, respectively. [3] These substances don't just linger in the environment; they actively accelerate climate change. Compounding the crisis, reefer refrigerants leak at rates as high as 25%, releasing devastating amounts of greenhouse gases – 3.74 million tonnes of CO_2-equivalent emissions (CO_2eq) in 2018 alone. [4]

The time to act is now

We are running out of time to curb these emissions. The transition to sustainable refrigeration technologies is no longer an option – it is an absolute necessity. This paper explores viable solutions that align with the latest regulatory frameworks, such as

Table 1. Overview of refrigerants used in reefers

Refrigerant	Energy-efficiency and Coefficient of performance (COP [5])	Global warming potential (IPCC AR 6) [6]	Costs of refrigerants [7]	End-of-life	Side products/ PFAS [8]	Service and serviceability [9]	Knowledge/ Application [10]	Flammability [11]	Toxicity of side products [12]	Summary
R134a	✓	✗ 1530	✗	✗	✗	✓	✓	✓	✓	✗
R1234yf	✓	✓ 0.5	✗	✗	✗✗	✓	✓	✗	✗	✗✗
R290	✓✓	✓ 0.02	✓	✓	✓	✓	✓	✗	✓	✓✓
R744 (CO_2)	✓	✓ 1	✓	✓	✓	✗	✗	✓	✓	✓

2 *Reefer Container Market Demand Outlook, 2024 Report*
3 GWP values as per IPCC Sixth Assessment Report (AR6)
4 E. Złoczowska, "ASSESSMENT OF THE ENVIRONMENTAL IMPACT OF REFRIGERATED CONTAINERS TRANSPORTED BY SEA," International Multidisciplinary Scientific GeoConference SGEM., Jun. 2018, doi: 10.5593/sgem2018/4.2/s19.043
5 Future refrigeration technologies with natural refrigerants.Comparison of Energy Efficiency – Safety – Standards & Costs, 2013, Intermodal Europe Hamburg Messe by Holger König
6 IPCC Assessment report 6 *Climate Change 2021: The Physical Science Basis*
7 *Significant price rise for higher GWP refrigerants - Cooling Post* Cooling Post 25.02.2025
8 European Commission 19.10.2023, News Article by Directorate-General for Environment *Health and environmental impacts prompt a call for strict ruling on ubiquitous 'forever chemicals'*
9 Future refrigeration technologies with natural refrigerants.Comparison of Energy Efficiency – Safety – Standards & Costs, 2013, Intermodal Europe Hamburg Messe by Holger König
10 Ibd.
11 UN Environment and ASHRAE Factsheet 1 "Update on New Refrigerants Designations and Safety Classifications" November 2022 *UNEP/ASHRAE Refrigerant Fact Sheet #1—Update on New Refrigerants Designations and Safety Classifications*
12 Michael Feller, Karin Lux, Christian Hohenstein, Andreas Kornath. Structure and Properties of 2,3,3,3-Tetrafluoropropene (HFO-1234yf). Zeitschrift für Naturforschung B, 2014; 69b: 379 DOI: 10.5560/ZNB.2014-4017

CO_2 (R744) and propane (R290), which offer a path to a cleaner, more sustainable future. It also compares to R1234yf, which is currently favoured by the industry due to its application in other mobile air conditioning systems.

Key challenges and urgent opportunities

Moving to natural refrigerants like CO_2 (R744) and propane (R290) – both with a GWP of ≤ 1 and zero PFAS – represents a crucial step forward. Yet, despite their promise, technical, safety, and regulatory barriers continue to slow adoption. The maritime sector must overcome these hurdles **immediately**. Standards like ISO 20854:2019 for flammable refrigerants, including R290 and R1234yf, must be swiftly adopted to enable their widespread use.

1. **Switching to natural refrigerants –** The use of R290 and R744 can drastically cut direct emissions, with R290 offering performance on a par with conventional refrigerants.
2. **Energy efficiency overhaul –** Innovations in insulation, temperature control, and logistics could cut indirect emissions by up to 20%, particularly when combined with natural refrigerants.

Regulatory pressure is mounting

The reefer industry is at a regulatory crossroads. International policies such as the Kigali Amendment to the Montreal Protocol and the European Union's F-gas Regulation are mandating the phase-out of HFCs. Meanwhile, mounting evidence on the toxic persistence of PFAS – which degrade into hazardous trifluoroacetic acid (TFA) – is adding further urgency. Companies that fail to transition risk not only regulatory penalties but also reputational and financial consequences.

What's at stake?

Using detailed emissions models, this paper presents stark projections. The analyses take into account the compliance and non-compliance of existing policies and the current and possible future reefer fleet composition:

- The difference between decisive action and inaction is staggering – 171.8 Mt CO_2eq, equivalent to the annual emissions of 40 coal-fired power plants.
- Transitioning to R290-based reefers immediately could drastically cut emissions and PFAS contamination.
- The IMO's 2050 greenhouse gas (GHG) reduction targets cannot be met without widespread adoption of green technologies and rigorous refrigerant leakage prevention.

The study projects substantial reductions in CO_2-equivalent emissions across different scenarios as well as PFAS, emphasising the need to transition to natural refrigerants. For instance, by 2050, adopting R290 in just 50% of new reefers could achieve significant GHG savings.

The path forward: scaling up R290 adoption

The adoption of propane (R290) in reefer containers is a game-changing opportunity to decarbonise the sector. However, its adoption is hindered by a complex interplay of technical, regulatory, and market challenges, including safety concerns, infrastructure compatibility, and limited financial incentives. To address these barriers, a multi-dimensional approach is required, integrating advancements in technology, robust international and national policy frameworks, capacity-building programmes, and innovative financing mechanisms. The sector must act decisively and at scale.

A successful transition requires:

- **Technology development and deployment** – Accelerating prototype testing and integrating energy-efficient designs.
- **Stronger regulations and policy support –** Global and national regulatory frameworks must incentivise the shift to sustainable refrigerants.
- **Capacity building –** Training technicians and raising awareness among key industry players, including shipping companies and regulatory bodies.
- **Financial mobilisation and partnerships** – Leveraging carbon markets, government incentives, and public–private partnerships to reduce the financial burden and foster collaboration across sectors.

A defining moment for the reefer industry

Achieving the 1.5°C target set by the Paris Agreement is becoming increasingly unlikely, as current efforts remain insufficient to curb global warming. To bridge this gap, the reefer industry must take immediate, bold action to accelerate emission reductions. At the same time, technological competition is intensifying, with emerging players rapidly developing and deploying innovative refrigeration solutions.

By fostering collaboration across manufacturers, logistics firms, and regulators, the reefer industry can unlock significant climate benefits while driving cost-effective solutions. The findings are clear: for container owners, standing still is not an option – investment in next-generation, climate-friendly technologies is essential to remain competitive in a market that is shifting towards sustainability. The transition to Greener Reefers is not just feasible – it is imperative. Companies that embrace natural refrigerants and energy-efficient technologies will lead the charge towards a cleaner, more competitive industry. Those that hesitate risk being left behind in a rapidly evolving regulatory and market landscape.

1 Introduction

Refrigerated maritime containers, or reefers, are a vital component of global trade, enabling the safe transportation of temperature-sensitive goods such as food, pharmaceuticals, and electronics. These containers are indispensable in maintaining the integrity of the cold chain, ensuring that perishable goods reach their destination in optimal condition. As international trade continues to grow, the demand for reefers has increased significantly, outpacing overall trade growth due to economic, technical, and locational factors. [13] Today, the global shipping industry is at a pivotal juncture as it must meet growing demands to decarbonise while maintaining the integrity of supply chains in a growing market.

In 2018, the International Maritime Organization (IMO) estimated that approximately 2.49 million refrigerated containers (reefers) were actively used in international maritime transport. This figure represents reefers employed specifically in international trade rather than the total global fleet, which also includes units used in domestic or non-maritime logistics. The number of reefers in international shipping is expected to grow significantly due to rising demand for temperature-controlled logistics. [14]

However, the widespread use of reefers poses significant environmental challenges, particularly in terms of energy consumption and emissions. For example, reefer refrigeration is estimated to account for 30% to 40% of energy consumption in container terminals worldwide. This growth underlines the urgent need to address their environmental impact. Current reefer technology relies predominantly on hydrofluorocarbon (HFC) refrigerants. Of these, R134a is the most widely used, accounting for over 95% of the global fleet. With a global warming potential (GWP) of 1,530, R134a is a significant contributor to greenhouse gas emissions. The second most common refrigerant, R404A, has an even higher GWP of 4,728. [15, 16, 17, 18, 19]

Based on academic research, leakage rates in refrigeration appliances are estimated to be between 15% and as high as 25% [20], increasing their environmental impact. Based on the Global Logistics Emissions Council (GLEC) Framework [21], which covers the emission calculations for road and maritime freight transport, this leakage rate can be as high as 32.5% for temperature-controlled mobile freight units. [22] In 2018 alone, it is estimated that 3.74 million tonnes of CO_2eq were emitted from leaking refrigerants. These emissions are not limited to direct releases, as the inefficiencies caused by refrigerant loss led to increased energy consumption, further exacerbating indirect emissions. These factors highlight the urgent need for sustainable alternatives. The transition to more sustainable refrigeration technologies must overcome several challenges, including the higher flammability of some natural refrigerants compared to synthetic refrigerants, the toxicity of ammonia, the risk of suffocation from CO_2 and the

13 Seatrade Maritime News. Reefer shipping outpaces dry cargo growth due to demand for perishables and pharmaceuticals. Retrieved December 12, 2024, from *Request Sample PDF - Reefer Container Market Size, Industry Share | Forecast, 2032*
14 IMO. (2020). Fourth IMO GHG Study 2020.
15 Van Duin, R., et al. (2018). Cooling down: A simulation approach to reduce energy peaks of reefers at terminals.
16 Van Duin, R., et al. (2019). Factors causing peak energy consumption of reefers at container terminals.
17 Wageningen Food & Biobased Research, ATO Certification of reefer containers, Wageningen University & Research, Retrieved May 2, 2024, from Reefertransport - Home
18 Smith, C. et al. (2021). The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity
19 Greenhouse Gas Protocol (2024), 2024 IPCC Global Warming Potential Values. Retrieved September 24, 2024, from *Microsoft Word - Global-Warming-Potential-Values.docx (ghgprotocol.org)*
20 E. Złoczowska, "ASSESSMENT OF THE ENVIRONMENTAL IMPACT OF REFRIGERATED CONTAINERS TRANSPORTED BY SEA," International Multidisciplinary Scientific GeoConference SGEM .., Jun. 2018, doi: 10.5593/sgem2018/4.2/s19.043
21 The leakage rate considered in this publication is used based on available public literature and due to lack of direct, crosschecked and trustworthy data related to refrigerant losses of systems it is assumed to be a conservative value and also typical to other application from transport refrigeration.
22 Global Logistics Emissions Council Framework for logistics Emissions Accounting and Reporting V3.1 (2024) *GLEC_FRAMEWORK_v3_UPDATED_04_12_24.pdf*

A view of a harbour in Morocco. © GIZ / Mohammed Bakir

need for improved safety standards. Current standards such as ISO 20854 provide a practical framework for the use of flammable refrigerants such as R290 in maritime transport, but wider adoption requires overcoming both technical and perceived safety barriers.

R290 is emerging as a sustainable refrigerant in mobile applications across various transportation sectors. In the automotive industry, initiatives like the Green Automobile Air Conditioner Technology Demonstration Program have successfully developed mobile air conditioning systems using R290, offering low GWP and enhanced energy efficiency. [23] Similarly, in the rail sector, companies such as Liebherr-Transportation Systems have begun supplying series-produced heating, ventilation, and air conditioning (HVAC) systems that use R290 as a natural refrigerant. [24] These developments underscore R290's potential to reduce environmental impact while maintaining efficiency across various modes of transportation.

23 Institute for Governance & Sustainable Development (IGSD,), News 10.02.2025, *How R-290 Cooling is Transforming the Automotive Sector and Fighting Super Pollutants - Institute For Governance & Sustainable Development*
24 Liebherr News 11.06.2024, Liebherr supplies series-produced propane-based HVAC systems for the first time, *Liebherr supplies series-produced propane-based HVAC systems for the first time - Liebherr*

1 Introduction

The long-term perspective, considering emerging regulations such as EU REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) and a growing demand for sustainable logistics options, emphasises that the global shipping industry must overcome those barriers and transition to reefer containers with natural refrigerants to avoid bad investments. Many HFCs such as R1234yf and their blends break down into per- and polyfluoroalkyl substances (PFAS), also known as 'forever chemicals', which persist in the environment and can be toxic to humans and animals. As a result, the sector is under increasing pressure to switch to natural refrigerants such as propane (R290) and carbon dioxide (R744), which have a low GWP of ≤ 1 and minimal environmental impact. [25]

This white paper examines the potential of natural refrigerants like propane (R290) and carbon dioxide (R744) as low-GWP alternatives, as well as the role of energy efficiency improvements to reduce indirect emissions. In the broader policy context, international regulations are driving change. Agreements such as the Kigali Amendment to the Montreal Protocol and the European Union's F-gas Regulation mandate a phase-down of HFCs. These policies not only set ambitious targets but also create opportunities for innovation in the maritime refrigeration sector.

After providing an overview of the main policy frameworks (Chapter 3) and the refrigeration sector, including technology (Chapter 4), this white paper explores different mitigation scenarios and analyses the potential reduction in greenhouse gas emissions and environmental footprint that can be achieved through the adoption of greener technologies (Chapter 5). By presenting detailed modelling and projections, it demonstrates the tangible benefits of switching to natural refrigerants.

The detailed examination of climate- and environment-friendly reefers, including addressing the shortage of skilled technicians, market opportunities and scaling up this technology, provides valuable insights (Chapter 6). By providing a comprehensive analysis of current technologies, regulatory frameworks and future scenarios, this report aims to guide stakeholders in the adoption of sustainable practices. The transition to Greener Reefer containers not only supports global climate goals but also ensures the long-term viability of the cold chain logistics sector.

This white paper, developed by the Greener Reefers Transition Alliance, an initiative by GIZ and the Kuehne Climate Center, aims to bridge this gap by addressing the lack of clear roadmaps and actionable strategies specific to transitioning the reefer sector towards sustainable and climate-friendly solutions. It provides a comprehensive overview of current reefer technologies, evaluates potential climate-friendly alternatives, and presents mitigation scenarios based on the adoption of natural refrigerants and energy-efficient solutions. By fostering collaboration among stakeholders, the Greener Reefers project aims to demonstrate the feasibility of greener refrigeration technologies and accelerate the industry's transition to a sustainable future.

25 International Maritime Organization (2023). 2023 IMO Strategy on Reduction of GHG Emissions from Ships. Retrieved May 3, 2024, from *2023 IMO Strategy on Reduction of GHG Emissions from Ships*

2 Background

Since the late 1950s, reefers have existed as refrigerated and insulated intermodal containers with built-in refrigeration units that can control temperature and humidity. They are used to transport products that are sensitive to these factors, such as food, flowers, pharmaceuticals, and chemicals. Many of these products are essential to daily life. With the decline of dedicated refrigerated vessels, reefer containers have become the standard solution for transporting perishable goods.

Reefers are durable and highly functional, capable of controlling the temperature of the cargo compartment within a range of -60°C to +30°C, as well as regulating humidity levels. Some models even regulate atmospheric levels of carbon dioxide and oxygen. Currently, most reefers in the fleet use R134a as the refrigerant, with a market share of 96%, and smaller shares for R404A, R452A, R513A, and R744 (CO_2). However, due to environmental and climate policies, there is a growing need to phase out R134a, which has a global warming potential of 1,530.

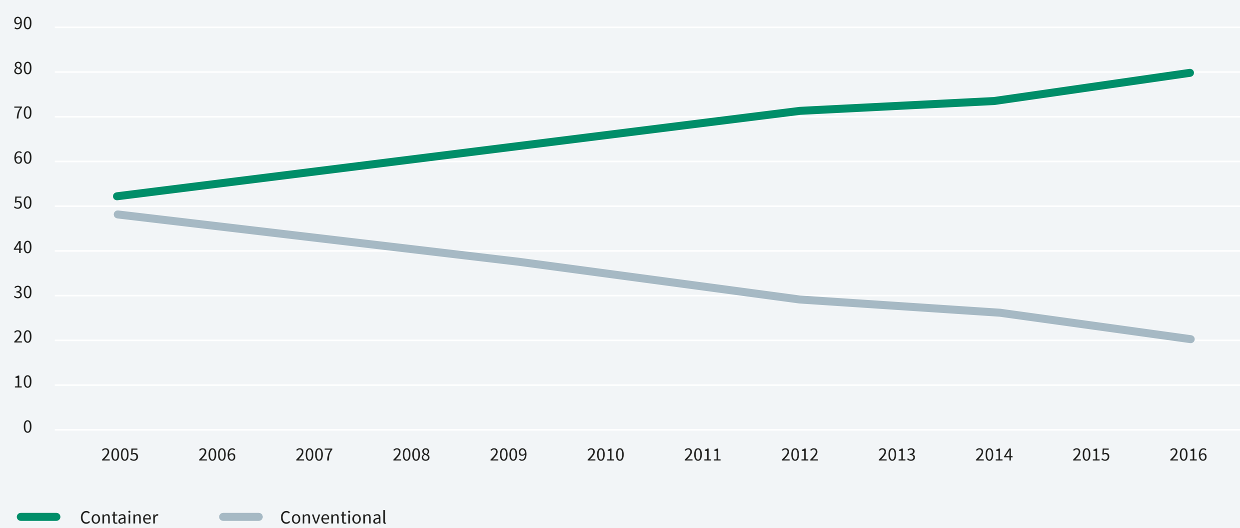
A reefer can be used as a stationary container, in which case it can store a variety of products, including pharmaceuticals or food and drink. Possible customers/users/locations are hospitals, laboratories, grocery stores, warehouses, bakeries, large sporting events or music festivals.

A reefer has two main components: 1) the cooling unit and 2) the insulated box. The refrigeration unit of a reefer reduces the temperature of the air circulated by fans. Low-temperature air is supplied to the hold at the bottom of the reefer through the so-called T-bar of the reefer floor, and higher temperature air is returned to the refrigeration unit at the top. The temperature of both the supply and return air is constantly monitored, allowing the refrigeration system to maintain the desired cargo temperature, relative humidity (RH),O_2 and/or CO_2 setpoints.

The reefers are insulated to prevent the surrounding temperature affecting the cargo and are painted white to limit the impact of solar radiation. Although the reefer is designed to maintain a constant temperature at the required setpoint, this depends on the control algorithm of the refrigeration system, the packaging conditions, a secure electrical power supply, and proper handling of the reefer at various transfer points. The temperature inside the reefer depends on the nature of the cargo, whether frozen, inert or live, as well as the external temperature and solar radiation. Reefers are built to keep a steady temperature inside the container from ca. -30°C to +30°C with external temperatures between -30°C and +40°C.

During transport, reefer containers are usually connected to the ship's electrical supply. Large fan banks are required to dissipate the excess heat generated by the containers, further increasing the indirect energy demand. Diesel generators, and lately also battery packs, usually installed on the reefer or truck trailer, power the reefer units for land transport on trailer chassis, or on rail on rolling stock. The power required as per ISO 1496-2 is 360–500 V and 50–60 Hz. During port operations, they are usually connected either to a diesel generator or to the electrical grid.

Figure 1. Modal split of maritime reefer cargo [26]

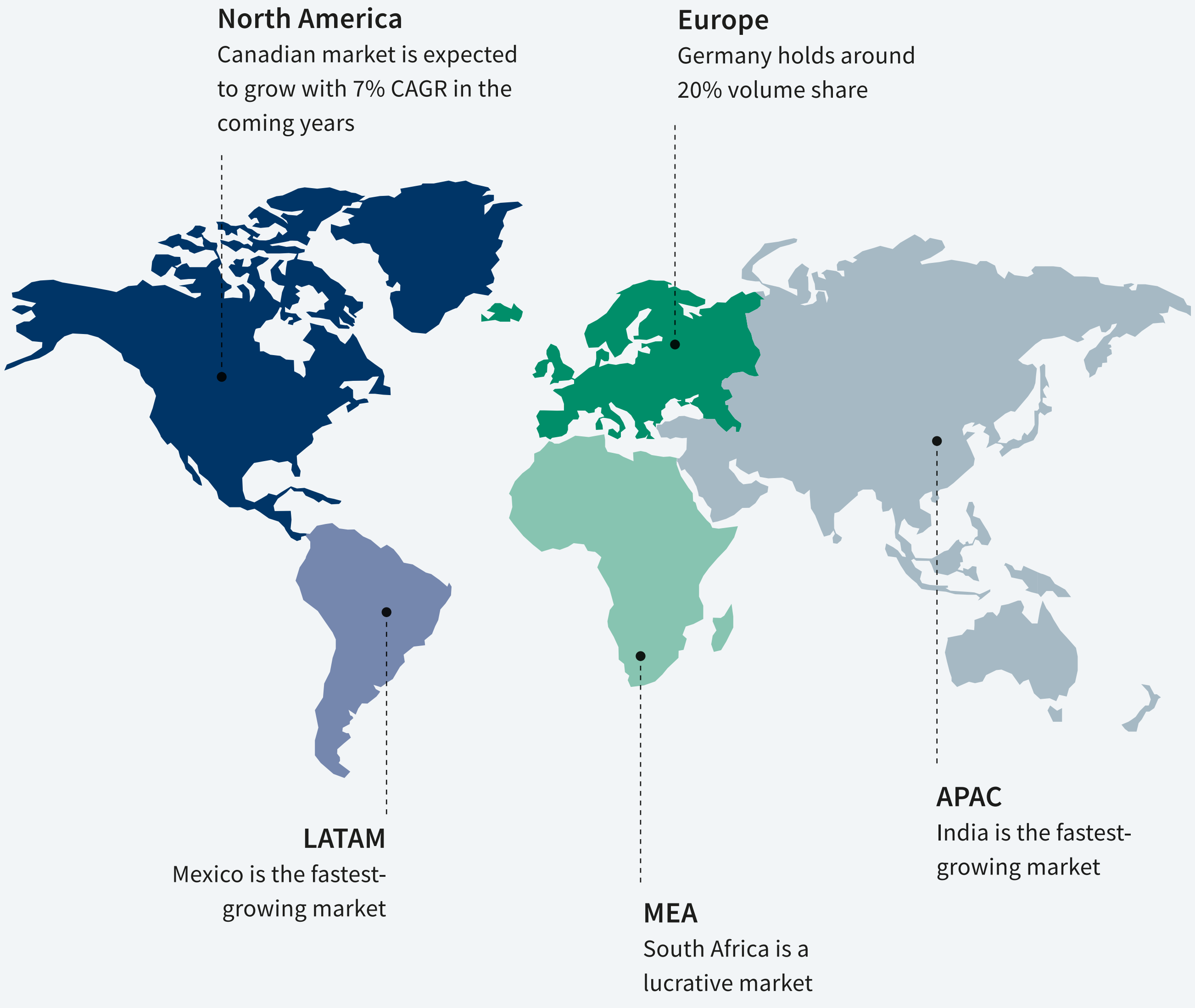


At each stage, reefers are a major contributor to energy consumption. The size of a reefer unit is strictly regulated by various standards to ensure compatibility between sea, road, and rail transport. Both the reefer unit and the container must comply with specific International Organization for Standardization (ISO) standards, such as ISO 1496-2:2018 for thermal containers. In addition, ISO 20854:2019 outlines the necessary design and operational requirements for exploring alternative refrigerants such as R290 (propane) and R1234yf, which are flammable. These regulations are shaping the reefer market and its growth.

Reefers are the preferred mode of transport because they can handle smaller consignments, offer more precise temperature control, and ensure better compatibility with land transport. Figure 1 illustrates the high demand for reefers, which have significantly increased their market share compared to dry containers.

26 Castelein, B., et al. (2020). The reefer container market and academic research: A review study.

Figure 2. Global reefer container market regional outlook [29]



Source: www.psmarketresearch.com

More perishable goods are transported by sea than by air because of the much smaller carbon footprint. The development of new niches, such as the transport of batteries and pharmaceuticals, are new opportunities for reefers, [27, 28] as are the environmental demands of retailers, which have, for example, increased the maritime transport of cut flowers.

Driven by global demand, the reefer market is expanding at an annual growth rate of up to 8%, with Latin America being the fastest growing region from 202x to 2030 and China ranking as the largest market by country in 2019 (see Figure 2). In addition, the use of dedicated reefer vessels is tending to decline as containerised reefer vessels continue to dominate the market, offering greater flexibility and integration into existing logistics chains. [30]

Operational practices and the quality of service and maintenance have a significant impact on the life of a reefer, which various reports estimate to be between 12 and 18 years. However, there is currently a lack of data on the 'second life' of reefers, referring to their repurposing for uses such as stationary cold storage or modular structures, and end-of-life solutions for the refrigerants used are largely non-existent. Meanwhile, the major reefer manufacturers have consistently produced over 100,000 new units per year for the past five years. [31, 32, 33]

Major shipping lines and operators, such as Maersk Line (Denmark), MSC (Switzerland) and Hapag Lloyd (Germany), and CMA CGM (France) remain mainly based in Europe.

The top five global suppliers of refrigeration units are Carrier Transicold (USA), Daikin (Japan), MCI (Denmark) and Trane Technologies/Thermo King (Ireland), followed by Klinge (USA). These suppliers have a wide range of products and production facilities around the world. Refrigeration units for reefers are mainly produced in Singapore and China, which are close to the reefer assembly plants. [34]

27 Ibid.
28 Lukasse, L., et al. (2023). Perspectives on the evolution of reefer containers for transporting fresh produce.
29 P&S Intelligence (2024). Reefer Container Market Report (2024 - 2030)
30 Dynamar. (2020). Reefer analysis 2020: Contents overview and introduction.
31 Ibid.
32 Wageningen Food & Biobased Research, ATO Certification of reefer containers, Wageningen University & Research, Retrieved May 2, 2024, from *https://www.reefertransport.nl/Reefertransport - Home*
33 The Drewry Report estimates between 115,000 and 190,000 new units since 2020.
34 Lundsgaard, C. A., et al. (2020). Preparatory study on Refrigerated Containers: Task 1 and 2 report. In Preparatory Study on Refrigerated Containers: Task 1 and 2 Report.

3 Political context for reefers today

The Paris Agreement of 2015 under the United Nations Framework Convention on Climate Change (UNFCCC) represents a historic commitment by countries and, on a voluntary basis, by companies to combat climate change, limit global warming to 1.5°C, degrees Celsius, and foster measures and investments aimed at achieving a low-carbon, climate-resilient, and sustainable future.

The efforts of the Paris Agreement are reflected in the countries' nationally determined contributions (NDCs), which outline each country's individual goals and strategies for mitigating emissions and adapting to climate change. National policies for their industry, and also companies' own strategies, commit to the goals of the Paris Agreement, such as owners and operators of maritime cargo.
By exploring and implementing Green Cooling, climate-friendly and energy-efficient cooling solutions and technologies, countries and businesses can reduce their greenhouse gas emissions and contribute to global efforts towards a sustainable cooling industry. Country NDCs have the potential to play a critical role in accelerating the uptake of Green Cooling technologies and practices, thereby reducing the environmental impact of the cooling sector.

While the adoption of Green Cooling technologies primarily targets reducing greenhouse gas emissions and improving energy efficiency, their impact extends beyond environmental benefits. These innovations are increasingly relevant across various sectors, particularly for those that rely heavily on temperature-controlled systems. For instance, in industries such as food and pharmaceutical logistics, the role of cooling technologies is not only about sustainability but also about ensuring product quality and minimising losses during transport.

The role of modern technology, particularly refrigerated containers (reefers), is crucial in maintaining an efficient cold chain. By ensuring proper temperature control during transport, reefers can help reduce global food losses. Although most food losses occur at the point of production, retailing and consumption, ensuring a functioning cold chain and temperature stability during containerised transport of consumables plays an essential role in minimising global food losses. A recent study published by IIR [35] estimated that in 2017, 12% of the food produced globally was lost due to an inadequate cold chain, equivalent to 526 million tonnes (Mt).

Table 2. Synthesis of IIR's study results on food losses and cold chain [36]

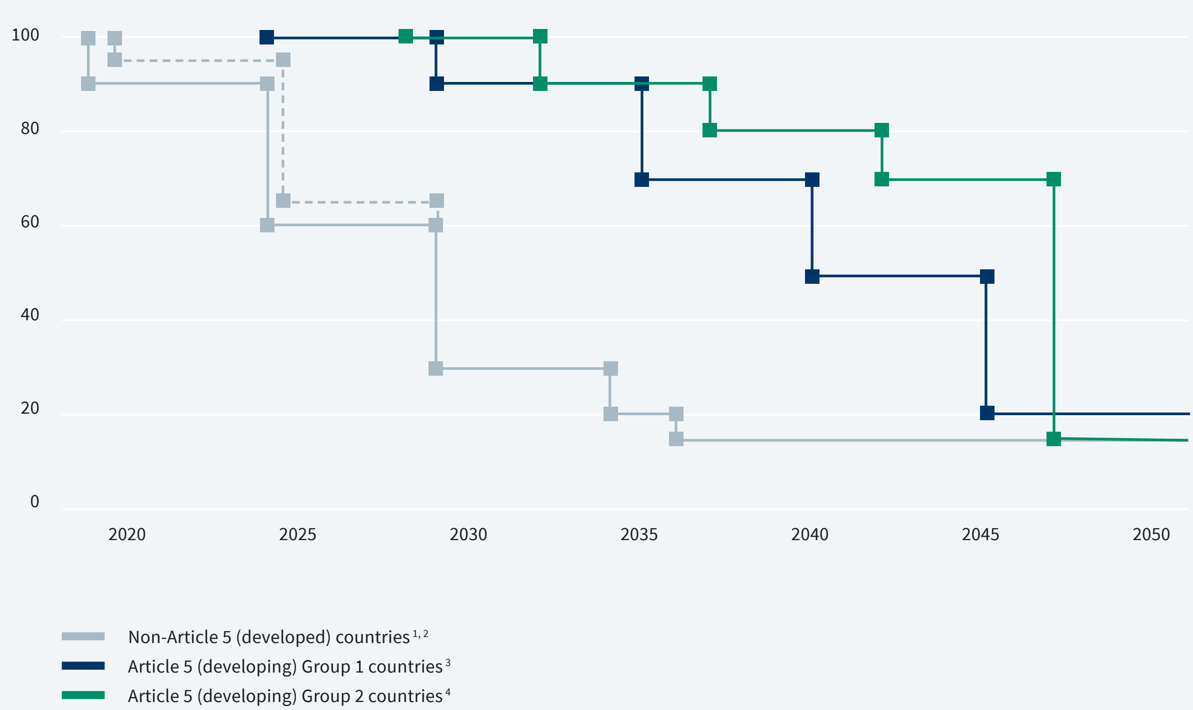
Designation	Value (current cold chain)	Value (improved cold chain)	Unit
Food losses due to lack of refrigeration	526	236	Mt
CO_2 emissions due to food losses	1004	76	Mt CO_2eq
CO_2 emissions from equipment	261	589	Mt CO_2eq
Total CO_2 due to cold chain	1265	665	Mt CO_2eq

35 Sarr, J., et al. (2021). The Carbon Footprint of the Cold Chain, 7th Informatory Note on Refrigeration and Food.
36 Ibid.

Increasing refrigeration coverage to the level of developed countries, by increasing the number of refrigeration units per capita in all countries, could reduce emissions from food losses by 47%, or about 600 Mt CO_2eq.

Expanding global refrigeration coverage to levels seen in developed countries has the potential to substantially cut emissions associated with food loss. When paired with international initiatives such as the Kigali Amendment, this strategy offers a significant opportunity to reduce greenhouse gas emissions and promote climate-friendly cooling technologies.

Figure 3. Phasedown schedule for allowed production and consumption, in percentages with respect to defined baselines, of controlled HFCs, expressed as CO_2eq, under the Kigali Amendment[37]



37 World Meteorological Organization (WMO). Scientific Assessment of Ozone Depletion: 2022.

The Kigali Amendment to the Montreal Protocol is an international agreement that aims to phase down the production and consumption of hydrofluorocarbons (HFCs), which are potent greenhouse gases commonly used in refrigeration and air conditioning systems (Figure 3). The amendment was adopted in 2016 and has been ratified by over 100 countries. The Kigali Amendment is expected to avoid up to 0.4 °C of global warming by the end of the century and is considered a significant step towards achieving the goals of the Paris Agreement. The amendment also provides an opportunity to promote the use of energy-efficient and climate-friendly cooling technologies, such as natural refrigerants, which can help reduce greenhouse gas emissions and improve energy efficiency.

Shipping emissions are generally divided into two categories: domestic and international. Domestic emissions result from shipping activities that take place within a country's territorial waters and ports, typically supporting national trade and transport. In contrast, international emissions are generated by ships travelling between different countries. This distinction is important because the methodologies for accounting for and managing these emissions are very different.

The International Maritime Organization (IMO) is responsible for regulating international maritime emissions and does not directly oversee domestic emissions. However, IMO regulations, including the development of fuel standards, efficiency measures, and decarbonisation strategies, often spill over into domestic maritime transport, influencing national policies and operational practices.

The 2023 **IMO Strategy on Reduction of GHG Emissions from Ships** [38] establishes a framework conducive to the proposal and development of projects and initiatives that promote the decarbonisation of the sector. The strategy encourages technological innovation for advanced propulsion systems and alternative fuels, with a focus on fuel efficiency. It also provides funding for research and development projects, facilitating partnerships and collaborations with other international organisations, industry stakeholders, and governments in search of new ways to reduce emissions. Furthermore, the IMO is laying the foundations for the establishment of an economic instrument, such as an emissions trading scheme, in which ships could buy and sell carbon credits. The revenues generated from such schemes can be used to expedite technological advancements within the sector. The IMO is also implementing the Montreal Protocol on Ozone-depleting Substances (ODS) – Regulation 12, which aims to phase out HFCs and chlorofluorocarbons (CFCs) commonly used in refrigeration systems, including those in refrigerated containers (reefer units). This development is expected to have a substantial impact on reefer technology, as it will encourage the adoption of alternative refrigerants that have a lower environmental impact. Examples of such refrigerants include R290 and R1234yf. [39]

Additionally, the International Convention for the Prevention of Pollution from Ships (MARPOL 2020) [40] and the International Convention for the Safety of Life at Sea (SOLAS) [41] are of pivotal significance. MARPOL 2020 establishes guidelines to control sulphur oxide emissions, thereby reducing the pollution

38 International Maritime Organization (2023) 2023 IMO Strategy on Reduction of GHG Emissions from Ships. Retrieved May 3, 2024, from *2023 IMO Strategy on Reduction of GHG Emissions from Ships*

39 *Ozone-depleting substances (ODS) – Regulation 12 (imo.org)*

40 International Maritime Organization(n.d.). IMO 2020 – cutting sulphur oxide emissions. Retrieved May 3, 2024, from *IMO 2020 – cutting sulphur oxide emissions*

41 International Maritime Organization (1974). International Convention for the Safety of Life at Sea (SOLAS). Retrieved May 3, 2024, from *International Convention for the Safety of Life at Sea (SOLAS), 1974 (imo.org)*

caused by ships. Conversely, SOLAS stipulates the standards for ship design, construction, and operation, with a view to ensuring minimal environmental harm. The IMO has set itself the ambitious target of reducing greenhouse gas emissions from the reefer sector by 50% by 2050, in line with the objectives of the Paris Agreement on climate change.

Another noteworthy international agreement is the European Union's F-gas Regulation, with its latest update, (EU) 2024/537, approved on 7 February 2024. [42] This regulation serves to amend the previous directive on fluorinated greenhouse gases (F-gases), including R134a, a prevalent refrigerant in refrigeration units. The regulation introduces a series of measures, including the establishment of a quota system for HFCs, the imposition of additional prohibitions, a revised phase-out calendar, and the implementation of more stringent rules for the prevention of emissions. It also entails enhanced control and enforcement measures for the implementation of these new regulations. This regulation is a substantial step towards achieving the EU's climate neutrality goals by 2050.

Refrigerants categorised as F-gases are also classified as per- and polyfluoroalkyl substances (PFAS), also known as 'forever chemicals' in European legislation. A significant proportion of refrigerants, notably R134a and R1234yf, undergo decomposition into trifluoroacetic acid (TFA), a specific type of PFAS characterised by an ultra-short chain structure. These substances are absorbed by soils or water bodies, thereby entering the water cycle. They substances have been detected in drinking water sources, and once ingested, they are difficult to eliminate from the body. The pervasiveness of PFAS in the environment has the potential to pose significant health risks to humans. In light of these concerns, the European Chemicals Agency (ECHA) has proposed a ban on all PFAS under the EU regulation REACH. [43] The proposal has already received a series of comments, which are currently undergoing evaluation and discussion by ECHA's committees. These comments were scheduled to be concluded by the end of 2024. [44]

The Green Cooling approach, as promoted by GIZ Proklima, has been shown to reduce GHG emissions from the refrigeration, air conditioning, and heat pump (RACHP) sector, thereby minimising environmental impact. The approach is in alignment with international commitments, and emphasises using highly energy-efficient technology that operates with natural refrigerants.

The refrigeration sector, while niche, has been identified as offering opportunities for improvement and alignment with international commitments. While the precise impact remains to be ascertained, it is anticipated that the design, production, and use of reefers will be influenced by one or more of the agreements outlined.
The present moment is thus seen as optimal for encouraging innovation in new reefer alternatives, with a view to enhancing efficiency and thermal insulation, while using natural refrigerants.

42 EUR-Lex (2024). Regulation (EU) 2024/573 on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No 517/2014. Retrieved May 3, 2024, from *Regulation - EU - 2024/573 - EN - EUR-Lex (europa.eu)*

43 European Chemicals Agency(2023, March 22). ANNEX XV RESTRICTION REPORT - PROPOSAL FOR A RESTRICTION. Retrieved May 3, 2024, from A*nnex XV reporting format 040615 (europa.eu)*

44 ECHA. (2024, March 13). Next steps for PFAS restriction proposal. Retrieved May 14, 2024, from *All news - ECHA (europa.eu)*

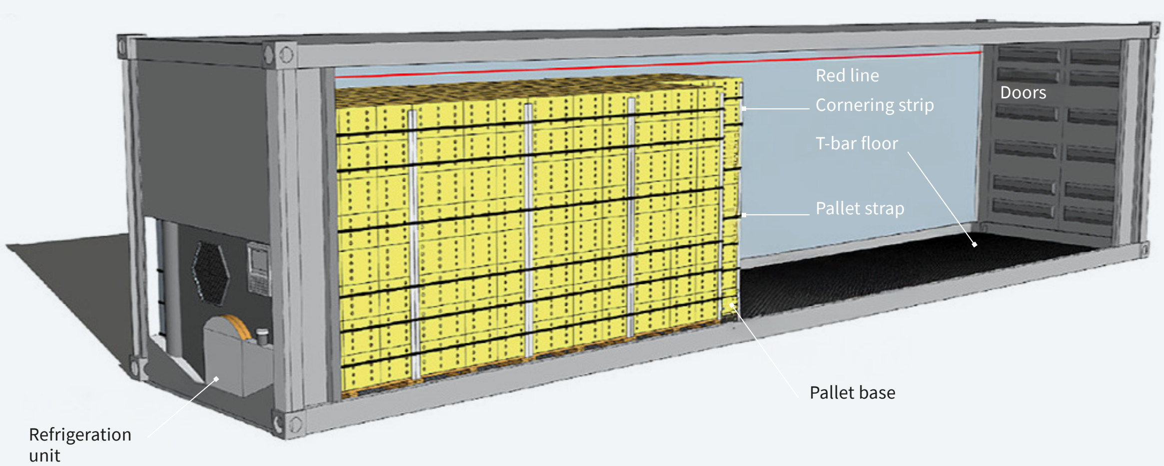
4 Reefer technologies and refrigerants

Nowadays, the vast majority of commodities are transported to distant markets via intermodal means (i.e., a combination of highway, ocean, and railroad transport). Refrigerated cargo containers, otherwise referred to as reefers, are employed to preserve temperature-sensitive commodities during global transportation.

Refrigerated cargo containers or mechanical refrigeration containers (reefers), are composed of two components: a thermal insulated container (box) and a mechanical refrigeration unit (refrigeration unit, cooling system). It is imperative for users to regard the refrigerated container as a system, particularly when making decisions regarding insulation and equipment sizing.

Refrigerated cargo containers are typically equipped with a single unit that constitutes the entire front wall of the container. The refrigeration unit is approximately 400 mm deep and provides both structure and insulation to the container front wall. The refrigeration system uses a vapour compression cycle, and the compressor and fan motors, resistance heaters, and operating controls are powered by an external electricity source. Typically, bottom air delivery is used. It is also noteworthy that the unit may be accompanied by a detachable diesel engine-generator set, which is equipped with an integral fuel tank, for travel by land.

Figure 4. Schematic of a reefer partially packed [45, 46]



45 Reefers are typically available in three lengths: 20 feet, 40 feet, and 40 feet high cube (with a higher ceiling).
46 Lukasse, L., et al. (2023). Perspectives on the evolution of reefer containers for transporting fresh produce.

According to American National Standards Institute (ANSI) Standard MH5.1.1.5 and ISO Standard 668, cargo containers are usually 2.4 m wide, 2.4 to 2.9 m high, and 6.1 or 12.2 m long. They have hinged doors in one end for loading cargo and for access to the inside. Containers have standard corner fittings to secure them to vessels, railway cars and highway vehicles. The outside dimensions of these containers are also governed by the same standards. The refrigeration system is made up of the compressor, fans, control and monitoring system, and refrigerant. [47, 48] Reciprocating and scroll compressors are both used in refrigeration units for reefers. Scroll compressors have the advantage of having fewer moving parts, being lighter and more compact, and being more efficient at low compression ratios. [49] Depending on the failure mode, they can also be repaired, provided a warning system to alert in the case of unacceptable conditions.

Reciprocating compressors have the advantage that they can be repaired and renovated, and also have a well-known supply chain. Frequency converters (inverters) are usually used to power the compressors to control how much air there is, which saves energy. To stop spoilage during transport, there is enough circulation of conditioned air around the cargo to remove heat that has been transferred into the cargo space. This is done by conduction and infiltration of fresh air. There is a free space between the top of the cargo and the ceiling and the floor has fixed T-bars (T-floor). The air is delivered at the bottom of the load through the T-floor (see Figure 4).

In a bottom air delivery system, it is important to maintain air pressure under the cargo. Respiring goods should be packed in cartons with aligned top and bottom vents to allow conditioned air to flow through and remove heat. The proper loading technique is essential to maintain good air circulation around the cargo and prevent spoilage, and partially loaded containers present particular cooling problems. [50, 51]

The functions of a refrigerated container control system include temperature control, defrosting and safety.

The return or supply temperature of the cargo air (and sometimes both) is monitored and thermostatically controlled. Additionally, even more efficient modes such as variable drive speed or frequency modulation solutions are used by reefers. Reefer efficiency is directly impacted by the regulation techniques.

Equipment control system functions may also include the following:

- Monitoring and displaying important operating parameters such as air supply and air return, and also relative humidity, CO, CO_2 and O_2 levels for the ‘Atmosphere Controlled’ mode
- Data logging of equipment performance parameters
- Alarms and alarm system in case of unacceptable conditions

47 ASHRAE (2010), ANDBOOK REFRIGERATION SI Edition, American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.
48 See also ISO1496-2:2018
49 Ibid.
50 Ibid.
51 McGregor, Brian (1987) Tropical products transport handbook, US department of Agriculture

- Temperature control for interior temperature (Tset), e.g., for commodity pulp temperature
- To improve fuel economy, providing stop and start signals to the engine-driven equipment, depending on the demand for cooling or heating
- Adjusting system capacity to match engine power supply during pulldown and function of ambient temperatures
- Monitoring and controlling cargo space atmospheric chemistry and relative humidity, such as CO, CO_2, O_2 and sometimes ethylene levels

Many of these control system functions are performed by microprocessors. They enhance equipment response to varying operating conditions, such as ambient temperature. Their ability to store data makes it easier to check the operation of equipment before it is used, and enables equipment performance to be tracked and possible faults to be analysed. Microprocessors can also be used with wireless telemetry to allow a central location to monitor thermostat setpoint, return and supply air temperature, operating mode and alarm status.

Equipment manufacturers use pre-trip inspection (PTI) tests to determine whether equipment meets the design criteria for operation. Users of equipment may wish to be guided by evidence of successful completion of appropriate tests or may wish to consider specific tests.

The energy consumption of a mechanically refrigerated container can be realised according to ISO 1496-2:2018 with the following test conditions: ambient temperature of 25°C and three temperature setpoints inside the container: 14°C, 0°C and -18°C. Cooling capacity or refrigeration capacity of a mechanical refrigerated container is usually realised at an ambient temperature of 38°C in North America and 30°C in Europe, with the following setpoints in the cargo hold: 2°C, -18C° and -29°C in North America and 0°C and -20C° in Europe. [52]

A functional test of a mechanically refrigerated container at high ambient temperatures is usually carried out in accordance with ISO 2018 standards. The test conditions include an ambient temperature of 50°C, with the hold setpoints set at 12°C, -30°C and/or the lowest setpoint achievable by the mechanical refrigeration unit.

4.1 Refrigerants in reefers

The refrigeration and air conditioning (RAC) sector is responsible for a significant proportion of global greenhouse gas emissions, directly through the use of high-GWP refrigerants and indirectly through the amount of energy used. The transition to ultra-low-GWP refrigerants, such as natural refrigerants like propane, ammonia and carbon dioxide, is critical to reducing greenhouse gas emissions and mitigating the impact on the environment and nature.

Reducing the production and emissions of HFCs is a critical step in reducing greenhouse gas emissions and mitigating environmental and human health impacts, in line with the objectives of the Montreal Protocol and its Kigali Amendment.

52 ASHRAE (2010), ANDBOOK REFRIGERATION SI Edition, American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.

Figure 5. HFC emissions (left) and their impact on global average surface temperature (right) according to four different scenarios[53]

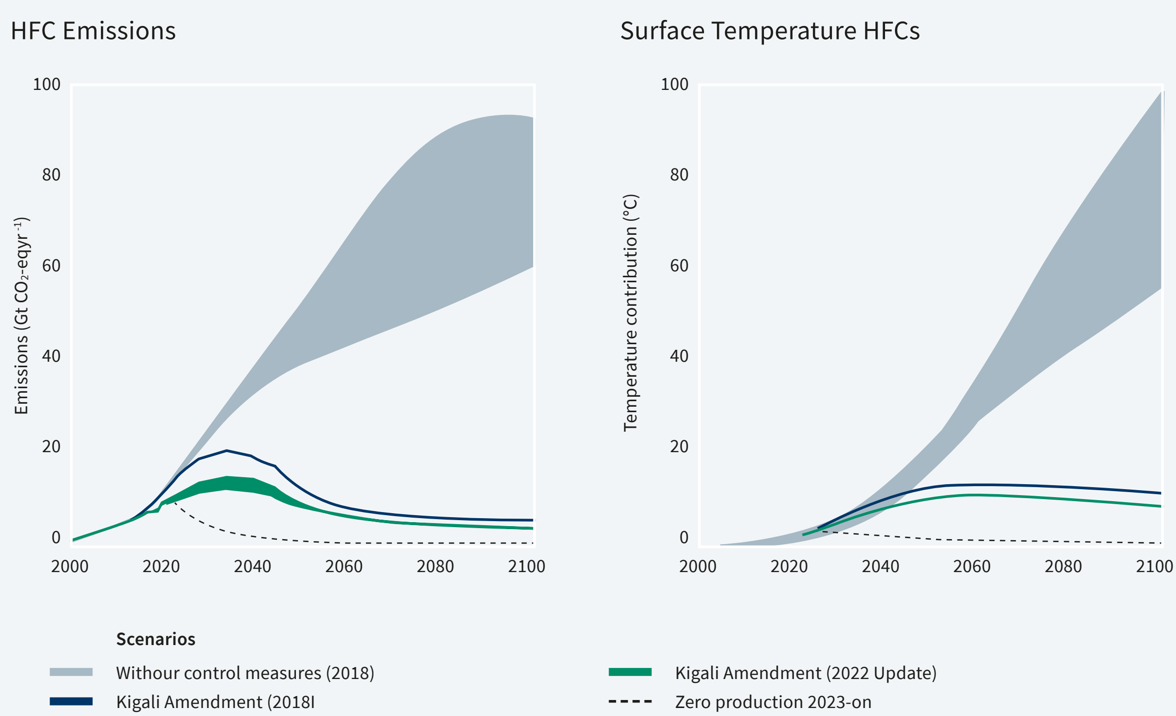
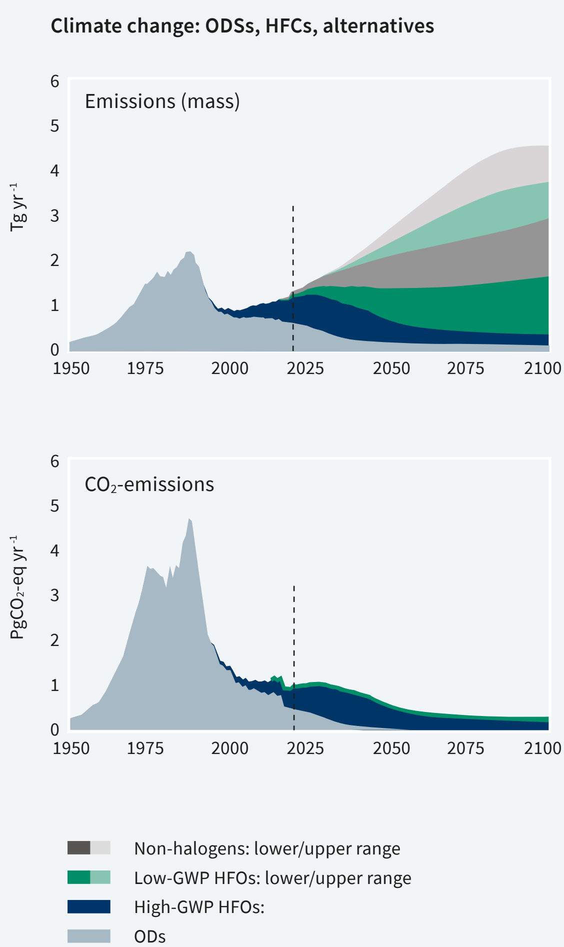


Figure 5 illustrates the potential impact that could be avoided by following the schedule presented in Figure 3 in Chapter 3. If no control measures are taken on emissions of HFCs by 2100, there will be 6 to 9 Gt CO_2eq per year, and the contribution to global average surface temperature will be between 0.3 and 0.5 Kelvin.

The dark blue and green areas in the graphs illustrate emissions and projected contributions to global average surface temperature, based on the scenario proposed in the Kigali Amendment in 2018 and its latest update in 2022. The latest scenario (from 2022) incorporates a range of factors, including national controls on consumption and production

53 World Meteorological Organization (WMO). Scientific Assessment of Ozone Depletion: 2022.

Figure 6. Historical and projected contributions to climate change from ODSs, high-GWP HFCs, low-GWP HFOs and non-halogenated alternatives, assuming full compliance with the provisions of the Montreal Protocol, including the Kigali Amendment [54]



of hydrofluorocarbons (HFCs) in non-Article 5 countries, lower reported consumption in China, updated historical information on the use of HFCs in non-Article 5 countries, observed blend ratios up to 2020 as a constraint, and assumptions on reduced use of HFCs for commercial and industrial refrigeration. The study further assumes that all countries will comply with the Kigali Amendment (see Figure).

The use of low-GWP alternatives within the RAC sector has resulted in a decline in emissions equivalents and their associated radiative forcing. This is despite an increase in atmospheric mass emissions, attributable to the sector's growth. In recent years, natural refrigerants have been adopted by some sectors, particularly commercial refrigeration, as a means of reducing direct greenhouse gas emissions and mitigating environmental impacts. Other low-GWP alternatives in use include new blends of HFC refrigerants with hydrofluoroolefins (HFOs) or, in some cases, natural refrigerants. HFOs have also been used, especially in the automotive industry. R1234yf, an HFO, is currently regarded as a promising alternative for a wide range of applications.

However, it should be noted that HFCs and HFOs are classified as PFAS (permanent chemicals), and it is proposed that they be prohibited under the ECHA proposal for REACH. The atmospheric degradation of HFCs results in the formation of TFA and has been identified as a major source of TFA in the environment. [55] A recent study of ice cores shows an increased deposition of TFA, TFA, perfluoropropanoic acid (PFPrA), and perfluorobutanoic acid (PFBA) since 1990,[56] and it is anticipated that the environmental levels of TFA will increase in the future as a

54 Ibid.
55 Kotamarthi, V.R, et al. (1998), Trifluoroacetic Acid from Degradation of HCFCs and HFCs: A Three-Dimensional Modeling Study. J. Geophys. Res. Atmos.
56 Pickard,H.M, et al. (2020), Ice Core Record of Persistent Short-Chain Fluorinated Alkyl Acids: Evidence of the Impact From Global Environmental Regulations. Geophys. Res. Lett

result of a shift from HFCs towards HFOs. TFA has been identified as a teratogen, capable of crossing the placental barrier and bioaccumulating in the foetal and amniotic fluid of rats, as well as being present in the breast milk of monkeys. Further experimentation has led to the discovery of persistent ocular malformations in rabbits. The potential reprotoxic effects on humans of these gases require further elucidation. There is already a track record of experiments that are trying to determine an ADI (acceptable daily intake) for humans, and these early results indicate that current exposure and TFA found in the environment are still far from being a health risk, yet the presence and emissions of TFA are ever increasing. [57]

The emission of TFA has not been the subject of comprehensive monitoring in many countries; however, there is sufficient data to distinguish and model the most likely sources of TFA. A plethora of publications have indicated that the source of TFA is predominantly anthropogenic, including direct release from specific industrial processes in chemical plants, from municipal and industrial waste management, and from atmospheric deposition of refrigerants and foams. [58] Emission from natural sources such as hydrothermal vents and microbe processes in the ocean have been found to be negligible in comparison to the anthropogenic sources. [59] Projections have already been made regarding future TFA emissions, particularly those resulting from atmospheric deposition of refrigerants. The majority of these projections indicate that the uptake of substances such as R1234yf could result in a significant alteration to future projections. [60]

Table 3. Projected annual TFA production rate due to the atmospheric conversion of R134a and R1234yf [61]

	R134a	R1234yf	Sum
Annual TFA Formation (Tg/year)			
2020	0,01–0,03	0,03–0,03	0,04–0,06
2050	0,02–0,05	0,34–0,49	0,36–0,54
2100	0,01–0,02	0,63–1,03	0,64–1,05
Sums of Deposited TFA (Tg)			
2020–2050	0,5–1,5	5,3–6,6	5,8–8,1
2020–2100	1,0–2,9	30,5–49,0	31,5–51,9

Refrigerants constitute a significant component of the insulation of the box, given their capacity to function as blowing agents, otherwise referred to as foams. The use of HCFCs and HFCs has been employed for both purposes. In accordance with the provisions of the Montreal Protocol, the use of HCFCs has been effectively phased out, whereas HFCs continue to be employed as refrigerants.

57 Brunn, H., Arnold, et al. (2023). PFAS: forever chemicals—persistent, bioaccumulative and mobile. Reviewing the status and the need for their phase out and remediation of contaminated sites
58 Freeling, F., & Björnsdotter, M. K. (2023). Assessing the environmental occurrence of the anthropogenic contaminant trifluoroacetic acid (TFA).
59 Adlunger, K., Anke, et al. (2021). Reducing the input of chemicals into waters: trifluoroacetate (TFA) as a persistent and mobile substance with many sources
60 Wang et al. estimate an upper limit deposition of 59.71 Gg yr-1 for TFA from HFO-1234yf, based on the following degradation path
61 World Meteorological Organization (WMO). Scientific Assessment of Ozone Depletion: 2022.

Significant progress has been made in certain sectors of the RACHP industry through the adoption of cyclopentane, an HC foam with an exceptionally low GWP (<1).

The insulation of new reefers in Europe is no longer permitted to contain HFCs or HCFCs as blowing agents. A similar situation is occurring in other parts of the world, where these agents are also being phased out. However, the older reefer fleet continues to use R141b as a foam blowing agent. Two main alternatives for this blowing agent are R365mfc and R245fa. [62, 63] The implementation of both alternatives as a replacement is straight-forward, with no requirement for significant alterations to the foam processing stage. Furthermore, formulations have been optimised to ensure an optimal cost-to-performance ratio. [64] Cyclopentane, an inexpensive blowing agent, has been demonstrated to produce low-density foams with low thermal conductivity and good mechanical properties. [65] However, it is a flammable substance that requires an investment to handle it safely. The fourth generation of foaming agents, including HFC-LBA and FEA-1100, emerged in 2013. These agents are characterised by their zero ozone depletion potential and a global warming potential of less than 10, suggesting minimal environmental impact. In 2020, significant research results were achieved with the FEA-1100 foaming agent. However, it is important to note that FEA-1100 is an HFO and could be considered within the PFAS definition.

In order to undertake a comprehensive evaluation of refrigerants, it is imperative to consider their GWP over both the short term (up to 20 years) and long term (up to 100 years). Furthermore, the assessment of flammability should adhere to the standards outlined in Standard 34 of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), which classifies refrigerants as A1 (non-flammable), A2L (lower flammability), A2 (mild flammability), or A3 (flammable). [66]

When considering the risk of PFAS, it is essential to consider the presence of PFAS/TFA in the refrigerant's composition. Table 2 provides specifications for known refrigerants that can be used in reefers or are considered to be alternatives.

The significance of PFAS for the industry is demonstrated by the over 5,600 comments on the EU PFAS restriction proposal by over 4,400 organisations, companies and individuals, as reported by ECHA. [67, 68] Due to the number of comments, the process is planned to enter into force in 2029.

62 Lundsgaard, C. A., et al. (2020). Preparatory study on Refrigerated Containers: Task 1 and 2 report. In Preparatory Study on Refrigerated Containers: Task 1 and 2 Report.
63 Wang, Y., et al. (2022). Technology trend forecasting and technology opportunity discovery based on text mining: the case of refrigerated container technology.
64 R, L., T, M., & N, M. (2015). Low GWP insulation blowing agents and methods of measurement of efficiency.
65 Wang, Zhiguo, Chengzhu Wang, Yuebin Gao, Zhao Li, Yu Shang, and Haifu Li. 2023. "Porous Thermal Insulation Polyurethane Foam Materials" Polymers 15, no. 18: 3818.
66 ASHRAE (2022). ANSI/ASHRAE Standard 15-2022. Safety Standard for Refrigeration Systems. Retrieved May 3, 2024, from *ASHRAE 15-2022 (packaged w/Standard 34-2022) | ASHRAE Store (accuristech.com)*
67 *All news - ECHA*
68 *PFAS are forever? | Corporate Europe Observatory*

As illustrated in Table 4, the current market share of refrigerant use in the global reefer fleet is specified. It is evident that HFC refrigerants R134a and R404A dominate the market. Alternatives already present for these refrigerants include HFC/HFO blend R513A (which replaces R134a) or R1234yf, and R452A (which replaces R404A).

It is noteworthy that R23, despite its limited market share, is also present. This refrigerant is used in models that allow for ultra-low temperatures down to -70°C for critical cargo such as vials, active pharmaceutical ingredients (APIs) and enzymes, but especially for the transport of fish. It is estimated that between 5,000 and 10,000 reefers operate at -60°C. These units are equipped with a cascade refrigeration system, comprising R134a in the high-temperature side and R23 in the low-temperature side. [69] R473A is considered a replacement for R23. Despite its superior cooling capacity, R473A exhibits a higher energy consumption at a given cooling capacity, primarily due to its reduced volumetric and isentropic efficiency.

High-GWP refrigerants face soaring prices as natural alternatives offer stability

The EU F-gas Regulation entered into force in March 2024. It has set ambitious targets for phasing out HFCs, leading to a dramatic rise in conventional refrigerant prices, which have increased by up to 1,000% from their 2014 levels of 3–5 EUR/kg. [70] In contrast, prices for alternative refrigerants have remained stable since 2020, according to the German environmental consulting firm Öko-Recherche. Currently, refrigerants with a high GWP are priced at 30–45 EUR/kg across various European suppliers, with prices steadily rising since 2014. In comparison, alternatives like propane (R290) and carbon dioxide (R744) remain considerably cheaper (~5–15 EUR/kg).

Another factor driving higher refrigerant prices is the ongoing EU discussions on regulating ‘forever chemicals’ such as per- and polyfluoroalkyl substances (PFAS). All refrigerants, except for natural ones like R290, R744, and R32, are known to break down into PFAS. This may lead to further price increases for refrigerants like R1234yf, which is used in automobiles and is being considered as an alternative.

Though these price trends are most notable in the European market, they are expected to impact other regions due to global commitments to the Montreal Protocol and its Kigali Amendment. While the higher initial cost of greener refrigerants can be a barrier, they typically offer at least 10% greater efficiency (e.g., R290 vs. R404A), resulting in lower energy consumption and reduced electricity costs. Additionally, the use of natural refrigerants, such as hydrocarbons, encourages a decrease in leakage rates from cooling devices, reducing the need for refills. The price increases in refrigerants are already influencing current and future policies aimed at promoting more sustainable cooling solutions.

69 R1150 (ethylene), a hydrocarbon with a GWP of 4, can also be used for low temperature application (< -70°C).

70 European Environment Agency (EEA) Background Document 24.02.2024 Results of Quarterly survey: Quarter 4/2024 *Reports - Fluorinated Greenhouse Gases – Climate Action*

Table 4. List of GWP values, flammability, and PFAS presence of selected refrigerants and foams (PFAS free alternative used in reefers highlighted) [71, 72, 73, 74, 75, 76]

Refrigerant / Foam	Type	Composition	Alternative for [77]	Market share (%) [78]	GWP 20 years	GWP 100 years	Flammability	PFAS	TFA (up to %)
R141b	HCFC	Pure	-	-	2170	860	A1	No	No
R23	HFC	Pure	R13	-	12400	14600	A1	No	No
R134a	HFC	Pure	R12, R22	97,80	4140	1530	A1	Yes (R134a)	R134a (20%)
R404A	HFC blend	R143a (52%), R125 (44%), R134a (4%)	R22, R502	1,68	7208	4728	A1	Yes (R143a, R125, R134a)	R143a (10%), R134a (20%)
R452A	HFC/HFO blend	R125 (59%), R1234yf (30%), R32 (11%)	R404A, R507A	0,18	4303	2292	A1	Yes (R125, R1234yf)	R1234yf (100%)
R473A	HFC/HFO/CO_2 blend	R744 (60%), R1132a (20%), R23 (10%), R125(10%)	R23	-	1915	1835	A1	Yes (R125)	No
R245fa	HFC	Pure	R141b	-	3170	962	A1	No	No
R365mfc	HFC	Pure	R141b	-	2920	914	A1	No	No
R513A	HFC/HFO blend	R1234yf (56%), R134a (44%)	R134a	0,03	1823	673	A1	Yes (R1234yf, R134a)	R1234yf (100%), R134a (20%)
R454A	HFC/HFO blend	R1234yf (65%), R32 (35%)	R404A	-	1037	270	A2L	Yes (R1234yf)	R1234yf (100%)
R1234yf	HFO	Pure	R407A, R410A, R134a	-	1,81	0,501	A2L	Yes (R1234yf)	R1234yf (100%)
R744	CO_2	Pure	R134a, R404A, R407A, R410A, R22	0,31	1	1	A1	No	No
R290	HC Propane	Pure	R134a, R404A, R407A, R410A, R22, R502	-	0,072	0,02	A3	No	No
R717	Ammonia	Pure	R134a, R404A, R407A, R410A, R22	-	<1	<<1	B2L	No	No
	Cyclopentane	Pure	R141b	-	<<1	<<1	A3	No	No

71 Smith, C., et.al., 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
72 World Meteorological Organization (WMO). Scientific Assessment of Ozone Depletion: 2022.
73 Everitt, N. (2023, February 13). PFAS ban affects most refrigerant blends. Cooling Post.
74 Behringer, D., et al. (2021). Persistent degradation products of halogenated refrigerants and blowing agents in the environment: type, environmental concentrations, and fate with particular regard to new halogenated substitutes with low global warming potential (ISSN 1862-4804). German Environment Agency.
75 Refrigerants. (n.d.). Linde (Former AGA) Industrial Gases.
76 Container Owners Association, COA, & COA Reefer Forum Work Group. (2022). REEFER CONTAINERS: REGULATORY ISSUES CONCERNING REFRIGERANT F-GASES.
77 Alternatives applies for various other applications. Not only reefers.
78 Wageningen Food & Biobased Research, ATO Certification of reefer containers, Wageningen University & Research, accessed 15 February 2024, *Reefertransport - Home*. Averages of the last five years. Refrigerants marked with a "-" are prospects and in development, they are not available on the market or no significant figures were found.

4.2 The challenges of flammability

The standard ISO 20854 provides the framework for the use of flammable refrigerants (currently classified as A2, A2L, A3 by standard ISO 817:2014) in maritime containers. [79] Discussions are ongoing regarding the potential future use of HFO-1234yf and R290 in this context. [80]

Despite the absence of a commercial solution employing flammable refrigerants, the plethora of relevant scientific studies presented at recent conferences on the management of flammability for transport applications is indicative of substantial research and development in this field. König et al. (2014) [81] have demonstrated that the frequency of hazards and the probability of fatalities for the global reefer container fleet would be reduced to below 10^{-6} (including human error) if adequate design changes were implemented and best practice guidelines were established. It is noteworthy that the maritime sector has extensive experience in handling and transporting highly flammable substances, including kerosene, methane, liquefied natural gas (LNG), and propane.

Additionally, in the mobile air conditioning (MAC) sector, R290 is successfully used in truck and trailer technology for transporting perishable commodities, and also for public transport solutions and pharmaceuticals. [82]

A paper by König, Bararu, and Holtappels examines the energy efficiency of various replacement options for containers or trucks/trailers and outlines three distinct design approaches to address flammability risks. [83]

The paper outlines three mitigation approaches: firstly, minimising joints, incorporating leak-proof components, and adding sensors, shut-off valves, door interlocks, and alarms; secondly, implementing a multi-circuit design to limit the refrigerant charge associated with potential leaks; and thirdly, using an indirect cycle with a non-flammable fluid in the secondary loop.

Despite manufacturers having expressed interest in developing an R290 reefer in recent years, no such model is currently available on the market. The primary challenge appears to be the implementation of the requisite Operating Mode Risk Assessment process for evaluating risks across the various stages of operationalisation.

However, there has been a recent emergence of new standards, technical specifications, and technical reports that focus on the safe use of flammable refrigerants. Specifically, ISO 20854:2019 details the industry's optimal practices for the safe operation of flammable refrigerants in refrigerating systems employed in maritime containers, operating on board ships, in terminals, and on road, rail, and land. [84]

79 ISO. (2019). ISO 20854:2019: Thermal containers — Safety standard for r efrigerating systems using flammable refrigerants — Requirements for design and operation. Retrieved June 21, 2024, from *ISO 20854:2019 - Thermal containers — Safety standard for refrigerating systems using flammable refrigerants — Requirements for design and operation*

80 Container Owners Association, COA, & COA Reefer Forum Work Group. (2022). REEFER CONTAINERS: REGULATORY ISSUES CONCERNING REFRIGERANT F-GASES.

81 König, H., Bararu M. (2014). Risk assessment for reefer containers with flammable refrigerants. 11th IIR Gustav Lorentzen Conference on Natural Refrigerants *Risk assessment for reefer containers with flammable refrigerants. - pap. ID109*

82 *Presentations - Transport refrigeration - ATMO Europe 2024*

83 König, H., Bararu, M., & Holtappels, K. (2016). Practical tests with R290 used in reefer container refrigeration leakage testing. 12th IIR Gustav Lorentzen Conference on Natural Refrigerants. *Practical tests with R290 used in reefer container refrigeration leakage testing. - pap. 1138*

84 ISO. (2019). ISO 20854:2019: Thermal containers — Safety standard for refrigerating systems using flammable refrigerants — Requirements for design and operation. Retrieved June 21, 2024, from *ISO 20854:2019 - Thermal containers — Safety standard for refrigerating systems using flammable refrigerants — Requirements for design and operation*

The engineering tools for determining the system safety has been an established practice for decades. In transport refrigeration, these risk assessment methodologies were formally adopted after the integration of R1234yf and R744 within the automotive industry (ISO 13043; ISO 17893:2024). [85]

Leakages are a prevalent malfunction in all RAC systems. These are typically observed in the joints of subcomponents and the elbows of heat exchanger coils. It is noteworthy that 90% of all leakages are micro-sized, with the majority of these being caused by mechanical wear and pipeline vibration. This category of leak presents a negligible explosion risk, as it does not generate a flammable atmosphere. However, it does generate an attenuation of cooling capacity and an increase in energy consumption over a long period of time. The remaining leaks are predominantly catastrophic in nature, arising from external forces. These leakages pose a significant risk of ignition due to the creation of a flammable atmosphere, and if a source of ignition is present, there is an elevated risk of explosion. [86]

The flammability of refrigerants has been the focus of extensive research over an extended period, leading to the development of effective mitigation measures. These measures have been designed to reduce the formation of flammable atmospheres and to minimise the probability of ignition. It is imperative that risk reduction measures are implemented in systems containing R290 and any other flammable refrigerants, such as R1234yf. The combustion of R1234yf results in production of toxic hydrogen fluoride. [87] As stated by the Green Car Congress in 2014: "The simplest fluoride, hydrogen fluoride (or hydrofluoric acid, HF) is also highly corrosive and so toxic that burns about as big as the palm of one's hand can be lethal. The agent binds avidly to calcium in body fluids, and this can result in heart failure unless an antidote is rapidly administered. […] If inhaled, it can damage the alveoli in the lungs, allowing it to reach the circulation and shut down vital functions." [88]

R290 has been found to have larger flammability limits in comparison to other selected refrigerants. [89] It has been demonstrated that the presence of airflow within the space where the refrigerant has been leaked can result in a substantial reduction in the risk of ignition. In circumstances where the airflow is sufficiently high, the flammable volume may ignite in a localised manner, yet the flame will be unable to propagate. [90] Therefore, simple infrastructural design choices can effectively reduce the risk of flammable atmosphere and ignition.

The flammability of refrigerants, and the additional measures deemed necessary to ensure adequate risk mitigation, represents a significant challenge in the adoption of R290 and other refrigerants. This challenge is further compounded by the percep-

85 ISO 13043:2011. (2011). ISO. Retrieved May 3, 2024, from *ISO 13043:2011 - Road vehicles — Refrigerant systems used in mobile air conditioning systems (MAC) — Safety requirements*

86 Li, Y., et al. (2023). Leakage, diffusion and distribution characteristics of refrigerant in a limited space: A comprehensive review.

87 Feller Michael, Lux Karin, Hohenstein Christian, Kornath Andreas (2014). Structure and Properties of 2,3,3,3-Tetrafluoropropene (HFO-1234yf). Zeitschrift für Naturforschung

88 Green Car Congress News 11.04.2014: LMU study finds 20% of gases from combustion of R1234yf MAC refrigerant consist of highly toxic carbonyl fluoride (correction and update) *LMU study finds 20% of gases from combustion of R1234yf MAC refrigerant consist of highly toxic carbonyl fluoride (correction and update) - Green Car Congress*

89 Li, Y., et al. (2023). Research on the field strength characteristics and the flammable area of refrigerants leakage into a confined space.

90 Li, Y., et al. (2023). Leakage, diffusion and distribution characteristics of refrigerant in a limited space: A comprehensive review.

tion of risk, which frequently exceeds the actual risk. In fact, the number of accidents derived from the use of hydrocarbons in a growing number of systems has not increased. [91] The success of isobutane (R600a, an A3 type flammable refrigerant) in domestic refrigerators and R290 in domestic tumble dryers and portable air conditioning units demonstrates that the implementation of flammable refrigerants is achievable when there is a convergence of political and technical will. [92]

The implementation of flammable refrigerants is further complicated by techno-economic barriers, including the high cost of the refrigerants themselves and the high cost associated with the abatement of harmful refrigerants, such as HFCs. Furthermore, safety requirements for flammable refrigerants have the potential to increase costs, despite the relatively low cost of the refrigerants themselves. Additional barriers of a commercial and consumer nature include the limited technical competence of local vendors, the absence of local service and maintenance teams, the restricted capability of using flammable refrigerants, the unavailability of qualified technicians to deal with problems, and the lack of awareness regarding the environmental benefits of natural refrigerants. [93]

Finally, the political commitment to promote the use of hydrocarbons as a cooling agent in all sub-sectors is pivotal in fostering acceptance and implementation of this technology. A comprehensive study on the practical tests conducted revealed that "The results of the R290 leak tests conducted within and outside of a reefer container demonstrated that the risk is frequently overestimated". [94]

4.2.1 Safety standard for flammable refrigerants ISO 20854:2019

The ISO 20854:2019 standard applies to thermal containers equipped with refrigerating systems that use flammable refrigerants. It establishes safety requirements for the design, operation, and maintenance of these systems to ensure their safe use in various transport modes, including ships, rail, road, and intermodal logistics.

The standard provides risk assessment methodologies such as HAZOP (hazard and operability analysis), FMEA (failure mode and effects analysis), and FTA (fault tree analysis) to evaluate potential hazards, ensuring compliance with safety and environmental regulations. It also defines testing procedures, alarm systems, ventilation requirements, and servicing guidelines to mitigate risks associated with flammable refrigerants.

By outlining operational safety practices, ISO 20854:2019 helps manufacturers, shipping companies, and container operators transition to refrigerants with lower environmental impact, aligning with global efforts to phase out high-GWP refrigerants.

91 M.G. Beasley, P.G. Holborn, J.M. Ingram, G.G. Maidment (2018): Cause, consequences and prevention of refrigeration fires in residential dwellings. Fire safety journal, vol 102, pages 66-76.

92 Conrad, Jobst (1995): Greenfreeze: environmental success by accident and strategic action, In: Martin Jänicke, Helmut Weidner (Ed.): Successful environmental policy: a critical evaluation of 24 cases

93 Vuppaladadiyam, A. K., et al. (2022). Progress in the development and use of refrigerants and unintended environmental consequences.

94 Ibid.

In practical applications, this standard is essential for companies involved in refrigerated transport, including shipping lines, logistics providers, and refrigerated container manufacturers.

Compliance with ISO 20854:2019 ensures that flammable refrigerants are managed safely, reducing the risk of fire, explosion, and toxic exposure during operation and maintenance. By implementing safety features like leak detection systems, ventilation mechanisms, and proper servicing protocols, companies can enhance operational reliability, meet regulatory requirements, and improve the sustainability of their cold chain logistics.

Some countries are implementing this standard to comply with industry requirements. In Costa Rica, INTECO, in collaboration with MINAE and GIZ, has translated, revised, and adopted the ISO 20854:2019 standard. While the standard is currently voluntary, it is anticipated that it will become mandatory in the near future. It is probable that other countries will adopt similar measures. In addition, the new standard has been recognised by the IMO. [95]

ISO 20854:2019 was published in October 2019 and aims to minimise the risks associated with the use of flammable refrigerants in such systems. It is particularly relevant for refrigerating systems integrated with or mounted on ISO thermal containers, as outlined in ISO 1496-2. standard's application is to these systems when they are operated in conjunction with the carriage of refrigerated cargo, whether functioning as operating reefers (OR), non-operating reefers (NOR), or when empty for positioning during intermodal transit. However, static land-based continuous operations are excluded from the scope of this standard. [96]

The development of ISO 20854:2019 was prompted by the anticipated impact of global and national regulations on HFCs used in thermal containers. These regulations, influenced by the Kigali Amendment to the Montreal Protocol, aim to address the high GWP of HFCs and phase down their use and availability, particularly for R134a, R404A, and R23 in intermodal transport refrigeration.

The purpose of ISO 20854:2019 is to facilitate the safe use of previously non-acceptable flammable refrigerants in refrigerated thermal containers. It provides container owners and operators with the knowledge and tools to understand and mitigate the risks associated with operating refrigerating equipment using flammable refrigerants. The overarching objective is to ensure that the safety levels of container refrigerating systems using flammable refrigerants are commensurate with those employing non-flammable refrigerants. [97]

Implementing ISO 20854:2019 can be straightforward for shipping lines, logistics providers, and refrigerated container manufacturers by following a structured approach:

95 International Organization for Standardization. (2019). Thermal containers — Safety standard for refrigerating systems using flammable refrigerants — Requirements for design and operation (ISO Standard No. 20854:2019)

96 International Organization for Standardization. (2018). Series 1 freight containers — Specification and testing (ISO Standard No. 1496-2:2018)

97 International Organization for Standardization. (2019). Thermal containers — Safety standard for refrigerating systems using flammable refrigerants — Requirements for design and operation (ISO Standard No. 20854:2019)

1. Assess risks and plan for safety

- Conduct a risk assessment using industry-standard methods like HAZOP, FMEA, or FTA to identify potential hazards with flammable refrigerants.
- Implement ventilation, leak detection, and fire prevention systems to minimise risks.
- Ensure compliance with ISO 5149 safety and environmental requirements for refrigerating systems.

2. Ensure equipment and design compliance

- Verify that all mechanical refrigeration units (MRUs) and thermal containers meet ISO 20854:2019 design and construction standards.
- Use approved materials and safety mechanisms, including automatic leak detection, emergency shut-off devices, and proper refrigerant containment.
- Perform required testing for durability, vibration resistance, and refrigerant charge safety to ensure system reliability.

3. Train staff and establish maintenance protocols

- Educate technicians and operators on safe handling of flammable refrigerants, routine maintenance, and emergency procedures.
- Implement preventive maintenance schedules to reduce the risk of system failures.
- Install alarm systems and monitoring tools to detect leaks early and alert operators to potential hazards.

4. Obtain certification and maintain compliance

- Work with certification bodies to ensure official ISO 20854:2019 compliance.
- Properly label and document refrigerating systems to meet international regulations.
- Establish clear procedures for servicing, disposal, and replacement of refrigerating units at the end of their lifecycle.

By integrating these steps into their operations, companies and operators can ensure safety, efficiency, and regulatory compliance.

This standard is intended to complement ISO 1496-2:2018, but does not aspire to supersede existing standards such as the ISO 5149 series. It employs a risk-based approach to design requirements, with the objective of reducing risks to people, assets, and the environment, albeit not eliminating them entirely. The development of ISO 20854:2019 involved a wide range of stakeholders, including manufacturers of refrigerating systems, refrigerated container box manufacturers, shipping lines, classification societies, equipment owners, and other industry experts. [98]

98 International Organization for Standardization. (2018). Series 1 freight containers — Specification and testing (ISO Standard No. 1496-2:2018)

4.3 Alternative refrigerants for future reefers

As demonstrated in Table 4, the reefer sector is predominantly characterised by the use of HFC refrigerants, which are subject to phase-down provisions outlined in various international agreements. Research and development (R&D) activity continues to assess non-flammable (A1) lower GWP solutions that could replace the dominant R134a and R404A. It is anticipated that R134a will be superseded by the HFC/HFO blend R513A, which has already begun to enter the market. [99] The blend under consideration consists of 56% R1234yf and 44% R134a, which gives this refrigerant excellent drop-in properties. [100] Nevertheless, R513A continues to exhibit a high GWP value of 673. Consequently, the transition may result in the adoption of R1234yf (A2L) by reefers. In addition, this refrigerant possesses favourable drop-in properties in comparison to R513A and R134a systems.

R404A is currently being substituted with R452A, despite the fact that it still has a high GWP value (2292), which is higher even than the GWP value of the currently used refrigerant R134a. [101] Consequently, there is a growing interest in exploring potential alternatives to R404A, such as R454A and R454C (A2L), which offer significantly lower GWP values. However, it should be noted that these alternatives are still in the development stage. They are regarded as transition refrigerants, and it is anticipated that they will not be widely available in the long term. It is notable that both R454A and R454C (A2L) exhibit high GWP values, with R454A in particular having a higher GWP than R134a. These high GWP values would see them phased out in accordance with the schedule of the Kigali Amendment.

However, it must be noted that the aforementioned options may not be regarded as sustainable or environmentally friendly. They all have high GWP and/or transform into TFA as part of their breakdown processes. Consequently, natural refrigerants emerge as the sole viable solution for environmentally sustainable refrigeration processes, particularly in the context of Green Cooling. For the application of reefers, R290 (propane), R744 (CO_2), and ammonia (R717) could be considered.

CO_2 is already present in the market, despite the apparent challenge of the requirement for a transcritical system for this refrigerant to function in the conditions where reefers operate (high ambient temperature). Conversely, there is currently no commercially available product for either propane [102] or ammonia. As part of the Greener Reefers [103] project, a prototype of a reefer with propane will be developed and tested on two shipping lines, with the aim of demonstrating its potential for decreasing indirect and direct CO_2-equivalent emissions.

99 Maersk Container Industry. (2022, September 15). Refrigerants - Maersk Container Industry. Maersk Container Industry -. Retrieved May 3, 2024, from *Refrigerants - Maersk Container Industry* (mcicontainers.com) *https://www.mcicontainers.com/products/refrigerants/*

100 Drop-in solutions for refrigerants are those that require little to no modifications to an existing system when replacing a refrigerant. Propane is rarely classified as a drop-in solution because its use often necessitates changes, such as a different compressor and compressor oil.

101 Trane Technologies' Thermo King to reduce global warming potential of transport refrigeration by nearly fifty percent. (n.d.). Retrieved May 3, 2024, from *Trane Technologies' Thermo King to Reduce Global Warming Potential of Transport Refrigeration by Nearly Fifty Percent | Trane Technologies*

102 A prototype was once developed by MCI which resulted in the development of the ISO standard 20854.

103 Internationale Klimaschutzinitiative (IKI). (n.d.) Greener Reefers in international maritime transport. Retrieved May 3, 2024, from *Greener Reefers in international maritime transport | Internationale Klimaschutzinitiative (IKI) (international-climate-initiative.com)*

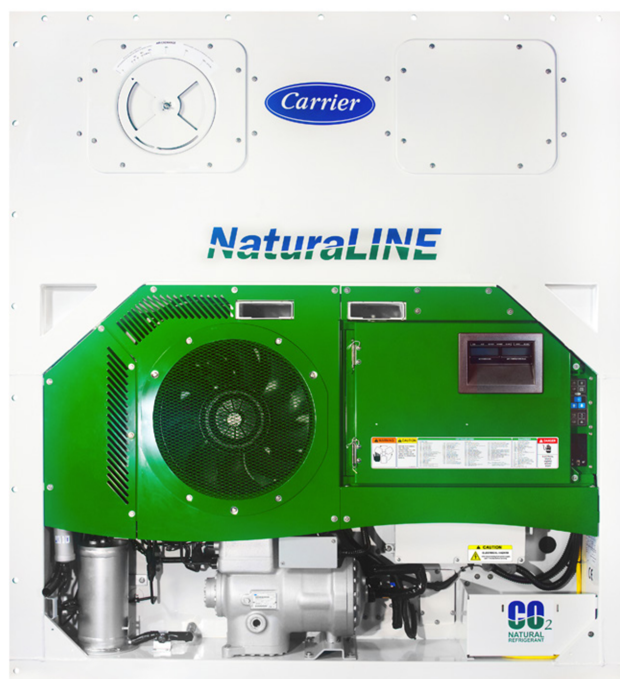
In addition to the aforementioned refrigerants, R23 is present in reefers, albeit in negligible quantities. These substances are used for ultra-low temperature applications, with operating temperatures ranging from -60 to -80°C. In this application, the only alternative under consideration by the industry to date is R473A (only to -70°C), a blend of HFC/HFO/CO_2, with a GWP of 1835. This represents a considerable impact, but is significantly low when considered against the GWP value of 14,600 of R23. This application poses significant challenges in reducing the GWP of refrigerants, underscoring the necessity for further research into alternative solutions. The introduction of R290 as a refrigerant for thermal containers would allow the use of other hydrocarbons for applications requiring ultra-low temperatures.

4.3.1 Carbon dioxide (CO_2/R744)

A marine reefer unit operating on R744 is commercially available, and it is designated as the Carrier NaturaLINE®. However, the uptake of this technology has been limited, with only a few thousand units currently in service.Uptake of this solution is slow due to challenges related to serviceability, including the need for specialised training, the availability of qualified technicians, and the global inventory and accessibility of spare parts. The trans-critical nature of the system necessitates additional training and preparation for most technicians, as it is a specific system not commonly included in national curricula for RAC technicians.

According to Carrier, the NaturaLINE® is as energy efficient as the top-of-the-range Carrier PrimeLINE® units. Consequently, Carrier's CO_2 reefer units are virtually climate neutral when it comes to the refrigerant and therefore offer a sustainable technology solution. Furthermore, Carrier asserts that both units exhibit a 95% recyclability rate, thereby underscoring their commitment to sustainability.

Figure 7. Carrier's NaturaLINE®, refrigeration unit for reefers that operates with R744 [104]



104 NaturaLINE® Container Refrigeration Unit | Carrier Transicold. (n.d.). Carrier. Retrieved May 3, 2024, from *NaturaLINE® Container Refrigeration Unit | Carrier Transicold*

R744 has been field-tested in reefers since 2011. Its non-flammable characteristics render R744 an attractive option; however, its relatively low critical temperature (30.98°C) hinders its applicability and efficiency in conditions with high ambient temperatures. Indeed, there have been instances of efficiency loss at 15°C ambient temperature. [105] R744 has been demonstrated to exhibit excellent thermodynamic properties, with comparable or superior performance in low-temperature applications, such as freezing. However, it has been observed to exhibit a higher energy consumption in medium temperature applications (cooling and chilling) when compared to R404A, a refrigerant that has been identified as one of the most effective in a range of applications. [106, 107]

4.3.2 Propane (R290)

From an environmental and economic sustainability standpoint, propane (R290) and other hydrocarbons (HCs) are recognised as the optimal refrigerant choice. These refrigerants are naturally occurring materials that possess excellent thermodynamic properties and are miscible with synthetic oils. [108]

R290 is already widely used as a refrigerant in various cooling applications due to its high energy efficiency [109] and low GWP. It is commonly found in household refrigerators and freezers, with many leading appliance manufacturers adopting R290 to comply with stringent environmental regulations. [110] In the commercial sector, R290 is extensively used in supermarket display cases, beverage coolers, ice cream freezers, and refrigerated vending machines, offering superior cooling performance while significantly reducing carbon emissions.

Additionally, air conditioning systems, particularly in Africa, Europe, and Asia, have started incorporating R290 due to its thermodynamic efficiency and compliance with global phase-down regulations on HFCs. In the transport sector, R290 is being tested and implemented in bus and train air conditioning systems, as well as in truck refrigeration units, contributing to greener freight and public transport solutions.

A comparison of R290 and R404A, two of the most effective refrigerants in all systems, reveals that R290 exhibits a 15–25% higher efficiency in mid-temperature (0°C) applications and a 10–30% higher efficiency in low-temperature (-20°C) applications. This suggests that propane has the potential to be an optimal long-term solution for reefers and cooling applications in general. The development of cooling solutions employing propane or other hydrocarbons necessitates the establishment of dedicated regulatory frameworks, comprehensive risk assessments, and meticulous maintenance procedures. [111]

A primary concern when contemplating the use of R290, or indeed the design of new equipment incorporating it, pertains to its flammability. According to ISO 817 and ASHRAE Standard 34, hydrocarbon-based refrigerants are classified as A3, indicating a high degree of flammability.

105 Girotto, S., et al. (2004). Commercial refrigeration system using CO_2 as the refrigerant.
106 Ge, Y., & Tassou, S. (2011). Thermodynamic analysis of transcritical CO_2 booster refrigeration systems in supermarket.
107 Gullo, P., et al. (2016). Energy and environmental performance assessment of R744 booster supermarket refrigeration systems operating in warm climates.
108 Vuppaladadiyam, A. K., et al. (2022). Progress in the development and use of refrigerants and unintended environmental consequences.
109 Superradiatorcoils, 10.03.2022: R-290: Pros, Cons, & Comparisons to R22, R404A, & R134a | Super Radiator Coils
110 CK Supply A Guide to R290 Refrigerant | CK Supply
111 Minetto, S., et al. (2023). A review on present and forthcoming opportunities with natural working fluids in transport refrigeration.

However, it should be noted that there are standards for the safe design and use of equipment with these refrigerants, including for reefers. [112]

In relation to the use of propane and reefers, MCI initiated a research project in 2012 with the objective of developing a new generation of refrigerants for use in reefer containers. A detailed thermodynamic study was conducted on the reefer operational profile energy performance, and the most promising refrigerant was identified as R290. In 2013, a risk assessment was conducted, which concluded that the risks associated with the lifecycle of refrigerated containers, encompassing operations on vessels, rail and trucks, and inspections, and service and maintenance activities, are comparably low and acceptably low for the intermodal industry. [113]

Consequently, prototype units equipped with R290 were developed and subjected to rigorous testing. The findings of these practical tests indicated that the risks associated with the operation of refrigeration systems employing R290 as a refrigerant are, in general, overestimated. The evaluation of potentially explosive atmosphere situations and the derivation of appropriate measures were found to be feasible. Furthermore, it was determined that minor and medium-sized leakage incidents are manageable. [114]

However, in 2018, MCI announced that, given the tense market situation, there was insufficient demand and willingness to trial and use technologies based on R290. As a provisional measure, R513A was suggested as a substitute for the existing refrigeration system design, with the subsequent intention of transitioning to R1234yf. [115, 116]

4.3.3 R1234yf

It is evident that a number of applications within the RACHP sector, MAC and transport refrigeration, are contemplating the adoption of R1234yf as a low-GWP alternative to R410A and R134a, two of the most prevalent refrigerants across numerous systems. [117] R1234yf has already been implemented in MAC, with some estimations stating that the refrigerant is present in over 50 million cars. Research has demonstrated that R1234yf is a suitable replacement for R134a in most systems; however, an optimisation process is required to ensure optimal operating conditions. Consequently, it cannot be regarded as a direct replacement, as there are compatibility issues with certain lubricants. [118]

R1234yf is regarded as a prospective substitute for reefers, given its low GWP and low flammability. MCI has been developing this option since the company transitioned away from propane in 2018. As of today, MCI have built more than a 1000 machines factory charged with R1234yf and will continue to built min. 5000 more in the coming weeks, providing evidence that there is in fact a commercial reefer solution with a flammable refrigerant. The interim solution, R513A, contains 56% R1234yf, thereby facilitating a seamless transition in the characteristics of the components employed in the refrigeration system. [119]

112 ISO 20854:2019. (2019). ISO. Retrieved May 3, 2024, from *ISO 20854:2019 - Thermal containers — Safety standard for refrigerating systems using flammable refrigerants — Requirements for design and operation*

113 König, H., et al. (2016). Practical tests with R290 used in reefer container refrigeration leakage testing.

114 Ibid.

115 Maersk is now looking to R1234yf as a future refrigerant for reefer containers. (2018, November 17). Retrieved May 6, 2024, from *Maersk is now looking to R1234yf as a future refrigerant for reefer containers (refindustry.com)*

116 WorldCargo News. (2018, November 12). MCI puts propane on ice > WorldCargo News. WorldCargo News > Leading site for cargo handling industry. Retrieved May 6, 2024, from *MCI puts propane on ice > WorldCargo News*

117 Climate-friendly alternatives to HFCs. (n.d.). Climate Action. Retrieved May 6, 2024, from *Climate-friendly alternatives to HFCs - European Commission (europa.eu)*

118 Pabón, J. J. G., et al. (2020). Applications of refrigerant R1234yf in heating, air conditioning and refrigeration systems: A decade of researches.

119 Maersk Container Industry. (2023, October 17). R1234YF and its relevance for the Reefer industry. Retrieved May 6, 2024, from *R1234yf and its relevance for the reefer industry | LinkedIn*

The Container Owners Association's technical guide on the regulatory issues concerning refrigerant F-gases assesses R1234yf as the most promising technical solution.[120] In this document, R1234yf is referred to as a possible transition solution, with a projected timeframe of two to three years for full market implementation. However, given the current political atmosphere regarding F-gases and PFAS and their possible implementations and new restrictions, the document illustrates that a 20-year transition period would be needed, meaning that more flexible regulations would be required.

A comparison of R1234yf and HFCs with propane reveals no clear superiority of the former. The thermodynamic properties and energy performance of these refrigerants are indistinguishable, including those of other hydrocarbons. Although drop-in characteristics appear to favour HFOs, they are not a readily available solution, as previously mentioned. From an economic perspective, considering supply chains and production costs, they both perform in a similar way, resulting in similar process costs.

However, a shift in balance becomes evident when environmental attributes and flammability are considered.[121, 122] In the discourse surrounding the adoption of R1234yf and other HFOs, there is a tendency to underplay the significance of PFAS and TFA. Additionally, R1234yf reefers also have to fulfil ISO 20854:2019 due to the classification of mildly flammable (A2L). Therefore, similar steps and investments are needed for R1234yf as for R290 in regard to necessary system adaptation, training of employees, and the mitigation of flammable atmospheres and ignition hazards.

Table 5. Overview of refrigerants used in reefers

Refrigerant	Energy-efficiency and Coefficient of performance (COP [123])	Global warming potential (IPCC AR 6) [124]	Costs of refrigerants [125]	End-of-life	Side products/ PFAS [126]	Service and serviceability [127]	Knowledge/ Application [128]	Flammability [129]	Toxicity of side products [130]	Summary
R134a	✓	✗ 1530	✗	✗	✗	✓	✓	✓	✓	✗
R1234yf	✓	✓ 0.5	✗	✗	✗✗	✓	✓	✗	✗	✗✗
R290	✓✓	✓ 0.02	✓	✓	✓	✓	✓	✗	✓	✓✓
R744 (CO_2)	✓	✓ 1	✓	✓	✓	✗	✗	✓	✓	✓

120 Container Owners Association, COA, & COA Reefer Forum Work Group. (2022). REEFER CONTAINERS: REGULATORY ISSUES CONCERNING REFRIGERANT F-GASES.
121 Wang, Y., et al. (2022). Technology trend forecasting and technology opportunity discovery based on text mining: the case of refrigerated container technology.
122 Yadav, S., et al. (2022). A comprehensive study on 21st-century refrigerants - R290 and R1234yf: A review.
123 Future refrigeration technologies with natural refrigerants. Comparison of Energy Efficiency – Safety – Standards & Costs, 2013, Intermodal Europe Hamburg Messe by Holger König
124 IPCC Assessment report 6 *Climate Change 2021: The Physical Science Basis*
125 *Significant price rise for higher GWP refrigerants - Cooling Post* Cooling Post 25.02.2025
126 European Commission 19.10.2023, News Article by Directorate-General for Environment *Health and environmental impacts prompt a call for strict ruling on ubiquitous 'forever chemicals'*
127 Future refrigeration technologies with natural refrigerants.Comparison of Energy Efficiency – Safety – Standards & Costs, 2013, Intermodal Europe Hamburg Messe by Holger König
128 Ibd.
129 UN Environment and ASHRAE Factsheet 1 "Update on New Refrigerants Designations and Safety Classifications" November 2022 *UNEP/ASHRAE Refrigerant Fact Sheet #1—Update on New Refrigerants Designations and Safety Classifications*
130 Michael Feller, Karin Lux, Christian Hohenstein, Andreas Kornath. Structure and Properties of 2,3,3,3-Tetrafluoropropene (HFO-1234yf). Zeitschrift für Naturforschung B, 2014; 69b: 379 DOI: 10.5560/ZNB.2014-4017

5 Mitigation potential

The adoption of R290 refrigerants presents a significant opportunity for emissions reduction in the refrigeration and cooling sector. This chapter explores its potential for scalability and environmental impact.

In order to visualise and comprehend the potential for reduction in CO_2-equivalent emissions through the implementation of Greener Reefers, the project has calculated a theoretical potential decrease in CO_2eq emissions of the whole fleet that could be achieved by introducing a reefer with R290 and enhanced energy efficiency across various scenarios, depending on different circumstances. Given the projected lifespan of 15 years for reefers, a transition to an alternative refrigerant would be a gradual process.

The present fleet has been found to generate annual emissions of 18.76 Mt CO_2, with 96% of these emissions being attributed to R134a, and smaller shares to R404A, R452A, R513A, and R744 (CO_2). This finding is based on the ATO database from WUR, which provided crucial data on reefer fleet size, refrigerant share, and growth rate.

The use of R290 within the domain of mobile air conditioning (MAC) has proven to be a successful endeavour, particularly in the context of trucks, trailers, and public transportation. Mobile HVAC systems for bus and rail services using R290 and R744 are already on the market. Currently, passenger vehicles with a combustion engine mainly use R1234yf in the EU. Fully electric cars are required to use natural refrigerants in their HVAC systems and battery thermal management system. However, a dual trajectory in the adoption of R290 has been anticipated, characterised by a gradual transition of the refrigeration fleet towards the use of this refrigerant.

The primary factor influencing the reduction of emissions is the adherence of the shipping industry and manufacturers to the IMO emission intensity reduction targets, as well as their investment in more energy-efficient technology. Furthermore, the growth rates of the reefer fleet have a direct impact on potential future emissions. The increase in the number of reefers is associated with elevated emissions over time, attributable to leakage and inadequate incentives for maintenance. In order to ascertain the most effective means of reducing emissions, a comprehensive analysis was conducted, encompassing four out of the thirty possible combinations of technology introduction and compliance with existing regulations for the emission development up to 2050 (see Annex for scenario exploration).

The discrepancy between the best possible scenario and the scenario in which the highest levels of accumulated emissions are reached by 2050 is 171.8 Mt CO_2eq. This is equivalent to the emissions of 40 coal-fired power plants in one year. It is important to note that this reduction in emissions is contingent upon two key factors: firstly, the industry must increase the energy efficiency of refrigeration technology; and secondly, R290 must be rapidly introduced to the market. Notably, this analysis does not consider additional measures that could significantly enhance the potential for emission reduction, such as the development of advanced engine technologies in vans or the adoption of hydrogen as a fuel source, among others.

5.1 Approach for mitigation potential calculation

The calculation of total emissions is conducted in accordance with the principles of the TEWI (Total Equivalent Warming Impact) formula. This formula encompasses both direct and indirect emissions, thereby providing a comprehensive assessment of the environmental impact of energy production. [131]

In the context of refrigeration systems, direct emissions are attributable to two primary sources: firstly, leakage of the refrigerants employed during operation, and secondly, their end-of-life disposal. Conversely, indirect emissions exhibit a direct proportionality with energy consumption, given the associated carbon intensity of the fuel or technology employed in the generation of electricity for the operation of reefers.

In order to facilitate this calculation, indirect emissions are defined as emissions occurring during voyage time, and are estimated in CO_2-equivalent function of the carbon intensity of the ship's fuel. The estimation of direct emissions is derived from the leakage of refrigerant during both the operational and decommissioning phases of thermal containers. The application of these equations is conducted for each year from 2018 to 2050, encompassing all operational units and those scheduled for decommissioning. It It is also pertinent to note that certain variables have been designated with the n subscript, given that their values are subject to alteration across the designated years.

131 Carel Industries. (2020, July 7). How to use TEWI to compare the environmental impact of a refrigeration system. Retrieved May 15, 2024, from *How to use TEWI to compare the environmental impact of a refrigeration system (carel.com)*

To quantify these benefits, the TEWI formula is applied, encompassing both direct and indirect emissions:

$$TEWI_n = \text{Direct emissions } (DE_n) + \text{Indirect emissions } (IE_n)$$

$$DE_n = Leakage_n + \text{End of Life}_n$$

$$Leakage_n = GWP_{avg,n}\ [kg_{ref}/kg\_CO_{2\,eq}] \times charge\ [kg_{ref}] \times \text{leakage rate } [\%]$$

$$\text{End of Life}_n = GW_{Pavg,n-15}\ [kg\_{ref}/kgCO_{2\,eq}] \times charge\ [kg_{ref}] \times (1 - \text{Recovery rate} - \text{leakage rate})[\%]$$

$$IE = \text{Base power demand}_n\ [kW] \times \text{Operating hours } [h] \times \text{Carbon intensity}_n\ [kgCO_{2\,eq}/kWh]$$

The mathematical reasoning employed for the calculation of TFA emissions from the decomposition of emitted refrigerants was consistent with the methodology outlined above. The TFA emissions were estimated with the information presented in Table 6. In instances where refrigerant blends are involved, the TFA emission is calculated as a function of blend composition.

Table 6. Calculated TFA emissions for relevant refrigerants in reefers [132, 133, 134]

Refrigerant	TFA equivalence
R134a	0,2
R404A	0,06
R452A	0,3
R513A	0,648
R1234yf	1
R744	0
R290	0

The following fundamental parameters of the calculation were estimated using data from the ATO database, academic literature, and industry comment.

In order to estimate the growth rate, the interannual relative difference in containers built each year was observed, from 2003 to 2023. The mean of the interannual relative difference was found to be close to 8%, which was thus selected as the estimated growth rate up to 2050.

The majority of extant literature and industry commentaries concur that the mean lifespan of a reefer unit is 15 years. [135] It is important to note that this figure is used to estimate the size of the fleet by calculating the sum of all new reefers constructed on an annual basis. The figure from the ATO database was corrected with the IMO's estimation of the reefer fleet size in 2018, which was 2.49 million reefer

132 Behringer, D., et al. (2021). Persistent degradation products of halogenated refrigerants and blowing agents in the environment: type, environmental concentrations, and fate with particular regard to new halogenated substitutes with low global warming potential (ISSN 1862-4804). German Environment Agency.

133 Harrison, J. J., et al. (2021). Fifteen Years of HFC-134a Satellite Observations: Comparisons With SLIMCAT Calculations. Journal of Geophysical Research: Atmospheres 126 (8)

134 Yi, L., et al. (2023). Atmospheric Observation and Emission of HFC-134a in China and Its Four Cities. Environ. Sci. Technol. 57 (12).

135 Lundsgaard, C. A., et al. (2020). Preparatory study on Refrigerated Containers: Task 1 and 2 report. In Preparatory Study on Refrigerated Containers: Task 1 and 2 Report.

containers. [136] This correction was then used to estimate new units back to 15 years, units that would subsequently be considered as decommissioned in the calculation from 2018 onwards.

Assumptions regarding the basic parameters were derived from academic research and feedback from industry experts (see Table 7). The leakage rate was set at 15%, representing a more conservative estimate compared to the 25% used in other studies. The leakage rate considered in this publication is used based on available public literature and due to lack of direct, crosschecked and trustworthy data related to refrigerant losses of systems it is assumed to be a conservative value and also typical to other application from transport refrigeration. The carbon intensity of electricity generated onboard the vessel is estimated at 0.7 kg CO_2/kWh, reflecting typical shipping engines, although a broader analysis yielded a figure of 0.91 kg CO_2/kWh. EU Regulation 2023/1805 poses an additional challenge for shipping lines to limit the GHG intensity of energy used on board of vessels with a emission decrease of up to 80% by 2025. [137] The annual operating hours at sea are assumed to be 4,800, with no distinction between loaded and unloaded conditions. [138]

The refrigerant charge is 5 kg per unit, with a recovery rate of 60% at decommissioning. The base power demand set at 2.5 kW, and the projected lifespan of the system is 15 years. The potential efficiency gains are estimated to range from 7.5% to 20%. [139, 140, 141]

To calculate the emission factor of the fuels used by the vessels, an average of the current used fuels was taken (Table7):

Table 7. Fuel mix used for the mitigation scenario based on GLEC Framework V3.1

Fuel	Share in per cent
Heavy fuel oil	50.42
Light fuel oil	30.25
Marine gas oil/ Marine diesel	12.49
Liquefied natural gas	6.72
Ethane	0.05
Biofuels	0.04
Liquefied petroleum gas	0.02
Methanol	0.00
Ethanol	0.00

136 IMO. (2020). Fourth IMO GHG Study 2020. In *Fourth Greenhouse Gas Study 2020 (imo.org).*

137 EU Regulation 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (*Regulation - 2023/1805 - EN - EUR-Lex*)

138 As industry have matured and stepped into digital era, today it is possible to measure different parameters that are considered in the calculated scenarios. As industry will become more transparent and data will be available, also the impact of emissions can be reconsidered. If we would compute the scenarios based on a specific operation time of one hour, the mitigation potential would have the same impact in terms of perceptual magnitude. Impact of each and every container could be calculated based on real data operation.
The indirect assumed emissions for operation of 4800 hours requires differentiating between power on and power off, which was not clearly stated in the referenced research paper.
We can amend this situation by introducing a variance input parameter, ranging from 2000 to 5000 of yearly operation hours which defines boundaries for calculation of emissions-lower and upper limits.

139 comments by shipping industry confirmed in project workshop 2024.

140 Ozone Secretariat. (2018). The potential to improve the energy efficiency of refrigeration, air-conditioning and heat pumps. *briefingnote-b_potential-to-improve-the-energy-efficiency-of-refrigeration-air-conditioning-and-heat-pumps.pdf (unep.org)*

141 The efficiency differences given by the thermo physical properties of the two refrigerants (R290 and R134a) are negligible. However this in turn implies that in practice the main contributors related to energy efficiency are given by the compressor technology some control strategy, type of fans, etc. Additionally among compressors, there is a high degree of efficiency variability which translates to energy consumption differences from -14% to +25% with R134a and from -10% to 17% with R290.

The emissions calculation considered several regulations and their possible implementation including:

- Compliance with the IMO decarbonisation strategy
- Compliance with the EU F-gas Regulation for reefers
- Compliance with the Kigali Amendment

For each of the scenarios, if the industry were to follow the political regulations, we differentiated between the possibility of no R290 reefer, a slow and a fast adoption of the technology into the market. Additionally, the energy efficiency gains for each possibility for the whole fleet were calculated.

The scenarios with the highest and lowest emissions are as follows:

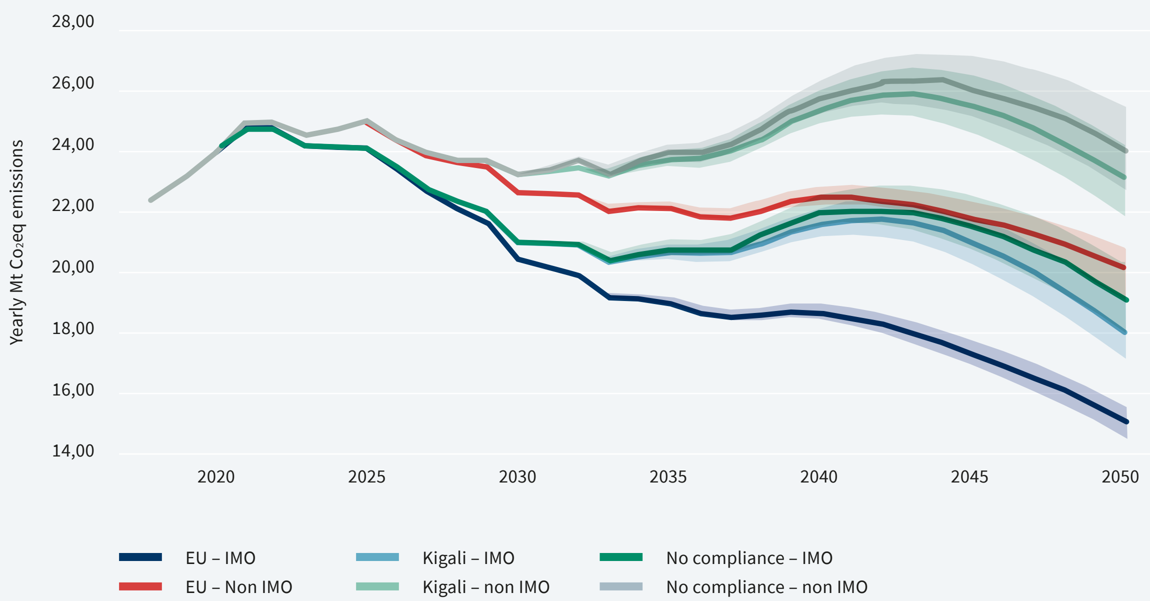
Scenario with the lowest emissions:
The shipping industry complies with the IMO and EU F-gas Regulation, achieves high energy efficiency gains for the whole fleet with mixed refrigerants, and foresees a fast adoption of R290 reefers in 2050 with 50% market share. This scenario indicates 638.92 Mt CO_2eq accumulated by 2050.

Scenario with the highest emissions:
This scenario is characterised by a failure to adhere to any policy regulation, no introduction of R290 reefer technology, and no allowance for energy efficiency gains. The cumulative emissions in this scenario are projected to reach 810.74 Mt CO_2eq by 2050.

The present study posits a middle ground, namely the implementation of the IMO strategy, albeit with setbacks regarding the other parameters. The highest emission scenario aligns with the IMO strategy yet does not incorporate additional policy implementation such as the Kigali Amendment or EU F-gas Regulation. This scenario also assumes no market introduction of R290 and no energy efficiency of the reefer fleet, with cumulative emissions of 747.64 Mt CO_2eq by 2050.

An alternative possible scenario is non-alignment with the IMO strategy. However, this scenario demonstrates significant emission reductions due to the combination of EU F-gas compliance, high energy efficiency improvements, and rapid R290 market adoption. The factors outlined above result in cumulative emissions of 700.3 Mt CO_2eq by 2050, emphasising the pivotal role of efficiency gains and refrigerant transitions.

Figure 8. Yearly emissions of average scenarios and their variability



In all scenarios, an increase in R744 reefers and the introduction of R1234yf into the market was also calculated. Consequently, the future amount of PFAS due to the use of R1234yf as a refrigerant for reefers was also calculated.

5.2 ‘Forever chemicals’ and reefers

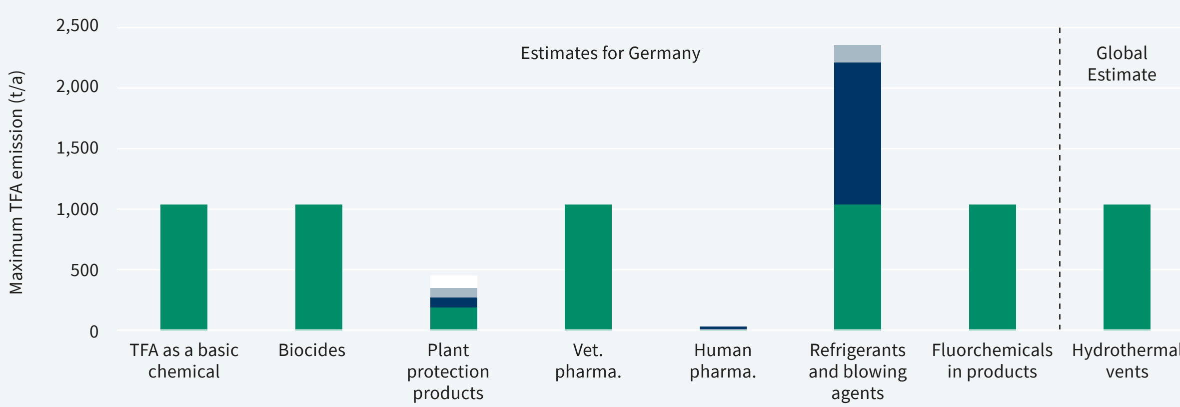
So-called ‘forever chemicals’, specifically PFAS, are chemical by-products of R134a or R1234yf that are released into the atmosphere. R134a is used in 96% of refrigeration equipment on the market today, while R1234yf is used in mobile air conditioning systems.

PFAS, an acronym for per- and polyfluoroalkyl substances, are synthetic chemicals that have been used in various industrial and consumer products since the 1950s. These chemicals are notorious for their resistance to degradation in the environment and their ability to accumulate in the human body.[142] TFA is formed as a degradation product of PFAS and is therefore part of HCFCs and HFCs, and is now identified in HFOs.

In Germany, the primary sources of TFAs are currently identified as refrigerants and propellants employed in mobile air conditioning systems (see Figure 9, dark-blue area). This observation underscores the compatibility of R1234yf, a refrigerant that can also be utilised in refrigeration units, with a high TFA content. However, it is noteworthy that this substance undergoes a complete breakdown when exposed to air, water, or soil.

While natural sources such as hydrothermal vents contribute to global TFA emissions, regional data for Germany and Europe are currently unavailable, leaving only global estimates. The two main sources of TFA are R134a (bottom colour) followed by R1234yf (second colour). The smallest amount is TFA from different sources.

Figure 9. Estimated maximum TFA emissions in tonne/year for relevant group of chemicals

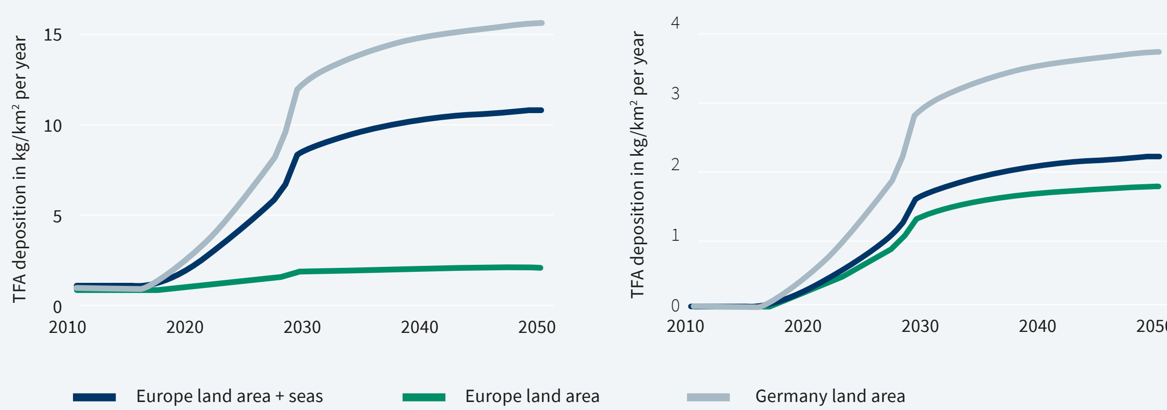


142 Mueller, R., & Schlosser, K. E. (2020). History and Use of Per- and Polyfluoroalkyl Substances (PFAS) found in the Environment. Retrieved June 25, 2024, from *History and Use of Per- and Polyfluoroalkyl Substances (PFAS) found in the Environment (itrcweb.org)*

In the field of refrigeration, there is an increasing focus on environmentally sustainable alternatives to conventional refrigerants. This includes the exploration of natural refrigerants for mobile air conditioning systems. [143]

The German Federal Environment Agency has predicted an increase in the presence of TFA in the atmosphere across Europe by 2050. This projection is attributable to the industrial use of R1234yf in MAC (Figure 10).

Figure 10. Estimated future TFA deposition and TFA deposition rates for Europe due the degradation of exclusively HFO-1234yf [144]



Evidence suggests the existence of other refrigerants, comprising blends of R1234yf or R404A with a 4% market share and R452A with an even more negligible 0.1% market share. In addition to the high-GWP refrigerant R134a, which has a 96% market share, it is also a constituent of TFA to the extent of 20%. This underscores the imperative for the marine industry to expedite the identification of a suitable alternative refrigerant.

143 Behringer, D., et al. (2021). Persistent degradation products of halogenated refrigerants and blowing agents in the environment: type, environmental concentrations, and fate with particular regard to new halogenated substitutes with low global warming potential (ISSN 1862-4804). German Environment Agency.
144 Ibid.

Table 8. Scenario designation for the TFA emissions projection

S1	EU F-gas / No adoption	**S4**	Kigali schedule / No adoption	**S7**	No compliance / No adoption
S2	EU F-gas / R290 Fast adoption	**S5**	Kigali schedule / R290 Fast adoption	**S8**	No compliance / R290 Fast adoption
S3	EU F-gas / R290 Slow adoption	**S6**	Kigali schedule / R290 Slow adoption	**S9**	No compliance / R290 Slow adoption

5.3 Results

The projections demonstrate an increase in TFA emissions across all scenarios, as the market penetration of R1234yf is assumed in the various scenarios. The analysis indicates that the EU F-gas Regulation exerts a substantial influence on the selection of refrigerants and has the potential to result in a broader adoption of R1234yf in refrigeration equipment as a medium-term solution. However, the employment of R1234yf will also lead to a substantial increase in TFA, owing to its status as a refrigerant with a low GWP. This is particularly pertinent if an R290 reefer is not available for market adoption. The most expeditious introduction of R290 reefers would have the most significant impact on reducing TFA without switching or permitting R1234yf.

The phase-out of R134a is predicted to have a beneficial effect on the climate protection efforts of the shipping industry and countries, as has been observed with other high-GWP refrigerants such as R513A. However, with the EU F-gas Regulation now in effect, customers are likely to prefer R744 reefers as a natural alternative with no GWP and no TFA. Nevertheless, due to its higher energy consumption, this technology is not expected to dominate the market in the near future. In the absence of adequate promotion and development of natural refrigerant alternatives such as CO_2 or R290, the sector may find itself compelled to engage in an unwarranted dilemma, characterised by the generation of TFA for the purpose of reducing GHG emissions, a matter of particular concern within the global environmental agenda. The reefer sector is poised to encounter numerous challenges in the years ahead, and the transition to R290 reefers has the potential to address two significant issues: R290 has no GWP and no propensity to form TFA, rendering it a crucial technology to explore in the near future for the purpose of ensuring a sustainable and environmentally friendly future.

6 The path forward: scaling up R290 adoption

The global cooling sector, which encompasses refrigerated shipping containers (reefers), is undergoing a substantial transformation to align with climate mitigation objectives. As part of this transition, propane (R290) is emerging as a promising natural refrigerant due to its low global warming potential (GWP). However, the transition to R290 is not without its challenges, including navigating technical, economic, and regulatory complexities, as well as numerous barriers and the implementation of comprehensive upscaling strategies. This chapter delineates the pivotal dimensions for fostering R290 adoption, with a focus on technical, regulatory, economic, and market-driven aspects.

6.1 Barriers to upscaling

The adoption of R290 in refrigerated containers is constrained by technical challenges, economic considerations, and institutional barriers. The following challenges must be addressed:

- **Technical challenges:** Demonstrating the feasibility of a highly efficient R290 reefer and ensuring its compatibility with existing refrigeration systems and infrastructure remain significant hurdles.
- **Safety concerns:** R290 is flammable, necessitating strict adherence to safety standards and appropriate handling protocols.
- **Market dynamics:** Competing technologies with lower upfront costs may delay adoption without sufficient incentives. Without a positive business case, companies will not invest in R290 systems.
- **Regulatory gaps and policy lag:** Delays in regulatory approval and enforcement slow down market transitions.

6.2 Upscaling strategies for R290 adoption in reefer containers

The successful implementation of R290 at scale necessitates a multifaceted strategy encompassing technological advancements, regulatory frameworks, capacity building, and market engagement. The prototyping and field testing of R290 systems, in conjunction with their integration into advanced energy-efficient designs, is instrumental in overcoming the prevailing technical challenges. Concurrently, the establishment of comprehensive international and national regulatory frameworks, exemplified by those advocated by the IMO, is paramount for the establishment of definitive standards and the promotion of adoption. Capacity-building initiatives, including technician training and stakeholder awareness programmes, ensure safe and effective use. Market development strategies emphasise collaboration with manufacturers and logistics firms to foster innovation and reduce cost barriers. This comprehensive approach emphasises the strategic pathway, delineated as follows, which is required to transform the reefer industry into a cornerstone of sustainable cooling technologies.

- **Technology development and deployment:**
  - Prototyping and field testing for R290 systems (see section 1.3.2 on future reefers with propane)
  - Integration with advanced energy-efficient designs.
- **Regulatory and policy support:**
  - Need for international regulations (e.g., through IMO or other platforms).
  - Role of national policies and government-driven initiatives supporting the fast transition

- **Capacity building:**
  – Training for technicians to handle natural refrigerants safely and effectively.
  – Awareness programmes for stakeholders, including shipping companies and regulatory bodies.
- **Opportunities for financing and building partnerships**
  – Encouraging partnerships between manufacturers and logistics companies for a positive financial turnover and avoiding bad investments in stricter regulated technology

6.2.1 Regulatory and policy support

Global frameworks play a pivotal role in guiding industries towards sustainable practices. The transition to R290 reefer systems represents a significant opportunity for the refrigerated shipping sector to align with global climate goals and nationally determined contributions (NDCs) under the Paris Agreement. However, this shift requires an effective interplay and the support of a robust regulatory and policy framework at both international and national levels to overcome current barriers and incentivise adoption.

For example, the IMO, as the key body governing shipping emissions, is uniquely positioned to accelerate the adoption of low-GWP refrigerants like R290 into its energy efficiency and decarbonisation frameworks. The following coordinated efforts at an international level could create a clear direction for shipping companies, manufacturers, and operators, ensuring alignment with global climate commitments:

– Establishing mandatory sector-specific guidelines for transitioning to low-GWP refrigerants
– Facilitating compliance through incentives such as reduced fees for vessels using greener reefer technologies
– Collaboration with organisations and other international regimes like the Montreal Protocol and Paris Agreement to harmonise global standards

National policies

At the national level, governments must bridge global frameworks with localised implementation to accelerate the adoption of R290 in the reefer sector. This can be achieved through:

1. **Integrating reefer modernisation into cooling action plans:** National cooling strategies can explicitly include the refrigerated shipping sector, highlighting its potential to contribute to climate and energy efficiency targets.
2. **Incentivising adoption:** Fiscal policies such as subsidies, tax benefits, and accelerated depreciation schemes can reduce the financial burden of adopting R290 technologies for stakeholders.
3. **Setting and updating MEPS (minimum energy performance standards):** Regular updates to MEPS can encourage continuous technological innovation and adoption of energy-efficient, R290-compatible systems.
4. **Introducing clear labels and standards:** Energy- and climate-friendly labelling systems can provide the private sector with clear guidance, enabling informed decision making by stakeholders.

The phase-out of HCFCs and the implementation of energy efficiency measures, together with the Kigali Amendment to the Montreal Protocol to phase down HFCs, have significantly advanced global efforts to reduce climate impact from cooling technologies. Countries that have implemented Kigali-compliant policies are already witnessing growing adoption of green refrigerants like R290 across multiple sectors, driven by government support and aligned private sector initiatives. These examples highlight the importance of proactive national policies in creating favourable conditions for technological transitions that promote sustainability and energy efficiency.

6.2.2 Capacity building of crucial stakeholder

Training for technicians

Successful R290 upscaling requires stakeholder capacity building:

Technicians must be equipped with the skills to safely handle and maintain R290 systems in the port as well as on the container ships or the road/ rail. This includes addressing the aforementioned flammability risks, and ensuring proper installation and maintenance protocols. Widespread adoption of R290 requires specialised certified training to ensure safety and efficiency in handling this flammable refrigerant. Key components for this target group must include:

- Establishing certified training programmes that focus on installation, maintenance, and repair of R290 systems in the shipping sector.
- Partnering with vocational schools, industry associations, and port authorities to expand the workforce skilled in handling natural-refrigerant reefer systems
- Providing online and hands-on modules tailored to regional contexts, leveraging international best practices.
- Incentive schemes for service personnel to aspire to the certification

Awareness programmes

Stakeholder awareness is critical to build confidence and demand for R290 technologies: Programmes targeting shipping companies, policymakers, and logistics operators can clarify the benefits and safety protocols for R290 systems. Awareness campaigns can dispel misconceptions about cost and performance barriers.

- Shipping companies: Demonstrate long-term cost and environmental benefits through pilot results and case studies.
- Regulators: Highlight the alignment of R290 adoption with national and global climate goals.
- Public campaigns: Showcase successful examples to foster acceptance and counter misconceptions about safety.

6.2.3 Opportunities for financing and building partnerships

Carbon markets

The reefer sector can leverage Article 6 mechanisms to trade emissions reductions achieved through R290 adoption. For example:

- Establishing methodologies to quantify emissions saved per container.
- Engaging with buyers in voluntary or compliance markets to finance transitions.

International initiatives

Programmes like the International Climate Initiative (IKI) and the Green Climate Fund, IMO, World Bank or others offer funding for initiatives that tackle climate change and offer support for countries of the Global South to adapt and implement mitigation action. These initiatives could:

- Co-finance pilot projects to demonstrate the feasibility of R290 systems.
- Provide grants for capacity-building programmes and stakeholder engagement.
- Provide grants for building up an international and national regulatory framework and support its enforcement

Public–private partnerships

Innovative partnerships and strategic partnerships can mobilise resources and share risks:

- Collaborations between governments, technology providers, and logistics firms to co-invest in infrastructure upgrades.
- Business models like lease-to-own systems or cooling, reducing upfront costs for adopters.
- Partnering with manufacturers to integrate R290 into production lines and innovate safety features.
- Engaging logistics companies to co-finance pilot projects and share operational insights.
- Developing industry consortia to collectively address shared challenges like supply chain constraints.

7 Conclusions

The global shipping industry is at a critical crossroads, facing mounting pressure to decarbonise while navigating the complexities of an expanding market. The urgency to act has never been greater – the choice of refrigerants will fundamentally determine the sustainability of refrigerated maritime transport. As this white paper underscores, refrigerant emissions are not a minor concern but a central issue in the battle to mitigate climate change. The environmental toll of refrigerant leaks – both direct and indirect – is substantial, making the swift transition to ultra-low-GWP and natural refrigerants non-negotiable for the future of the sector.

One of the most pressing challenges the industry faces is the TFA–CO_2 dilemma. Many widely used synthetic refrigerants, including HFCs and HFOs, break down into trifluoroacetic acid (TFA), a toxic, persistent substance that poses serious health and environmental risks. Reducing greenhouse gas emissions without considering the impact of TFA could inadvertently worsen environmental damage. Natural refrigerants like propane (R290) and carbon dioxide (R744) offer an immediate and effective solution, eliminating this risk while aligning with international climate goals and regulatory frameworks. The higher energy consumption of R744 reefers, however, poses another challenge for container manufacturers and shipping lines, and adjustments are needed to decrease overall emissions by maritime freight. These alternatives not only significantly reduce environmental impact but also offer a clear path towards compliance with global climate targets.

This white paper highlights the urgent need to adopt natural refrigerants like R290 and R744. These options provide a lower GWP and align with critical international regulations such as the Kigali Amendment and the EU F-gas Regulation. The potential for emission reductions is profound, with scenario analyses predicting significant CO_2-equivalent savings by 2050. However, to achieve these reductions, national governments and international bodies like the IMO must urgently implement policies that fast-track the transition to Greener Reefers.

The need to enhance sustainability in maritime refrigeration extends beyond simply choosing the right refrigerant. Improvements in energy efficiency, maintenance practices, and operational standards are equally critical to minimise emissions. Technologies that improve temperature control, reduce fluctuations, and optimise energy use – such as advanced insulation, cutting-edge control systems, and temperature lift management – are vital. These improvements will not only reduce indirect emissions but also extend the lifespan of reefers, decreasing their overall environmental footprint. Steps that the shipping industry could implement include:

Technology development and deployment:
- Prototyping and field testing for R290 systems
- Integrating with advanced energy-efficient designs

Regulatory and policy support:
- Creating international rules, such as through the IMO, to guide the shift to greener technologies
- Strengthening national policies and government programmes to speed up the transition

Capacity building:

- Training technicians to safely use natural refrigerants
- Educating key stakeholders, such as shipping companies and regulators, on the benefits of sustainable solutions

Opportunities for financing and building partnerships

- Encouraging partnerships between manufacturers and logistics companies to share knowledge and drive innovation
- An agreement between shipping lines, manufacturers and customers to avoid bad investments and identify synergies.

Beyond refrigerant choice, the industry must embrace further mitigation measures. Innovations in reefer design, such as energy-efficient components and improved insulation, are key to reducing emissions. By optimising temperature control, reducing temperature increases, and refining maintenance practices, the sector can significantly decrease energy consumption and emissions. When combined with natural refrigerants, these measures present a comprehensive, sustainable solution for maritime refrigeration.

To address the industry's challenges effectively, global collaboration is essential. Establishing international standards, sharing data, and fostering cross-border initiatives will help create a cohesive strategy for reducing emissions and improving sustainability. By working together, stakeholders can ensure a smooth and effective transition to greener technologies. National governments and international organisations such as the IMO need to adopt policies and regulations that support the fast transition of the maritime refrigeration sector to Greener Reefers.

This transformation demands urgent and unified action across the industry. The Greener Reefers Transition Alliance, led by GIZ and Kuehne Climate Center, plays a pivotal role in accelerating the adoption of sustainable technologies. By facilitating collaboration, sharing knowledge, and tackling regulatory and technical challenges, the Alliance is driving forward a cohesive strategy for change.

The time to act is now. Manufacturers investing in synthetic refrigerants for cost reasons today will soon face the reality of needing to switch to more sustainable options. The shift towards natural refrigerants like R290 is inevitable and offers a forward-thinking solution. Although hurdles like flammability and regulatory alignment remain, successful prototype testing and risk assessments demonstrate that these challenges are surmountable. Stakeholders must prioritise investments in R290-based technologies, develop robust safety standards, and focus on capacity building through training and education.

In conclusion, the transition to Greener Reefers is not just a technological challenge; it's a critical opportunity to redefine the future of maritime transport. By prioritising natural refrigerants, improving operational efficiency, and supporting global collaboration, the shipping industry can meet its climate goals and avoid the pitfalls of synthetic refrigerants. The time for action is now – the path forward is a sustainable, climate-friendly future for refrigerated shipping.

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Annexes

8 Detailed emission mitigation scenario

In order to visualise and comprehend the potential for reduction in CO_2-equivalent emissions through the implementation of a Greener Reefer, the project has calculated a theoretical potential decrease in CO_2eq emissions p, that could be achieved by using a reefer with R290 and enhanced energy efficiency across various scenarios. The foundation for this estimation was laid by the ATO database from Wageningen University, which provided crucial data on reefer fleet size, refrigerant share, and growth rate. [146]

The calculation of total emissions is conducted in accordance with the principles of the TEWI (Total Equivalent Warming Impact) formula. This formula encompasses both direct and indirect emissions, thereby providing a comprehensive assessment of the environmental impact of energy production. [147]

In the context of refrigeration systems, direct emissions are attributable to two primary sources: firstly, leakage of the refrigerants employed during operation, and secondly, their end-of-life disposal. Indirect emissions exhibit a direct proportionality with energy consumption, given the associated carbon intensity of the fuel or technology employed in the generation of electricity for the operation of reefers.

In order to facilitate this calculation, indirect emissions are defined as emissions occurring during voyage time and are estimated in CO_2-equivalent function of the carbon intensity of the ship's fuel. The estimation of direct emissions is derived from the leakage of refrigerant during both operational and decommissioning phases of thermal containers. These equations were applied for every year n from 2018 to 2050 for all units in operation, and for the units expected to be decommissioned. It is also pertinent to note that certain variables have been designated with the n subscript, given that their values are subject to alteration across the designated years.

$$TEWI_n = \text{Direct emissions } (DE_n) + \text{Indirect emissions } (IE_n)$$

$$DE_n = Leakage_n + \text{End of Life}_n$$

$$Leakage_n = GWP_{avg,n}\ [kg_{ref}/kg\_CO_{2\,eq}] \times \text{charge } [kg_{ref}] \times \text{leakage rate } [\%]$$

$$\text{End of Life}_n = GWP_{avg,n-15}\ [kg\_{ref}/kgCO_{2\,eq}] \times \text{charge } [kg_{ref}] \times (1 - \text{Recovery rate} - \text{leakage rate})[\%]$$

$$IE = \text{Base power demand}_n\ [kW] \times \text{Operating hours } [h] \times \text{Carbon intensity}_n\ [kgCO_{2\,eq}/kWh]$$

146 Wageningen Food & Biobased Research, ATO Certification of reefer containers, Wageningen University & Research, Retrieved May 2, 2024, from *Reefertransport - Home*

147 Carel Industries. (2020, July 7). How to use TEWI to compare the environmental impact of a refrigeration system. Retrieved May 15, 2024, from *How to use TEWI to compare the environmental impact of a refrigeration system (carel.com)*

The mathematical reasoning employed for the calculation of trifluoroacetic acid (TFA) emissions from the decomposition of emitted refrigerants was consistent with the methodology outlined above. The TFA emissions were estimated with the information presented in Table 6. In instances where refrigerant blends are involved, the TFA emission is calculated as a function of blend composition.

Table 9. Calculated TFA emissions for relevant refrigerants in reefers [148, 149, 150]

Refrigerant	TFA equivalence
R134a	0,2
R404A	0,06
R452A	0,3
R513A	0,648
R1234yf	1
R744	0
R290	0

The following fundamental parameters of the calculation were estimated using data from the ATO database, academic literature, and industry comment.

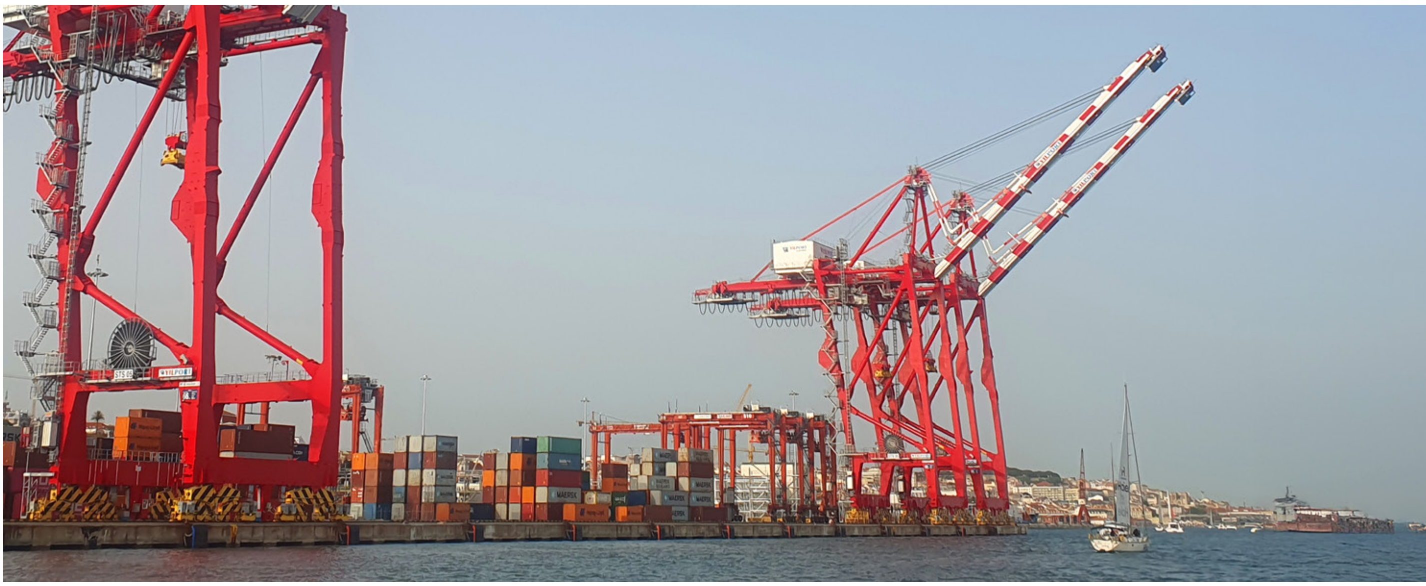
In order to estimate the growth rate, the interannual relative difference in containers built each year was observed, from 2003 to 2023. The mean of the interannual relative difference was found to be close to 8%, which was thus selected as the estimated growth rate to 2050.

The majority of extant literature and industry commentaries concur that the mean lifespan of a reefer unit is 15 years. [151] It is important to note that this figure is used to estimate the size of the fleet by calculating the sum of all new reefers constructed on an annual basis. The figure from the ATO database was corrected with the International Maritime Organization's (IMO) estimation of the reefer fleet size in 2018, which was 2.49 million reefer containers. [152] This correction was then used to estimate new units back to 15 years, units that would subsequently be considered as decommissioned in the calculation from 2018 onwards.

The ATO database proved to be a valuable source of information, particularly the records of refrigerant share per year. These records were specific and provided a foundation upon which elaborate possible future schedules of refrigerant use could be developed.

Assumptions regarding the basic parameters were derived from academic research and feedback from industry experts (see Table 5). The leakage rate was set at 15%, representing a more conservative estimate compared to the 25% used in other studies. The carbon intensity of electricity generated onboard the vessel is estimated at 0.7 kg CO_2/kWh, reflecting typical shipping engines, although a broader analysis yielded a figure of 0.91 kg CO_2/kWh. The annual operating hours at sea are assumed to be 4,800 for this emission calculation, although this can be lowered to 3,840 operating hours depending on the operator.

148 Behringer, D., et al. (2021). Persistent degradation products of halogenated refrigerants and blowing agents in the environment: type, environmental concentrations, and fate with particular regard to new halogenated substitutes with low global warming potential (ISSN 1862-4804). German Environment Agency.
149 Harrison, J. J., et al. (2021). Fifteen Years of HFC-134a Satellite Observations: Comparisons With SLIMCAT Calculations. Journal of Geophysical Research: Atmospheres 126 (8)
150 Yi, L., et al. (2023). Atmospheric Observation and Emission of HFC-134a in China and Its Four Cities. Environ. Sci. Technol. 57 (12).
151 Lundsgaard, C. A., et al. (2020). Preparatory study on Refrigerated Containers: Task 1 and 2 report. In Preparatory Study on Refrigerated Containers: Task 1 and 2 Report.
152 IMO. (2020). Fourth IMO GHG Study 2020. In *Fourth Greenhouse Gas Study 2020 (imo.org).*



A view of the harbour Lisbon, Portugal © GIZ / Kirsten Orschulok

The refrigerant charge is 5 kg per unit, with a recovery rate of 60% at decommission. The base power demand is 2.5 kW, and the system lifespan is projected at 15 years. Potential efficiency gains are estimated to range from 7.5% to 20%.

The leakage rate considered in this publication is used based on available public literature and due to lack of direct, crosschecked and trustworthy data related to refrigerant losses of systems it is assumed to be a conservative value and also typical to other application from transport refrigeration. As industry have matured and stepped into digital era, today it is possible to measure different parameters that are considered in the calculated scenarios. As industry will become more transparent and data will be available, also the impact of emissions can be reconsidered. If we would compute the scenarios based on a specific operation time of one hour, the mitigation potential would have the same impact in terms of perceptual magnitude. Impact of each and every container could be calculated based on real data operation.

The indirect assumed emissions for operation of 4,800 hours requires differentiating between power on and power off, which was not clearly stated in the referenced research paper.

We can amend this situation by introducing a variance input parameter, ranging from 2,000 to 5,000 of yearly operation hours which defines boundaries for calculation of emissions-lower and upper limits. It was up to the modeler choice to use an R290 system with additional features to enhance energy performance. The focus of the study is to propose efficient energy system, especially with R290. Of course other refrigerants could benefit from various enhancements.

8 Detailed emission mitigation scenario

Table 10. Description of the main assumptions

Name	Description	Value	Unit
Refrigerant charge	Usual value of refrigerant for the operation of a reefer unit.	5 [153, 154]	kg
Leakage rate	Leaked refrigerant in a year from a reefer unit.	15 [155, 156]	%
Recovery rate	Refrigerant recovered at decommission. Very influenced by the formality of the service sector. A conservative figure is considered.	60 [157, 158, 159, 160]	%
Base power demand	Base operating power demand of the reefer unit.	2.5 [161, 162, 163, 164, 165]	kW
Hours of operation at sea	Estimate of laden voyages in a year.	4,800 [166]	hours
Carbon intensity	Carbon intensity of the ship's energy, used to provide electricity to the reefer.	0.7 [167, 168, 169]	$kgCO_2eq$ / kWh
Life span	Estimated life span of a reefer container.	15 [170, 171]	Years
Efficiency gains	In the scenarios, efficiency gains are proposed. A plausible range of improvement is proposed by considering techniques or methods that could apply to all reefers (insulation and temperature control), and some exclusively for R290.	7.5–20 [172, 173]	%

153 Ibid.
154 Zloczowska, E. (2018). ASSESSMENT OF THE ENVIRONMENTAL IMPACT OF REFRIGERATED CONTAINERS TRANSPORTED BY SEA. International Multidisciplinary Scientific GeoConference SGEM
155 Ibid.
156 *EPA. (2017). EPA'S VINTAGING MODEL OF ODS SUBSTITUTES. EPA'S VINTAGING* MODEL OF ODS SUBSTITUTES: A Summary of the 2017 Peer Review
157 Behringer, D., Martens, K., & Gschrey, B. (2023). Recovery of Fluorinated Refrigerants from Decommissioned RAC Equipment in Germany—Implications for National Emission Reporting under the UNFCCC. Atmosphere, 15(1), 35.
158 Godwin, D. S., & Ferenchiak, R. (2020). The implications of residential air conditioning refrigerant choice on future hydrofluorocarbon consumption in the United States. Journal of Integrative Environmental Sciences, 17(3), 29–44.
159 De Aguiar Peixoto, R., et al. (2005). IPCC/TEAP Special Report: Safeguarding the ozone layer and the global climate system. In M. Kaibara & A. D. Pasek (Eds.), IPCC/TEAP Special Report: Safeguarding the Ozone Layer and the Global Climate System (p. 271). *SROC Chapter 5 (ipcc.ch)*
160 Duan, H., Miller, et al. (2018). Chilling Prospect: Climate change effects of mismanaged refrigerants in China. Environmental Science & Technology, 52(11), 6350–6356.
161 Budiyanto, M. A., & Shinoda, T. (2018). The effect of solar radiation on the energy consumption of refrigerated container. Case Studies in Thermal Engineering, 12, 687–695.
162 Van Duin, R., et al. (2019). Factors causing peak energy consumption of reefers at container terminals. Journal of Shipping and Trade, 4(1).
163 Pei, R., Xie, J., Zhang, H., Sun, K., Wu, Z., & Zhou, S. (2021). Robust Multi-Layer energy management and control methodologies for Reefer Container park in port terminal. Energies, 14(15), 4456.
164 Syam, M. M., et al. (2022). Mini containers to improve the cold chain energy efficiency and carbon footprint. Climate, 10(5), 76.
165 Kim, K., et al. (2018). Analysis of Battery/Generator Hybrid Container ship for CO_2 reduction. IEEE Access, 6, 14537–14543.
166 Zloczowska, E. (2018). ASSESSMENT OF THE ENVIRONMENTAL IMPACT OF REFRIGERATED CONTAINERS TRANSPORTED BY SEA. International Multidisciplinary Scientific GeoConference SGEM
167 Ibid.
168 Acciaro, M., T. Vanelslander, C. Sys, C. Ferrari, A. Roumboutsos, G. Giuliano, J.S.L. Lam, and S. Kapros. 2014. Environmental sustainability in seaports: A framework for successful innovation. *Maritime Policy & Management* 41 (5): 480–500.
169 Nguyen, K. T., et al. (2022). CO_2 emissions in a global container shipping network and policy implications. Maritime Economics & Logistics, 26, 151-167.
170 Lundsgaard, C. A., et al. (2020). Preparatory study on Refrigerated Containers: Task 1 and 2 report. In Preparatory Study on Refrigerated Containers: Task 1 and 2 Report.
171 Comments from industry partners.
172 Ozone Secretariat. (2018). The potential to improve the energy efficiency of refrigeration, air-conditioning and heat pumps. *briefingnote-b_potential-to-improve-the-energy-efficiency-of-refrigeration-air-conditioning-and-heat-pumps.pdf (unep.org)*
173 Minetto, S., et al. (2023). A review on present and forthcoming opportunities with natural working fluids in transport refrigeration.

8.1 Scenario exploration

A review of the literature on the subject was conducted for the purpose of this document, with a particular focus on the mitigation potential. This review revealed a paucity of studies conducted in the refrigeration and air conditioning (RAC) sector in general. While there exist notable examples of household split AC unit development, [174] such examples are less prevalent in the refrigeration sector, and to the best of the authors' knowledge, none are extant. Consequently, there is an absence of established or recognised scenarios for modelling these applications and equipment. Therefore, for the purpose of this particular mitigation potential, certain variables were selected for the purpose of testing and exploring different possible scenarios.

The majority of the key assumptions are considered to be parameters of the model. Consequently, no enhancement in the service sector is contemplated within the present exercise, leading to a constant leakage rate, recovery rate, refrigerant charge, and lifetime over the course of all years. Furthermore, it is hypothesised that the number of operating days will remain constant, thereby negating any enhancement in transport logistics, a salient issue given the propensity of reefers to travel repeatedly unloaded.

The exploration of scenarios by combining variables resulted in 30 possible scenarios. It is important to note that the variables in question are subject to continuous change on an annual basis, with the objective of achieving predetermined targets for the relevant years as stipulated in the schedule. This process of iteration between the specified years is a fundamental aspect of the methodology.

8.2 Adoption scenarios for R290 refrigerants

The Greener Reefer under consideration for its mitigation potential employs R290 as a refrigerant. The initial scenario posits a scenario in which the Greener Reefer is not adopted, while two alternative scenarios explore different rates of uptake: slow and fast adoption. In these scenarios, R290 reefer units are integrated into the total fleet as a percentage of new refrigerated units each year. The use of R290 has been demonstrated to result in a reduction of the average global warming potential (GWP) of the fleet, consequently leading to a decrease in direct emissions, including TFA.

Table 11. Schedule of adoption of R290, in percentage of new units

Year	No R290	Slow R290	Fast R290
2025	0.00	0.00	0.00
2030	0.00	5.00	10.00
2040	0.00	10.00	20.00
2050	0.00	20.00	50.00

8.2.1 Energy efficiency gains

The subsequent level of combinations pertains to the enhancement of reefers' efficiency, a measure that will result in a reduction of energy consumption and, consequently, indirect emissions. Numerous strategies have been identified as potential avenues for

174 Purohit, P., et al. (2022). The key role of propane in a sustainable cooling sector.

enhancing efficiency, including the implementation of enhanced insulation measures, the development of inverters and compressors, the optimisation of temperature control systems, the integration of monitoring mechanisms, the design of commodity-specific programmes, the streamlining of port logistics processes, and the strategic placement of reefers on ships in accordance with the vessel's trajectory and the sun's position. [175]

The potential for enhanced efficiency in these methodologies has been theorised to reach up to 35%. [176] With regard to R290, a number of studies have established its noteworthy thermodynamic properties for both chilled and frozen applications, suggesting a potential efficiency enhancement of 15–30% in comparison with R404A. [177]

It is proposed that a conservative estimation be made of the base improvement for all reefers, and that a moderate and high gain for R290 reefers be considered (see Table 7).

Table 12. Schedule of energy efficiency gains, in percentage of decreased energy consumption

Year	Base efficiency	R290 moderate efficiency gains	R290 high efficiency gains
2025	0.00	0.00	0.00
2030	2.00	5.00	10.00
2040	5.00	7.50	15.00
2050	7.50	10.00	20.00

8.2.2 Refrigerant use schedules

The pivotal question that this model seeks to address is the projected trajectory of refrigerant use in the future. Secondly, it is crucial to ascertain how these changes will affect direct emissions.

To address these challenges, three phase-down schedules and one phase-out schedule for refrigerants were considered. The three phase-down schedules correspond to the Kigali Amendment, the EU F-gas Regulation and a scenario where no specific schedule is followed. The phase-out scenario is applied in the event that the IMO emission intensity reduction targets are not met. The impact of these schedules on the production of new units is expected to be significant, while existing units are projected to continue operating until the end of their designated lifecycle. As demonstrated in Table 3, the current refrigerant composition of reefers is predominantly R134a, which complicates the adherence to any predetermined timeline.

Table 13. Average share of refrigerants from new reefers in the past five years (2019–2023) and their GWP100 years value [178]

R134a	R404A	R452A	R513A	R744
97.80%	1.68%	0.18%	0.03%	0.31%
1,530	4,728	2,292	673	1

175 Ozone Secretariat. (2018). The potential to improve the energy efficiency of refrigeration, air-conditioning and heat pumps. *briefingnote-b_potential-to-improve-the-energy-efficiency-of-refrigeration-air-conditioning-and-heat-pumps.pdf (unep.org)*
176 Ibid.
177 Ibid.
178 Wageningen Food & Biobased Research, ATO Certification of reefer containers, Wageningen University & Research, accessed 15 February 2024, *Reefertransport - Home.*

The most ambitious timetable is that which has been proposed by the latest EU F-gas Regulation, the implementation of which was scheduled for 11 March 2024. [179]

The compatibility of refrigeration equipment with the equipment described in Annex IV remains to be clarified. Moreover, the current proportion of refrigerants indicates that meeting the stipulated deadline will be a considerable challenge. For the majority of applications, the 2030 deadline stipulates a prohibition on all equipment with a GWP above 150 or 750, depending on the category applicable for reefers. Acknowledging the challenge of meeting this deadline, an alternative timeline with a certain degree of compromise has been proposed. It is assumed that refrigeration equipment will also be covered by this regulation, requiring the industry to phase out F-gases accordingly.

Table 14. Schedule inspired by the EU F-gas regulation, share of refrigerant use in new reefers without R290 in percent

Year	R134a	R404A	R452A	R513A	R744	R1234yf
2025	95	1	1	1	1	1
2030	15	0	10	20	15	40
2040	0	0	5	10	20	60
2050	0	0	0	0	25	75

The most pertinent global agreement pertaining to the use of refrigerants is the Kigali Amendment to the Montreal Protocol. [180] The following table provides a comprehensive overview of the production, consumption, exports and imports of refrigerants. It delineates the calculation method to establish a baseline and the percentage reduction steps according to the baseline. The establishment of the baseline for new refrigeration equipment was facilitated by leveraging historical data from the ATO database. It is imperative to note that the stipulated schedule is exclusively applicable to new refrigeration equipment.

Table 15. Schedule inspired by the Kigali Amendment, share of refrigerant use in new reefers in percent

Year	R134a	R404A	R452A	R513A	R744	R1234yf
2028	90.33	1.67	3.00	5.00	0.00	0.00
2032	81.29	1.50	2.70	4.5	2.00	8.00
2037	72.26	1.50	2.40	4.00	4.00	16.00
2042	63.23	1.17	2.10	3.50	6.00	24.00
2047	13.55	0.25	0.45	0.75	17.00	68.00
2050	7.00	0.00	0.00	0.00	20.00	73.00

179 REGULATION (EU) 2024/573 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 7 February 2024 on Fluorinated Greenhouse Gases, Amending Directive (EU) 2019/1937 and Repealing Regulation (EU) No 517/2014. (2024, February). *https://eur-lex.europa.eu/eli/reg/2024/573/oj*

180 OzonAction & UNEP. (2016). The Kigali Amendment to the Montreal Protocol: HFC phase-down. In OZONACTION FACT SHEET. Retrieved June 12, 2024, from unep-fact-sheet-kigali-amendment-to-mp.pdf (3m.com)

Finally, a worst-case scenario was formulated. This schedule is simply non-compliance with the Kigali schedule.

Table 16. Non-compliance schedule, share of refrigerant use in new reefers in percent

Year	R134a	R404A	R452A	R513A	R744	R1234yf
2025	95.00	1.00	3.00	1.00	0.00	0.00
2030	90.00	1.00	4.00	5.00	0.00	0.00
2040	75.00	1.00	2.00	10.00	2.40	9.60
2050	25.00	0.00	0.00	10.00	13.00	52.00

It is imperative to acknowledge that these schedules are modelled in conjunction with the introduction of R290 (see section 6.1.1). The share of R290 is incorporated by decreasing the shares of all other refrigerants in a proportional manner. The following equation is applicable to each refrigerant in the context of R290 adoption:

$$\begin{aligned}\textit{Share of refrigerant}\\ &= \textit{Schedule's original share}\\ &\times (1 - \textit{Share of R290 adoption})\end{aligned}$$

The incorporation of R290 results in alterations to the aggregate share of novel refrigerants within each schedule across diverse scenarios. For instance, in Table 17, the impact of the Kigali Amendment and the accelerated adoption of R290 on the composition of the schedules is demonstrated.

Table 17. Schedule inspired by the Kigali Amendment, share of refrigerant use in new reefers, including fast adoption of R290 in percent

Year	R134a	R404A	R452A	R513A	R744	R1234yf	R290
2025	96.65	1.35	0.75	1.25	0.00	0.00	0.00
2030	77.23	1.43	2.57	4.28	0.90	3.60	10.00
2040	53.48	0.99	1.78	2.96	4.16	16.64	20.00
2050	3.50	0.00	0.00	10.00	10.00	36.50	50.00

8.2.3 IMO emission intensity reduction goals

Finally, the final level of scenario exploration is concerned with the question of whether or not the sector meets the IMO emission intensity reduction targets. The proposed targets represent a preliminary iteration and, as such, are excessively broad for the shipping industry in its entirety. The distribution of emission reductions across all potential mitigation measures remains ambiguous.

For the purposes of this calculation, the targets include a reduction in the carbon intensity of the electricity consumed by reefer containers on board. The scenario analysis considers two possible outcomes: one where the reduction in carbon intensity aligns with the proposed targets, and another where the reduction falls short of the targets set.

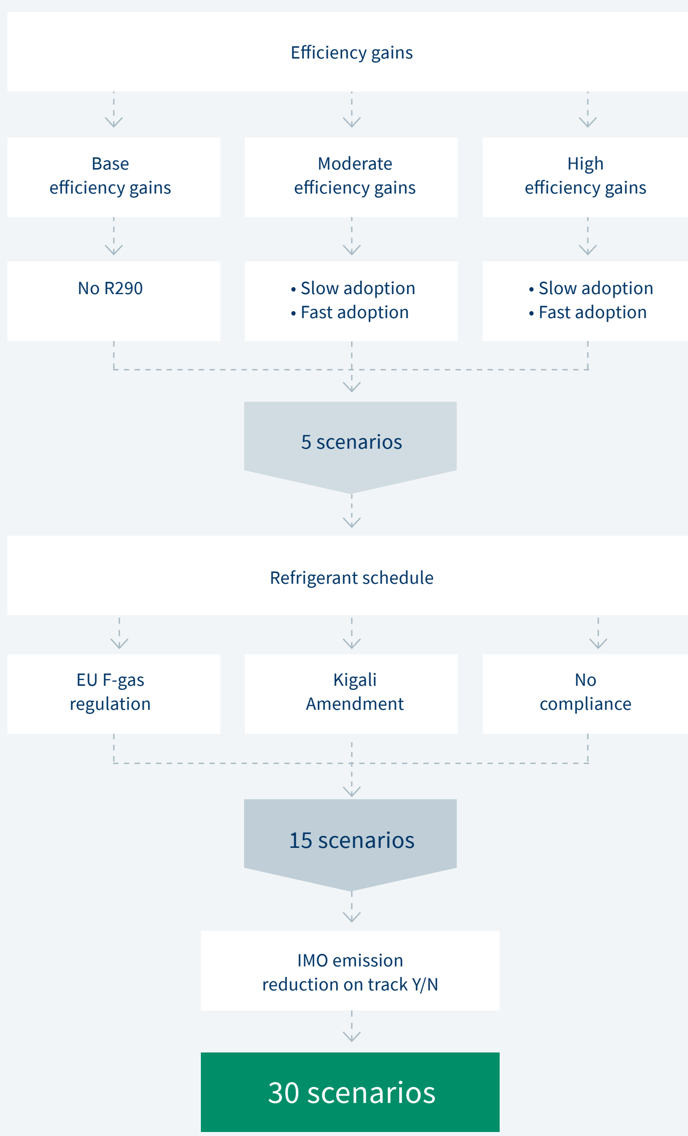
Table 18. Schedule for the reduction of carbon intensity according to IMO's reduction goals in percent

Year	IMO goals on track	IMO goals not on track
2030	40.00	30.00
2050	70.00	60.00

8 Detailed emission mitigation scenario

The following diagram (Figure 11) illustrates the combination process that rendered all 30 scenarios explored.

Figure 11. Illustration of the scenario exploration



8.3 Results

8.3.1. Carbon emissions

The analysis of abatement potential indicates that the IMO emission intensity reduction targets have the greatest impact on reefer energy consumption. Consequently, the identification of scenarios with the lowest and highest emissions was undertaken under this assumption. Initially, the scenarios with the best emission reduction potential and the scenarios with the highest emissions were identified. It is noted that all scenarios include the current refrigerant mix in the fleet, as mentioned in the preceding chapter.

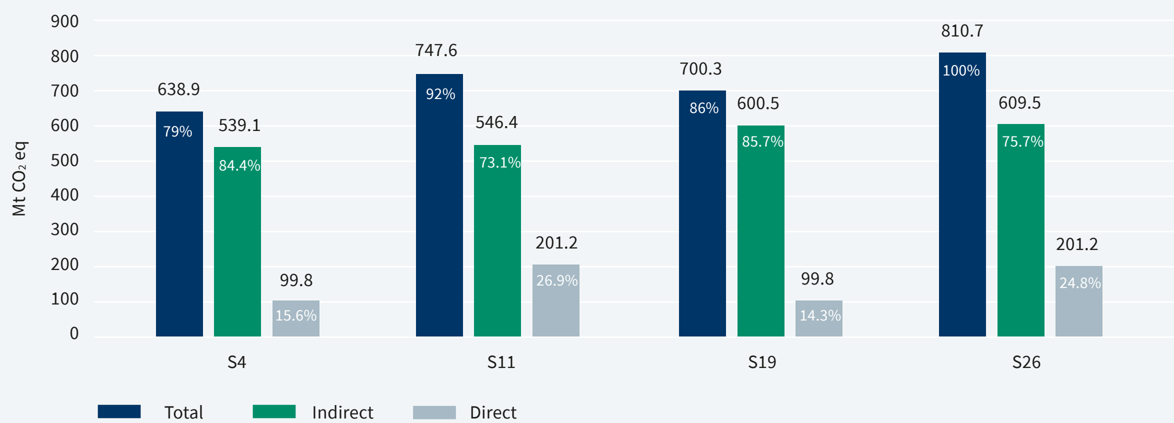
Table 19. Scenarios overview

Scenario	IMO	F gas	Efficiency	R290 adoption
S4	Yes	Yes	High	Fast
S11	Yes	No	Base	No
S19	No	Yes	High	Fast
S26	No	No	Base	No

In accordance with the strategy outlined by the IMO, the lowest emissions are achieved through adherence to EU F-gas compliance, substantial fleet energy efficiency gains, and expeditious introduction of R290 into the market. Projections indicate cumulative emissions of 638.92 Mt CO_2eq by the year 2050 (Scenario 4, S4). The highest emission scenario aligns with the IMO strategy yet does not incorporate additional policy implementation such as the Kigali Amendment or EU F-gas Regulation. This scenario also assumes no market introduction of R290 and no energy efficiency of the reefer fleet, with cumulative emissions of 747.64 Mt CO_2eq by 2050 (Scenario 11, S11). Scenario 19 (S19) does not align with the IMO strategy, yet it demonstrates significant emission reductions due to the combination of EU F-gas compliance, high energy efficiency improvements, and rapid R290 market adoption. These factors lead to cumulative emissions of 700.3 Mt CO_2eq by 2050, underscoring the critical role of efficiency gains and refrigerant transitions.

The scenario with the highest cumulative emissions by 2050 with 810.74 Mt CO_2eq does not follow any policy regulation, assumes no R290 reefer market introduction and no reefer technology improvement by 2050, and makes no allowance for energy efficiency gains at all (Scenario 26, S26). The final scenario does not align with the IMO strategy; however, it incorporates the impact of the EU F-gas Regulation on the refrigerant mix of the reefer fleet, assumes a substantial energy efficiency enhancement of the fleet in the years leading up to 2050, and incorporates the market introduction of R290 reefers. The projected emissions in 2050 are estimated at 700.3 Mt CO_2eq, which is marginally lower than in Scenario 11. This outcome underscores the significance of the reduction in reefer energy consumption on the overall emissions profile.

Figure 12. Behaviour of Direct and Indirect Emissions of selected scenarios, average off all years



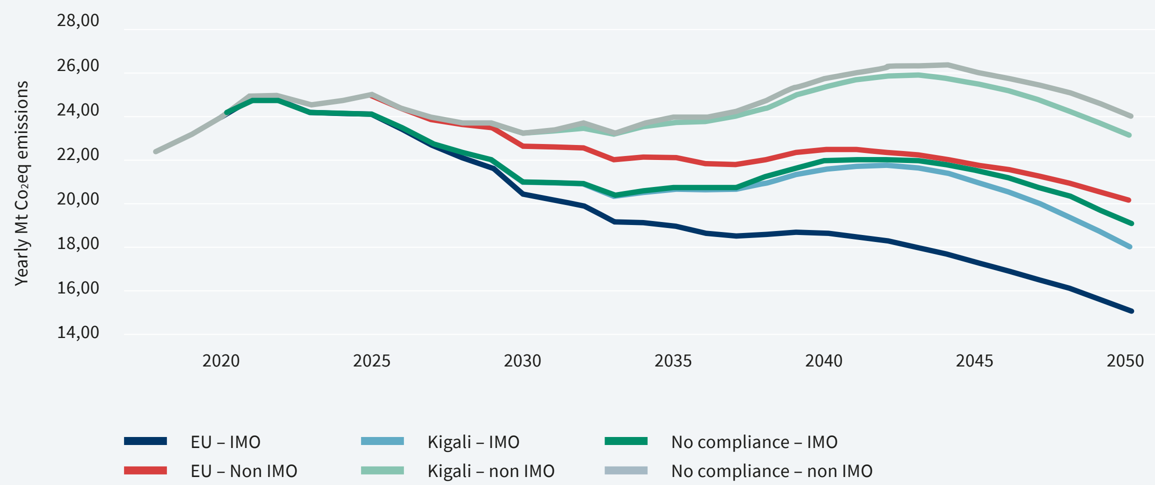
The analyses further demonstrate the impact of the EU F-gas Regulation and the Kigali Amendment on reefer emissions: in the event of the refrigeration industry disregarding these directives, it is projected that emissions from refrigerants will increase two-fold (see Figure 12). The replacement of refrigerants in the reefer fleet with natural refrigerants such as CO_2 or R290 would result in the elimination of these emissions.

Table 20. Emissions overview

Emissions	Unit	Scenarios			
		S4	S11	S19	S26
Direct	$MtCO_2eq$	99.8	201.2	99.8	201.2
Indirect	$MtCO_2eq$	539.1	546.4	600.5	609.5
Total	$MtCO_2eq$	638.9	747.6	700.3	810.7
D%	%	15.6	26.9	14.3	24.8
I%	%	84.4	73.1	85.7	75.2

The discrepancy between the best possible scenario and the scenario in which the highest levels of accumulated emissions are reached by 2050 is 171.8 Mt CO_2eq. This is equivalent to the emissions of 40 coal-fired power plants in one year. It is important to note that this reduction in emissions is contingent upon two key factors: firstly, the industry must increase the energy efficiency of refrigeration technology; and secondly, R290 must be rapidly introduced to the market. Notably, this analysis does not consider additional measures that could significantly enhance the potential for emission reduction, such as the development of advanced engine technologies in vans or the adoption of hydrogen as a fuel source, among others.

Figure 13. Yearly emissions of average scenarios and their variability



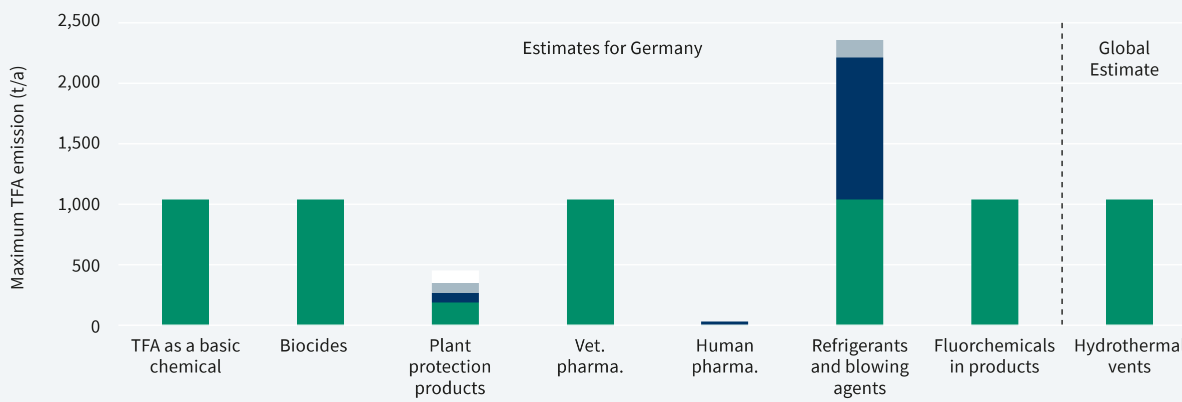
In order to illustrate the potential magnitude of emissions reductions within the different scenarios, they are grouped into five different scenarios based on their alignment with IMO targets and refrigerant phase-down schedules. Within each group, variations arise from differences in efficiency gains and the rate of uptake of the R290 refrigerant. The scenario characterised by the highest efficiency gains and rapid adoption of R290 constitutes the lower boundary of each group's variability, while the scenario featuring baseline efficiency gains and no adoption of R290 forms the upper boundary. The shaded areas around each curve in Figure 13 illustrate the range of variability due to varying speeds of R290 technology adoption.

The impact of the Kigali Amendment and the EU F-gas Regulation is shown by the step-like appearance of the curves until approximately 2037–2040. Subsequent to this period, the more gradual decline in the curves signifies that the influence of refrigerants is waning, and efficiency gains in conjunction with carbon intensity reductions become the predominant drivers of emissions reductions.

The shipping industry's commitment to the IMO strategy is set to be the most significant driver of reefer development. With the implementation of requisite safety measures, the industry can transition to R290 reefers, exerting a substantial positive impact on its emissions balance in the long term. While current fuels include diesel and various fuel oils, future decarbonisation options may include electrification, hydrogen-based fuels, LNG, biofuels, methanol, and ammonia.

The emissions reduction analyses demonstrate the impact of introducing R290 technology to the market, coupled with lower energy consumption targets for reefers. Greener reefers, characterised by reduced

Figure 14. Estimated maximum TFA emissions in tonne/year for relevant group of chemicals. While natural sources such as hydrothermal vents contribute to global TFA emissions, regional data for Germany and Europe are currently unavailable, leaving only global estimates [182, 183]



energy consumption and the use of R290 as the refrigerant, are instrumental in assisting the shipping industry in achieving the IMO's decarbonisation targets, in accordance with the Paris Agreement and the commitment to a sustainable future.

8.3.2 'Forever chemicals' and reefers

So-called 'forever chemicals', specifically PFAS, are chemical by-products of R134a or R1234yf that are released into the atmosphere. R134a is used in 96% of refrigeration equipment on the market today, while R1234yf is used in mobile air conditioning systems.

PFAS, an acronym for per- and polyfluoroalkyl substances, are synthetic chemicals that have been used in various industrial and consumer products since the 1950s. These chemicals are notorious for their resistance to degradation in the environment and their ability to accumulate in the human body. [181] TFA is formed as a degradation product of PFAS and is therefore part of HCFCs and HFCs, and is now identified in HFOs.

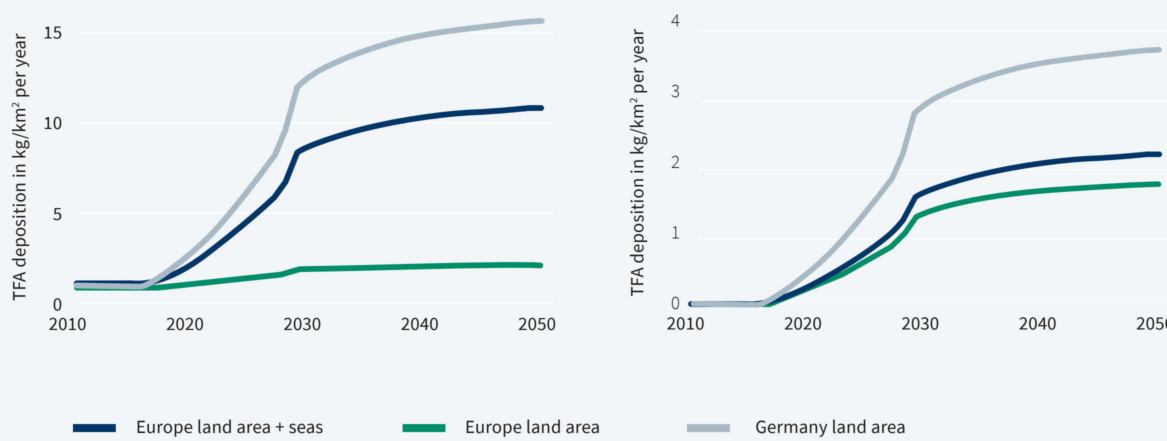
In Germany, the primary sources of TFAs are currently identified as refrigerants and propellants employed in mobile air conditioning systems (see Figure 14, bottom area). This observation underscores the compatibility of R1234yf, a refrigerant that can also be used in refrigeration units, with a high TFA content. However, it is noteworthy that this substance undergoes a complete breakdown when exposed to air, water, or soil.

181 Mueller, R., & Schlosser, K. E. (2020). History and Use of Per- and Polyfluoroalkyl Substances (PFAS) found in the Environment. Retrieved June 25, 2024, from *History and Use of Per- and Polyfluoroalkyl Substances (PFAS) found in the Environment (itrcweb.org)*

182 Adlunger, K., et al. (2021). Reducing the input of chemicals into waters: trifluoroacetate (TFA) as a persistent and mobile substance with many sources (ISSN 2363-829X). Umweltbundesamt (German Environment Agency). *Background 11/2021: Reducing the input of chemicals into waters: trifluoroacetate (TFA) as a persistent and mobile substance with many sources (umweltbundesamt.de)*

183 Blue: TFA from refrigerant R-134a; orange: TFA from refrigerant R-1234yf; grey: TFA from other refrigerants.

Figure 15. Estimated future TFA deposition and TFA deposition rates for Europe due the degradation of HFO-1234yf exclusively [185]



While natural sources such as hydrothermal vents contribute to global TFA emissions, regional data for Germany and Europe are currently unavailable, leaving only global estimates. The two main sources of TFA are R134a (bottom colour) followed by R1234yf (second colour). The smallest amount is TFA from different sources.

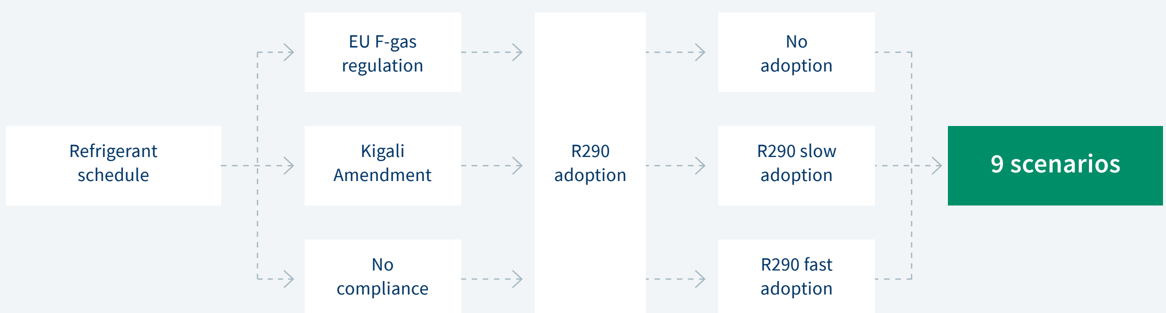
In the field of refrigeration, there is an increasing focus on environmentally sustainable alternatives to conventional refrigerants. This includes the exploration of natural refrigerants for mobile air conditioning systems. [184]

The German Federal Environment Agency has predicted an increase in the presence of TFA in the atmosphere across Europe by 2050. This projection is attributable to the industrial use of R1234yf in MAC. (Figure 15).

Evidence suggests the existence of other refrigerants, comprising blends of R1234yf or R404A with a 4% market share and R452A with an even more negligible 0.1% market share. In addition to the high-GWP refrigerant R134a, which has a 96% market share, it is also a constituent of TFA to the extent of 20%. This underscores the imperative for the marine industry to expedite the identification of a suitable alternative refrigerant. [186, 187]

184 Behringer, D., et al. (2021). Persistent degradation products of halogenated refrigerants and blowing agents in the environment: type, environmental concentrations, and fate with particular regard to new halogenated substitutes with low global warming potential (ISSN 1862-4804). German Environment Agency.
185 Ibid.
186 Adlunger, K., et al. (2021). Reducing the input of chemicals into waters: rifluoroacetate (TFA) as a persistent and mobile substance with many sources (ISSN 2363-829X). Umweltbundesamt (German Environment Agency). *Background 11/2021: Reducing the input of chemicals into waters: trifluoroacetate (TFA) as a persistent and mobile substance with many sources (umweltbundesamt.de)*
187 World Meteorological Organization (WMO). Scientific Assessment of Ozone Depletion: 2022.

Figure 16. Illustration of the scenario exploration for the TFA emissions projection



As demonstrated in Table 3, each refrigerant blend with R1234yf has 'forever chemicals' as a by-product. For the TFA analyses, the direct emissions from the TEWI formula and the equivalences are analysed. The degradation of refrigerants to TFA has been considered as conservative as possible, i.e. R134a and R1234yf can degrade up to 20% and 100% to TFA, respectively. The breakdown for R1234yf is a conservative assumption, as studies have shown that this percentage can reach 29–36%. [188, 189]

The scenarios proposed in this paper explore only the aspects related to direct emissions, i.e. refrigerant phasing and R290 adoption, resulting in nine scenarios, as illustrated in Figure 16 and detailed in Table 21.

188 Adlunger, K., et al. (2021). Reducing the input of chemicals into waters: rifluoroacetate (TFA) as a persistent and mobile substance with many sources (ISSN 2363-829X). Umweltbundesamt (German Environment Agency). *Background 11/2021: Reducing the input of chemicals into waters: trifluoroacetate (TFA) as a persistent and mobile substance with many sources (umweltbundesamt.de)*

189 World Meteorological Organization (WMO). Scientific Assessment of Ozone Depletion: 2022.

Table 21. Scenario designation for the TFA emissions projection

S1	EU F-gas / No adoption	S4	Kigali schedule / No adoption	S7	No compliance / No adoption
S2	EU F-gas / R290 Fast adoption	S5	Kigali schedule / R290 Fast adoption	S8	No compliance / R290 Fast adoption
S3	EU F-gas / R290 Slow adoption	S6	Kigali schedule / R290 Slow adoption	S9	No compliance / R290 Slow adoption

The projections show there is an increase in TFA emissions in all scenarios as the market penetration of R1234yf is assumed in the different scenarios. The analysis indicates that the EU F-gas Regulation exerts a substantial influence on the selection of refrigerants and has the potential to result in a broader adoption of R1234yf in refrigeration equipment as a medium-term solution. However, R1234yf will also increase the TFA significantly due to its low GWP as a refrigerant and if an R290 reefer is not ready for the market (Scenario 1). The most expeditious introduction of R290 reefers would have the most significant impact on reducing TFA without switching or permitting R1234yf (Scenario 8).

Figure 17. Illustration of the scenario exploration for the TFA emissions projection

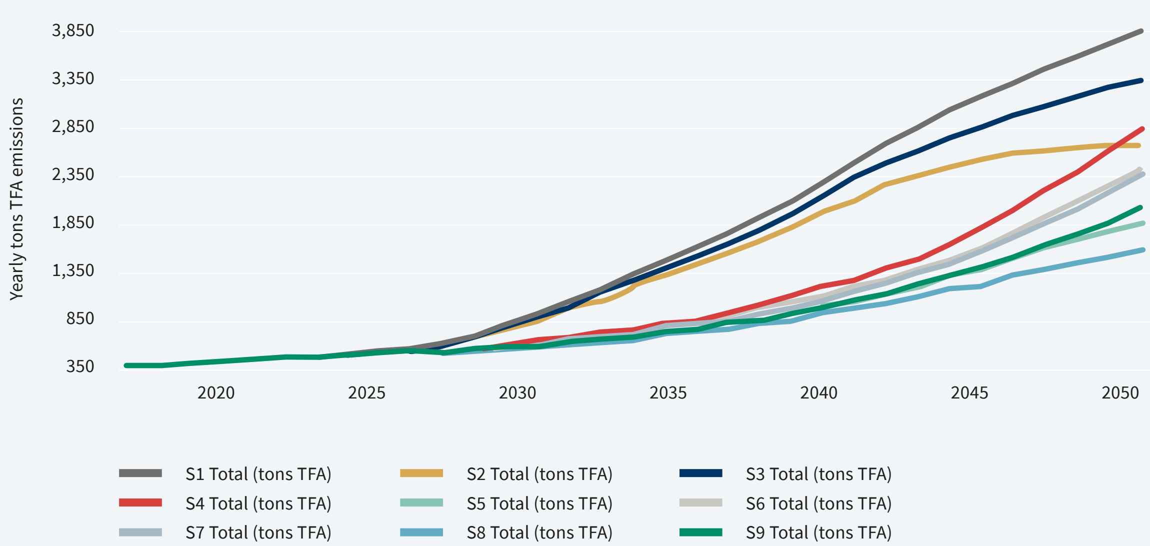
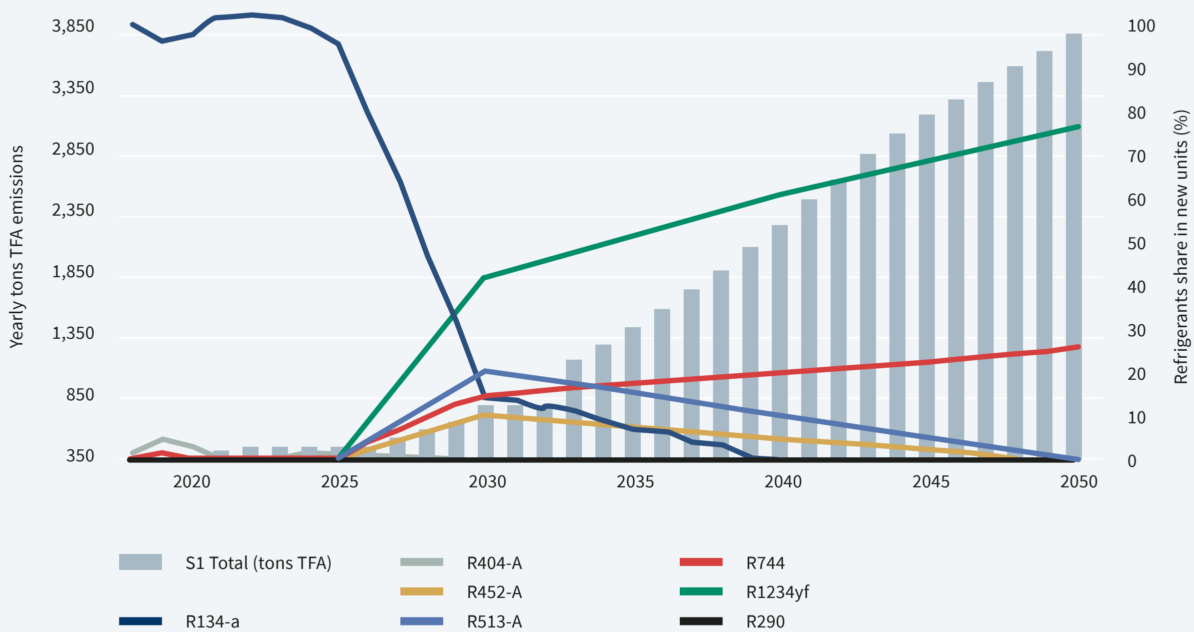


Figure 18. Refrigerant share in new units and the corresponding TFA emissions projection for scenario 1 (EU F-gas / No adoption)



The phase-out of R134a will have a beneficial effect on the climate protection efforts of the shipping industry and countries, as has been observed with other high-GWP refrigerants such as R513A. However, with the EU F-gas Regulation in effect, customers are likely to prefer R744 reefers as a natural alternative with no GWP and no TFA. Nevertheless, due to its higher energy consumption, this technology is not expected to dominate the market in the near future. In the absence of promotion and development of natural refrigerant alternatives such as CO_2 or R290, the sector may find itself compelled to engage in an unwarranted dilemma, characterised by the generation of TFA for the purpose of reducing GHG emissions, a matter of particular concern within the global environmental agenda. The reefer sector is poised to encounter numerous challenges in the forthcoming years, and the transition to R290 reefers has the potential to address two significant issues: R290 has no GWP and no propensity to form TFA, rendering it a crucial technology to explore in the near future for the purpose of ensuring a sustainable and environmentally friendly future.

8.3.3 Sensitivity analysis

This section presents a sensitivity analysis and its role in evaluating the potential impact of various input factors on CO_2-equivalent (CO_2eq) emissions by 2050, specifically within the context of calculating mitigation potential. The calculations were carried out by a team from Wageningen University, led by Josianne Cloutier and Leo Lukasse, with support from GIZ. The overall goal was to assess how different scenarios and input factors influence the potential for reducing CO_2eq emissions.

The sensitivity analysis considered a range of scenarios involving different regulatory frameworks, such as the EU F-gas Regulation, the Kigali Amendment, and a scenario without a specific regulatory schedule. This analysis also accounted for the role of the IMO emission intensity reduction targets, as well as varying technological advancements, including the potential adoption of R290 refrigerants. These scenarios helped identify how different policies and technological changes could influence CO_2 emissions.

To conduct the sensitivity analysis, various combinations of regulatory frameworks, technological advancements, and market conditions were modelled. Key input factors tested included refrigerant charge (measured in kilograms), leakage rates (percentage of refrigerant lost annually), recovery rates (percentage of refrigerants reclaimed), energy demand per unit (kW), and efficiency improvements over time. Additionally, the introduction of alternative refrigerants, such as R290, was assessed under three different conditions: no introduction, gradual introduction, and a rapid introduction.

By comparing outcomes across the scenarios, the sensitivity analysis highlighted which factors have the greatest impact on the potential for reducing emissions. The findings help to identify key focus areas for policymakers and industry stakeholders aiming to maximise the mitigation of CO_2eq emissions through targeted regulatory and technological measures.

The sensitivity analysis included a wide range of variations in key input factors to explore potential impacts on CO_2 emissions. Table 22 below provides a detailed overview of the input changes considered in the analysis:

Table 22. Overview of Input changes

Input	Unit	Scenarios	Reference
Charge	Kg	3	5
		8	
Leakage rate	%	2	15
		20	
Recovery rate	%	30	60
		98	
Growth factor	%	6	8
		10	
Energy demand per unit (base power)	Kw	1.5	2.5
		4	
High efficiency gains R290	%	15	20
		30	

Each input was varied to explore a wide range of possible outcomes, using both low and high values for key factors. For instance, energy demand was tested with values ranging from 1.5 kW to 4 kW, while leakage rates ranged from 5% to 20%.

Refrigerant charge was set between 3 kg and 8 kg, and recovery rates were evaluated from 30% to 98%. Growth factors were also tested between 6% and 10%. By modelling 30 distinct scenarios, the analysis aimed to capture the sensitivity of emissions to changes in these variables.

The outcome of each scenario was compared to a reference case to highlight the relative impact of each input. This approach enabled the identification of the most significant drivers of CO_2eq emissions and provided insights into the potential for reducing emissions under different regulatory and technological pathways.

The sensitivity analysis revealed several critical factors that influence future CO_2-equivalent emissions, with some inputs having a far more pronounced effect than others. The most significant factor was energy demand per unit, which had the largest impact on emissions. In scenarios where energy demand was high (4 kW), emissions soared to 58.54 million tonnes (Mt) of CO_2eq by 2050. In contrast, when energy demand was reduced to 1.5 kW, emissions were much lower, at **28.23 Mt**. This underscores the central role of energy efficiency in shaping future emissions pathways.

Leakage rates and refrigerant charge also emerged as major drivers of emissions, particularly in scenarios governed by the Kigali Amendment or where no regulatory schedule was followed. When leakage rates were high (20%) and refrigerant charge per unit increased to 8 kg, emissions spiked dramatically. In some cases, the difference between high and low leakage and charge scenarios led to a variation of up to 21.44 Mt CO_2eq, underscoring the importance of reducing leaks and optimising refrigerant management.

The recovery rate of refrigerants – ranging from 30% to 98% – also played a significant role, albeit to a lesser extent than energy demand. Higher recovery rates helped lower emissions, with a potential difference of up to 17.00 Mt of CO_2 emissions across different scenarios. This variation of 17.00 Mt reflects the impact that effective recovery can have in minimising the release of refrigerants during the disposal or recycling phase. Improving refrigerant recovery, especially at the end of a product's life-cycle, can therefore contribute meaningfully to reducing overall greenhouse gas emissions.

When it came to the introduction of R290 refrigerants, the analysis found that their impact on emissions was relatively small. Even though R290 offers efficiency improvements, its overall contribution to reducing emissions was limited in the broader context of the scenarios tested. This is in contrast to PFAS emissions, in which R290 plays a crucial role in avoiding 'forever chemicals' as by-products of reefer refrigerants, such as R134a and R1234yf.

These findings highlight the critical importance of managing both energy demand and growth rates for policymakers and industry stakeholders seeking to reduce CO_2eq emissions by 2050.

The analysis further demonstrates that leakage rates, refrigerant charge, and recovery efficiency also have significant effects, especially in scenarios where no regulatory schedules are followed. Efficiency gains from R290 refrigerants, however, appear to have a limited impact on overall emissions. To achieve meaningful reductions in CO_2eq emissions by 2050, policymakers and industry stakeholders must prioritise energy efficiency measures, reduce energy consumption of reefers, and ensure stringent regulatory compliance.

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