Net-zero emission solutions for transport refrigeration in a sustainable cold chain

Technology paper

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Executive summary

Key messages :

- Transport refrigeration is an integral part of the cold chain and critical for sustainable and climate-resilient development. It contributes towards alleviating malnutrition through avoiding major losses of harvested food and providing services for healthcare and pharmaceutical supply.

- The number of refrigerated vehicles on the road is increasing in countries of the Global South. To achieve the Sustainable Development Goals (SDGs), an even higher number of refrigerated vans, trucks and trailers is required, contributing further to an increase in greenhouse gas (GHG) emissions.

- Reaching net zero emissions in the sector is possible by introducing zero emission vehicles, electrically driven refrigeration units and the use of natural refrigerants with negligible global warming potential.

- The goal of net zero emissions can be reached most effectively by banning the most polluting vehicles, refrigeration units and refrigerants in the medium term whilst introducing short-term financial incentives for the development of net zero technologies and their use.

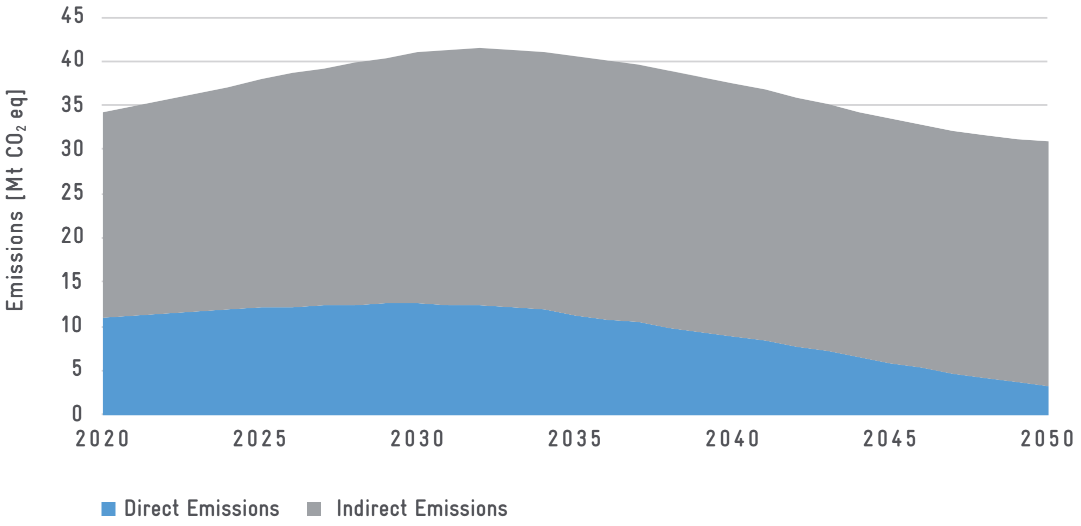
- The journey towards net zero transport refrigeration requires a comprehensive set of policy and financial measures as well as support of technical development. However, there are steps that can be implemented relatively easily on many different levels in order to reduce emissions in the transport refrigeration sector.

The roadmap estimates the climate impact of transport refrigeration units (TRU) on a global level, anlyses technical developments and lists policy and financing options that will support the introduction of zero carbon technologies. Each chapter contains specific action steps regarding the roadmap towards net zero emissions in transport refrigeration. Together, these build a comprehensive set of measures for reaching a zero carbon target in 2050.

The number of refrigerated vehicles was deteremined on a global level for two scenarios. In the Business as usual (BAU) scenario, growth is limited due to a decreasing population in countries of the Global North and a generally low ratio of refrigerated vehicles per inhabitants in countries of the Global South. In a Sustainable Development scenario, where food safety and security are taken into account, the number of refrigerated vehicles is 2.5 times higher than in the BAU scenario and increasing considerably.

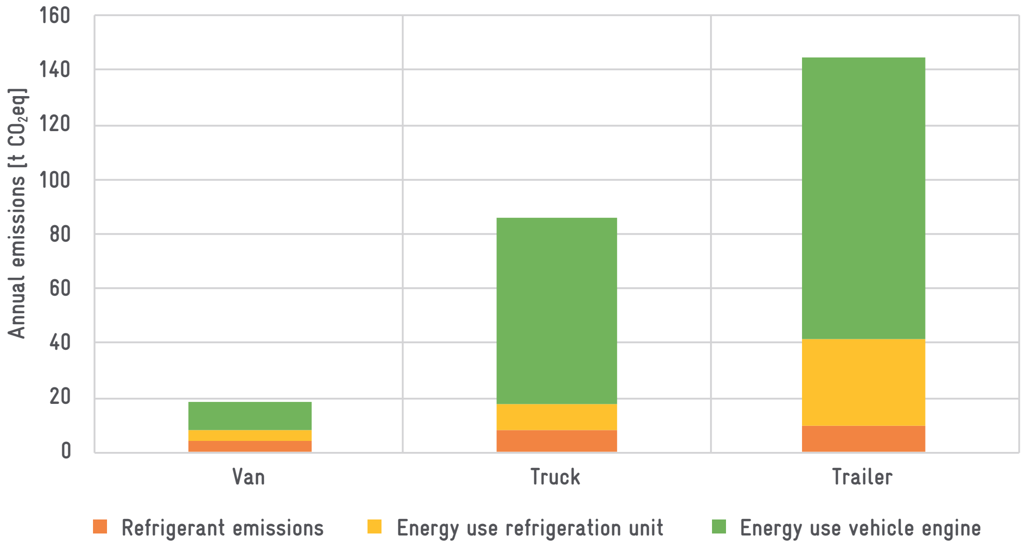
Emissions in the transport refrigeration sector are direct emissions of refrigerants with high global warming potential (GWP) or indirect emissions for powering the TRU, either from the vehicle engine, the diesel generator of the TRU or for electricity generation. Emissions were estimated for the BAU scenario to increase from nearly 35 Megatonnes (Mt) carbon dioxide equivalent (CO_2eq) in 2020 to more than 40 Mt CO_2eq between 2030 and 2035 before decreasing to just over 30 Mt CO_2eq in 2050. The decrease is a direct result of the Kigali Amendment to the Montreal Protocol and a growing electrification rate of vehicles based on existing legislation.

Figure 1: Global direct and indirect emissions of TRUs until 2050



For three standard use cases of vans, trucks and trailers, annual emissions were further calculated for the vehicle engine. Of the overall emissions of vehicle, TRU power and TRU refrigerants, the combined effect of the TRU emissions contribute between 20-45% depending on the vehicle and use case.

Figure 2: Annual emissions of a refrigerated transport vehicle



Apart from California, there are no regulations regarding emissions of TRUs. However, refrigerants in TRUs are affected by the global phase-down of hydrofluorocarbons under the Kigali Amendment of the Montreal Protocol and synthetic substances with lower GWPs are introduced in the sector. Refrigerated transport vehicles, however, are affected by regulations demanding higher electrificiation rates, which might also increase the electrification of TRUs. Integrating transport refrigeration into National Cooling Action Plans (NCAPs), Nationally Determined Contributions (NDCs) or National Freight Plans will enable the setting of key milestones in a transition towards zero emissions, the integration of the sector into emission monitoring and access to more funding options.

For many years, mainly the high-GWP refrigerants R404A, R410A and, for vans, R134a have been used in refrigerated transport and this is still the case in countries of the Global South. Because of the phase-down of hydrofluorocarbons, the refrigerant R452A with a GWP of over 2,000 has been rapidly introduced in the European Union (EU) and other developed nations with strict phase-down targets. R452A is still highly harmful to the environment and will not be sufficient for reaching the targets under the Kigali Amendment. Only the transition towards natural refrigerants, such as hydrocarbons or CO_2 with negligible GWPs can reduce the environmental impact. So far, there are only very few projects using such equipment. However, technical development is moving towards flammable refrigerants and CO_2 with more and more demonstration projects, technical standard development and the first series production of hydrocarbon TRUs.

Initial costs of electric vehicles, battery driven TRUs and TRUs with natural refrigerants are still higher compared to internal combustion engine vehicles and diesel generators. Countries are implementing subsidies to decrease these initial and operating costs for environmentally friendly technologies or penalties for those harming the environment. International financing options are available for technology demonstration projects or policy support in the sector.

Our roadmap towards net zero emissions in the transport refrigeration sector shows necessary milestones for a phase-out of high-GWP refrigerants, switch to electrically driven TRUs and net zero emission vehicles. These are supported by policy measure and financial incentives that also enable technical development. In countries of the Global North, emissions of TRUs are reduced from over 19 Mt CO_2eq in 2020 to 0.05 Mt CO_2eq in 2050. In countries of the Global South, emissions of TRUs increase until 2030 due to the increased demand and a slow uptake of natural refrigerants and electric vehicles. From 2030 onwards, there is a steady decrease to 1.4 Mt CO_2eq in 2050.

Figure 3: Countries of the Global North: Emission reductions according to net zero carbon transport refrigeration strategy

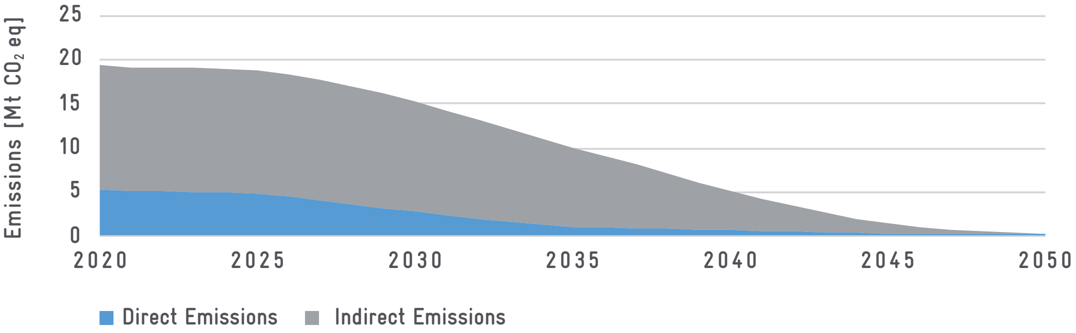
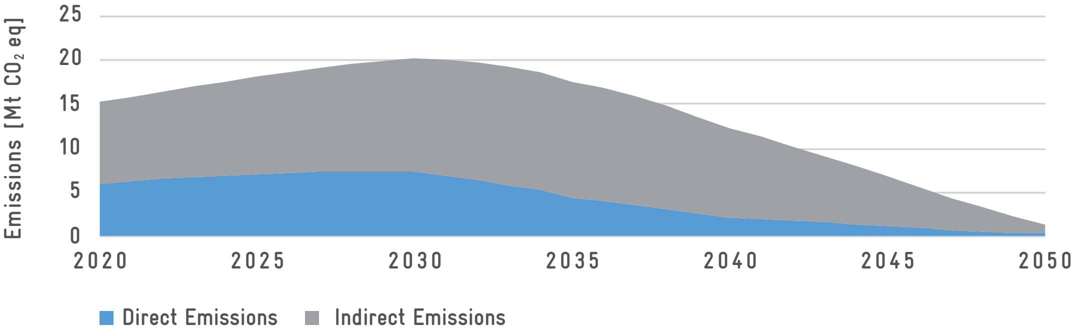


Figure 4: Countries of the Global South: Emission reductions according to net zero carbon transport refrigeration strategy



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List of abbreviations

A	**ATP**	Agreement on the International Carriage of Perishable Foodstuffs
B	**BAU**	Business as usual
	BEV	Battery Electric Vehicle
	BMUV	German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection
	BTR	Biennial Transparency Report
C	**CFC**	Chlorofluorocarbon
	CO_2	Carbon dioxide
	CO_2eq	Carbon dioxide equivalent
E	**EC**	European Commission
	EE	Energy efficiency
	EEA	European Environmental Agency
	EoL	End of life
	EPS	Expanded polystyrene
	ETS	End of life
	EU	Emission Trading System
F	**FAO**	Food and Agriculture Organisation
	F-gas	Fluorinated gases
G	**GCF**	Green Climate Fund
	GDP	Good Distribution Practices
	GEF	Global Environment Facility
	GHG	Greenhouse gas
	GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
	GWP	Global Warming Potential
H	**HACCP**	Hazard Analysis Critical Control Point
	HC	Hydrocarbon
	HCFC	Hydrocholoroflurocarbon
	HD	High duty
	HFC	Hydroflurocarbon
	HFO	Hydrofluoroolefins
	HACCP	Hazard Analysis Critical Control Point
I	**ICE**	Internal Combustion Engine
	IEA	International Energy Agency
	IKI	International Climate Initiaitve
	IPCC	International Panel on Climate Change
K	**KIP**	Kigali Implementation Plan
	kW	Kilowatt
	k-value	Heat transfer coefficient
L	**LD**	Light duty
M	**m·K**	Meter Kelvin
	MDB	Multilateral Development Bank
	MLF	Multilateral Fund
	MRV	Measurement, Reporting & Verification
	Mt	Megatonne
	mW	Megawatt
	mW/(m·K)	Megawatt per meter per kelvin
N	**NAMA**	Nationally Appropriate Mitigation Actions
	NCAP	National Cooling Action Plan
	NCCD	National Centre for Cold-Chain Development
	NDB	National Development Bank
	NDC	Nationally Determined Contribution
	NDE	National Designated Entities
	NEV	New Energy Vehicle
	NOU	National Ozone Unit
	NOx	Nitrogen oxyde
O	**ODP**	Ozone Depletion Potential
P	**PFAS**	Per- and polyfluoroalkyl substance
	PM	Particulate matter
	PU	Polyurethane
R	**RAC**	Refrigeration and Air-Conditioning
	REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
	RDD	Research, Design and Development
S	**SDG**	Sustainable Development Goal
T	**TRU**	Transport Refrigeration Unit
U	**UNECE**	United Nations Economic Commission for Europe
	UNEP	United Nations Environment Program
	UNFCCC	United Nations Framework Convention on Climate Change
W	**W/(m·K)**	Watt per meter per kelvin
	W/m^2K	Watt per square metre and Kelvin
X	**XPS**	Extruded polystyrene
Z	**ZEV**	Zero Emission Vehicle

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1 Introduction

This study addresses climate neutral solutions for refrigerated transport with a focus on refrigerated road transport. Refrigerated trans port is an essential part of the cold chain. This study complements earlier publications by Proklima[1] on related other elements of the cold chain.

The cold chain is a critical element for sustainable and climate-resilient development and adaption to climate change. It critically contributes towards alleviating malnutrition through avoiding major losses of harvested food and providing services for healthcare and pharmaceutical supply.

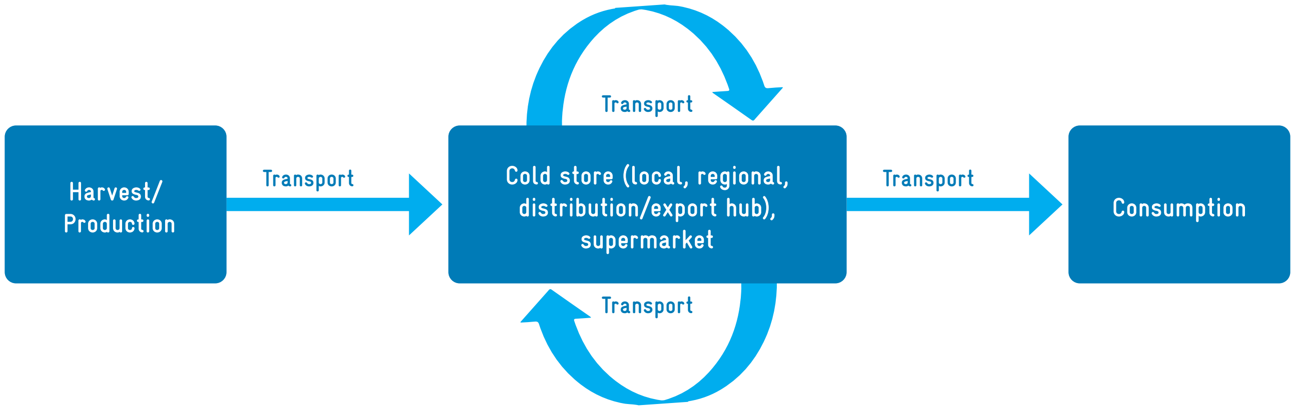
In many countries, the cold chain is still insufficiently developed. The Food and Agriculture Organisation (FAO) estimates that globally about 14% of food globally are wasted before being sold (FAO, 2019). For different food products and different regions, this can be higher, for example up to 50% for fruits and vegetables in Africa (FAO, 2019). Similar challenges and gaps exist for a functioning cold chain for healthcare and pharmaceutics. Closing gaps in cold chains is therefore highly important and transport refrigeration plays an integral role in connecting the different cold chain links.

Transport refrigeration consumes energy, most of which currently is still generated from fossil fuel power sources. In addition, transport refrigeration still relies on the use of refrigerants and foam blowing agents with a significant global warming potential (GWP). A climate-friendly and energy efficient cold-chain free of fossil fuels and high-GWP refrigerants is an essential element for moving to the required climate neutral solutions under the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) with the goal of limiting global warming to 1.5°C.

This roadmap towards climate neutrality for transport refrigeration provides the urgently needed guidance to countries, public and private sector actors on setting appropriate milestones for the transformation of the sector towards climate neutrality. This paper first describes the policies, technology options and financing framework for making this transformation possible. Each chapter includes concrete actions that can be implemented immediately and at different steps in the process. To conclude, it highlights a pathway towards zero emission transport refrigeration, combining actions into an overall strategy.

For maintaining an efficient, energy and product conserving cold chain, products need to keep the same, pre-defined temperature or temperature range between production and consumption and, critically, also transport between these points by means of refrigerated transport (Figure 5).

Figure 5: Elements of the cold chain



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[1] Lange, B., Priesemann, C., Geiss, M., Lambrecht, A. (2016). Promoting Food Security and Safety via Cold Chains. Technology Options, cooling needs and energy requirements. Deutsche Gesellschaft für internationale Zusammenarbeit (GIZ) GmbH, Eschborn, Germany. Available at: https://www.green-cooling-initiative.org/news-media/publications/publication-detail/2016/12/01/promoting-food-security-and-safety-via-cold-chains, accessed 13/04/2022.

Denzinger, P. (2021). COVID-19 and how to establish a sustainable and climate resilient vaccine cold chain. Deutsche Gesellschaft für internationale Zusammenarbeit (GIZ) GmbH, Proklima Eschborn, Germany. Available at: https://www.green-cooling-initiative.org/news-media/publications/publication-detail/2021/04/21/covid-19-and-how-to-establish-a-sustainable-and-climate-resilient-vaccine-cold-chain, accessed 13/04/2022.

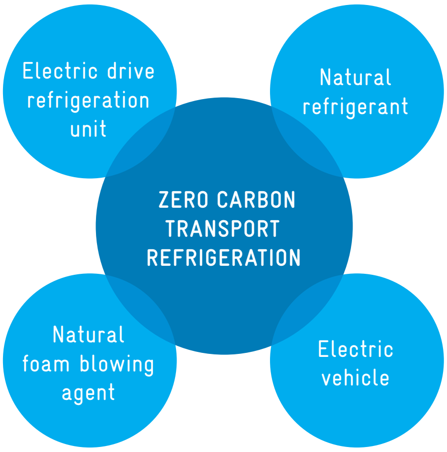
Igor, C. & Oppelt, D. (2021). Construction of a fish cold store in Kenya. Guidelines for the installation, design and calculation of a highly efficient solar-powered cold store using natural refrigerants. Deutsche Gesellschaft für internationale Zusammenarbeit (GIZ) GmbH, Proklima, Eschborn, Germany. Available at: https://www.green-cooling-initiative.org/news-media/publications/publication-detail/2021/12/03/construction-of-a-climate-friendly-fish-cold-store-in-kenya, accessed 13/04.2022.

Temperature control is provided mostly by active refrigeration during the transportation phase, coupled with insulation of the storage facility or transport vehicle. Active refrigeration by a refrigeration unit has the advantage of providing not only cooling but making it possible to adjust the temperature to a specific setting. This is especially important for vaccines and medicine, but also fruits and vegetables that easily spoil when temperatures are either too high or too low. The most widely applied refrigeration units are using refrigerants in a vapour compression system to provide cooling.

Requirements for refrigerated transport are high: The units have to work at a wide range of different ambient temperatures, they have to be robust to withstand the constant movement and impacts and be light and small to minimise the overall weight of the transport (UNEP, 2013). At the same time, costs should be kept at a minimum: If the cost of food increases, the poorest will not be able to afford it anymore (Global Panel, 2016). Initial cost as well as operating costs should therefore be as low as possible.

In zero carbon transport refrigeration, there are no emissions released into the atmosphere. This can be achieved by:

Figure 6: The four prerequisites for zero carbon transport refrigeration



- Zero emission vehicles, such as battery electric vehicles (BEV) operated by electricity from renewable sources, fuel cell powered vehicles powered by green hydrogen (renewable electricity sources only) or vehicles linked to a zero emission grid through overhead lines. The vehicle engine contributes by far the most emissions to refrigerated transport. Light and heavy trucks are most likely to be in the future battery electric, large heavy trucks and trailers have a potential for both battery electric drive and green hydrogen fuel cell technology.

- Electrically driven refrigeration units that are charged by electricity from renewable sources. Most transport refrigeration units (TRU) are being driven by an external diesel engine or for smaller vehicles are connected to the motor engine of the vehicle. These diesel engines are usually not regulated and emit far more emissions than a normal vehicle engine.

- Using natural refrigerants with zero or negligible global warming potential. Synthetic refrigerants that are being used in transport refrigeration have high GWPs of up to 4,000. Even newer drop-in solutions have GWPs of more than 2,000 and there are currently no synthetic low-GWP refrigerants commercially available for this application. Transport refrigeration further has high leakage rates of refrigerants into the atmosphere as connections are being loosened by the constant movement on roads. Synthetic foam blowing agents still in use contribute to the destruction of the ozone layer and/or to global warming. Natural foam blowing agents for insulated body with zero or negligible global warming potential are available.

A note on renewable energy sources: Renewable electricity generation from wind, sun, water etc. is increasing more and more. If global carbon emissions are to be cut dramatically, as is necessary to halt climate change, there is currently no alternative to a wide electrification of transport and 100% renewable energy sources. Currently, zero carbon transport cannot be reached even if electric vehicles and electric drive TRUs are used as the renewable electricity production is still lagging behind.

Similarly, the production of batteries is associated with emissions. Of these, about half are due to electricity generation (Hall & Lutsey, 2018). Decarbonisation of electricity generation will therefore reduce emissions in the manufacturing of batteries considerably. Further emission reductions are related to higher energy densities, new battery chemistries that use less energy intensive minerals, higher efficiencies of scale in larger production facilities, the use of recycled materials and the decarbonisation of the supply chain (Transport & Environment, 2020).

2 Understanding the baseline – transport refrigeration cooling needs and business as usual emissions

Knowing how many refrigerated transport vehicles are on the road and how they contribute to GHG emissions is necessary for planning relevant and effective mitigation measures. It is also only possible to monitor emission reductions and verify policy measures once a good baseline has been established. Projecting the number of vehicles and emissions into the future will provide a planning tool for setting emission targets in the sector.

Collected data can further be used to integrate the transport refrigeration sector into National Cooling Action Plans (NCAPs) and Nationally Determined Contributions (NDCs) if proper methodologies are being used (see Chapter 3.4).

Here we show the results of the modelled global number of refrigerated vehicles on the road, a projection until the year 2050 under two different scenarios and an estimation of business as usual (BAU) emissions from the refrigeration units on the vehicles.

Steps towards setting up an inventory of refrigerated vehicles are described at the end of the chapter.

2.1 Number and type of refrigerated vehicles on the road

Most of refrigerated transport is done by trailers (heavy commercial vehicles), trucks (medium and heavy commercial vehicles, rigid trucks) and vans (light commercial vehicles, small rigid trucks)[2]. Trailers are used in country-wide, cross-country, or regional transport, where long distances are covered with large quantities of product. This allows for the specialisation of markets, e.g., for seasonal fruits and vegetables and economy of scale for farmers (Rodrigue & Notteboom, 2020). Trucks can be used for long distance transport, but because of their limited load capacity, their main application lies in regional and city transport, e.g. from farmers to packing stations or distribution centres to supermarkets. Vans are mainly used in the last mile distribution of goods to shops, restaurants, and consumers.

Two scenarios were applied to determine the number of vehicles globally.

1. Business as usual: The rate of refrigerated vehicles per population in countries of the Global North is high but only low to very low in countries of the Global South. The number of refrigerated transport vehicles depends mainly on population growth and numbers are increasing relatively slowly even though the potential demand could be very high.
2. Sustainable Development Goal (SDG) scenario: Refrigerated transport is an important missing link in the cold chain in many countries of the Global South. This not only leads to food wastage or food that is not safe to eat, but also hinders the success of vaccination campaigns or distribution of medicine. The SDGs No. 2 – No Hunger – No. 3 – Good Health and Well Being - can be supported by establishing uninterrupted cold chains. We have therefore assumed a scenario that increases the number of refrigerated vehicles per 1000 inhabitants in countries of the Global South to about 2/3 of the level found in countries of the Global North.

Box 1 describes the methodology that we use for calculating stock as well as emissions.

Box 1: Methodology used for determining transport refrigeration emissions

Methodology

- Stock of refrigerated transport vehicles is estimated based on the ratio approach (Green Cooling Initiative Database, 2016; Heubes & Papst, 2013), where a factor describes the relationship between population and refrigerated transport vehicles. This factor still increases slightly for countries of the Global North and has a steeper growth in countries of the Global South, depending on the two scenarios mentioned above.
- The annual growth is hence the result of population growth and the ratio applied.
- Annual sales are calculated from stock, assuming a product lifetime of 15 years.
  A distribution of utilised refrigerants is projected based on the constraints of the Kigali Amendment.
- Parameters are included in the Annex.

Scenario 1: Realistic

Figure 7 shows the number of vehicles on the road globally until 2050.

- The number of vehicles in countries of the Global South increases from just under 3 million vehicles in 2020 to over 4 million in 2050.
- The number of vehicles in countries of the Global North increases very slowly until 2035, followed by a small decrease as the population shrinks in several big nations.
- The number of vehicles in countries of the Global South increases steadily until 2050 and from around 2040 onwards there are expected to be more refrigerated vehicles in countries of the Global South than in countries of the Global North.

Figure 7: Number of refrigerated road vehicles until 2050 globally under a realistic scenario

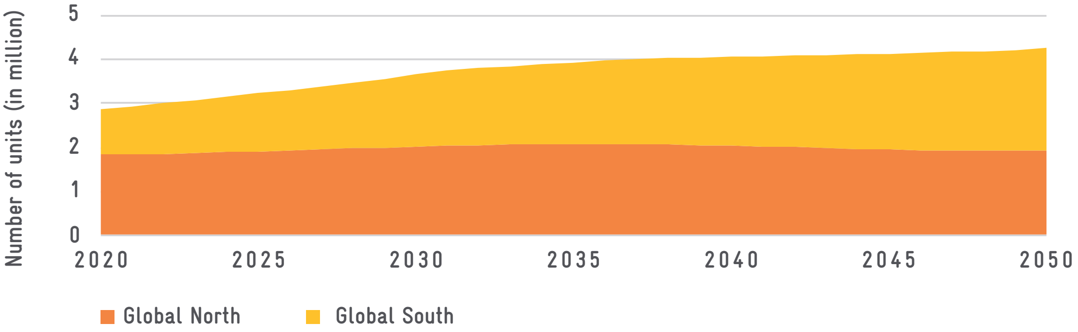
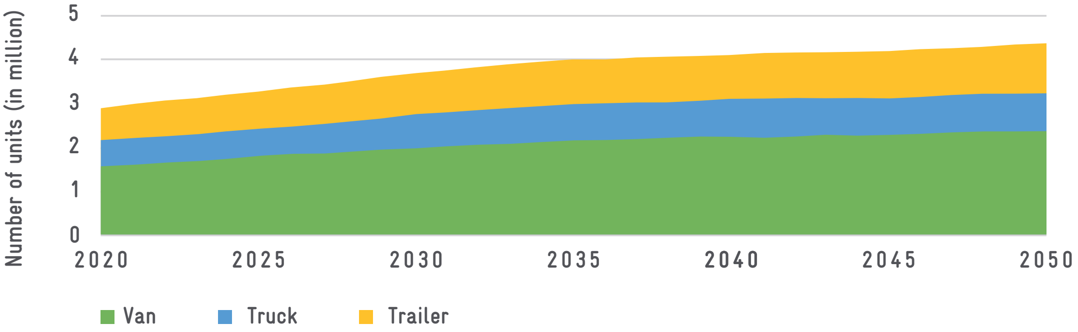


Figure 8 shows the share of the categories van, truck, and trailer. It is estimated that in the EU currently about 50% of refrigerated road transport is done by vans, and 25% each is covered by trailers and heavy trucks (Dearman, 2015). A report by Fortune Business Insights puts the global share of refrigerated vans and light trucks in 2019 at only 10% with heavy trucks and trailers making up most of the refrigerated transport (Fortune Business Insights, 2020). However, the same source also expects the share of van transport to grow considerably, as there is more and more delivery, a share similar to the one in the EU was considered.

Figure 8: Number of refrigerated transport vehicles until 2050 according to vehicle category



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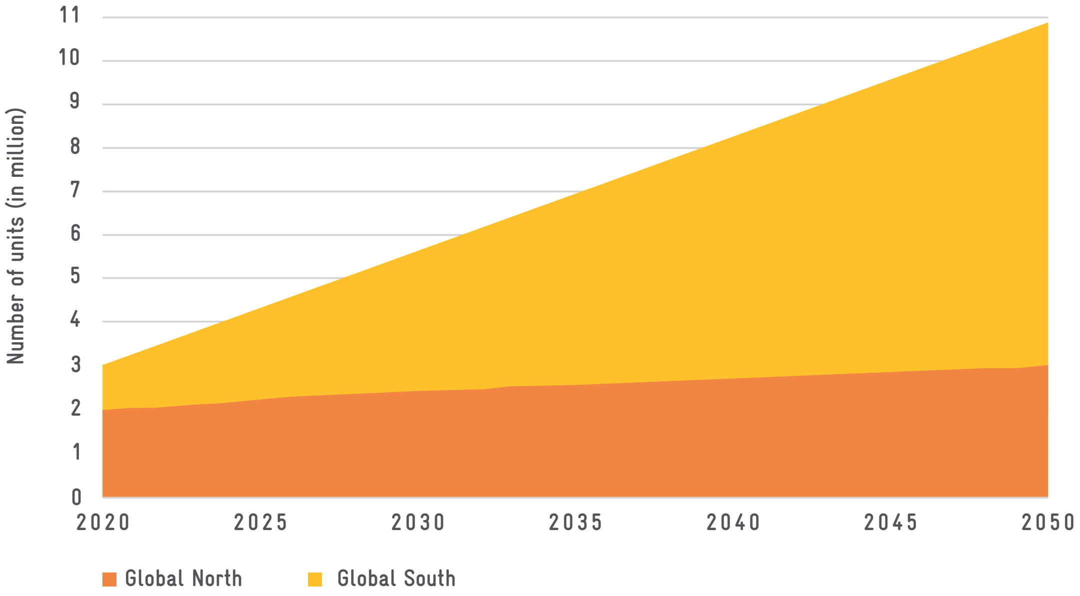
[2] Refrigerated air freight is becoming more and more important, however, it is not using vapour compression refrigeration units. The same is true for motorbikes that are used in last mile distribution but are not properly refrigerated and might only be using ice if the goods are cooled at all. Trains do not contribute much to the overall refrigerated transport.

Scenario 2: Sustainable Development Goals

Figure 9 shows the number of vehicles under a food safety scenario. The number of vehicles in countries of the Global South is increasing from around 1 million in 2020 to about 8 million in 2050, whilst the number in countries of the Global North stays relatively stable around 2 million vehicles. The total number of vehicles in this scenario is about 10 million, 2.5 times higher as under the realistic scenario.

The differences between the existing fleet and expected business as usual development in comparison to the necessary growth to support an improvement in food availability and safety are often large.

Figure 9: Number of refrigerated road vehicles until 2050 in countries of the Global South and Global North under a food safety scenario



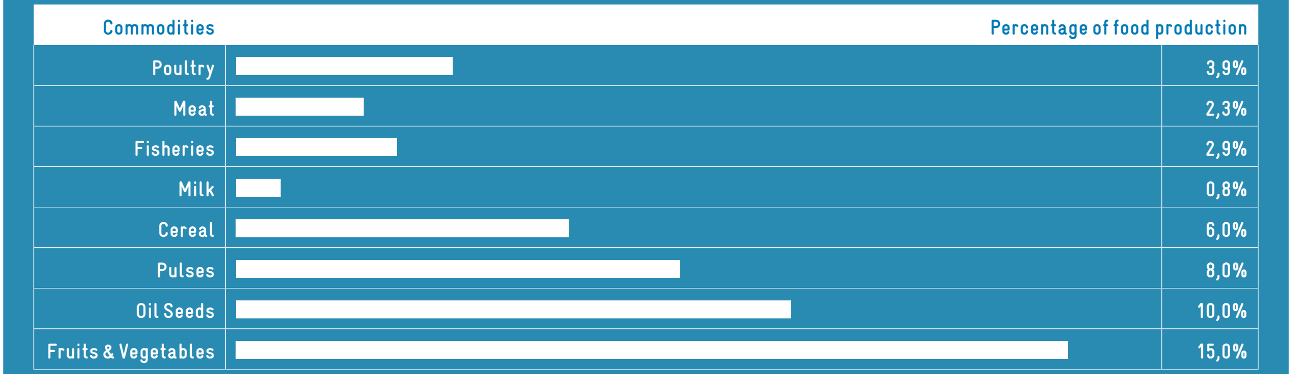
Box 2 highlights the problems associated with a lack of refrigerated transport as well as barriers to a wider penetration of the technology using the example of India.

Refrigerated transport in India

India is one of the largest countries in the world with a population of 1.27 billion and their main source of income is agriculture. The country is not only the world´s largest milk producer but also the fifth largest producer of meat and meat products (Reddy, 2021). Both dairy and meat products as well as the nearly 300 million tonnes of fruits and vegetables that are produced annually are rarely refrigerated (Reddy, 2021). In the mainly tropical and hot climate of India, it is estimated that the cold chain fleet has less than 10,000 refrigerated trucks to transport perishable goods (Frost & Sullivan, 2018). This accounts for about 3-4 % of all perishable goods.

Although India theoretically produces sufficient food to feed its entire population, about 25-40% of the total food produced in India is spoiled due to the lack of a proper cold chain systems and handling isssues at the consumer level (Qazī, 2017). Losses per commodity differ widely (see Figure 10). While 15% of the total fresh fruits and vegetables produced annually is spoiled because of bad post-harvest management (CIPHET, 2019), only 0.8% of produced milk is wasted as it is transported in insulated - though not refrigerated – tankers (Emerson Climate Technologies, n.d.).

Figure 10: Percentage of food production that is spoilt annually for different commodities in India (Singh, 2019)



Based on the amount of perishable products produced each year, there is currently a gap of 85 % between the required and available fleet of refrigerated trucks (Frost & Sullivan, 2018). The potential of the cold chain is not exhausted because of several reasons:

- There is a high need for initial investment and the investment into cold chains is not being seen as a priority. If investment takes place, 90% is targeted into warehouses, making transport the weakest link in the cold chain.
- A lack of enabling infrastructure such as the power grid and roads. There is no local production of refrigeration units, making expensive import necessary.
- Seasonality of cold chain activities. Different areas in India have different requirements depending on the local focus of agriculture and fisheries as well as dominant commodities.
- A lack of drivers trained in the use of refrigerated vehicles. Drivers are further paid badly. There is a general lack of awareness amongst drivers and the general population regarding the need for refrigeration for perishable goods.

The government of India has started to promote cold chain development by providing financial assistance, tax rebates, rewards and soft loans (Reddy, 2021). It has also established the National Centre for Cold-Chain Development (NCCD), which is implementing standards and protocols, undertaking research and development works required in cold chain development and increasing public awareness on the importance of refrigerated transport.

Box 2: Case study refrigerated transport in India

2.2 Environmental impact of transport refrigeration units

The environmental impact of both the energy use of the refrigeration unit and the consumption of refrigerant with high global warming potential was determined for a business as usual (BAU) scenario.

Box 3: Business as usual scenario

Under the BAU scenario

- Existing legislation is taking into account:
  - Phase-down of refrigerants with high GWP under the Kigali Amendment
  - Some policies regarding the introduction of electric vehicles and thereby electric refrigeration units
- Planned legislation or technology change is neglected as the uncertainty of implementation is very high.
- Grid emission factors are seen as stable
- **Emissions were calculated based on the methodology described in Heubes & Papst (2013).** Additionally, an electrification rate for new vehicles sales was assumed based on existing legislation for each category of vans, trucks and trailers.

Figure 11 shows the direct and indirect emissions of refrigeration units estimated until 2050. Total emissions increase from nearly 35 Mt CO_2eq in 2020 to more than 40 Mt CO_2eq between 2030 and 2035 before decreasing to just over 30 Mt CO_2eq in 2050. Direct emissions contribute about 30% in 2020 and decrease to about 10% in 2050 as a direct result of the Kigali Amendment to the Montreal Protocol. They are thereby mainly responsible for the decrease in emissions. Indirect emissions increase first as more refrigeration units are coming into use and then slowly decrease because of a growing electrification rate. The electrification rate somewhat balances the increase in vehicles overall, so that final indirect emissions in 2050 are about the same as in 2020.

Figure 11: Global direct and indirect emissions of TRUs until 2050

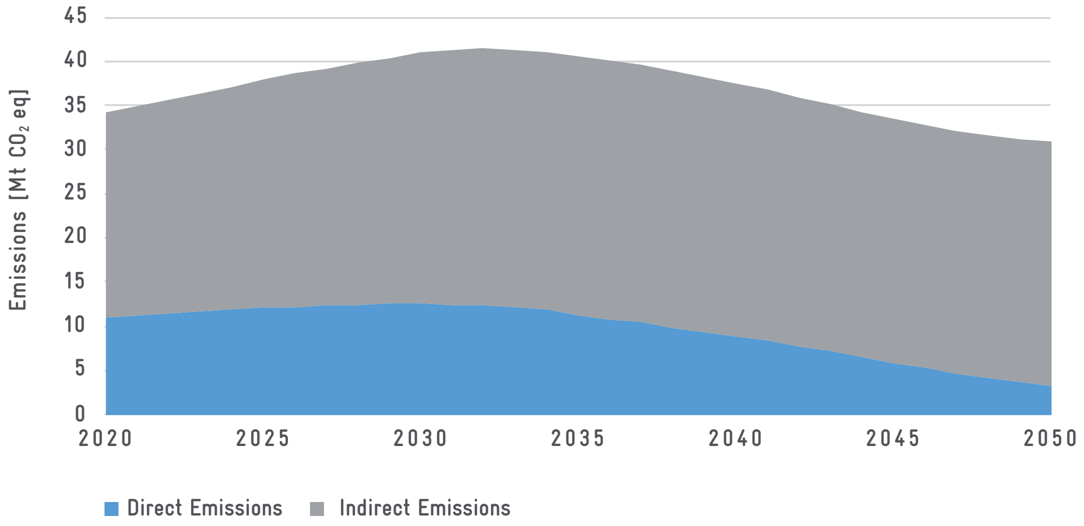


Figure 12 shows direct and indirect emissions in countries of the Global North. Emissions are decreasing from just under 20 Mt CO_2eq in 2020 to 10 Mt CO_2eq in 2050. Because of reductions in the consumption of hydroflurocarbons (HFC), due to the Kigali Amendment, direct emissions only contribute 26% to total emissions in 2020, which is reduced to 4% in 2050. Indirect emissions also decrease, though to a lesser extent. Even though the use of electric vehicles is increasing, grid emission factors in many countries are still high as the share of renewable energies is low.

Figure 12: Direct and indirect emissions of transport refrigeration units in countries of the Global North until 2050

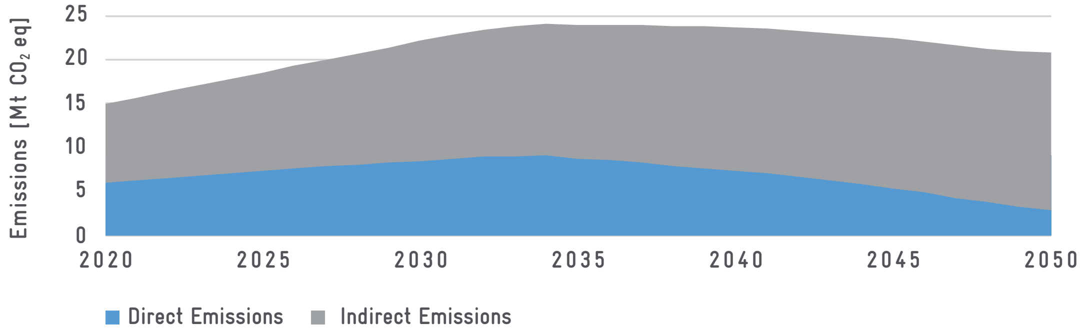


Figure 13 shows direct and indirect emissions in countries of the Global South. Total emissions increase from 15 Mt CO_2eq in 2020 to 24 Mt CO_2eq around the year 2035 before decreasing to 20 Mt CO_2eq in 2050. The share of direct emissions is as high as 39% in 2020, assuming higher leakage rates on roads that are often in bad condition and the still wide-spread use of high-GWP refrigerants. The share decreases to about 14% in 2050 due to the phase-down under the Kigali Amendment.

Figure 13: Direct and indirect emissions of transport refrigeration units in countries of the Global South until 2050

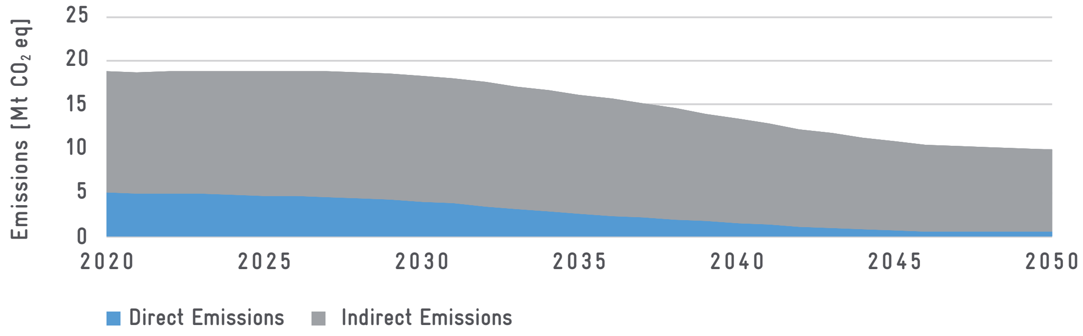
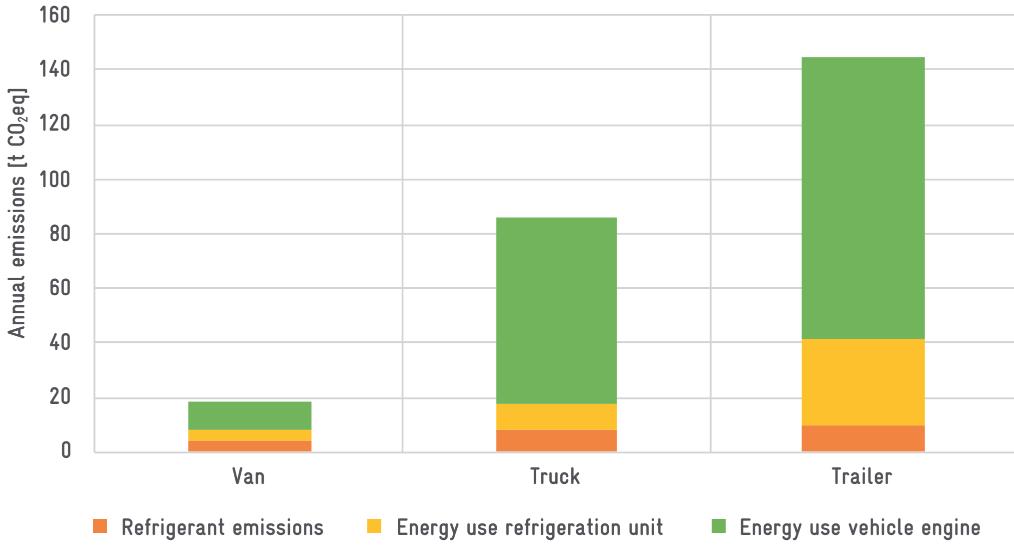


Figure 14 shows the current annual emissions from the vehicle engine, the refrigeration unit and refrigerant emissions[3]. The three cases shown here present the following scenarios:

- **Delivery van in urban traffic** with a daily route of less than 100 km, but high motor idling times
- **Regional distribution truck** with a daily route of 200-300 km between distribution centres and supermarkets.
- **Long-haul transport in trailer** with a daily route of 500-600 km and long operating hours of the refrigeration unit during overnight stops

Figure 14: Annual emissions of a refrigerated transport vehicle



A pathway towards net zero carbon emissions will be shown in Chapter 6, integrating policies, technology developments and financing options.

The goal of zero carbon cooling can still seem very far away for many countries, especially if the expansion of refrigerated transport in the cold chain in order to improve food security and medicine supply is a current priority. However, there are many steps that can be implemented, which can reduce emissions whilst working towards the SDGs and reducing operating costs. The appropriate measures can for example be identified based on inventories and surveys and specific activities are included at the end of each chapter.

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[3] Assumptions are included in the Annex.

2.3 Data collection activities to support moving towards net zero transport refrigeration

- Determine the number and kind of TRUs (van/truck/trailer; diesel/electric drive) in the country to identify priorities for further action

  – Possible information sources: vehicle registration statistics (available in some countries); producers/importers/distributors of TRUs (homogeneous market makes this straightforward), users of TRUs (logistics companies, supermarkets, dairy companies), specialist servicing stations

  – An extensive description on how to collect data can be found in the GIZ publication "Measurement, Reporting & Verification (MRV) in practice" (Kotin-Förster et al., 2021)

- Determine the environmental impact of TRUs

  – Calculate greenhouse gas emissions using inventory results of TRU size (cooling capacity), TRU fuel consumption or efficiency (e.g. in fuel use/hour), annual operating hours (e.g. based on operator surveys; establish operator database with the obligation to annually report energy and refrigerant consumption), type and initial charge of refrigerant in-use and end-of-life leakage rates of refrigerant and lifetime of TRUs

  – A detailed calculation method for greenhouse gas emissions in the Refrigeration and Air-Conditioning (RAC) sector is available in the GIZ publication "NAMAs in the refrigeration, air conditioning and foam sectors. A technical handbook. Module 1 Inventories" (Heubes & Papst, 2013).

- Determine key industry stakeholders, e.g. body builders, producers or distributors of refrigeration units, servicing companies, logistics companies, supermarket chains, agricultural cooperatives, industry associations, technician associations, training institutions for refrigeration and air conditioning as well as vehicle mechanics and the trucking industry.

Based on the results of these surveys, further actions can be determined, e.g. the implementation of regulations and standards, or trainings for companies and drivers.


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3 Policy and Legislation

Industry rarely changes towards more environmentally friendly technology or substances voluntarily. Unless the friendlier solution has clear economic advantages, strict regulation and policies are necessary. In the case of transport refrigeration, these are for example bans and phasedowns of refrigerants with high GWPs, bans of internal combustion engine vehicles or highly restrictive fuel economy standards or CO_2 emission performance standards for vehicle fleets. For industry, they represent drastic interventions into their business. However, if well planned and executed, they also have advantages. With the associated planning security, companies can adapt their strategies accordingly, make long-term investments and introduce necessary capacity measures for employees.

Policies can be introduced to support companies in the transition period. These are often measures that reduce the initial cost difference between old and new technologies and support the necessary infrastructure. These measures are usually based on legislation but will be described in more detail in Chapter 5 (commercialisation and financing options).

In countries of the Global South, additional support is often necessary: companies might not have the financial power to invest in new technologies or the government might not be able to support the general infrastructure such as charging points for electric vehicles or trainings in the use of low-GWP refrigerants for technicians. Here, climate funding can close a gap. If the transport refrigeration sector is integrated into National Cooling Action Plans (NCAPs), National Freight & Logistics Plans and Nationally Determined Contributions (NDC), more funding options might be available.

The following chapters discuss existing regulations regarding the vehicle, refrigerants and the TRU itself. While the focus of the paper are TRUs and the refrigerants within, zero carbon transport refrigeration is only possible if vehicle emissions are considered as well. However, vehicle emissions are only discussed briefly as there are already many publications focusing on decarbonising transport in general.

3.1 Refrigerated transport vehicles

Several countries have introduced legislation that promote commercial electric vehicles or those using hydrogen fuel cell technology. The way this is to be achieved differs, e.g., through CO_2 reduction targets for vehicle fleets that can only be used by introducing high numbers of electric or hydrogen fuel cell vehicles or a percentage of new vehicles per fleet that will have to be electric or using alternative zero emission vehicles. A comparison between legislation in China, the EU and California is presented in Table 1.

Table 1: Comparison of legislation in China, the EU and California that influence the introduction of electric light & heavy duty vehicles

	China	EU legislation	California
Name of legislation	China New Energy Vehicle (NEV) regulation (Mao & Rodgriguez, 2021)	Regulation (EU) 2019/1242 of the European Parliament and of the Council setting CO_2 emission performance standards for new heavy-duty vehicles. Proposed Emission Trading System (ETS) for building and road transport (European Commission, n.d.)	California Zero Emission Vehicle regulation (California Air Resources Board, 2021a)
Goal	Promoting new energy vehicles and providing compliance flexibility to existing fuel consumption	Zero emission large vehicles by 2035 Reduce GHG emissions	To limit smog-forming and GHG emissions
Emission / sales targets	2023: 10–12% Light duty (LD)-NEV 2025: 12% High duty (HD)-NEV 2030: 17% HD-NEV 2035: 20% HD-NEV	2025: onwards 15% reduction in CO_2 emission. 2030: onwards 30% reduction in CO_2 emission	Sales targets for zero-emission medium and heavy-duty vehicles: 2024: 5% class 2b-3 9% class 4-8 straight trucks 5% truck tractor 2035: 55% class 2b-3 75% class 4-8 straight trucks 40% truck tractor
Other related goals	2025: 12% High duty (HD)-NEV	Net zero GHG emissions by 2050	

3.2 Refrigerants

Synthetic refrigerants and foam blowing agents are substances that are responsible for the destruction of the ozone layer and can contribute significantly to global warming. Refrigerants with Ozone Depletion Potential (ODP) are under the control of the Montreal Protocol on Substances that Deplete the Ozone Layer. Chlorofluorocarbons (CFCs) have been banned in countries of the Global North in 1996 and in countries of the Global South in 2010. Hydrochlorofluorocarbons (HCFCs), which have lower ODP, will be phased-out in countries of the Global South until 2030. As a replacement to refrigerants with ODP, hydrofluorocarbons (HFCs) were introduced. They have no ODP, but still considerably high GWP. The latest amendment to the Montreal Protocol, the Kigali Amendment of 2016, requires the freeze and subsequent phase-down of HFCs. The phase-down by 85% for countries of the Global North and 80% for countries of the Global South compared to the current consumption, is determined on the emitted CO_2 equivalent. This means that the GWP as well as the amount of the substance are important to consider.

In the EU, HFCs are already being phased down by 79% of current levels by 2030 thanks to the fluorinated gases (F-gas) Regulation (Regulation EU No 517/2014; European Commission (2014)). The regulation not only limits the total amount of most important F-gases based on their GWP weighting that can be sold in the EU from 2015 onwards, but also bans their use in those sectors where low-GWP alternatives – including natural refrigerants – are available. The F-gas Regulation has already led to a decline in the use of high-GWP refrigerant. However, these are often replaced by synthetic medium- and low-GWP refrigerants that are or contain hydrofluoroolefins (see Box 4) (EEA, 2021).

Box 4: Unsaturated refrigerants

Unsaturated hydrofluorocarbons, also called hydrofluoroolefins (HFOs) are the latest generation of refrigerants of the chemical industry, have no ODP and low GWP, but are slightly flammable, form the persistent degradation product trifluoroacetic acid and contribute to the depletion of natural resources. Trifluoroacetic acid has no natural degradation pathway and accumulates in the hydrosphere where it has a weak phytotoxic effect (Luecken et al., 2010).

Synthetic "medium" or "low"-GWP refrigerants or refrigerant blends usually are or contain HFOs.
This is also the case for R452A or R448A/R449A, which are used in transport refrigeration (see Chapter 4.3.2).

The replacement of high-GWP HFCs with HFOs has benefits for the climate but comes at the expense of potential damages to the environment. Several European countries are currently carrying out an assessment on restricting the use of per- and polyfluoroalkyl substance (PFAS) under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), Regulation (EC) No 1907/2006 (Simpson, 2020). These include F-gases and their products of decay, such as trifluoroacid

The F-gas regulation does not include specific refrigerant bans for transport refrigeration. The transport refrigeration sector will, however, have to follow a leak checking regime (once a year). Moreover, refrigerants will have to be recycled by trained personnel at their end-of-lifeif one unit contains an amount of refrigerant that would be equivalent to emissions of more than 5 t CO_2.

3.3 Transport refrigeration unit

3.3.1 Legislation

There is very little legislation regarding the environmental impact of refrigeration systems. So far, California is proposing legislation that would transition new TRUs to zero carbon emissions by 2030 with requirements for trucks, trailers, railcars, and shipping containers. The GWP of refrigerants in TRUs will be limited to 2,200 from 2023 onwards (California Air Resources Board, 2022) .

3.3.2 The Agreement on the International Carriage of Perishable Foodstuffs (ATP)

In order to guarantee hygienic conditions of perishable foodstuffs, an international treaty specifying conditions for refrigerated transport was designed as early as 1970: The Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be used for such Carriage (French and international abbreviation: ATP). It includes a categorisation of refrigerated transport vehicles according to their refrigeration (and, if applicable, heating) unit, insulation (which can be normal or reinforced) and the temperature class that the unit is suitable for (ATP, 2013). Here, the aim of saving energy and reducing GHG emissions through good insulation is coinciding with the original hygienic ambitions of the ATP. Today, in many parts of the world where the ATP is implemented, (e.g., Europe), it has become the de facto standard for energy efficiency through its minimum insulation values and requirements for the energy efficiency of the refrigeration equipment.

The ATP standard is required for all refrigerated vehicles with perishable goods crossing borders of countries that are included in the agreement. New types of vehicles within the framework of the ATP need to be tested and certified according to ATP standards. In some countries, such as Italy, also transport refrigeration vehicles in operation must be retested according to the ATP standards. Apart from regulating cross-border traffic, the ATP standard is also used in many national standards and simply to define product quality levels in the market which producers use as manufacturing standards.

Member countries are Albania, Andorra, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, Ireland, Italy, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Luxembourg, Moldova, Monaco, Montenegro, Morocco, Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, San Marino, Saudi Arabia, Serbia, Slovakia, Slovenia, Spain, Sweden, Tajikistan, Republic of Macedonia, Tunisia, Turkey, Ukraine, United Kingdom, United States of America, Uzbekistan.

3.3.3 Hazard Analysis Critical Control Point (HACCP)

Most countries have implemented national legislation, standards, or voluntary agreements on food safety. These can contain requirements for refrigerated transport units and insulation or focus on conditions of the food to be transported, e.g., temperature ranges.

In countries of the Global South, a high proportion of produce is sold on informal markets (Global Panel, 2016). Training and certification as well as the support of storage facilities and transport can support these markets whilst keeping them accessible for affordable food supply (Global Panel, 2016).

3.4 Integrating the transport refrigeration sector into National Cooling Action Plans and Nationally Determined Contributions

3.4.1 National Cooling Action Plans

National Cooling Action Plans (NCAPs) are strategic documents integrating national policies affecting the refrigeration and air conditioning sector (UNESCAP, 2021). This allows to address topics such as refrigerant phase-outs and energy efficiency improvements at the same time, creating synergies and avoiding conflicts of interest.
Developing NCAPs requires:

- The mapping of related policies, technology and market trends, stakeholders, and current practices in the cooling sector.
- A cooling demand assessment, both regarding existing equipment as well a need-based growth projection is further necessary. These can be used to assess required energy consumption on a sub-sector basis.
- In a last step, NCAPs give recommendations regarding key actions to be taken, including an assessment of impacts and costs.

This document contains information that will greatly support the work necessary to integrate the transport refrigeration sector into NCAPs. Each chapter gives actions that will support the development of NCAPs or can already be seen as key actions to be taken to reduce emissions in the transport refrigeration sector.

3.4.2 Nationally Determined Contributions

Under the United Nations Framework Convention on Climate Change (UNFCCC), every country must develop Nationally Determined Contributions (NDCs). The NDCs show how the country is planning to contribute to achieving the Paris Agreement Goals of limiting global warming to 1.5°C. These mitigation measures should be achievable and measurable and can be supported by national efforts or international funding.

Both direct as well as indirect emission reduction targets in the transport refrigeration sector can be integrated into NDCs. For reporting purposes, the following categories are of relevance:

- Refrigerant emissions from transport refrigeration units are a sub-application under the category 2.F.1.a – Refrigeration and Stationary Air Conditioning of the International Panel on Climate Change (IPCC).

- Vehicle emissions can fall under several sub-categories of 1.A.3.b – Road Transport. It is possible that transport emissions are recorded in an aggregated top-down approach. Here, fuel or electricity consumption based on the amount that was sold over a certain time are used to determine emissions using combustion emission factors or national grid emission factors. The disaggregation into sectoral uses does not take place. This considerably reduces the effort of monitoring but makes it harder to assign emission reductions to certain measures.

3.4.3 National Freight and Logistics Plan

National Freight and Logistics Plans analyse the status quo of the national logistics sector and define policies and actions for its sustainable development (UNECE, 2021). They highly depend on the current situation within the country and the target vision on how it should develop based on internal and global challenges of the sector. With regard to rerigerated transport, potential policies and actions are on research and innovation, the development of logistics infrastructure for the electrification, education and professional training of drivers, revision of toll system to support environmentally friendly refrigerated transport or emission policies for TRUs. The master plans can show the combination of measures that are necessary to achieve a sector transformation. Policy actions to support moving towards net zero transport refrigeration.

Transport refrigeration is a cross-sectoral topic. Defining and implementing policies requires identifying and engaging with key policy stakeholders from different backgrounds, such as

- National Ozone Unit (NOU) for the implementation of the Montreal Protocol and its Kigali Amendment, Ministry of Environment, Ministry of Transport, Ministry of Agriculture, City Administration and Planning Offices, Urban Development Authorities, Standardisation Committees, National Designated Entities (NDEs) under the UNFCCC responsible for the development and transfer of technologies and focal points for interacting with the Climate Technology Centre and Network, Refrigeration and Air Conditioning/Trucking Associations, Traffic Police.

Regulations and mandatory or voluntary standards can reduce the emissions of vehicles and TRUs as well as improve behavioural aspects. It should first be analysed if relevant regulations or standards already exist and might only need to be updated.

This applies for example to the following:

- Storage and transport of perishable goods: These can be defined in regulations, standards or industry guidelines and often contain temperature set-points for certain goods. Requirements regarding the insulation of the vehicle body, pre-cooling requirements or instructions on air-flow management might also be included.

- ATP Agreement: Accession to the Agreement is possible and thorough guidelines and information are available on the website (https://unece.org/road-map-accession-and-implementation-atp). The ATP includes standard measurement techniques for the capacity of TRUs and the quality of insulated bodies. It further includes requirements regarding the quality control of both TRUs and bodies as well as their combinations. Each new body and TRU has to be type approved and regular in-service testing is necessary to guarantee that the quality has not deteriorated.

- A national standard regarding the quality control of transport refrigeration can be set up. The ATP agreement is widely available and can be used as a starting reference.

- Regulation regarding the emissions of TRUs: These are still highly unregulated and any regulation limiting CO_2, nitrogen oxyde (NOx) or potentially carcinogenic particulate matter (PM2.5) emissions would encourage the transition to electrically driven units that are now entering the market.

- Regulation regarding the GWP of refrigerants in TRUs and their leakage (e.g. yearly inspections) will transition the national market towards the newer units with refrigerants that have lower GWPs.

- Mandatory certification and training of servicing technicians will guarantee a minimum knowledge and skills level for those practicing in the field.

- Check existing regulation on food safety. Harmonising standards with neighbouring countries will enable trading of safe food products (Gross, 2020).

- Monitoring existing policies is generally highly important to make them effective. This is facilitated by embedding the transport refrigeration sector into the NDCs, NCAPs or National Freight and Logistics Plans (see also below).

Use data collection strategy as described in Chapter 2 to set up a transport refrigeration MRV system.

Integrating the transport refrigeration sector into the NDCs requires the combined effort of policy makers from the departments of climate, energy and refrigerant under one responsible ministry. The following steps are part of integrating a measure into the NDCs:

- Define a baseline, e.g., using bottom-up inventory data as described at the end of Chapter 2. Both direct and indirect emissions should be captured.

- Set sectoral targets, e.g., 80% of emissions of baseline until 2050.

- Define actions and set milestone indicators that will make it possible to reach the target, e.g. policy and financing measures regarding low-GWP refrigerants, efficiency standards and the transition towards electric mobility and battery driven refrigeration units.

Set up an MRV system to track the progress as part of the enhanced transparency framework that links financial support with mitigation actions. The collecte d data will also have to be reported under the Biennial Transparency Report (BTR) starting in 2024. See Chapter 2 for more information.

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4 Technical requirements for the development of sustainable refrigerated road transport

4.1 Overview of emission reductions options in transport refrigeration

There is potential for emission reductions in transport refrigeration at the technical level, looking at the mode of transport, the vehicle and its engine, the TRU engine and the refrigerant used. It is also possible to reduce the need for refrigeration by improving the material and design of the insulated vehicle body. Standards for testing and regular checks of the efficiency of both vehicle insulation and TRU are proven policy measures to guarantee a minimum standard for units on the road. Other approaches to reducing emissions are improving logistics and servicing of the vehicle and TRU, both of which will reduce the refrigeration need, e.g. through smaller units, lower runtimes or part-load run times and improve the efficiency of the TRU operation.

In the following we will outline the technology options on the technical milestone for reaching net-zero refrigerated transport vehicles.

Box 5: Alternatives to the technical cold chain

The study “Cooling Solutions for Cold Chains” (2018) by Sustainable Energy for All and the Kigali Energy Efficiency Program focuses on alternatives to the technical cold chain, e.g. natural cooling solutions that reduce the need for refrigeration or electricity. Examples are drones in the supply of vaccines that reduce the need for transport refrigeration or pop-up cold stores for farmers on a pay-as-you-go scheme. These are exciting developments that will improve the cold chain, especially in countries of the Global South.

4.2 Refrigerated transport vehicles

Most of the refrigerated transport is done by conventional vans, trucks and trailers that are diesel powered. Intermodal refers to transport where two modes are combined, e.g., trailer and train or ship and trailer. In many countries of the Global South, short distances are often covered by motorcycle or cargo bike. Table 1 shows the different transport modes including their range, status of zero carbon drive implementation and the most used power source of the refrigeration unit.

Table 2: Overview of transport modes, including status of zero carbon/electric drive implementation and most commonly used refrigeration method

	Trailer (Heavy commercial vehicles)	**Truck** (Medium and heavy commercial vehicles, rigid trucks)	**Van** (Light commercial vehicles, vans, small rigid trucks)	**Motorcycle, cargo bike**
Range	Long-range	Long- to Medium-range	Short-range	Short-range
Status of zero carbon drive implementation	Prototypes	Limited series production starting in 2021	Limited series production	Electric drive well established
Power for refrigeration unit (majority of cases)	External diesel unit	External diesel unit	Belt-driven	Ice/dry ice

Vehicle engines have gotten considerably more efficient and less polluting over the last 20 years and fuel efficiency standards are being more and more tightened (ICCT, 2018). Only recently, however, has the industry been pushed towards developing alternative drive solutions for heavy duty vehicles by stricter regulation (see Chapter 3.1). The International Energy Agency (IEA) requests in its Net Zero 2050 Report (IEA, 2021a) that by 2050, the share of electric heavy-duty vehicles stock needs to reach 60%, the share of electric vans on the road should be at 84% and two-three wheelers should be 100% electric. This means that light-duty vehicle sales must reach 75% in 2030 in advanced economies and 50% in countries of the Global South. About 20% of heavy truck sales need to be battery electric in 2030 and more than 60% in 2050 with the rest being fuel cell electric vehicles. As more and more companies are committing to electric drive vehicles, it is not surprising that the market for commercial vehicles is predicted to grow at a rate of nearly 30% until 2026 (Mordor Intelligence, 2021).

Technology

More and more battery electric light commercial and medium to heavy freight trucks are on the market or expected within the next couple of years (IEA, 2021b). By contrast, much fewer fuel cell models are expected, and these are mainly in the category of heavy trucks and trailers. The switch from a diesel-powered internal combustion engine (ICE) to battery electric vehicle (BEV) makes it necessary for operators to consider several new aspects. The speed of transitioning to new technologies depends on whether there are increasing taxes, carbon price levies or bans regarding the more polluting and climate intensive options and whether the more environmentally and climate friendly versions make financial sense to operating companies. This aspect and ways of bridging the financial gap will be discussed in Chapter 5.

Different supply chains have different demands on BEV technology. Batteries have limitations and the optimum conditions must be chosen based on these demands, reaching an equilibrium between:

- Range requirements – how long does the vehicle have to travel per day/with one charge
- Available charging infrastructure at the location of the operator, e.g., at warehouses/depots or along major driving routes
- A workable charging schedule and time availability for recharging
- The weight of the battery pack and available payload – the larger the battery, the higher the range but the lower the payload. As future batteries will have increasing energy density, this restriction might ease over time.
- The corresponding cost, which mostly depend on the installed battery.

Lithium-ion battery chemistry has so far mainly been used in the powertrains of electric vehicles. Whilst they have been shown to be efficient and effective, they also have the lowest energy density among available energy options (Hayes et al., 2018). Large batteries can be heavier than full diesel tanks, thereby reducing the available cargo weight (Cunanan et al. 2021). The battery life is limited to about 6-8 years with continuous degradation over time. Its full capacity is never available during its operational life as it should be kept at 15-85/90% for optimal utilisation. Its capacity further depends on the ambient temperature range, charging speed, vehicle operation and road conditions.

Charging

The charging speed depends on the size of the battery and the available output of the charging station. There are three charging options:

- Slow charging: Limited output resulting in charging of several hours, usually done overnight at the depot or operating base of the vehicle.
- Fast charging: High voltage results in short charging times that require an established infrastructure, e.g., at servicing stations. Mega-chargers delivering one megawatt (mW) of power or more are in the planning stage but not yet operational.
- Battery swapping: A fully charged battery replaces a depleted battery. The vehicle can be in operation continuously. It is often used for 2/3-wheelers and auto-rickshaws.

Latest developments

As a result of the introduced EU legislation, the main European producers are starting limited series production of trucks with battery electric drive in 2021 (Daimler Truck, 2021; Scania, n.d.; Volvo Trucks, n.d.) . With a range of 200-300 km, the vehicles are developed for regional distribution, e.g., from the cold store to the supermarket. During normal condition, it will be possible to drive the whole day and charge the vehicle overnight at the depot (VDA, 2021).

Long-distance vehicles are still in development. Most producers in Europe are researching both battery electric as well as fuel cell technologies powered with hydrogen (VDA, 2021). For battery electric drive, the main limitation is the lack of a charging infrastructure on the road (VDA, 2021), which is a major barrier for vehicles with frequently changing and long-distance routes. About 10,000 to 15,000 charging points are necessary in the EU by 2025 and 40,000 to 50,000 by 2030 based on estimations on how many battery electric medium and high duty vehicles will be on the

Box 6: Battery recycling

Battery recycling and management

While traditional lead-acid batteries are widely recycled, the same cannot be said for lit hium-ion batteries used in electric vehicles. Recycling methods are only just being established and a collection infrastructure is still missing. Lithium-ion batteries contain hazardous materials that can lead to environmental pollution and damage to human beings if disassembled incorrectly. Many of the contained materials are also rare, so that recycling is crucial. Recovery from waste batteries can create a reverse supply chain, which in turn will reduce the uncertainties in the availability of raw materials and their prices. Another advantage of battery recycling is that it limits the amount of waste that needs to be further managed. Recycling of batteries includes sub-processes such as collection of waste batteries, logistics, discharging, disassembly / dismantling and recycling (Steward et al. 2019).

Battery re-utilisation or battery re-purposing means that batteries that are no longer useful for electric vehicles are used in other applications such as secondary storage. This is possible as electric vehicles tend to discard batteries when they reach 80% of their initial capacity. However, these batteries can still be used to store energy in a stationery environment. This strategy allows further use for many more cycles until the capacity goes down to about 50%. This might especially compliment, over time, the transition to renewable energy systems where the discarded batteries can be successfully deployed for several more years of useful life.

It is important to consider the collection and management of old lithium-ion batteries before or when they are introduced. How many batteries are expected to reach the waste stream each year? Are there established collection strategies, e.g., from lead-acid batteries that can be utilised? Does the local recycling industry have the technical and personal capacities to handle lithium-ion batteries? Which investment or training is necessary?

road by then (acea, 2021). A joint venture was recently founded by trucking companies with the aim of establishing 1,700 charging points along major European motorways (Mercedes Benz Group, 2021). Charging times are feasible within the mandated breaks for drivers every four hours. The infrastructure for hydrogen service stations is also not yet developed and green hydrogen is not yet available in significant amounts, which is a necessity for CO_2 reductions (VDA, 2021).

China is the largest market for heavy duty vehicles with more than 5 million vehicles on the roads. Of these, about 65,000 units are refrigerated trucks (Mao & Rodriguez, 2021). Because of several strong incentive programmes, sales of zero emission vehicles, including battery electric, fuel cell technology and to some extent plug in hybrids, have been increasing over the last years (Mao & Rodriguez, 2021).

Box 7: E-fuels

E-fuels

So-called e-fuels, have a very low overall efficiency and are highly expensive to develop. They are only environmentally friendly when CO_2 is captured from air and renewable electricity sources are used (this would also require an extensive expansion of renewable energies far beyond what is necessary for the battery electric driven vehicles. No meaningful investments into production or plans to employ this technology for road transport have been made so far (Transport & Environment, 2017).

4.3 Transport refrigeration unit

The refrigeration unit of transport refrigeration vehicles in most cases (over 90% of long-distance transport (Süß & Altebäumer, 2021) is based on compressor driven refrigeration systems. Existing refrigeration systems using compressors are mostly either powered directly by the vehicle engine or by a separate diesel engine. There is however a niche market for electrically powered TRUs.

4.3.1 TRU energy system

Separate diesel engine
Most refrigeration units, especially with higher cooling capacities, are driven by separate diesel engines. The advantage of these systems is their complete independency of the engine. However, they consume between 2 and 4 l additional fuel per hour and are relatively noisy, which can lead to restrictions during night-time deliveries. These diesel units are hardly ever regulated and have far higher emissions of potentially carcinogenic particulate matter and NOx than the diesel engines of the vehicles. These are up to 90% higher than the Euro 6 standard for vehicle engines (Süß & Altebäumer, 2021). Over the course of one year, a TRU unit will emit about 90 times the amount of NOx and 165 times the amount of potentially carcinogenic particulate matter (PM2.5) (Dearman, 2015).

Belt driven
In smaller refrigerated vehicles, and/or when the cooling need is relatively low, the compressor of the refrigeration system is often directly connected to the vehicle's engine via a belt system. These direct drive refrigeration units are comparable to air conditioning units in passenger cars. Because of the open compressor and the refrigerant tubes between engine room and body, leakage of refrigerant is typically rather high. The compressor speed and therefore the amount of generated cooling are related to the engine speed and can be low if the engine is idling or driving at low speed.

Electrically driven
Moving towards zero-carbon emissions requires the transition to electrically driven TRUs. These can be powered by alternators or batteries and theoretically also by fuel cells once the technology is developed to market readiness.

Alternator-driven units have been on the market for several years for vans and smaller trucks. Here, a compressor is driven by an alternator, which in turn is connected to the vehicle's diesel engine. The mechanical energy of the motor is converted into electrical energy via an alternator. Sometimes the engine can charge a battery at the same time, which can be used to power the TRU when the engine of the vehicle is switched off during deliveries or other stops.

These systems are considered more environmentally friendly compared to TRUs with their own diesel unit as the vehicle engine is much more efficient (around 45 %) compared to the separate diesel generator of a refrigeration unit (with efficiencies of 20-25%) and also emits less harmful substances and CO_2. These systems are also inverter driven and are associated with lower refrigerant emissions (Carrier, 2021) than belt-driven systems.

There are several manufacturers offering electric coupling and electrically driven refrigeration systems, such as Frigoblock (Germany), Carrier (the Pulsor product range), Zanotti (the Transblock range). For large trucks and all kinds of trailers, independent cooling systems are the only option merely due to the needed output power.

Battery driven units are now on the market for vans and small trucks, but this sector is very much still in development. Products are on the market for example by Thermoking (n.d.), Daikin/Zanotti (2020), VoltaAir (n.d.) and Kingtec (n.d.). The systems are plugged into the power grid when the vehicles are stationed for charging. Carrier has developed a system that can be re-charged during operation by a generator on the axle of the vehicle (Carrier, 2020). While the weight of batteries is often quoted as being important for the range of electric vehicles, the electric TRU systems including battery are said to be lighter than conventional units including a full diesel tank (Carrier, 2020).

Batteries have advantages over belt-driven systems as they are fully independent of the motor and motor speed. They are also quieter than diesel generators and can be regulated very well depending on the cooling demand of the system.

Integrating battery electric vehicles and TRU
The TRU can be either be connected to the vehicle's battery or come with its own battery (see above). When connected to the vehicle battery, we have estimated that the TRU would consume only up to 20% of the battery power. In most cases, the vehicles would still be able to meet the usual range requirements.

Regenerative breaking is implemented in more and more commercial vehicles. Here, electricity is generated during breaking and can for example be used to recharge the battery of an electric vehicle. The range can be extended by about 20% (Morgan, 2021) The system is especially useful in combination with refrigerated vehicles, even on internal combustion engine vehicles. Several systems are already marketed or in development. They promise extensive energy savings and replacement of diesel units (THT New Cool (n.d.), Cousineau (2022) providing energy for up to one hour when the vehicle is standing (Nallinger, 2016). Payback time in one example is estimated to be about two years of operation (Gustafson, 2018).

Similarly, solar panels on the truck roof or its sides can also contribute electricity to the battery of the refrigeration system, an air conditioing unit or the truck itself (e.g. ISE, n.d.; Volkswagen, 2020).

4.3.2 TRU refrigerants

Transport refrigeration is, similarly to mobile air conditioning, a global market with relatively few global manufacturers dominating the market of refrigeration units. This has led to relatively uniform technology solutions, including the use of refrigerants, both in countries of the Global North and countries of the Global South (Clodic et al., 2013). It further means that regional legislation, such as the EU F-Gas regulation will have an impact on the global technology market. In transport refrigeration, currently only HFCs are used. They have no ozone depleting potential (ODP), but very high GWPs.

- The main refrigerant used in trucks and trailers is R404A. It has the highest GWP (3,922) of all commonly used HFC refrigerants (UNEP, 2019).

- Especially smaller trucks used for cooling only (no freezing), run on R134a with a GWP of 1300 (UNEP, 2019).

Current and future trends

- The following synthetic refrigerants have now been introduced or are in discussion for an introduction:

- Since 2015, R452A has been introduced in Europe in order to meet restrictions on refrigerant use due to the F-gas regulation. It has a GWP of 2,141, which is too high to achieve a significant reduction in emissions.

- Refrigerants R448A and R449A have GWPs around 1,400 and could be used in an adjusted TRU design (UNEP, 2019). As of yet, it has not been adopted by industry and due to its relatively high GWP can only be considered as an intermediate application. It is not clear if the necessary research and development will be done.

In order to profoundly reduce direct refrigerant emissions and achieve zero emission transport refrigeration, natural refrigerants with zero or negligible GWPs have to be used if the cooling demand by vapour compression refrigeration cannot be reduced.

Box 8: Case study R290 TRU "productbloks"

Productbloks: First R290 TRU in series production

The company has developed the first zero emission electric R290 transport refrigeration unit to become market ready. The unit has been field tested since 2020 and production has started in 2021.

The unit has been specifically designed for electric vehicles and is connected to the traction battery of the electric vehicle. This reduces the range by only 5-7%. It can also be connected to cargo bikes.

The refrigeration unit is hermetically sealed and only contains 140 g of R290 refrigerant. Leakage is therefore unlikely or not dangerous (for comparison: household refrigerators contain up to 150 g hydrocarbon refrigerants). In case of maintenance and repair, the unit can be removed from the vehicle for repair by people with the relevant knowledge.

The unit is certified according to:
- ATP (in process)
- DIN EN 60204-1:2019-06: Safety of machinery – Electrical equipment of machines. General Requirements
- EN 378-1-4 Refrigerating systems and heat pumps – Safety and environmental requirements
- CE (in process)
- Good distribution practices (GDP) certification for pharmaceutical industry

Information can be found at pbx.at.

- The hydrocarbon refrigerants propene (R1270) and propane (R290) are both very suitable for transport refrigeration from a thermodynamic point of view. Hydrocarbon units are estimated to be between 5-15% more efficient than units running on R404A or R410A. They will not be subjected to restrictions because of environmental reasons as they have a GWP of below 1 and no toxic degradation products. They are easily available and cheap and not subjected to intellectual property rights. They therefore have a high security of investment for companies.

- Because of their flammability, they have long been perceived as dangerous. However, with a move towards low-GWP refrigerants due to the Kigali Amendment and the EU F-gas Regulation, most future refrigerants will be flammable. This means that the focus in research and development has switched towards increasing safety concepts and leak tightness as well as risk evaluation (Koenig, 2021). A newly established standard committee has started to work on establishing a safety standard for temperature-controlled systems using flammable refrigerants for the transport of goods – requirements and risk analysis process (as part of CEN TC 413). With proper safety measures, training and information systems in place, the real dangers of hydrocarbons in refrigerated transport are smaller than perceived and manageable. CO_2 (R744) is a very environmentally-friendly refrigerant with a GWP of 1 and low toxicity. It has been shown to be more efficient than synthetic refrigerants in mobile air conditioning systems at ambient temperature of up to 30°C (Hrnjak, 2010). Carrier Transicold has developed a refrigerated container using CO_2 refrigerant, NaturaLine, which is available on the market (Container Management, 2019, Global Cold Chain News, 2021) and more than 2,200 units are in operation already (RTOC, 2019). For road transport, there are trials using adapted NaturaLine systems for road transport since 2013 (RTOC, 2019).

The natural refrigerant ammonia is not considered for transport refrigeration apart from fishing vessels.

Safety concept for flammable refrigerants
Systems using flammable refrigerants require a safety concept that reduces their risk by making sure that refrigerant does not leak or only minimally and that if it does leak, it does not come in contact with a source of ignition. As part of a GIZ project in South Africa on environmentally friendly transport refrigeration, a demonstration unit using R290 as refrigerant was developed (Colbourne et al., 2017). The safety concpet included the following steps (Colbourne et al., 2017), unless otherwise stated):

- Reducing charge size: The amount of R290 refrigerant reduced whilst maintaining the same cooling capacity of the system. This was achieved by e.g., reducing condenser and evaporator tube size, liquid receiver and accumulator. The charge size was reduced to just over 0.6 kg for a system with a capacity of 8 kilowatts (kW) at medium temperatures. Reduction of charge size was also the first risk reduction measure implemented by Productbloks (see Box 8).

- Reducing leakages by using semi-hermetic (Colbourne et al., 2017) or hermetic design (Productbloks): This was achieved by using components that comply with standards on the tightness of components and joints, protection against ice damage, the elimination of vibrations and a strong steel housing that protects against damage. It was based on a thorough analysis of frequently occuring leaks at conventional units with a similar design.

- Removing sources of ignition in areas where high refrigerant concentrations might occur: In leak simulation experiments, areas where flammable concentrations of refrigerants could occur were identified. In those areas, potential sources of ignition were then eliminated. Examples are the cover of the electrical panel that seals against refrigerant and explosion proof cable glands. Further, the starter motor and diesel engine air intake were identified. Here, pre-purge ventilation was impmlemented before the diesel engine can be initiated.

- Installing automatic shut-off in case of (catastrophic) leakage: A regular leak detection sensor was not found suitable for the installation in a transport refrigeration unit. A system was therefore developed based on system parameters, such as standard temperature and pressure measurements. In case of a leak, paramters deviate from their set-points and the system shuts down automatically, thereby reducing the amount of leaked refrigerant. The driver is further notified by an alarm system. While this system is less sensitive than a gas sensor, it is reliable in the long-term and no calibration or maintenance is necessary.

- Risk assessment and compliance with safety standards: A risk assessment of the prototype was conducted, assessing different optating modes, load conditions etc. Compliance of the R290 unit with relevant safety standards from the refrigeration and air conditioning field was further tested.

- Capacity development/ servicing and maintenance procedures: Handling of units during servicing and maintenance always increases the risk as the skills and knowledge of technicians have to be taken into account and increased appropriety. For a company, it is therefore important to offer trainings to all their technicians and put in place procedures that ascertain that the units are only handled by trained technicians.

Leakage
The charge sizes of refrigerant ranges from several hundred grams in small trucks to 10 kg for large trucks and trailers (RTOC, 2010).

Yearly leakage rates of refrigerant in transport refrigeration are high compared to other cooling applications because of the constant strain on system parts on the roads. Yearly emissions are higher in small trucks where the refrigeration unit is often belt-driven and the compressor needs to be a non-hermetical system; annual leakage here can be 25% and 30% of total charge for older vehicles (Clodic et al., 2013). In new trucks the initial leakage can be as low as 13% (Clodic et al., 2013). The average for all trucks, trailers and vans is estimated at 20% in the EU and 25% in countries of the Global South (Schwarz et al., 2011). Apart from the yearly leakage, considerably leakage also happens at the end of the lifetime of the equipment, where in many countries all remaining gas is released into the atmosphere. A factor for refrigerant leakage is the service frequency and quality: Proper maintenance by professional mechanics can reduce leakage significantly.

4.4 Vehicle insulated bodies

The body of a refrigerated vehicle has a high influence on the energy use of the refrigeration system. Its walls are thermally insulated, and the material used for insulation is usually rigid polyurethane (PU) foam. Extruded polystyrene (XPS) or expanded polystyrene (EPS) are sometimes used. All have high durability and stability and are produced by a foaming process where blowing agents are added to the raw materials. Blowing agents can have high ODPs and GWPs, but natural blowing agents are available with no or negligible GWPs.

Both the material used and the design and manufacturing quality contribute to the ability of the refrigerated vehicle to reliably hold the set temperatures. Insulation qualities of the bodies are a parameter which can vary much more than for the refrigeration units themselves as there is often no comparative testing of products. Poor quality results in higher fuel consumption, but as the fuel consumption also depends on the refrigeration system, operation practices etc., a poorly insulating body is not spotted easily.

The established industry standard for insulation is the heat transfer coefficient, or k-value (in Watt per square metre and Kelvin, W/m2K) as established through the ATP requirements. It is determined for the whole vehicle and depends on the thermal conductivity, which describes the heat transfer through the insulation material (in Watt per meter per kelvin, W/(m·K) or megawatt per meter per kelvin, mW/(m·K)), and the thickness of the material as well as on the quality of workmanship. The lower the k-value, the lower the heat transfer and therefore the better is the insulation.

Refrigerated vehicles should have a maximum k-value of 0.4 W/m2K for frozen goods and of 0.7 W/m2K for chilled goods according to the international ATP agreement on food safety. There is a trade-off as thicker walls result in higher insulation, but reduce cargo volume and increase weight, which increases fuel consumption and thereby emissions. Typical wall dimensions are 80 mm for the roof, 100 mm for the floor and 65 mm for the sides, the front and the doors. The thickest walls on the roof and the floor protect from high solar radiation load and the hot road surface.

The importance of the k-value for food security (Estrada-Flores & Eddy, 2006)

Five comparable vans, which were only distinguished by their k-value, were tested for the pull-down time from 38°C to 2°C and for their ability to always cycle back to the set temperature of 2°C after multiple door opening.
The pull-down time of a van with the k-value of 1.24 W/m2K was twice as long (3.6 h) as that of a van with a k-value of 0.88 W/m2K (1.77h). In a slightly larger van with a k-value of 1.11 W/m2K, the set-temperature was not reached at all. High k-values also led to the set-temperature not being reached after multiple door openings.
Because of the higher heat load, bigger refrigeration units have to be installed, and more energy is consumed in order to reach set temperatures. In the worst case, bad insulation means non-compliance with food security regulations if temperature levels are exceeded or goods can be lost because they spoil.

Material used
The insulation efficiency depends on the blowing agent and thereby the thermal conductivity of the foam, the foaming technology and manufacturing process used, the kind of facings that are applied, the cell structure and the thickness of the foam panels. Insulation efficiency values can be determined according to standards, which take all these factors into consideration.

The thermal conductivity of PU (20-22 mW/m·K) is lower than that of XPS (30 to 35 mW/m·K) or EPS (28 to 35 mW/m·K), which makes it more suitable for the transport of frozen goods. Because of the lower thermal conductivity of PU foam, for the same thickness of panels a better insulation value is achieved than with XPS panels.

The blowing agent is added to the raw materials to generate the foam structure. HCFCs are still used in some countries of the Global South, but often HFCs, natural blowing agents such as hydrocarbons or CO_2/water, or other substances like methyl format are used.

In countries of the Global South, HCFC-141b is still often used (FTOC, 2019). The Multilateral Fund of the Montreal Protocol is supporting the conversion to low-GWP blowing agents, but the process is slow. A wide range of companies is involved, and it takes time to assess their needs, purchase equipment for alternatives and commission new plants (FTOC, 2019). However, the cost of HCFCs is increasing and this is speeding up the conversion (TEAP, 2021).

The conversion to high-GWP HFC blowing agents, e.g. HFC-365mfc, HFC-245fa (both with GWPs of around 800, higher if HFC-227ea is mixed in), is relatively easy. Even though the chemicals are more expensive, there is little need for expensive equipment (FTOC, 2019). In the EU, their use will be forbidden from 2023 onwards because of their high GWPs.

Hydrocarbon (HC) blowing agents (cyclo-, iso-pentane and blends thereof) have been used for a long time with very good results regarding the foam properties. Operating costs are very low, but high investment in equipment is necessary, as well as training for staff on the safe use of flammable substances. More than half of the blowing agent demand is met by HC blowing agents (FTOC, 2019).

Unsaturated HFCs and HCFCs (also called HFOs/HFCOs for marketing purposes) are being introduced, though they are still very expensive and especially in the last year there have been supply shortages (TEAP, 2021). The following substances are on the market: HFO-1234ze(E)20 (, HFO-1233zd(E), and HFO-1336mzz(Z); chemical companies have received patents for HCFO-1224yd and HFO-1336mzz-E as foam blowing agents only recently (FTOC, 2019). HFOs/HCFOs can be used where flammable substances are not allowed, e.g. spray foam.

HC with HFO/HCFO or HFC blends are reported to have even better thermal insulation properties compared to HCs or HFO/HCFOs alone (FTOC, 2019).

In Europe, methyl formate is hardly ever used as blowing agent for rigid PU panels. Higher densities in the foam would be necessary, which increases the weight and therefore the fuel consumption whilst decreasing the possible cargo load.

Table 3: Comparison of the quality of different blowing agents in PU

	Foam insulation
Pentane	+++
Methylformate	++W
HCFC-141b	++++
HFC-245fa	++++

Source: HEAT

Every year, 0.2-0.5% of blowing agent escapes from rigid PU panels (SROC, 2007). As there is no established recovery method for foam blowing agents or recycling for PU panels in transport refrigeration, it is assumed that all the blowing agent is eventually released in the atmosphere. Proper dismantling and disposal require specialist facilities and/or high-temperature incinerators.

Manufacturing process
There are two dominant manufacturing processes which influence the insulation qualities of foam panels:

- Directly injected PU foam is injected into a mould (press) with a foaming machine where the facings are placed. The facings can be steel or glass fibre, with glass fibre insulating better and being lighter but less robust and stable. The advantage of this method is a generally high insulation value, making this the highest quality panels. However, initial investment costs are high as a press is needed that can sustain a pressure of 2 bar and additional foaming equipment.

- Composite panels are made from PU boards to which either glass fibre epoxy is sprayed, or steel facings are glued. Using a press is recommended for this, but it is possible to use a press with lower clamping force compared to directly injected PU, which brings down investment costs. The press uses a vacuum to clamp and a heating system for optimal application of the epoxy. Not using a press is possible but is likely to create gaps between the beams and the core, which lead to reduced structural strength. The heating accelerates/activates the polymerisation.

Composite panels allow for greater product flexibility and are a lightweight option if used with glass fibre for maximum loading weight. Their thermal conductivity is higher, and the quality highly depends on the quality of the press. Furthermore, glass fibre panels are easy to repair, and less steel working equipment is needed.

The degradation of the insulation performance (measured as k-value) is approximately 3-5% per year. A truck body that just passes certification according to ATP when it is new might not do so after a few years.

An alternative to PU foams are vacuum panels. Vacuum insulation panels (VIP) have thermal conductivities about 5 times lower than PU (Fricke et al., 2008). Sheets as thin as 20 mm can have long-term insulation effects and are used in the insulation of buildings. The probably biggest challenge for road transport is the fact that when a sheet gets damaged, the vacuum normally is lost, together with the insulation effect. Transport refrigeration with its constant impacts during road transport puts much more stress on the insulation panels than the use in stationary applications.

Design

Transport refrigeration vehicles are designed and constructed in a way to meet several objectives, in particular a high insulation, minimum weight, robustness and a maximum loading volume.

Materials with excellent insulation values, produced in state-of-the-art manufacturing processes will only improve refrigerated transport if they are designed and assembled properly. The following problems are identified:

- Lack of dimensional stability and accuracy leads to thermal bridges, e.g. gaps in the body structure.
- Steel plates supporting the frame of doors can enter the body and are not decoupled from the outside structure (chassis), thereby leading outside heat directly to the inner body.
- Lack of dimensional accuracy of the steel support frames for doors results in doors not being closed properly or the rubber sealings being compressed unequally. This leads to a non-airtight body and resulting thermal loss.
- Thermal bridges such as structural pockets, air gaps, metallic latches, structural ribs, hinges, rivets or screws (Estrada-Flores & Eddy, 2006).

Multi-temperature units allow for the transport of frozen, fresh and non-refrigerated goods in the same vehicle, reducing the number of vehicles used for distribution. In these vehicles, inside insultation is also included to keep different compartments at different temperatures.

There are no significant hurdles for small companies from general body construction or other related industries to enter into producing and offering insulated bodies for refrigerated transport. It can generally be assumed that markets without standardized testing procedures have lower quality standards for insulated bodies than countries with a rigorous testing regime as e.g. applied in Europe.

Box 9: GIZ Project in South Africa

Mitigating emissions in the transport refrigeration sector in South Africa

The project was implemented between 2012 and 2016 with the goal to introduce innovative logistics and supply structures in the South African transport refrigeration sector. As a result: :

- A thermal test chamber was installed in South Africa with the ability to test the quality of insulated bodies and refrigeration equipment.
- A South African standard for testing refrigeration units and the insulation quality was developed.
- Manufacturers of insulated bodies were supported in improving their processes and design. This reduced the needed capacity of the refrigeration unit.
- A prototype R290 refrigeration unit for trucks was developed in cooperation with a South African manufacturer. The unit is driven by an alternator-electric compressor and has improved energy efficiency compared to comparable diesel units.
- Trainings for logistics companies were conducted.

4.5 Logistics and operation

The fuel consumption of the refrigeration system is not only influenced by the refrigeration system design and quality and the insulation qualities of the body, but also by operational practices.

Operational practices are often not standardized and rules on cold chain and food product quality are loose or non-existing. Accordingly, practices still have scope for improvement, which would lead to better food product quality and safety, and mostly also to lower emissions.

4.5.1 Minimising thermal load increase due to door openings

The main increase of the heat load within the refrigerated body depends on the type of transport. For long-distance transport in large trucks or trailers, this is through the surface of the body. For vehicles in the distribution of goods on a local or regional level, the number of door openings is the main source for heat load increase. The heat load increases linearly with the number of door openings.

The required cooling capacities of a TRU, based on the different heat loads, such as through the walls, door opening or thermal bridges, must exceed the expected heat load by a reasonable margin to achieve the pull-down directly after door openings etc. Reducing heat loss therefore reduces the needed capacity of the TRU and thereby GHG emissions.

Table 4 illustrates the required cooling capacities for four different cases. These differ by the quality of the insulation, as indicated by the k-value, and the number of door openings per hour. One extra door opening per hour approximately increases the required cooling capacity by 2.5 kW for this vehicle size class. A higher k-value, represented by an older body, increases the required cooling capacity by about 2 kW.

Table 4: Required cooling capacities in relation to the number of door openings and insulation properties (based on ATP requirements for TRU capacities depending on door openings and k-values)

	K= 0.4 (new)	K=0.6 (9 years)
2 door openings/h (3 min each)	5.7 kW	7.1 kW
5 door openings/h (3 min each)	13.8 kW	15.7 kW

The higher cooling need for vehicles with frequent door openings is due to two factors. Firstly, every door opening is connected to an influx of hot air, which in turn needs cooling down. Secondly, the refrigeration unit is usually switched off during door openings in order to prevent condensation of hot and humid air on the evaporator. This frosting leads to inefficient operation and the need for regular defrosting. The accumulated time where the refrigeration unit is not operating has to be balanced by higher cooling capacities.

There are several options to reduce the higher energy requirements due to door openings:

- Logistics and planning: Minimising door openings by optimising delivery routes and schedules. Many European countries have sophisticated bar code scanning systems in place where goods are commissioned and pre-packaged just-in-time according to the customer needs prior to loading. This way, the unloading times and heat losses during unloading are minimised. Goods are traceable throughout their journey, ascertaining food safety.
- Installing automatically/easily closing doors decreases the time hot and humid air can enter the vehicle body.
- Plastic strip curtains or air curtains. Plastic curtains have been shown to reduce energy use by up to 30% (Tassou, 2009). They are easy to install, cheap and effective if used correctly. Tying curtains to the side (which happens in practice for practical reasons) obviously renders them ineffective. They can also yield to be counterproductive if their presence leads to insulated doors being open for longer. Proper training is therefore advisable. Air curtains, where conditioned air is blown vertically over the truck opening could even save up to 40% compared to no barrier (Tso et al., 2002). However, these are only effective in temperatures below 40°C, are more complicated to handle and expensive.

4.5.2 Air flow management

Air flow management is important in trucks for regular temperature distribution throughout the cargo. The evaporator is usually located towards the front of the body, but thermal load increase takes place all over the body's surface and especially at the door if it is opened frequently. The air flow management is influenced by the design of the refrigerated bodies and also by the placement of the loads, i.e. the loading management practice.

Air flow management can be improved by using air ducts, which lead the cooled air to the back of the body. It has been shown that the temperature in a body is more homogeneous throughout compared to a similar body without air ducts (Moureh & Flick, 2004).

Equally important is sufficient free space for the air flow on the back, top, bottom, sides and front of the load. This is often not considered as it is sometimes in a trade-off with the loading area; however, it is absolutely essential to ascertain that all parts of the loaded goods can be cooled (Moureh & Flick, 2004). Some body builders include structures (stoppers etc.) that make it impossible to block these air flow corridors. An alternative is the training of drivers on air flow management.

4.5.3 Precooling

Transport refrigeration units are, however, not optimally designed for the cool-down of goods to the required temperature, which is meant to be done by stationary cooling equipment at the loading site. Neglecting the pre-cooling of goods can result in perishing of goods as well as increased energy consumption of the refrigeration unit. Cold store design, especially including a protected loading bay, is also important to transfer goods with as little exposure to heat as possible.

4.5.4 Train & Intermodal transport

The emissions from the vehicle engine contribute the highest share to overall emissions from refrigerated road transport. Transferring goods to intermodal transport where containers and trailers are loaded on trains for part of their transport distance can reduce emissions, especially if the country has a high share of renewable energy sources. High emission reduction can be achieved if distances are very long, goods are always transported along certain corridors and goods are easily palletizable (Havenga et al., 2012).

A comparative study between different transport modes found intermodal to be the transport with the lowest amount of energy use considering both transport and spoilage of goods (Vanek & Sun, 2008). Not all rail transport is more environmentally friendly than road transport. Rail can for example have a higher rate of perishable goods than road transport (Vanek & Sun, 2008).

4.6 Service & Repair

Leakage of refrigerants with high GWP occurs during use, repair/maintenance and at the end of life of a TRU. Leakage during repair, maintenance and at the end of life can be reduced by using recovery units and storing recovered refrigerant for recycling, reclamation or proper disposal. However, only few technicians are equipped with recovery units and cylinders as well as the knowledge on how to properly recover refrigerants. This usually results in venting refrigerants to the atmosphere.

It is further possible to reduce in-use leakage and need for repair by regular maintenance of TRUs. Also here, it is important that technicians are well educated in their use. Regularly maintained TRUs will also have higher energy efficiency and less breakdowns. This can be especially costly if high-quality goods are transported over long distances.

4.7 Technical requirements and capacity building to support moving towards net zero transport refrigeration

Survey the quality of insulated bodies and the state of manufacturing

- Which foam blowing agents are used (HPMPs and National Ozone Units are likely to have all relevant information)?
- Survey body builders on manufacturing processes and designs used
- Use infrared cameras to identify heat bridges
- Use simple pull-down tests, where it is measured how long it takes to reach a set temperature within the insulated body. Ideally, this is done in a temperature-controlled environment or under similar conditions for the comparison of different vehicles. Results will differ for different ambient temperatures.

Survey current logistics practices

- Is pre-cooling of goods being practiced?
- How are door openings being handled during loading and distribution?
- What is the availability of technical tracking options, e.g. real-time temperature monitoring, route planning, monitoring of door openings?
- Are drivers equipped with guidelines or handbooks on good practices? Which trainings are given to drivers? Is transport refrigeration included in vocational education programmes?

Based on the results of these surveys, further actions can be determined, e.g. the implementation of regulations and standards (see above), or trainings for companies and drivers.

Key areas to be addressed through servicing & repair trainings are:

- Improvement of maintenance capacity by introducing training of teachers. The quality of maintenance has an effect both on the leakage of refrigerant (high-GWP emissions) and the efficiency of the units (fuel emissions).
- Improved inspection & maintenance practices: Trainings on awareness building for a better floor and roof inspection (to operators), infra-red camera training in order to detect thermal bridges of body.
- Refrigerant recovery during repair.
- Handbook/guideline development and training on logistics, including pre-cooling, door-opening, air-flow management and the importance of regular maintenance activities.
- Analyse vocational education programmes for drivers and servicing personnel and, if necessary, include information on TRUs and their proper operation, maintenance and repair.
- Integrate knowledge on battery electric vehicle into existing training programmes, e.g., on electric truck technology and its operational requirements and operating guidelines for battery usage efficiency.

5 Commercialisation and financing options

5.1 Cost comparison

For a cost comparison, the total cost of ownership of the vehicle is considered. This includes initial, operating and maintenance costs. If the total cost of ownership of electric drive vehicles and TRUs is lower compared to internal combustion engine (ICE) vehicles, a high market penetration can be reached even before restrictive legislation is introduced or implemented.

The development of prices depends highly on technical development. However, it can also be steered by introducing incentives and supporting legislation or disincentives for ICE vehicles.

The main driving factor in are battery costs and those for the fuel cell technology, which make potentially zero emission vehicles considerably more expensive than diesel trucks.

On the other hand, in many countries costs for electricity are already cheaper than diesel costs. If a vehicle is used for long distances, the lower operating costs might then set off the high investment costs for the vehicle.

Maintenance costs are estimated to be 20 – 50% lower (Cunanan et al., 2021; Burke & Sinha, 2020) than those for ICE vehicles as the powertrain is much simpler and does not have as many moving parts as the engine in diesel vehicles that need servicing and replacing regularly.

Figure 15 shows an overview of different costs associated with refrigerated vehicles.

Figure 15: Overview cost comparison between battery electric vehicle (BEV) and internal combustion engine (ICE) refrigerated vehicle.

Initial cost vehicle	• 1.3–>4 times cost of diesel truck (higher factor for larger vehicles). estimated to go down to about 1.5 times the cost in 2030
Initial cost refrigeration unit	• 1.6–2.8 times higher for electric drive TRU (including battery pack)
Operating cost	• Electricity vs. diesel cost depends on local conditions • Operating cost for battery electric vehicle estimated cheaper than for fuel cell • Natural refrigerants are cheaper than low-GWP HFO options
Maintenance cost	• 20-50% cheapter than diesel vehicle and diesel generator of TRU • Increased servicing cost for flammable refrigerants
Charging infrastructure	• Fast charging more expensive than slow charging infrastructure • Charging infrastructure hydrogen estimated more expensive than charging infrastructure battery electric vehicle

Sources: Cunanan et al., 2021; Burke & Sinha, 2020; Basma et al., 2021; California Air Resources Board, 2021b.

Cost/effort charging infrastructure

Table 5 shows that there is no clear-cut winner between fast and slow charging strategies. The strategy to be chosen depends highly on the supply chain in question and already available infrastructure along the major routes.

For battery electric vehicle () refrigerated vehicles with ranges of 200-300 km that are now coming on the market, a slow charging strategy might be optimal. Charing can take place at the daily terminal station of the trip. Investment in slow-charging points is then comparably cheap.

Investment in fast charging infrastructure on the other hand cannot be achieved by a single operating company of refrigerated vehicles. Joint ventures by several big companies or a publicly supported or run network are necessary. In Europe, several trucking companies are currently planning to invest 500 million Euros in the establishment of 1,700 fast charging points only (Mercedes Benz Group, 2021).

Table 5: Comparison of fast and slow charging strategies

Parameter	Fast charging	Slow Charging
Battery size	Smaller batteries suffice and they bring down initial cost and overall weight, thereby reducing operating costs.	Large battery needed to meet required range over a day's work.
Location of charging stations	Needs network of fast charging stations enroute for top up of battery charging in addition to those at terminal nodes (cold storage, warehouses, processing units, dairy plants).	Needs charging stations only at terminal nodes.
Initial and operating costs	Reduced initial cost because of smaller battery. Reduced operating cost because of lighter vehicle.	Higher initial cost and operating cost on account of bigger and heavier batteries.
Battery life	Battery deteriorates much faster leading to early battery replacement.	Battery lives longer and reaches its end of life (EoL) closer to the rated values.
Operational ease	Much less flexibility due to limited spread of opportunity charging infrastructure.	Provides flexibility to operate anywhere within the limits imposed by range per charge.
Power infrastructure	Will require upgrades to power transmission network to manage surges in power withdrawals from the network. Long-term planning for fast/rapid/ultrafast mega-charger infrastructure alongside the provision of charging stations in order to avoid negative impacts on the electrical grid.	No immediate need for major upgradations for smaller and spread-out charging stations while it gets necessitated with increased electric fleet induction and power demand over time.

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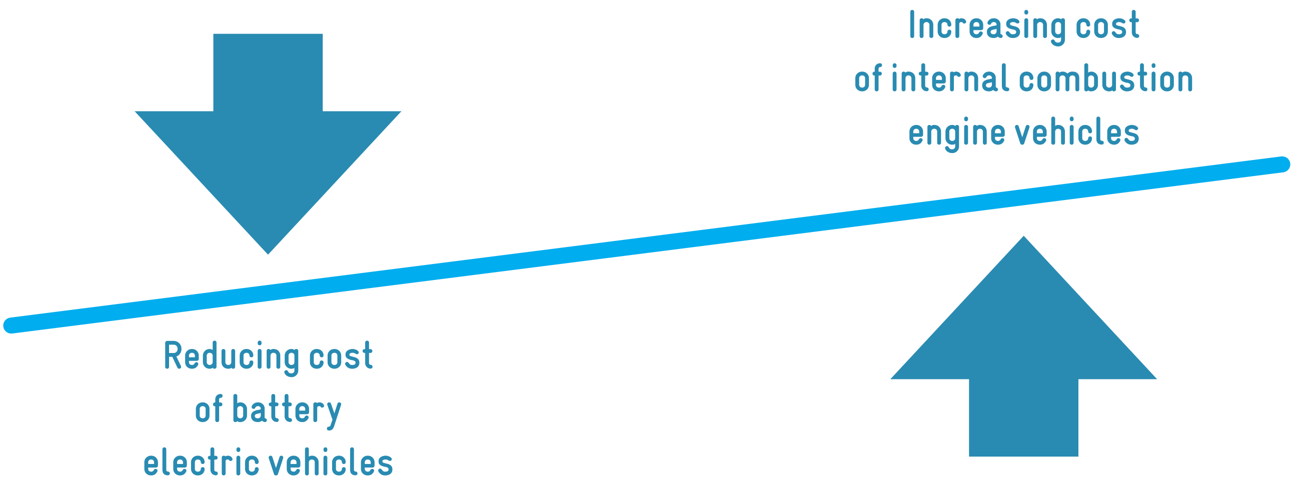
5.2 Policy measures to close financing gaps

From the cost comparison, it can be seen that there are still high differences in initial cost for battery electric vehicle (BEV) and electrically driven TRUs compared to internal combustion engine and TRUs operated by diesel generators or the vehicle motor. Operators also have to invest in charging infrastructure as a public net of charging points has not yet been developed. There are several policy measures that can be implemented with the aim of decreasing total cost of ownership of BEVs and at the same time increasing it for internal combustion engine vehicles. A comparison is shown in Figure 16.

Figure 16: Policy measures promoting the use of battery electric vehicle (BEV).



Sources: IEA (2021b), Basma et al. (2021).

Making electric vehicles/natural refrigerant TRU cheaper or more desirable	Making internal combustion engine vehicles more expensive
• Purchase subsidies • Subsidies for charging infrastructure	
• Differentiated taxes on fuel and vehicles	• Differentiated taxes on fuel and vehicles • Taxes on high-GWP refrigerants
• Road toll reduction, extra bonus for natural refrigerants	• Road tax on diesel truck operation • CO_2 external cost added to road tolls (including refrigerants)
• Free parking • Allowed to exceed class weight limits • Zero emission zones • Permitted nighttime deliveries of refrigerated goods	• Battery lives longer and reaches its end of life (EoL) closer to the rated values.
• Much less flexibility due to limited spread of opportunity charging infrastructure.	• Prohibited circulation zones
• Financing for research and development (R&D) of battery technology	

Basma et al. (2021) have identified effective policies that will lower the battery electric vehicle (BEV) truck total cost of ownership to levels similar to that of diesel trucks. Assuming that the cost of the vehicle is similar globally, national differences in total cost of ownership are due to the operating costs such as electricity prices, taxes, and road tolls. The analysis shows that especially high purchase incentives and a reduction of road tolls for electric vehicles or increasing road tolls based on CO_2 emissions can significantly lower the total cost of ownership of BEVs, thereby making them commercially viable.

5.3 Financing options

Figure 17 illustrates climate financing options for the transition from conventional refrigerated transport to electric refrigerated transportation with natural refrigeration TRUs.

Public climate finance, international or national, is critical for financing the development of electric transport vehicles and their infrastructure at the research, design and development (RDD) and demonstration stage.

Public grants play an essential role for kick-starting and implementing the regulatory policy framework and for initiating **public-private partnerships**. These are important to initiate and develop the engagement of the private sector and their **equity investments** along the value chain, e.g., investing in charging infrastructure, in vehicles and their TRU on pilot routes or developing servicing models such as leasing models etc.

Concessional or soft loans are critical for financing the upscaling of the business case and the transformation to net zero transport refrigeration and its necessary infrastructure, particularly in countries of the Global South. Countries of the Global South usually have significantly higher risk premia and interest rates for loans. Soft loans or concessional loans have the potential to significantly lower the effective interest rates of lending and catalyse the financing of electrified refrigerated transport solutions, e.g., through a dedicated loan facility for this purpose.

Electrified transport vehicles and their infrastructure (load stations etc.) require a higher upfront investment but have lower operational costs through better energy efficiency and lower maintenance costs as well as lower fuel and refrigerant costs. Concessional or soft loans are an effective instrument for bridging the gap between higher upfront investment costs and lower running operational costs. Through the engagement of private banks, during the demonstration and initial deployment phase, in concessional loan schemes, the transition to the deployment and diffusion phase can be strategically integrated.

Figure 17: Climate finance options for the transformation to electric refrigerated transportation

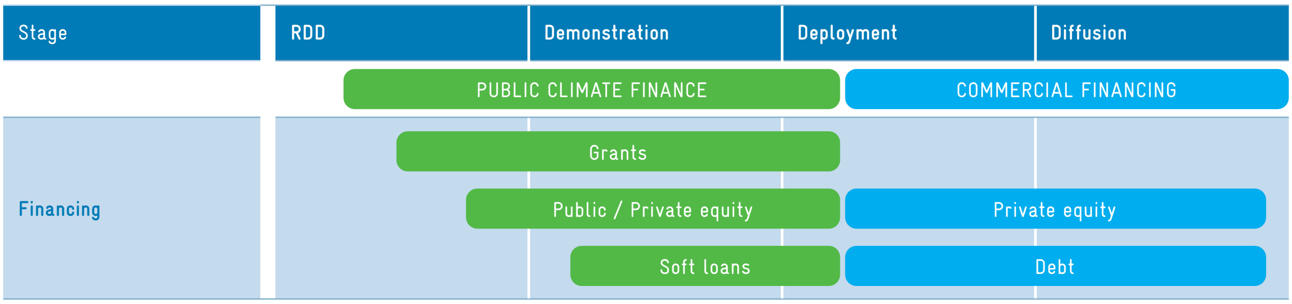


Figure 18 illustrates specific financial instruments which are available for targeting the sectoral transformation from conventional refrigerated transport to electrified refrigerated transport with natural refrigerants in the TRUs.

Figure 18: Low carbon cooling specific climate financing options

Funding/Financing	MLF	International climate	Public national	Private
	• MLF grant funding fill public financing gaps • Incremental funding principal • Co-financing with EE	• GCF/Readiness • GEF • MDB (Taxonomy, Blending) • IKI/NAMA	• Tax on HFCs • Tax on energy • Carbon credits/ destruction • NDBs	• Take back schemes • Bulk financing accross the fleet • Cooling as a service, contractual, leasing models • Climate/Green Bonds

- Multilateral Fund (MLF) of the Montreal Protocol: For the implementation of the phase down of HFCs, the MLF provides support for the implementation of the Kigali Implementation Plans (KIPs). The funding for the implementation of the KIP can be used for sectoral strategic planning of the phase down of HFCs for refrigerated transport, including the data collection for baseline determination and phase down and HFC reduction step planning, for the review and upgrading of sub-sector specific policies and regulation, the planning and implementation of the legal compliance framework, the implementation of quota and licensing systems. The MLF also encourages integrated strategies. Here a combined strategy, phasing down or phasing out HFC refrigerants with the transition to electrified refrigerated transport is a well-fitting strategy providing the synergies targeted under the KIPs.

- International climate financing from the Green Climate Fund (GCF), Global Environment Facility (GEF), International Climate Initiaitve (IKI) of the German Federal Ministry for the Environment, Nature Conservation, Building, Nuclear Safety and Consumer Protection (BMUV) or Nationally Appropriate Mitigation Actions (NAMA) can specifically address sectoral transformations with an integrated policy, technical and financial approach. Multilateral Development Banks (MDBs) and their corresponding National Development Bank (NDBs) can play an essential role in providing soft or concessional loans as described above.

- HFC taxes or levies on fossil fuel energy use can provide income and provide disincentives for the use of conventional high carbon refrigerated transport. The generated income can be used for providing incentives for the use of electrified refrigerated transport solutions. The destruction of HFCs possibly can be supported through market mechanism instruments under the Article 6 of the Paris Agreement.

- Private sector finance instruments include leasing models such as cooling as a service model, bulk fleet financing arrangements, also in combination with green or climate bonds. The combination of private sector financing and public financing instruments and the collaboration of private and public sector financing actors is advisable particularly during the initial phase.

5.4 Financing options to support moving towards net zero transport refrigeration

- Integrate TRU emission reductions into NDCs, NCAPs, KIP strategies in order to access international financing

- Develop proposals for international climate funding, e.g. for demonstration projects or policy support that introduce environmentally friendly refrigerated transport solutions.

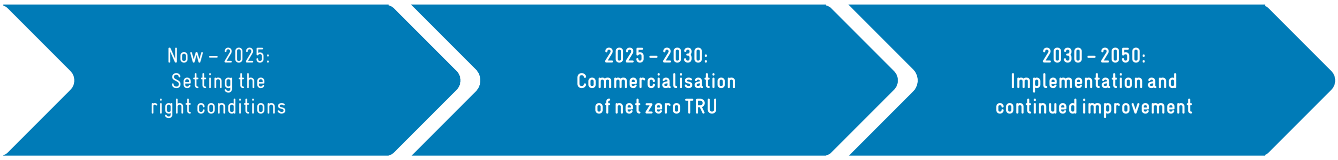
- Assess business cases in cooperation with local companies, e.g., on RDD projects and set up public-private partnerships.

6 Roadmap to zero carbon transport refrigeration

Reaching zero carbon emissions in transport refrigeration requires developments on the technical level, restrictive legislation and supporting policies regarding financing and building local infrastructure. The following timeline shows how these actions can be combined into reaching the goal of net zero carbon emissions by 2050.

Countries of the Global North

Figure 19: Roadmap to zero carbon transport refrigeration in countries of the Global North



- Commercialisation phase up to 2025: small city trucks with repetitive routes
- Commercialisation phase up to 2027: larger trucks
- Commercialisation phase up to 2030: trailers

Now – 2025: Setting the right conditions

Setting conditions for automotive companies and producers of TRUs to invest into the development of electric commercial vehicles and electrically driven TRUs using natural refrigerants and to expand their production capacities in these fields:

- Introducing bans of internal combustion engine motor vehicles for commercial and heavy-duty vehicles in countries of the Global North until 2040 as well as external diesel generators for refrigerated vehicles until 2035.

- Supportive financial incentives, e.g. purchase incentives, tax reductions and road toll reductions for electric vehicles with extra incentives given for battery electric refrigeration units and natural refrigerants.

- Supporting natural refrigerants in transport refrigeration, e.g., by developing technical standards on the safe use of flammable refrigerants and CO_2 in TRUs and offering training on the safe use of flammable refrigerants. Setting disincentives on high-GWP refrigerants such as taxes and higher road tolls and increasing responsibilities of operators with regards to leak checking and reporting of high-GWP refrigerant usage in TRUs.

2025 – 2030: Commercialisation of net zero TRU

- Expansion of charging infrastructure along major trade networks to enable long distance transport.

- Extend training of technicians regarding the use of flammable refrigerants and CO_2.

- Increased demand caused by incentives and regulatory measures enables series production of R290 and CO_2 TRUs

2030 – 2050: Implementation and continued improvement

- All new sales of TRUs and vehicles will be net zero.

- Review phase-down of high-GWP refrigerants use and increase effort in order to reach net zero emissions by use of natural refrigerants only.

Countries of the Global South

Figure 20: Roadmap to zero carbon transport refrigeration in countries of the Global South

Now – 2025:
Stocktaking and initiation

- Stocktaking of refrigerated vehicles and expected growth in order to meet cooling needs of Sustainable Development Goals scenarios.
- Assessment of required technical support, e.g., for logistics companies, body builders, training of technicians.
- Seek national cooperation between NOU and agencies responsible for traffic and agriculture
- Assess need for national investments and international finance support, both for industry players as well as on the national government level.
- Integrate transport refrigeration sector into NDCs and NCAPs and identify milestones for mitigation.

2025 – 2030:
Setting the right conditions & implementing demonstration projects

- Introducing bans of internal combustion engine motor vehicles for commercial and heavy-duty vehicles until 2050.
- Introducing bans of external diesel generators for refrigerated vehicles until 2040
- Implement technical demonstrations projects and policy support regarding net zero TRU introduction under NDCs, NCAPs or other international financing programmes.
- Incentive programme for logistics companies to set up charging structure at warehouses and depots. Extra support for renewable energy connection.
- Introduce mandatory certification of technicians that are servicing TRUs. Training of technicians in the safe use of flammable refrigerants and leakage reduction as well as recovery of refrigerants. Develop handbooks and training materials and integrate content into national capacity development programs.

2030 – 2050:
Implementation and continued improvement

- Infrastructure development – support electric of hydrogen long distance transport along main corridors.
- Supporting further improvement of local producers of insulated vehicles.
- Encourage local standards and testing of refrigerated vehicle bodies and TRU to reduce energy use. Support ATP membership and introduce testing infrastructure.

Table 6 shows key milestones in emission reductions based on the implementation of the described measures. Assumptions are included in the annex. Calculations were done according to the methodology described in Chapter 2.

Table 6: Key technical milestone on the pathway to net-zero for refrigerated transport

		2025	2030	2035	2040	2050
Technical development		Battery development – TRU integration R290 TRU development for all size classes	R290 TRU serial production all size classes CO_2 TRU serial production	Energy efficiency gains Reduced weight of batteries		
TRU: share of electric drive sales	Global North	15%	80%	100%	100%	100%
	Global South	2%	10%	50%	100%	100%
TRU: yearly efficiency gains		1%	1%	1%	1%	1%
TRU: Refrigerant	Global North	10% R290	15% R290 5% R744	25% R290 20% R744	100%	100%
	Global South	5% R290	10% R290 3% R744	15% R290 7% R744	45% R290 10% R744	70% R290 10% R744
Electricity production from net zero sources		Country-specific emission factor	75% net zero sources	Interpolated	Interpolated	100% net zero sources
Service and repair: Yearly leakage rate	Global North	16%	10%	5%	5%	5%
	Global South	25%	25%	15%	10%	5%
Refrigerated transport percentage of electric vehicles sales	Global North	15%	50%	80%	100%	100%
	Global South	2%	10%	40%	80%	100%

Figure 21 shows the resulting TRU emission reductions based on the strategy described above for countries of the Global North. Emissions remain relatively constant until 2025, when about 15% of TRUs are expected to be electrified and natural refrigerants are slowly coming on the market. From 2025 to 2040, emissions decrease considerably as the number of electric TRUs increases constantly, while electricity production moves fast to renewable energy sources. Refrigerant emissions decrease mainly between 2025 to 2035 due to the high share of natural refrigerants and the reduced leakage rate. Emissions are reduced from over 19 Mt CO_2eq in 2020 to 0.05 Mt CO_2eq in 2050.

Figure 21: Countries of the Global North: Emission reductions according to net zero carbon transport refrigeration strategy

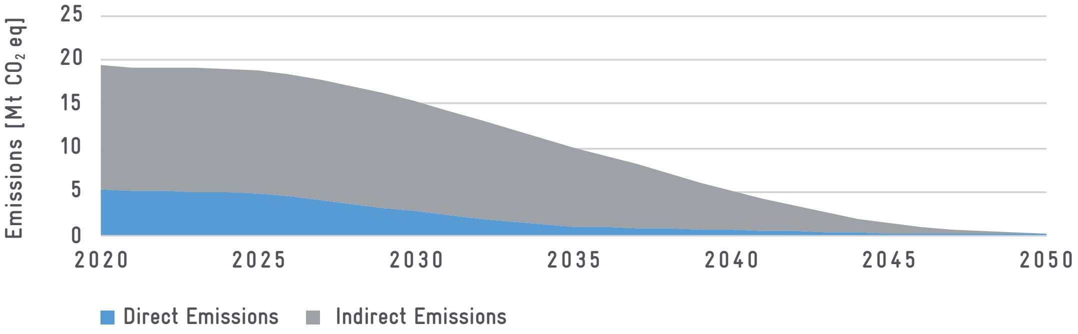


Figure 22 shows the same data for countries of the Global South. TRU emissions increase until 2030 due to the increased demand and a slow uptake of natural refrigerants and electric TRUs to counterbalance it. After 2030, the increase in electrification of TRUs, coupled with the decarbonisation of electricity generation leads to a steady decrease of emissions until 2050. Emissions increase from 15 Mt CO_2eq in 2020 to 20 Mt CO_2eq in 2030 before decreasing to 1.4 Mt CO_2eq in 2050. Because of the long lifetime of refrigerated transport vehicles, emissions are estimated to reach zero a few years later.

Figure 22: Countries of the Global South: Emission reductions according to net zero carbon transport refrigeration strategy

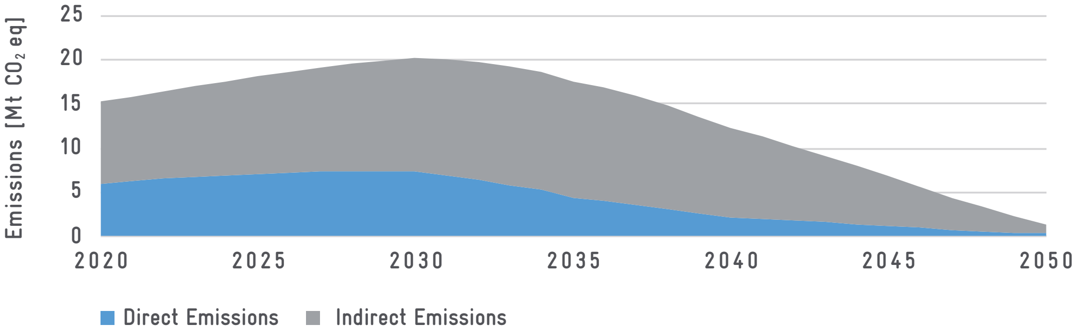


Figure 23 shows how annual emissions can be reduced on a per vehicle basis.

1. R290 or R744 (CO_2) refrigerant with negligible GWP and highly reduced leakage eliminates the global warming impact of refrigerants in TRU. It accounts for nearly 25% of total emissions in vans to 10% in trucks and 6% in trailers where the high emissions of the vehicle engine and truck have a much higher share.

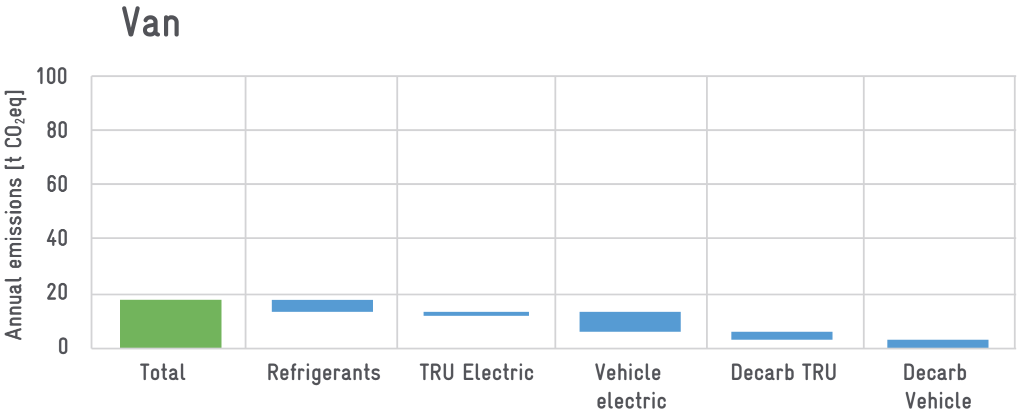
2. Electrification of TRU reduces emissions to a small extent only even though the TRUs energy use contributes between 11% (truck) to just over 20% (vans and trailers) to total emissions of a refrigerated vehicle. The reason for this is the high grid emission factor of 0.45 kg CO_2e/kWh. This was calculated based on the sales-weighted average of all countries of the Global South (IFI, 2019).

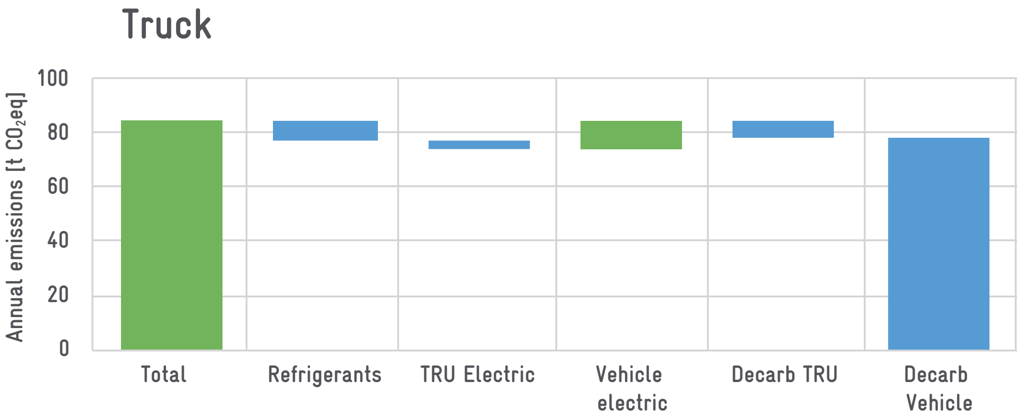
3. Electrification of vehicle engines leads to a small reduction – in the case of vans - or even a significant increase – in the case of trucks and trailers - of emissions because of the high grid emission factor.

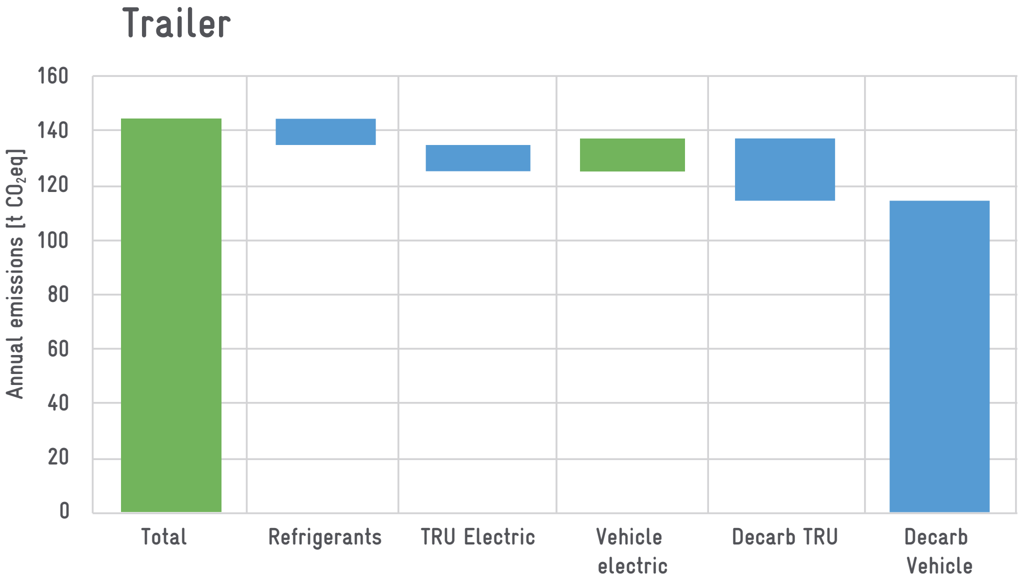
4. Decarbonisation of electricity production, that is the increased use of renewable energies, and to some extend nuclear energies and carbon storage will eliminate indirect emissions of the TRU.

5. Decarbonisation of the electricity production contributes the highest emission reduction for trucks and trailers.

Figure 23: Step-wise reduction of annual emissions for vans, trucks and trailers.







Concluding remarks

Sustainable growth in the transport refrigeration sector is highly important to ascertain food safety and security. A transition to net zero emissions in the transport refrigeration sector is possible. Because of the long lifetimes, it is important to act soon in order to reach the target by 2050 and reach first reductions within the next 10 years, which are vital for reducing the damage of climate change.

Restrictive policies with a long-term strategy, such as emission reduction goals for the next 10-20 years for internal combustion engines and TRUs, are seen as most effective to support a sector transformation. Supported by financial measures, such as direct subsidies and financial instruments that affect the total cost of ownership of both polluting and environmentally friendly systems, industry can appropriately react to the challenge and invest in research and development.

Regulations on TRU emissions have so far been neglected, but California has now started to request zero emission systems and has further limited the GWP of the refrigerant to 2500 after an in-depth analysis of the costs and benefits of such a regulation. The technology is available and costs are manageable, especially when supporting finanical instruments are implemented. The regulation can therefore be used as a template for implementing similar regulations globally.

Over the last 5-10 years, the industry in Europe has completely switched from predominantly using R404A with a GWP of nearly 4000 to R452A with a GWP of 2,141 as a reaction to the F-gas regulation and Kigali Amendment, which limit the use of refrigerant overall based on GWP. Whilst the climate impact of this refrigerant is still too high, it shows that transport refrigeration with its relatively few industry players can implement change very fast. A transition to using climate-friendly natural refrigerant has so far only started slowly with some demonstration projects and very limited series prouduction on one or two products. It is therefore highly important to create a supportive environment for natural refrigerants for transport refrigeration in the short term, e.g. by supporting the fast implementation of safety standards, subsidising research and development and encouraging training activities in the sector.

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ANNEX

ANNEX

Data in tables 7-11are expert estimates based on market knowledge and comparable country experience.

Table 7: BAU refrigerant distribution

Subsector	Countries	Refrigerant	2020	2030	2040	2050
VAN	Global South	R404A	75%	35%	0%	0%
		R134a	25%	15%	0%	0%
		R452A	0%	40%	40%	0%
		GWP 300 HFC	0%	10%	60%	100%
		R744	0%	0%	0%	0%
		R290	0%	0%	0%	0%
	Global North	R404A	5%	0%	0%	0%
		R134a	10%	0%	0%	0%
		R452A	80%	0%	0%	0%
		GWP 300 HFC	0%	90%	90%	90%
		744	0%	5%	5%	5%
		R290	0%	5%	5%	5%
TRUCK	Global South	R410A	0%	0%	0%	0%
		R404A	100%	50%	0%	0%
		R744	0%	0%	0%	0%
		GWP 300 HFC	0%	0%	60%	100%
		R452A	0%	50%	40%	0%
		R290	0%	0%	0%	0%
	Global North	R410A	5%	0%	0%	0%
		R404A	5%	0%	0%	0%
		R744	0%	5%	10%	10%
		GWP 300 HFC	0%	95%	90%	90%
		R452A	90%	0%	0%	0%
		R290	0%	0%	0%	0%
TRAILER	Global South	R410A	0%	0%	0%	0%
		R404A	100%	50%	0%	0%
		R744	0%	0%	0%	0%
		GWP 300 HFC	0%	0%	60%	100%
		R452A	0%	50%	40%	0%
		R290	0%	0%	0%	0%
	Global North	R410A	5%	0%	0%	0%
		R404A	5%	0%	0%	0%
		R744	0%	5%	10%	10%
		GWP 300 HFC	0%	95%	90%	90%
		R452A	90%	0%	0%	0%
		R290	0%	0%	0%	0%

Table 8: Zero carbon refrigerant distribution

Subsector	Countries	Refrigerant	2020	2030	2040	2050
VAN	Global South	R404A	75%	25	0%	0%
		R134a	25%	15	0%	0%
		R452A	0%	40	30%	0%
		GWP 300 HFC	0%	10	35%	65%
		R744	0%	0	0%	0%
		R290	0%	10	25%	35%
	Global North	R404A	5%	0%	0%	0%
		R134a	10%	0%	0%	0%
		R452A	80%	70%	0%	0%
		GWP 300 HFC	0%	75%	20%	0%
		744	0%	5%	20%	30%
		R290	0%	20%	60%	70%
TRUCK	Global South	R410A	0%	0%	0%	0%
		R404A	100%	40%	0%	0%
		R744	0%	5%	10%	10%
		GWP 300 HFC	0%	0%	60%	45%
		R452A	0%	50%	15%	0%
		R290	0%	5%	15%	45%
	Global North	R410A	5%	0%	0%	0%
		R404A	5%	0%	0%	0%
		R744	0%	10%	25%	40%
		GWP 300 HFC	0%	80%	20%	0%
		R452A	90%	0%	0%	0%
		R290	0%	10%	55%	60%
TRAILER	Global South	R410A	0%	0%	0%	0%
		R404A	100%	40%	0%	0%
		R744	0%	5%	10%	10%
		GWP 300 HFC	0%	0%	60%	45%
		R452A	0%	50%	15%	0%
		R290	0%	5%	15%	45%
	Global North	R410A	5%	0%	0%	0%
		R404A	5%	0%	0%	0%
		R744	0%	10%	25%	40%
		GWP 300 HFC	0%	80%	20%	0%
		R452A	90%	0%	0%	0%
		R290	0%	10%	55%	60%

Table 9: Electrification rate of TRU BAU Scenario

Countries	Subsector	2020	2030	2040	2050
Global South	Van	0%	40%	100%	100%
	Truck	0%	27%	80%	100%
	Trailer	0%	27%	80%	100%
Global South	Van	0%	5%	60%	100%
	Truck	0%	5%	40%	100%
	Trailer	0%	5%	40%	100%

Table 10: Electrification rate of TRU Net Zero Scenario

Countries	Subsector	2020	2030	2040	2050
Global South	Van	0%	100%	100%	100%
	Truck	0%	80%	100%	100%
	Trailer	0%	60%	100%	100%
Global South	Van	0%	20%	100%	100%
	Truck	0%	10%	90%	100%
	Trailer	0%	3%	50%	100%

Table 11: Technical parameters

	Van	Truck	Trailer	Source
Initial charge in new units [kg]	2.5	5.5	7.5	Oppelt et al. (2015)
Servicing emission factors per year DC	30%	25%	20%	Oppelt et al. (2015)
Disposal emission factors DC	100%	95%	95%	Oppelt et al. (2015)
Servicing emission factors per year IC	16%	16%	16%	Green Cooling Database (2016)
Disposal emission factors IC	60%	60%	60%	Green Cooling Database (2016)
Refigerating unit Lifetime [years]	15	15	15	Green Cooling Database (2016)
Average cooling capacity per unit [kW]	4	7	17	Oppelt et al. (2015)
Average COP	1.5	1.5	1.5	Oppelt et al. (2015)
Resulting average consumption [l/h]	0.6	1.05	2.56	Oppelt et al. (2015)
Refrigeration Unit compressor run times per year [h]	Country specific depending on climate conditions			Calculated
Efficiency gains BAU per year	0.25%	0.25%	0.25%	Assumption
Efficiency gains Net Zero per year	1%	1%	1%	Assumption
Annual mileage	20000	87333	116480	Rodriguez et al. (2018), Dun et al. (2015), Ragon & Rodriguez (2021)
Daily milage [km]	87	291	560	Rodriguez et al. (2018), Dun et al. (2015), Ragon & Rodriguez (2021)
Fuel consumption vehicle [l/100 km]	12	27	31	Rodriguez et al. (2018); IEA (2011); IEA (2020), Ragon & Rodriguez (2021)
Electricity consumption vehicle [kWh/km]	0.35	2	2.2	Fiat (2021); Earl et al. (2018)
Fuel use during idling	1	3	3	Kotz & Kelly (2019); estimate
Daily idling hours	6	2	4	Kotz & Kelly (2019)

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