ENOUGH

EUROPEAN FOOD CHAIN SUPPLY TO REDUCE GHG EMISSIONS BY 2050

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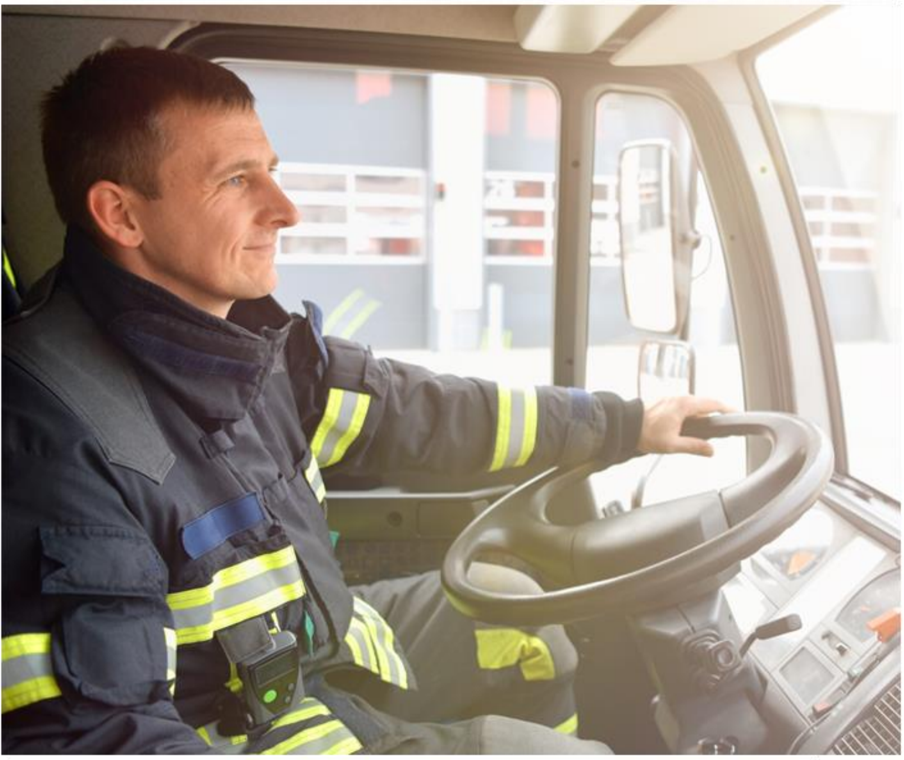

Food transport road map

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036588

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NOMENCLATURE

AI	Air intelligence
ANN	Artificial neural networks
ATP	Accord Transport Perishable
CA	Controlled atmosphere
CAPEX	Capital expenditure
CCF	Cold Chian federation
CFD	Computational fluid dynamics
CFU	Colony forming unit
CNG	Compressed natural gas
CNN	Convolutional neural networks
CO_2	Carbon dioxide
COP	Coefficient of performance
CRC	Conventional refrigerated container
DC	Direct current
DFDS	Det Forenede Dampskibs-Selskab
DL	Deep learning
DLG	Daily Logistics Group
DLT	Distributed ledger technologies
EC	European Commission
ECHA	European Chemicals Agency
eLCV	Electric light commercial vehicle
EMS	Energy management system
EPP	Expanded polypropylene
EPS	Expanded polystyrene
ETS	Emissions Trading System
EU	European Union
EV	Electric vehicles
FLOPS	Floating point operations per second
GHG	Greenhouse gas
GLEC	Global Logistics Emissions Council
GO	Guarantees of origin
GPS	Global positioning system
GPU	Graphics processing units
G-VRP	Green vehicle routing problem
GWP	Global warming potential
HC	Hydrocarbon
HFC	Hydro fluorocarbon
HFO	Hydrofluoro olefins
HGV	Heavy goods vehicle
HPRS	Hydrogen powered refrigeration system
ICE	Internal combustion engine
IHX	Internal heat exchanger

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IIR	International Institute of Refrigeration
IoT	Internet of things
IP	Integer programming
IPCC	Intergovernmental Panel on Climate Change
ISO	International standards organisation
KPI	Key performance indicator
kWh	Kilo Watt hour
LAN	Local networks
LBG	Liquefied biogas
LCA	Life cycle analysis/assessment
LCO_2	Liquid carbon dioxide
LCV	Light commercial vehicle
LGV	Light goods vehicle
LH_2	Liquid hydrogen
LN_2	Liquid nitrogen
LNG	Liquid nitrogen gas
LP	Linear programming
LPG	Liquid petroleum gas
LPI	Logistics performance index
LPR	Low pressure receiver
LT	Low temperature
LULUCF	Land use, land-use change, and forestry
MA	Modified atmosphere
MAP	Modified atmosphere packaging
PFAS	Polyfluoroalkyl substances
MIP	Mixed integer programming
MHCV	Medium heavy commercial vehicle
ML	Machine learning
MLP	Multi-layer perception
MOPS	Millions of operations per second
MP	Mathematical programming
MT	Medium temperature
NOx	Nitric oxide (NO) and nitrogen dioxide (NO_2)
NRMM	Non-road mobile machinery
NWF	Natural working fluid
OPEX	Operating expense or expenditure
OR	Operational research
PAN	Personal area networks
PCM	Phase change material
PEMFC	Polymer electrolyte membrane fuel cell
PP	Poly propylene
ppm	Parts per million
PU	Polyurethane
PUE	Power usage effectiveness

PUR	Polyurethane
PV	Photo voltaic
PVC	Polyvinyl chloride
QAC	Quaternary ammonium compound
RCP	Representative concentration pathway
RF	Random forest
RNN	Recurrent neural networks
SVHC	Substance of very high concern
SVM	Support vector machine
tCO_2e	Tonnes of CO_2 equivalent
TES	Thermal energy storage
TEU	Twenty-foot Equivalent Units
TEWI	Total equivalent warming impact
TFA	Trifluoroacetic acid
THC	Total hydrocarbon emissions
TPU	Tensor processing units
TRL	Technology readiness level
TRU	Transport refrigeration units
UK	United Kingdom
UNRCCC	United Nations Framework Convention on Climate Change
VAR	Vapour absorption refrigeration
VARS	Vapour absorption refrigeration system
VIP	Vacuum insulated panels
VRP	Vehicle routing problem
WAN	Wide area networks
XPS	Expanded polystyrene

EXECUTIVE SUMMARY

In this roadmap we question how the refrigerated food transport sector can decarbonise and rapidly reach zero carbon emissions. As part of the work, we provide independent reviews of 29 different technologies/strategies that refrigerated transport vehicles could apply to reduce carbon emissions and energy consumption. Scope 1 and 2 emissions are covered which encompass emissions from fuel used, emissions from leakage of refrigerants (scope 1) and emissions from electricity provided from the national grid (scope 2). Scope 3 emissions have not been considered.

Technology/strategy reviews were used to identify the individual technologies/strategies that had the most potential to reduce greenhouse gas (GHG) emissions in refrigerated transport vehicles. Only technologies with a high technology readiness level (TRL) were considered, this meant that technologies/strategies considered were already available on the market. The carbon emissions from those technologies/strategies that had a low TRL were often not available or had very varied application times and the claimed savings often varied widely. Therefore, these technologies/strategies were very difficult to quantify. Results were presented as potential carbon savings (high/medium/low) and payback time.

Mathematical modelling was then used to assess impacts from 2020 through to 2050 taking into account changes due to global warming and changes in the grid carbon emission factor as well as the impact of the combined technologies/strategies. Six different vehicle types with associated varied delivery missions were considered.

The vehicle missions considered were:

1. Long haul medium temperature (MT)
2. Long haul low temperature (LT)
3. Regional transport MT
4. Regional transport LT
5. Last mile multi-temperature (MT and LT)
6. Last mile frozen thermal energy system (TES) (LT)

Baseline distances, speed, journey duration, number of stops and refrigerant in the transport refrigeration unit (TRU) were varied across the missions (see Table 8). The impact of these vehicle missions was predicted across 6 locations (UK, France, Lithuania, Norway, Italy and Poland) which were selected for their varied climatic conditions and grid carbon intensity.

The technologies modelled were:

1. Adding door curtains on the TRU (60% infiltration reduction).
2. Better TRU insulation. The reference value for k was assumed to be 15% better than the least stringent requirement of ATP agreement for the corresponding temperature class (K = 0.60 W/m^2 K for chilled applications and K = 0.35 W/m^2 K for frozen applications.
3. Electrification of the TRU.
4. R744 TRU.
5. R290 TRU.

Technologies were then combined as follows and energy and carbon emissions calculated:

1. Better door curtains and TRU insulation with a R744 TRU.
2. Better door curtains and TRU insulation with a R290 TRU.
3. Better door curtains and TRU insulation with electrified R744 TRU.
4. Better door curtains and TRU insulation with electrified R290 TRU.

Results from the reviews and modelling identified routes for refrigerated transport vehicles to reduce emissions and enabled the creation of a roadmap through to 2050. Climate alone had limited impact on the overall carbon emissions from the baseline long haul and regional transport vehicles. For the last mile multi temperature vehicles the difference in emission between the 2020 baseline and 2050 (2040 for Poland) were slightly higher (up to 2.1%). The last mile frozen TES where electricity was used to charge the TES showed reduction in GHG emissions of up to 3.5%.

The ranking of the carbon savings achieved by each technology when applied to the TRU were similar in order in each country. The exception was electrification of the TRU which had variable impacts in the different countries. This was related to the grid carbon emission factor in each country. Countries with low grid carbon factors showed the most benefit of electrification. Grid carbon factors will likely remain low or decrease in all countries moving forward and so this will change the impact that electrification of the TRU has on overall carbon emissions.

In all countries application of low global warming potential (GWP) natural refrigerants had a large impact. R290 has slight advantages over R744 in almost all locations. To be able to get close to zero carbon today, several technologies needed to be applied together. Better insulation, curtains (for vehicles where there were door openings), low GWP natural refrigerants and electrification were all needed to get close to zero carbon in all the countries. In the future as the grid decarbonises it is possible to almost get TRU emissions to zero carbon in the UK, France and Lithuania. Norway already has very low grid carbon factor and so could be almost zero carbon today if the technologies were applied. Poland has much higher grid carbon emission factors and so looked less likely to be able to decarbonise the TRU by 2050.

Our recommendations to reduce carbon in food transport vehicles are presented graphically below:

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TRANSPORT ROAD MAP

1 ABOUT THIS ROAD MAP

Globally, greenhouse gas emissions (GHG) emissions from the food chain are estimated to account for 33% of the total GHG emissions [1] [2]. Emissions related to post farm gate (post-harvest/slaughter) which are the focus of the ENOUGH project are thought to account for around 20% of total emissions.

The transport sector covers the transportation of food on the road, rail, rivers, sea and air. In Europe, maritime transport (for all products, not just food) accounted for 68% (5,135 billion tonne-km) of freight transport in 2021. Road transport accounted for 25% (1,863 billion tkm), rail 5% (410 billion tkm), inland waterways 2% (136 billion tkm) and air 0.2% (15 billion tkm). The level of maritime transport in individual countries tends to be related to whether the country had a coastline. Maritime freight was the main mode of transport in 15 EU counties (out of 22 with a coastline). Road transport was the main mode of transportation in 10 EU member countries and was >70% in Luxembourg (84%), Czechia (77%) and Poland (70%). Rail transport was only the main mode of freight transport in Lithuania (53%)[3] (Figure 1).

Eurostat figures from 2022 indicate that approximately 12% by mass and 17% by tkm of the total products that were transported by road in Europe were categorised as food, beverage and tobacco products[4]. Levels of food transported by road have remained relatively stable over the past few years[5]. Most transportation is less than 150 km[6].

This road map focuses on the food transport sector. The focus of this road map is on road transportation as this is the major method to transport food within Europe. It is claimed that in the EU 77% of food freight is by road[7]. The road map presents quantified evidence on the levels of carbon that could be saved, the technologies and strategies that could be applied and looks forward to 2050 to predict whether a zero-carbon food transport sector is feasible.

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[1] Poore, J., and Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. Science, 360(6392), 987-992.

[2] Crippa, M., Solazzo, E., Guizzardi, D. et al. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food (2021).

[3] https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20230316-2.

[4] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Road_freight_transport_by_group_of_goods_(NST_2007),_EU,_2022_(%25_share_in_tonnes_and_tonne-kilometres).png#file.

[5] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Road_freight_transport_statisticsandoldid=575068#The_top_goods_categories_transported_in_2022_in_terms_of_both_tonnes_and_tonne-kilometres_were_the_same_as_in_2021

[6] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:From_farm_to_fork_-_food_chain_statisticsandoldid=60237#Food_transport_within_the_EU

[7] https://spotos.eu/blog/food-transportation-safety-best-practices-for-a-secure-supply-chain.

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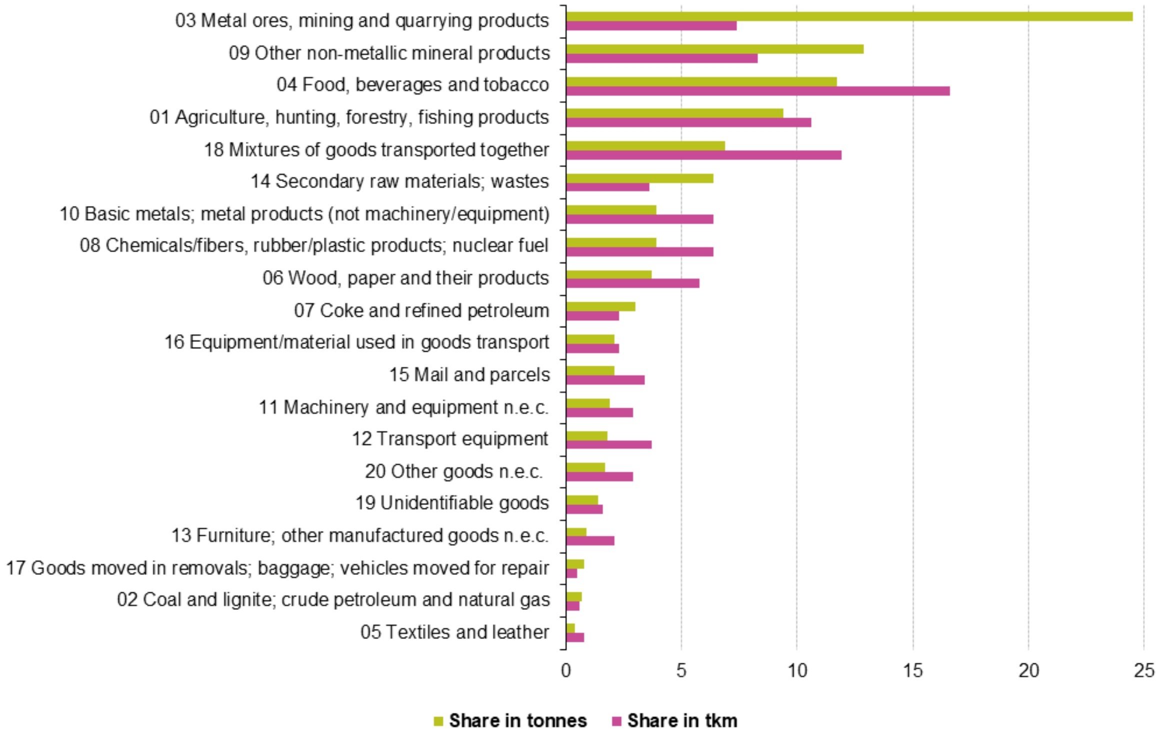

Figure 1. Road freight from Eurostat by type of goods in EU in 2022 (% share in tonnes and tonne-kilometre)[3].

2 INTRODUCTION

In June 2021, the EU adopted a European Climate Law which aims to reach net zero GHG in the EU by 2050. In addition, the EU has a goal of reducing emissions by at least 55% below 1990 levels by 2030 (including land use, land-use change, and forestry (LULUCF)). This is implemented through the 'Fit for 55' package which is a set of policy proposals by the European Commission to achieve the 55% reduction target. To achieve this target the EU has proposed a number of measures which include:

- the strengthening of the emissions reduction targets for each Member State;
- a Carbon Border Adjustment Mechanism, putting a carbon price on imports of iron and steel, cement, aluminium, fertilizers and electricity;
- an increase of the target for renewable energy production to 40% by 2030;
- an update of energy efficiency targets for each Member State to 36-39% by 2030;
- a revision of the EU Emissions Trading System (ETS), and a new ETS for road transport and buildings;
- a revision of the Energy Taxation Directive, introducing an EU-wide minimum tax rate for polluting aviation and shipping fuels;
- higher CO_2 emission standards for cars and vans, requiring average emissions of new cars to come down by 55% from 2030 and 100% from 2035 compared to 2021 levels;
- an obligation for fuel suppliers at EU airports to blend increasing levels of sustainable aviation fuels in jet fuel through the ReFuelEU Aviation Initiative;
- a maximum limit on the GHG content of energy used by ships calling at European ports through the FuelEU Maritime Initiative;

- the introduction of an overall EU target for carbon removals by natural sinks, equivalent to 310 million tonnes of CO_2 emissions by 2030; and
- a new EU Forest Strategy, setting out a plan to plant three billion trees across Europe by 2030.

All this impacts the food cold chain which has significant emissions of carbon. In particular the food transport sector in Europe generates significant quantities of carbon emissions and so has a major role to play the aimed for 55% reduction target.

2.1 Food transportation

2.1.1 Trade in food

Transport of food is an international activity, as food is both exported from and imported to the EU. The EU is the world's largest exporter of agri-food products (in economic terms). It is also the world's third largest importer (after US and China) [8]. In 2022 the EU exported €229.8 billion of agricultural products and imported products valued at €172 billion. Primary exports were dairy products (€20.4 billion) and meat (€13.8 billion). The largest imports were oilseeds and protein crops (€25.8 billion) (Figure 2). In terms of trading partners, the greatest exports are to the UK (20% of total exports) followed by the US (13% of total exports). Twelve percent of imports originate from Brazil and 9% from the UK[9].

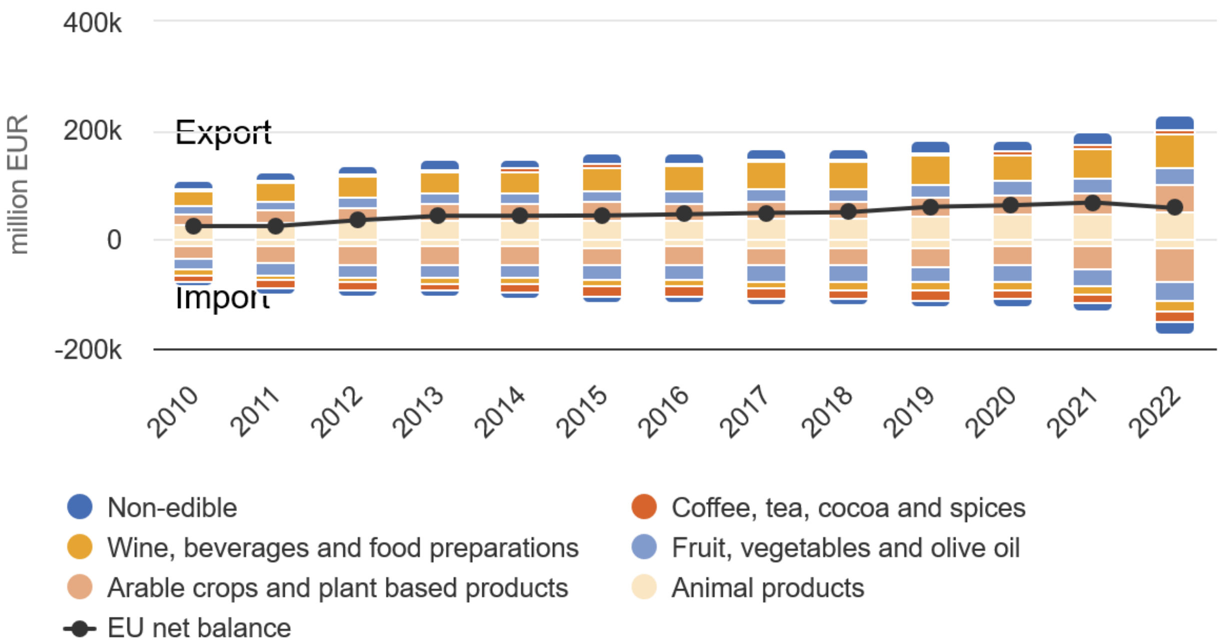

Figure 2. Agri-food trade in EU 2010-2022 (source Eurostat).

2.1.2 Transportation methods

Information on how food is transported in and into/out of the EU is difficult to obtain. Information is available from Poore and Nemecek (2018) on how food is transported worldwide[1]. This presents how food is transported by varied methods in tonnes-kilometres (Figure 3). Most food travels by sea or road and very little is transported via air.

[8] Mirazo, J. R. Europe eats the world. How the EU's food production and consumption impact the planet. WWF. https://wwfeu.awsassets.panda.org/downloads/europe_eats_the_world_report_ws.pdf.

[9] https://agriculture.ec.europa.eu/news/good-performance-eu-agri-food-trade-2022-despite-challenges-2023-04-13_en.

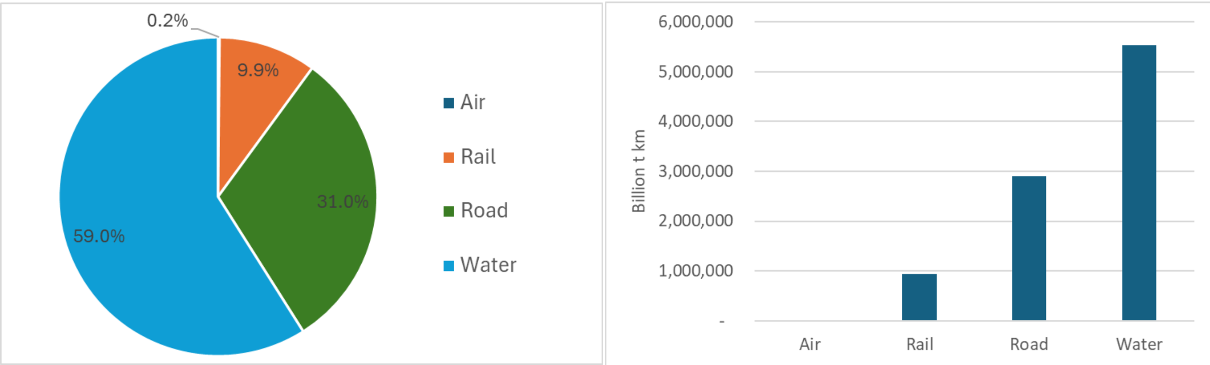

Figure 3. Share (in % and t km) of global food miles by transport method (from Poore and Nemecek, 2018).

2.2 Refrigerated transport systems

Transport systems for food fall broadly into the following categories:

- Small road vehicles (light goods vehicle (LGV), light commercial vehicle (LCV)). These usually have a refrigeration compressor located in the main engine compartment. The evaporator is mounted inside the cooled space and the condenser is mounted at roof level outside often above the driver's cab. Usually, the vehicle body builder installs the refrigeration system. Often the refrigeration system will be operated from a direct drive from the vehicle engine.
- Larger road vehicles (medium heavy commercial vehicle (MHGV), heavy goods vehicle (HGV)). These usually have a refrigeration unit mounted at the front of the trailers. These systems are factory built and charged with refrigerant and so do not require any refrigeration work to install the systems. Most units operate using a dedicated diesel engine.
- Intermodal containers. These have a dedicated refrigeration unit that is factory built and pre-charged with refrigerant.
- Ships may also have cooling systems either to keep products cool over long journeys or to chill/freeze products such as fish. These systems can operate on a wide range of refrigerants including ammonia and often more commonly today R744. Passenger ships and naval vessels also often have cooling systems to store the food required for the restaurants/canteens.

- Other delivery systems such as trains, airplanes, bikes and drones also exist.

Most of the refrigerating and heating systems for food transportation are based on the vapour compression cycle. These units can provide the required heating or cooling demand provided an energy source, mechanical or electrical, is available. Mobile transport systems are subject to tough requirements related to size and weight; they are subject to extremely variable environmental conditions such as temperature, direct solar radiation, atmospheric events, external icing, marine environments (high salt and humidity), vibration, and acceleration/deceleration. There is a huge need for standardised components, as maintenance and assistance must be available worldwide.

The lay-out of the units can vary significantly depending on the actual service and application. Units can be divided into two groups:

1. Monobloc systems are self-contained units which include both evaporator and condenser and are typically pre-charged with refrigerant.
2. Split systems offer greater flexibility in the coupling between condensing unit and evaporator(s).

2.3 Types of refrigerated transport vehicles

2.3.1 Refrigerated road transport

Most vehicles are classed by the gross vehicle weight. These weight restrictions may limit the volume of denser produce which can be carried. Generally, this is a greater issue with frozen than chilled foods (as density is greater). Vehicles can be designed to operate in ambient temperatures of up to 50°C[10].

2.3.1.1 Semi-trailers

For longer transport distances on the road, the most commonly found vehicle is the semi-trailer. Semi-trailers are typically 13.6 m x 2.6 m. Occasionally insulated curtain side vehicles can be used for delivery of fruit and vegetables and have a mounted refrigeration system similar to that found on trailers. Semi-trailers are moved by a detachable tractor unit.

The refrigeration system on semi-trailers is usually driven by a 2-speed diesel engine which drives the compressor, condenser and evaporator fans. On some units an electric drive motor is available to operate the refrigeration system in standby mode and is used when the vehicle is stationary and has access to the electricity grid.

In semi-trailers, trucks and vans, a top air delivery system is commonly used. Fans circulate cold air from the refrigeration system across the roof and around the inside of the body of the unit to remove the heat gain from outside the unit. Air is returned via the floor or the space under pallets (Figure 4). Bottom air flow systems can also be found but are less common (Figure 5). For chilled cargoes some air should also be ducted through the cargo (especially when carrying fruit and vegetables which are respiring) and producing heat). In frozen cargoes often product is block stowed. In all cases it is important to ensure that air channels are created to enable the cold air to flow around the vehicle body.

The heat gained is removed by the refrigeration systems evaporator. As air flows around the unit, it picks up moisture from the product and some moisture may be added from the air vents in the unit. The moisture will freeze onto the evaporator and start to restrict the air flow. When airflow is reduced to ~75% of the frost-free rate, a defrost will be applied. Temperature is controlled by a thermostat mounted on the front wall of the unit (in the return air stream). Generally, a thermometer is placed in a position where the driver can see it or there is a display in the cab.

[10] https://www.carrier.com/truck-trailer/en/eu/solutions/extreme-climates/

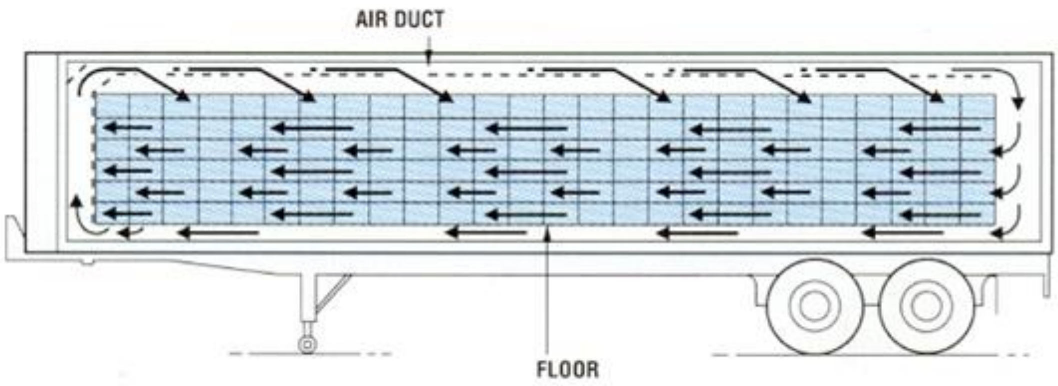

Figure 4. Top air delivery system.

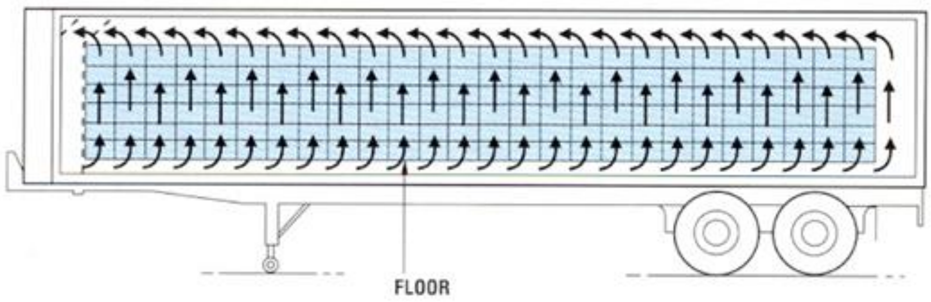

Figure 5. Bottom air delivery system.

2.3.1.2 Small rigid vehicles and vans

Smaller rigid vehicles or small vans are generally used for local deliveries and short haul operations. Most vehicles operate from a compressor that is driven from the main engine often via a belt drive. Some smaller vehicles have an electric standby option which can be plugged into the electrical grid when not being driven.

2.3.2 Intermodal containers

Intermodal containers are commonly used on ships and can be stacked up to 10 high using the ship's stowage slots (90-ton corner posts).

Containers can be towed using on road tractor units or placed on rail trucks. They are commonly transported on skeletal trailers with corner casting locating locking pins and are hauled by a diesel tractor unit once unloaded at the port. The containers have inbuilt vapor compression refrigeration units similar to those applied on refrigerated semi-trailers. The external dimensions of the containers are typically either 40' x 8' x 8'6"/9'6" or 20' x 8' x 8'/8'6". Most tend to be 40' models.

On the ship, the containers refrigeration system is electrically driven from the ship's generators or the container diesel generator. On land when units are transported using a skeletal trailer, they are powered from a diesel generator which is either attached to the refrigeration unit or slung beneath the trailer.

Air flow in containers is generally ducted from the bottom of the container. Air from the evaporator is blown into a plenum chamber which distributes the air evenly across the floor. The air is passed through the cargo and then returns to the evaporator via the roof void (Figure 6). As with semi-trailers chilled foods generally allow airflow through the cargo and frozen cargoes can be block stowed. Most marine containers have T-section floors (road vehicles generally use flat metal checker plate floor suitable for pallets) (Figure 7). The refrigeration system evaporator distributes air through the container with often air changes of 60-90 per hour. Condensers are usually air cooled, but some containers have combined condenser systems which can be air- or water-cooled. The water-cooled condensers are generally used when containers are stored below deck. All marine containers are designed to be able to achieve at least -25°C in an ambient of up to 50°C. They also have heating systems for cold ambient conditions where the storage temperature required is higher than the ambient temperature.

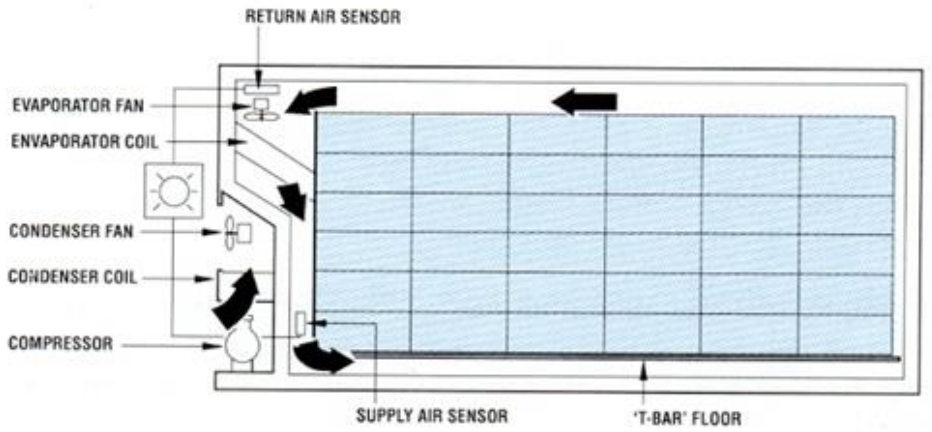

Figure 6. Container refrigeration system.

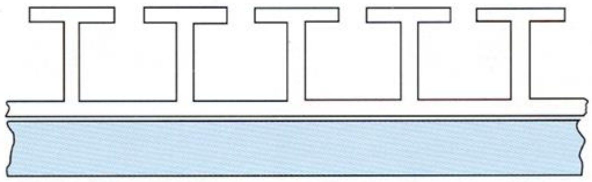

Figure 7. Section of container T-Bar floor.

2.3.3 Eutectic plates

Vehicles can be fitted with eutectic plates. These can be charged overnight using electricity from the grid or can be charged from the vehicles whilst in operation. The main disadvantage is the weight and also potentially the stability of the vehicle if fitted to the ceiling. Temperature control can also be an issue as the thermal store may run out during transportation. Advantages are that systems can use cheaper night-time grid electricity rather than diesel or daytime grid electric and have no issues with loss of refrigerant from the vehicle itself.

2.3.4 Storage boxes

Insulated storage boxes with thermal storage can be used for transportation over periods of generally less than 12 hours. A method to charge the thermal storage system (usually a eutectic solution in an encased plate) is essential. An alternative option is to use solid CO_2 pellets in a chamber at the top of the storage box. A vent is used to control the cooling from the CO_2 into the storage area of the box. Liquid nitrogen can also be used either directly or via a heat exchanger. For direct systems there may be some impact on products (particularly fruit and vegetables) and care needs to be taken to vent vehicle enclosures before operators can enter due to potential asphyxiation.

2.4 Insulation

Most bodies of containers or trucks are insulated with 100 or 150 mm of polyurethane (PU) foam. Sometimes the side walls of road vehicles are thinner (55-60 mm). This allows an internal width of ~2.4

m which means that two 1.2 m pallets can be placed side by side. Containers have 75 mm side walls and 100 mm thick roof and floor.

Vehicles in most of Europe (not the UK) must comply with ATP (agreement on the international carriage of perishable foodstuffs) regulations. This regulates the heat transfer of the body of vehicles. A 'K' value lower or equal to 0.4 $W/m^2.K$ for frozen and 0.7 $W/m^2.K$ for chilled is required. Insulated marine containers need to comply with ISO 1496 and when new should have a 'K' value better than 0.4 $W/m^2.K$.

Generally, today the blowing agent used for the insulation is cyclopentane. Insulating foams can deteriorate over time mostly due to the uptake of moisture and heat transfer can increase by 30% after six years[11].

It is important to repair damaged panels quickly to protect the foam from contact with moisture. Door seals also need to be maintained in good condition to prevent air (heat and moisture) leakage which can generate local hot spots in the load. Generally, containers are more robust as they have steel walls which protect the insulation.

2.5 Emissions from food transport vehicles

To contribute to the overall climate neutrality objective for 2050, the GHGs of the transport sector in 2050 must be reduced by 90% compared to the baseline of 1990, as announced by the European Commission[12]. According to the European Environmental Agency, transport is responsible for 27% of Europe's total GHG emissions and is a major contributor to climate change[13].

Emissions are generated in refrigerated transport vehicles from:

1. The fossil fuels used to drive the vehicles and if applicable the refrigeration system (scope 1).
2. Grid electricity to operate the refrigeration system when the vehicle is not in motion or for pre-charging electrical (batteries) or thermal storage (e.g. PCMs) (scope 2).
3. Refrigerant leakage (scope 1).

European nations are committed to reaching net zero carbon emissions by 2050. This offers a greater challenge to transport refrigeration than stationary refrigeration due to the high leakage of refrigerants and the inability to connect to mains electricity whilst mobile.

Up until 31 December 2020, the emissions allowed for new cars and light commercial vehicles was set at European level by Regulation (EU) 2019/631 (Regulation (EU) 2023/851 amending Regulation (EU) 2019/631 as regards strengthening the CO_2 emission performance standards for new passenger cars and new light commercial vehicles in line with the Union's increased climate ambition). In 2020, a fleet-wide average emissions target for vans of 147 g CO_2/km applied to the entirety of the EU/Iceland/Norway and UK (reduced from 175 g CO_2/km in 2019). In 2019 the first-ever EU-wide CO_2 emission standards for heavy-duty vehicles were adopted (Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 setting CO_2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of the Council and Council Directive 96/53/EC). This set targets for reducing the average emissions from new lorries for 2025 and 2030.

[11] Chatzidakis, S.K. and Chatzidakis, K.S., 2004. Refrigerated transport and environment. International journal of energy research, 28(10), pp.887-897.

[12] https://climate.ec.europa.eu/eu-action/transport/overview_en.

[13] https://www.eea.europa.eu/en/topics/in-depth/transport-and-mobility.

2.5.1 Reported emissions

Emissions from varied transport systems are presented in Table 1. Water (sea and inland) is by far the lowest carbon form of transport followed by rail and then road. Air transport has extremely high carbon emissions (for example air transport has 50 times more emissions than sea transport). The amount of food transported by air is however low (only 0.16% of food miles[1]). Even though the emissions per tonne kilometre are high this results in relatively small overall emissions from air transport.

Table 1. Emission factors for freight by transport mode (kilograms of CO_2eq per tonne-kilometre) (from Poore and Nemecek, 2018, extracted from Ecoinvent 3.3).

Mode of transport	Ambient transport (kg CO_2eq per tonne-kilometre)	Temperature-controlled transport (kg CO_2eq per tonne-kilometre)
Road	0.2	0.2 to 0.66
Rail	0.05	0.06
Water (sea / inland water	0.01	0.023
Air	1.13	1.13

2.5.2 Use of fossil fuels

Typical diesel usage for a refrigerated food vehicle varies from 0.5-5 litres/hour depending on how the vehicles is operated and what level of cooling is being achieved.

Refrigerated containers which are electrically driven can consume up to 12 kW when actively cooling. Typically, 7.5 kW is used as the design condition for ships but nowadays many containers can consume 2.5-3.5 kW.

2.5.3 Alternative fuels

A number of alternative fuel options are available. The EU Expert Group on Future Transport Fuels[14] state that the main alternatives for diesel are:

- For road transport: electricity for short distances, hydrogen and methane up to medium distance, and biofuels/synthetic fuels, LNG and LPG up to long distance. Freight vehicles lag behind passenger vehicles, in regard to electrification. In the UK, according to Department for Transport 54,000 new MHCVs were registered in 2019 and only 0.2% were electric or gas, the overwhelming majority being diesel driven vehicles[15].
- Railways: electricity or where not feasible the use of biofuels.
- Aviation: biomass derived kerosene.
- Waterborne transport: biofuels (all vessels), hydrogen (inland waterways and small boats), LPG (short sea shipping), LNG and nuclear (maritime).

In addition, options such as absorption, adsorption, air cycle and thermoelectric have been suggested as alternatives[19]. However, to date they have had limited commercial development for markets in Europe.

[14] https://ec.europa.eu/commission/presscorner/detail/el/MEMO_11_41.

[15] Department for Transport. Future of Freight: a long-term plan. June 2022. https://assets.publishing.service.gov.uk/media/62b9a2ec8fa8f53572e3db68/future-of-freight-plan.pdf

2.6 Fuel use

Fuel use is often presented as a metric for efficiency of a vehicle. However, although information on fuel use is perhaps simpler to obtain, it overlooks whether a vehicle is loaded and is actually efficient in terms of utilisation. Energy efficiency expressed as fuel consumption per pallet kilometre or per tonne-kilometre are more meaningful metrics.

Figures for fuel use are available from McKinnon et al. (2002)[16], the UK government's Continuing Survey of Road Goods Transport (2001)[17] and ICCT[18] (Table 2). The surveys excluded the energy used for the refrigeration systems which could add 10-31% onto the energy used[19]. The KPI survey also divided the vehicles into distribution sectors which indicated that tertiary distribution had the highest energy intensity but also the greatest variability in energy intensity. Primary distribution had the lowest energy intensity (Table 3). Multi-drop delivery deliveries require more energy than single drop deliveries (Figure 8)[20].

Table 2. Fuel efficiency for different vehicles.

Vehicle type	McKinnon et al (2002) km/l	CSRGT (2001) km/l	ICCT (2018) km/l
Small rigid less than 7.5 ton	4.0	4.1	
Medium rigid (7.5–18) ton	3.6	3.7 (7.5–14.0 t) 3.3 (14–17 t)	
Large rigid greater than 18 ton	3.1	2.9 (17–25 t) 2.7 (>25 t)	
City semi-trailer	3.2	–	
32-ton articulated vehicle	3.2	3.2 (<33 t)	
38–44-ton articulated vehicle	2.9	2.9 (>32 t)	
Typical tractor (typical Euro VI tractor-trailer used for long-haul operation)			2.9-3.1
Best in class tractor (Euro VI tractor-trailer)			3.2-3.3
Rigid truck (18-tonne, Euro VI rigid truck used for mid-distance distribution)			3.2-4.6

[16] D.K. McKinnon, Y. Ge, D. Leuchars, Analysis of Transport Efficiency in the UK. Food Supply Chain – Full Report of the 2002 Key Performance Indicator Survey, 2002.

[17] Department for Transport, Transport of Goods by Road in Great Britain, Transport Statistics Bulletin SB (02), 17, London, 2002.

[18] ICCT. Fact sheet: Europe, April 2018. Comparison of fuel consumption and emissions for representative heavy-duty vehicles in Europe.

[19] Tassou, S.A., De-Lille, G. and Ge, Y.T., 2009. Food transport refrigeration–Approaches to reduce energy consumption and environmental impacts of road transport. Applied Thermal Engineering, 29(8-9), pp.1467-1477.

[20] Tassou, S.A., De-Lille, G., Ge, Y.T., 2009. Food transport refrigeration - approaches to reduce energy consumption and environmental impacts of road transport. Appl. Therm. Eng. 29 (8–9), 1467–1477. https://doi.org/10.1016/j.applthermaleng.2008.06.027.

Table 3. Energy intensity for different distribution sectors.

Distribution type	Average energy intensity (ml fuel/pallet km)	Standard deviation (ml fuel/pallet km)
All fleets	25.4	7.4
Primary distribution (temperature controlled)	19.3	4.9
Primary distribution (ambient)	12.2	6.5
Secondary distribution	19.2	4.9
Tertiary distribution	37.3	12.3
Mixed distribution	30.1	4.4

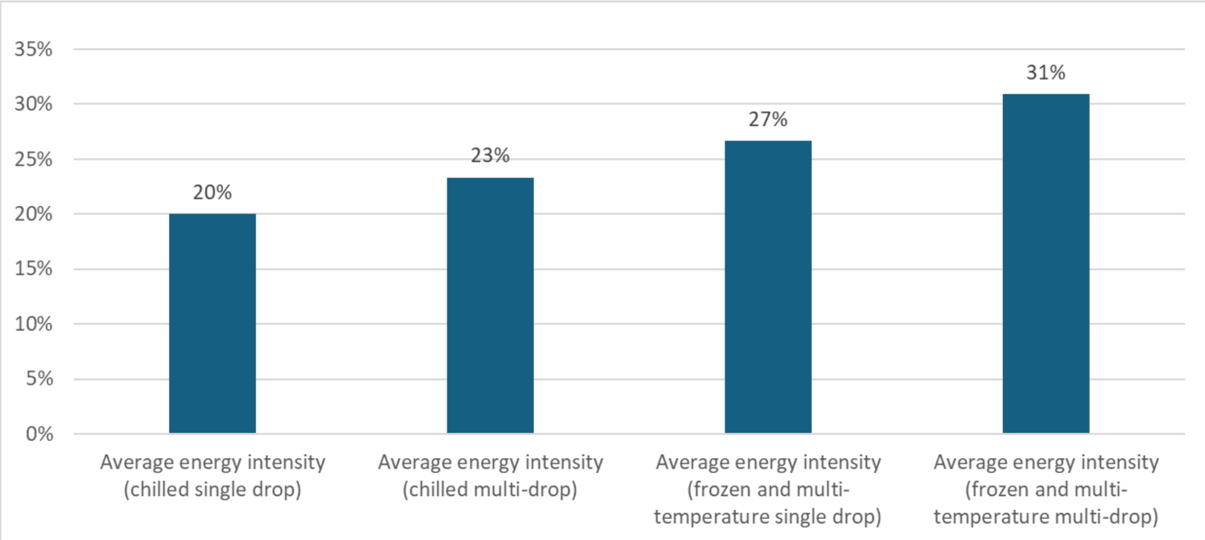

Figure 8. Increase in energy (ml/pallet-km) for refrigerated single and multi-drop delivery.

2.6.1 Green transport/retail

Transport is a major component of retailing, and it is one of the most polluting activities (Ramanathan et al., 2014[21]). The environmental impact of retailers can be substantially reduced by improving transportation practices. Green transportation with low environmental impact has been suggested as a key component of green retailing, since it reduces materials, energy consumption, and increases efficiency. This can include the appropriate selection of vehicle types, delivery schedules, freight flow consolidation and replacement of existing heavy goods vehicle fleets with less polluting vehicles (Naidoo and Gasparatos, 2018[22]).

[21] Ramanathan, U., Bentley, Y., and Pang, G. (2014). The role of collaboration in the UK green supply chains: an exploratory study of the perspectives of suppliers, logistics and retailers. Journal of Cleaner Production, 70, 231–241. doi:10.1016/j.jclepro.2014.02.026.

[22] Naidoo, M., and Gasparatos, A. (2018). Corporate environmental sustainability in the retail sector: Drivers, strategies and performance measurement. Journal of Cleaner Production, 203, 125–142. doi:10.1016/j.jclepro.2018.08.253.

2.7 KPIs

The Global Logistics Emissions Council (GLEC) Framework[23] states that reporting a tonne-kilometre-based emission intensity KPI is the best method to assess performance and compare it to others. GLEC provide indicative figures for vehicle emissions (this excludes refrigerant emissions). High level figures for unrefrigerated and refrigerated vehicles are shown in Table 4. The GLEC report provided much more detailed figures for varied vehicles which can be used as the basis for comparison[23].

Table 4. Road emission intensity factors.

Vehicle type	Unrefrigerated	Refrigerated
	g CO_2e/t-km (well to wheel)	
Van (<3.5 t Gross vehicle weight (GVW)	680	782
Urban truck (3.5-7.5 t GVW)	370	414
Medium goods vehicle (7.5-20 t GVW)	200	224
Heavy goods vehicle: (>20 t GVW)	92	103

[23] Smart Freight Centre. Global Logistics Emissions Council Framework for Logistics Emissions Accounting and Reporting. (2019). ISBN 978-90-82-68790-3.

2.8 Legislation

2.8.1 Refrigerants

The F-gas phase down (EC, 2014) will reduce CO_2e of all gasses in use to 63% of the baseline by 2018-2020 and 21% of the baseline by 2030. For TRU there are currently no product bans, but there are service bans precluding R404A in large systems (>10 kg), however most TRUs are smaller systems, therefore the F-gas regulations do not have much impact on reducing fugitive emissions in this sector. However, industry bodies such as the Cold Chian federation (CCF) have an industry target not to sell TRUs with a GWP >300 by 2025 and to completely phase out TRUs with GWP >300 by 2035[24].

> ***New F-gas gas regulation (January 2024)***
>
> *The new regulation requires:*
>
> *Operators and manufacturers of equipment that contains 5 tonnes of CO_2 equivalent or more of fluorinated greenhouse gases listed in Annex I (of the Regulation) or 1 kg or more of fluorinated greenhouse gases listed in Section I of Annex II of the Regulation that is not contained in foams, shall ensure that the equipment is checked for leaks.*
>
> *Hermetically sealed equipment shall not be checked for leaks provided that it is labelled as hermetically sealed equipment and that it complies with one of the following conditions:*
>
> *(a) it contains less than 10 tonnes of CO_2 equivalent of fluorinated greenhouse gases listed in Annex I (of the Regulation); or*
>
> *(b) it contains less than 2 kg of fluorinated greenhouse gases listed in Section I of Annex II (of the regulation).*
>
> *For most transport vehicles the clauses prescribing refrigerants checks will only apply to higher GWP refrigerants (such as R404A) or refrigerant charges of greater than 2 kg.*
>
> *The above checks shall apply to operators and manufacturers of the following mobile equipment:*
>
> *(a) refrigeration units of refrigerated trucks and refrigerated trailers;*
>
> *(b) refrigeration units of refrigerated light-duty vehicles, intermodal containers, including reefers, and train wagons;*
>
> *(c) air-conditioning equipment and heat pumps in heavy duty vehicles, vans, non-road mobile machinery used in agriculture, mining and construction operations, trains, metros, trams and aircraft.*
>
> *For mobile equipment the checks shall be carried out by natural persons holding at least a training certificate that covers them to carry out installation, maintenance or servicing, repair or decommissioning of the equipment.*

On 16 January 2024 the European Parliament approved a revision of the F-gas regulation that has been under consideration and review for some time[25]. The revision was strongly supported by the Parliament (79% of members voted in favour). The new regulation has been now endorsed by the European Council in a vote at the end of January 2024. The updated regulation will introduce strict requirements on F-gases, their use and phase out dates, for gases in markets where technically it is feasible to switch to alternatives. For transport systems the only clause that covers transport refrigeration systems covers leak checking and record keeping (see box above). This reduces the level where leak checking is a requirement which potentially encourages manufacturers and end users to apply lower GWP natural refrigerants for transport vehicles.

[24] CCF, 2021. Shaping the cold chain of the future: the road to net zero - Part three – the journey to emission free temperature-controlled refrigeration on road vehicles. Cold Chain Federation, UK.

[25] https://www.europarl.europa.eu/plenary/en/texts-adopted.html.

2.8.1.1 Refrigerant leakage

Refrigerant leakage is a major challenge in transport refrigeration. Apart from the environmental issues in releasing often high GWP refrigerants, the loss of refrigerant can result in breakdowns and temperature breaches in the food cold chain.

TRUs tend to have higher leakage and higher GWPs than refrigeration in other sectors of the food chain. This is due to nature of their use, e.g. vibration and that they have not been regulated to the same extent as other sectors. TRUs are categorised in policy as Non-Road Mobile Machinery (NRMM), which means they have not been subject to the same regulation, or research into emissions and are also not included in emissions estimates for the transport sector[26].

Recent published information on refrigerant leakage from transport vehicles is limited. For light commercial vehicles annual leakage of the total refrigerant charge has been reported to be equal to 10-37% by Tassou et al. (2009)[20], 10-25% by Li (2017)[27] and 5-25% by Wu et al (2022)[28]. The United Nations (2017) report leakage of 165 % of the initial charge over a 10-year lifetime. Leakage can also occur during refrigerant charging and has been reported to be 2% of the system refrigerant charge by Wu et al. (2013)[29]. Evans et al (2019) found that the annual leakage rates for small belt driven refrigerated delivery vehicles varied from 3 to 30%. This variability was found across 3 vehicles models and age of vehicle had little impact on leakage rates. Most leaks originated from the high-pressure side of the refrigeration system with most leaks being from the condensing unit [30].

Information of fugitive emissions from specific vehicle types is also relatively scarce. Foster et al (2023)[31] present some data for the UK from the UK GHG Inventory. This indicates that total fugitive emissions in 2019 from large trucks and iso-containers was 0.23 $MtCO_2e$ and emissions from vans and light trucks was 0.02 $MtCO_2e$ (total of 0.25 $MtCO_2e$). Marine refrigeration was stated to have fugitive emissions of 0.44 $MtCO_2e$, giving a total for the sector of 0.69 $MtCO_2e$. This equated to 13% of the UK food sector fugitive emissions in 2019 (Figure 9).

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[26] CCF. Shaping The Cold Chain of The Future: The Road To Net Zero - Part Three – The Journey To Emission Free Temperature-Controlled Refrigeration On Road Vehicles Cold Chain Federation, UK (2021).

[27] Li, G., 2017. Comprehensive investigation of transport refrigeration life cycle climate performance. Sustain. Energy Technol. Assess. 21, 33–49. https://doi.org/10.1016/j.seta.2017.04.002.

[28] Wu, J., Li, Q., Liu, G., Xie, R., Zou, Y., Scipioni, A., Manzardo, A., 2022. Evaluating the impact of refrigerated transport trucks in China on climate change from the life cycle perspective. Environ. Impact Assess. Rev. 97, 106866 https://doi.org/10.1016/j.eiar.2022.106866.

[29] Wu, X., Hu, S., Mo, S., 2013. Carbon footprint model for evaluating the global warming impact of food transport refrigeration systems. J. Clean. Prod. 54, 115–124. https://doi.org/10.1016/j.jclepro.2013.04.045.

[30] Evans, J., Francis, C, Davies, G., Maidment, M. Hammond, E. and Gigiel, A. Sustainable Refrigerated Road Transport–Investigating the Scale of Carbon Emissions from Direct-Drive Last Mile Refrigerated Vehicles. IOR proceedings, 2019.

[31] Foster, A., Brown, T. and Evans, J. Carbon emissions from refrigeration used in the UK food industry. International Journal of Refrigeration (2023).

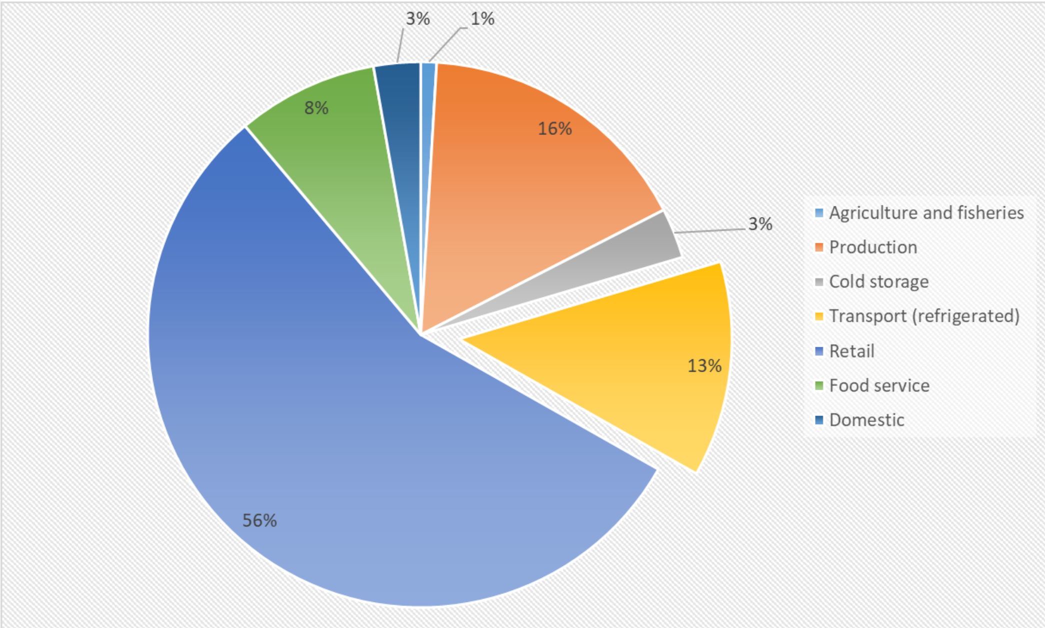

Figure 9. Refrigeration fugitive emissions from the UK food sector in 2019 (from Foster, Brown and Evans, 2019[31]).

2.8.1.2 PFAS

Some HFC and HFO refrigerants are also considered to be per- and polyfluoroalkyl substances (PFAS). PFAS substances are known to be highly persistent in the environment, contaminating groundwater, surface water and soil, and causing serious health effects. In Europe the current working definition of a PFAS substance is that it contains at least one fully fluorinated methyl (CF_3) or methylene (CF_2) group not directly attached to any hydrogen, chlorine, bromine or iodine atom. This covers refrigerants such as R134a which is still used in transport vehicles and is one of the constituents of R404A which may still be used in transportation. PFAS substances include substances such as trifluoroacetic acid (TFA). TFAs are deposited on land and in water where there is the potential to accumulate in terminal water bodies and plants. Currently it is unclear whether TFAs have significant environmental impact, but ultimately, under the precautionary principle, the risk should be mitigated if possible. The overall impact of these issues related to refrigerants is the subject of ongoing debate and object of a joint proposal of five EU Countries to ECHA[32]. Responsible end-users, reporting annually their sustainability achievements (taxonomy), will find it more difficult to justify use of PFAS refrigerants.

In early February 2023 the EU European Chemicals Agency (ECHA) published a proposal from Denmark, Germany, the Netherlands, Norway and Sweden to restrict PFAS chemicals under the EU's chemicals REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation. This proposes a restriction on the manufacture, use and sale of certain f-gas substances and blends. Refrigerants included are both HFCs and HFOs and include HFC-125, HFC-134a, HFC-143a, HFO-1234yf, HFO-1234ze(E), HFO–1336mzz(Z) and HFO-1336mzz(E). A consultation was held in 2023 which closed in September to enable ECHA to consult with industry. After assessment of the review submissions the European Commission and EU Member States will decide on potential restrictions. However, irrespective of whether this initiative becomes a legal requirement, there is now considerable ongoing risk when applying HFC and HFO refrigerants.

[32] https://echa.europa.eu/registry-of-restriction-intentions/-/dislist/details/0b0236e18663449b.

2.8.2 ATP

The Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be Used for such Carriage (ATP)[33] is the regulation for refrigerated transport at controlled temperatures of perishable goods. The ATP regulation;

- imposes certain rules on the construction of isothermal equipment for refrigerated transport;
- imposes certain prescriptions for users;
- prescribes the types of perishable foods to be transported under a controlled temperature regime and the temperatures at which refrigerated transport must be carried out.
- The regulation requires vehicles to be tested by accredited test laboratories. This involves a;
  - K-value test which determines the insulation value of transport equipment, known as Type Test.
  - Effective refrigeration capacity test: determines the maximum capacity of the refrigeration unit.
  - Verification of effectiveness of equipment in service (pull down test): measures how fast the temperature of the cargo hold decreases.

ATP covers road vehicles, railway wagons and (for sea journeys under 150 km) sea containers. Non-processed fruit and vegetables and air transport is not covered by ATP.

The type test takes about 24 hours to conduct and lasts about 24 hours. The heat exchange across the body must meet the values defined by ATP. These are 0.70 $W/m^2/K$ for normally insulated equipment and 0.40 $W/m^2/K$ for heavily insulated equipment. This test on new equipment last 6 years. After 6 years, re-testing of the insulating capacity of the body is required. This may be done by a visual inspection of the equipment by experts. Further re-tests are required every 3 years. Not all countries apply the same tolerances to allow for ageing of insulation.

The pull-down test requires the unit to pull down to Class temperature within 6 hours.

The refrigeration capacity test is measured at 30°C ambient and at three of four possible storage temperatures (–20°C, -10°C, 0°C and +12°C). The capacity of the refrigeration system is required to be 1.35 times that needed to maintain temperature. This is conducted by placing a heater in the trailer which is 35% of the heat required to maintain temperature.

3 CURRENT AND FUTURE TRENDS

3.1 The environment

The world is experiencing higher temperatures due to global warming. Globally mean near-surface temperature were 1.11 to 1.14°C warmer between 2012 and 2021 than during the pre-industrial level. This makes the last decade the warmest on record. 2020 was the warmest year in Europe since instrumental records began. In particular high levels of warming were observed across Eastern Europe, Scandinavia and the eastern part of Iberian Peninsula.

[33]https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://unece.org/DAM/trans/main/wp11/ATP_publication/ATP-2016e_-def-web.pdf&ved=2ahUKEwjz84HrpMSFAxX6XUEAHdk1CkkQFnoECBgQAQ&usg=AOvVaw2WItMZTddlD3AlnVr1PqQT

United Nations Framework Convention on Climate Change (UNFCCC) member countries have committed to the Paris Agreement. This aims to limit global temperature increase to below 2°C (above pre-industrial levels) by 2050 and ideally to limit the increase to less than 1.5°C[34].

Projections on future temperatures from climate change models indicate that in Europe, land areas will continue to increase in temperature throughout the century at a rate higher than the global average. Depending on the assumptions applied to the models, temperatures could at best increase by 1.2 to 3.4°C and at worst by 4.1 to 8.5°C (by 2071-2100, compared to 1981–2010). Areas of particular concern are north-eastern Europe, northern Scandinavia and inland areas of Mediterranean countries, whereas western Europe, especially in the United Kingdom, Ireland, western France, Benelux countries and Denmark expect the lowest levels of warming.

It is clear that extreme temperature events are becoming more common, and this is having an impact on transport systems. This can have several impacts:

1. Refrigeration system breakdowns due to refrigeration systems not being able to cope with the ambient conditions.
2. Excessive heat causing issues for personnel operating the transport systems.
3. Flooding and extreme weather conditions (storms, hurricanes) affect the ability for transportation systems to operate.
4. Reduced water levels affecting river transport. For example, disruptions have occurred on 3 out of 5 years (2018-2023) along the Rhine (one of Europe's major waterway highways). In some years (e.g. 2018) barges struggled to travel[35].
5. Damage to roads caused by extreme heat causing tarmac to melt.

Although increasing ambient temperatures impact the performance of equipment, the impact of climate change goes much further. Associated issues such as droughts and reduced availability of water have an impact on the whole food chain. Food may no longer be able to be grown in certain locations and the whole cold chain system may need to be redesigned to cope with these changes. Climate change may also have wider ranging impacts such as migration of populations from areas where crops can no longer be grown and may have significant impacts on the food security of nations.

3.2 Alternative propulsion systems

A number of alternative propulsion systems are available for food transport vehicles which traditionally use diesel or petrol for propulsion and refrigeration. Alternatives include biofuels, synfuels or low carbon liquid fuels which are mainly produced from agricultural crops or occasionally waste. LNG or compressed natural gas (CNG) can also be used. Other alternatives are biomethane, hydrogen fuel cells (to generate electricity), electric batteries (which can be fully electric or hybrid) and electric roads (electric vehicles with an external energy source such as overhead catenary).

For smaller vehicles, electrification of both the vehicle propulsion and refrigeration system is a new development, and systems are commercially available. For larger vehicles electrification of the refrigeration system is a relatively new development (at high TRL) whereas electric, hydrogen, LNG/LBG or hybrid propulsion systems are undergoing development.

A number of alternative propulsion systems are available for shipping. These include LNG/ liquefied biogas (LBG) hybrid propulsion, use of hydrogen and batteries. Such systems have been deployed in

[34] https://www.eea.europa.eu/ims/global-and-european-temperatures

[35] https://www.ft.com/content/4ca7ac75-ab0a-4808-9b6b-d6695cd333c4

Europe as demonstration projects and are becoming more widely available. Many of these developments are suited to inland water ways and are being used on large rivers and fjords in Europe.

3.2.1 Electrification of vehicles

Until 31 December 2020, vehicle (new cars and LCVs/vans) CO_2 emissions regulation had been set at a European-wide level (Regulation (EU) 2019/631[36]). In 2020, a fleet-wide average emissions target for vans of 147g CO_2/km applied to the entirety of the EU/Iceland/Norway/UK new car fleet, down from 175g CO_2/km in 2019.

On 19 April 2023, the European Parliament and the Council adopted Regulation (EU) 2023/851 amending Regulation (EU) 2019/631 to strengthen the CO_2 emission performance standards for new passenger cars and new LGCVs in line with the European Union's increased climate ambition. In particular, the amendment strengthens the emission targets applying from 2030 (55% reduction compared to 1990) and sets a 100% reduction target for both cars and vans from 2035 onwards. The UK has adopted similar targets as the EU with 80% of new cars and 70% of news vans sold in GB to be zero emission by 2030 and 100% by 2035.

Regulation (EU) 2019/1242[37] is the first-ever EU-wide CO_2 emission standards for MHCVMHCVs, adopted in 2019, set targets for reducing the average emissions from new lorries for 2025 and 2030. These targets are to reduce emissions by 15% in 2025 and 30% in 2030 compared to 2019/2020.

In 2023, the Commission proposed a revision of the Regulation on CO_2 emission standards for MHCVs. If adopted, the proposal would introduce new, stronger CO_2 emission standards for MHCVMHCVs from 2030 onwards, and extend the scope of the Regulation to cover smaller trucks and trailers. The new targets will reduce emissions by 45% (2030), 65% (2035) and 90% (2040), compared to 2019/20. The UK has targets for decarbonising diesel freight[38] that states that the 2035 phase out date will apply to rigid vehicles with a gross vehicle weight less than or equal to 26 tonnes, and any articulated MHCVMHCVs with a gross combination weight of 26 tonnes and under. The 2040 phase out date applies to articulated MHCVMHCVs with a gross combination weight greater than 26 tonnes.

While electric van sales are behind those for cars, major manufacturers are expanding their ranges and sales are increasing. In 2022, around 56,500 electric vans were sold in the EU-27, representing 5.5% of the market share and an increase of around 2.0 percentage points from 2020. The majority of electric vans sold were BEVs[39].

[36] https://www.europeansources.info/record/proposal-for-a-regulation-amending-regulation-eu-2019-631-as-regards-strengthening-the-co2-emission-performance-standards-for-new-passenger-cars-and-new-light-commercial-vehicles-in-line-with-the-un/#:~:text=Regulation%20(EU)%202019%2F631%20set%20new%20targets%20for%20the,achieve%20climate%20neutrality%20by%202050.

[37] https://eur-lex.europa.eu/eli/reg/2019/1242/oj

[38] https://www.gov.uk/government/consultations/heavy-goods-vehicles-ending-the-sale-of-new-non-zero-emission-models/outcome/outcome-and-response-to-the-consultation-on-when-to-phase-out-the-sale-of-new-non-zero-emission-hgvs#:~:text=The%202035%20phase%20out%20date,weight%20greater%20than%2026%20tonnes.

[39] https://www.eea.europa.eu/en/analysis/indicators/new-registrations-of-electric-vehicles#:~:text=In%202022%2C%20around%2056%2C500%20electric,of%20the%20European%20cars%20fleet.

MHCVs are lagging behind in becoming zero emission. EVs made up only 0.6% and alternative fuel (natural gas, LPG, biofuels and ethanol) vehicles, 2.8% of the EU truck market in 2022[40]. It is important to note that electric vehicles increased from 0.5 to 0.6% from 2021 to 2022, but alternative fuel vehicles reduced from 3.6 to 2.8%.

A widely held view is that electric-drive MHCV technologies are essential to fully decarbonise the transport sector[41]. Electrically driven TRUs offer a number of advantages. Stationary refrigeration and alternator driven TRUs are already electrically driven. Many trailer based TRUs offer an electric drive from overnight parking hookups. To reach commercial scale there will need to be considerable and rapid scaling up of the technology.

Apart from pantograph charging there are two likely ways of providing the electricity directly for both the TRUs and vehicle powertrain, these are either an electric battery (e.g. Lithium ion) or a hydrogen fuel cell. The former, is by far the most common in passenger electric vehicles. The latter is not common but allows longer ranges and faster recharging. The disadvantage of hydrogen is that it requires renewable energy to produce it at low efficiency. Therefore, a substantial amount of Europe's renewable energy generation would need to be set aside for making green hydrogen to power transport vehicles. This puts a greater burden on the electrical grid which is not currently able to cope with future electrical demand. There is currently limited infrastructure to provide zero carbon hydrogen at scale (currently <1% of current production).

Battery driven electric vehicles show great promise in light and medium duty vehicles. In the heavy-duty long-haul sectors uptake is more problematic. This is due to the long distances driven, which require large batteries which take up space and gross vehicle weight and also lack if time and facilities to recharge. Vehicles are also mainly driven on motorways where there are less benefits in regenerative braking (that are seen in light commercial vehicles). Overall, where countries that have enacted targeted policy measures there is more promise for short term uptake of larger vehicle electrification[42].

With smaller vehicles there is more progress with manufacturers of electric vehicles expanding their ranges and sales are increasing[43]. It is claimed that for the UK that the zero-emissions vehicle mandate is a credible plan for driving this market forward.

Diesel refrigeration systems in semi-trailers are starting to be replaced by zero-emission battery-electric systems. A partnership between TIP Trailer Services, Unilever, Maxwell and Spark, and Daily Logistics Group (DLG) has developed an entirely renewable electricity powered refrigerated trailer that can operate down to -25°C. The system is currently being tested. The trailer can operate completely on electricity during working hours, charging the battery during points from a conventional three-phase power connection. Once the full pilot has completed, the technology is planned to be rolled out.

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[40] https://www.acea.auto/fuel-cv/fuel-types-of-new-trucks-electric-0-6-diesel-96-6-market-share-full-year-2022/#:~:text=In%202022%2C%20the%20EU%20saw,in%20Germany%20(829%20units).

[41] Moultak, M., Lutsey, N. and Hall, D., 2017, September. Transitioning to zero-emission heavy-duty freight vehicles. Washington DC: ICCT.

[42] Noll, B., del Val, S., Schmidt, T.S. and Steffen, B., 2022. Analyzing the competitiveness of low-carbon drive-technologies in road-freight: A total cost of ownership analysis in Europe. Applied Energy, 306, p.118079.

[43] Progress in reducing emissions 2022 Report to Parliament Climate Change Committee. June 2022. https://www.theccc.org.uk/wp-content/uploads/2022/06/Progress-in-reducing-emissions-2022-Report-to-Parliament.pdf

Thermo-King have developed an all-electric refrigeration unit for small delivery vehicles. The refrigeration system is integrated into an ELMS' urban delivery electric vehicle. The system is currently being piloted with refrigerated transport customers.

3.3 Hydrogen fuel cells

Fuel cells operating on hydrogen are potentially an efficient, environment-friendly (depending on how the hydrogen is produced) direct current (DC) power source that is already applied to heavy-duty bus, truck and train applications. Bosch and STEF are testing a hydrogen fuel cell powered semi-trailer (FresH2). The hydrogen fuel-cell powered refrigeration unit is produced by Carrier Transicold. The fuel cell is powered by hydrogen tanks. An electronic unit converts the direct current provided by the cell into the alternating current to operate the refrigeration unit. The fuel cell is directly interfaced with the refrigeration unit without the need for a bulky and expensive on-board buffer battery system.

3.4 The move to low GWP refrigerants

Table 5 presents refrigerants used in the food transportation sector, their replacements and typical duties, charge and leakage. Traditionally R404A (GWP 3922) and R507A (GWP 3985) has been used in larger vehicle refrigeration systems. This is being replaced by R452A (GWP 2100). R134a (GWP 1430) has often been applied in smaller vehicles. R134a or R404A are predominantly used in marine containers.

Lower GWP refrigerant drop in options are available for R404A. R407A (GWP of 2107), R407F (GWP of 1824) and R442A (GWP of 1888) can in most cases be a drop in for R404A. All these refrigerants are A1 (non-flammable or toxic).

R134a has been replaced in passenger vehicles and some new small vehicles with R1234yf (a low-flammable refrigerant with GWP of 1[44]). R134a can be replaced with non-flammable R513A (GWP 600) but has not been widely adopted. R471A (with a GWP of 148) has recently entered the market as a replacement for R134a. It is not toxic and non-flammable (A1 classification) and so has potential as an intermediate replacement for chilled transport.

Other natural refrigerant options are being developed. Propane (R290) has been used in the refrigeration system for light commercial vehicles[45][46] and R744 (carbon dioxide) has been used in larger vehicles[47].

Table 5. Refrigerants used and options for replacement.

Sector	Current (GWP)	Replacement (not retrofit) (GWP)	Typical charge	Typical leakage	Typical duty
Road vehicles	R404A (3922) R507A (3985) R134a (1430)	R452A (2140) R407A (2107) R407F (1825) R448A (1387)	1-8 kg	8-20%	3-20 kW

[44] https://www.sae.org/news/2022/03/commercial-vehicles-shift-to-r-1234yf-refrigerant.

[45] https://pbx.at/solutions/

[46] Colbourne, D., Solomon, P., Wilson, R., de Swardt, L., Nosbers, R, Schuster, M. (2017). Development of R290 Transport Refrigeration System. Presented before the IOR on 2nd March 2017.

[47] https://r744.com/co2-transport-unit-found-to-have-26-2-lower-carbon-footprint-than-r134a-unit/

Sector	Current (GWP)	Replacement (not retrofit) (GWP)	Typical charge	Typical leakage	Typical duty
		R449A (1397) R513A (631) R450A (601) R471A (148) R744 (1) R32 (675) R1234yf (<1) R290 (3) R1270 (2)			
Containers	As above	As above	4-8 kg	3-12%	5-15 kW
Ships	As above R22 (art 5)	As above R717 (0)	20-1,000 kg	5-30%	10-2,000 kW

Non flammable/toxic A2L (mildly flammable) HC (high flammability)
B2L (high toxicity, mildly flammability)

3.5 Economic pressures

The financial crisis has impacted both operators and customers. The COVID-19 pandemic had a huge impact with transport vehicles being a vital part of the covid response. The transport sector was an essential part of ensuring food was available to consumers. Inflation and the economic crisis have had impacts on maintenance and equipment costs as well as restricting investment due to higher interest costs. At the same time labour costs have increased and the costs for transportation have increased due to unstable fuel prices, changes in transportation regulations, and disruptions in supply chains.

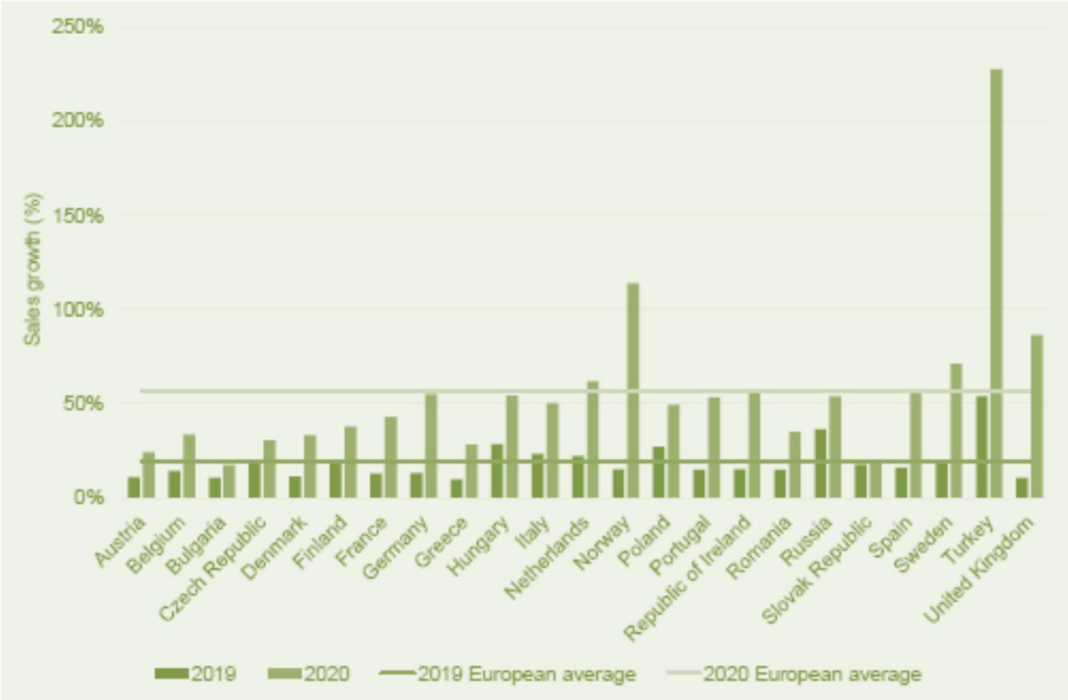
3.6 The increase in e-commerce and home delivery

E-commerce and home delivery have been growing and are predicted to further increase. The use of internet shopping saw rapid increases during the COVID 19 pandemic in some countries. For example, in the UK, pre-pandemic ecommerce accounted for 8.7% of all grocery sales. This rose to 15.4% in the pandemic and has since fallen back to 13.3% of all grocery sales[48]. Increases in ecommerce during the pandemic in other European countries were not as significant and this was partially related to the ability of retailers in these countries to service the home delivery demand. Figure 10 shows the sales growth in home delivery in European countries between 2019 and 2020. In all cases sales growth increased or remained stable with an overall increase in growth of 36.6% (overall online sales growth from 19.5% in 2019 to 56.1% in 2020). Certain countries (in particular, The Netherlands, Norway, Sweden, Turkey and the UK) all saw particularly high growth in ecommerce sales in 2020.

Although demand for home delivery has decreased since the pandemic it appears that a significant number of consumers who used home delivery during the pandemic will continue to use home delivery.

48 https://www.retailgazette.co.uk/blog/2022/03/two-years-on-how-covid-has-changed-the-uks-grocery-sector-forever/

More than 50% of consumers intend to continue e-commerce shopping for at least some or part of their grocery needs[34].



Source: European Commission Directorate-General for Economic and Financial Affairs

Figure 10. Online food and grocery sales 2019 versus 2020.

3.7 Efficiency

Reduction in energy consumption saves operational costs. With increases in global energy price, the need to improve efficiency is never more relevant.

At least 80% of the fuel is used for the vehicle propulsion. Therefore, efficient vehicle driving has huge potential to save fuel use. Training or incentivising drivers to drive in a more fuel-efficient style has significant benefits.

3.8 Vehicle routing

Many vehicle routing platforms and models exit to optimise routing for vehicles (delivery as well as freight). Systems are capable of identifying optimal delivery routes, loads, fleet dispatching and departure times as well as costs and emissions. Often systems do not include any assessment of product quality which prevents product deliveries being optimised for freshness. This area has rapidly developed due to the increase in e-commerce where the logistics of how you select the order and deliver them is a vitally important part of making the process efficient.

A number of constraints exist around routing systems. These include vehicle capacities, time windows for delivery, vehicle-specific constraints (e.g., restrictions on certain roads for large vehicles), and customer-specific constraints. Routes may need to be updated dynamically in response to real-time changes such as traffic congestion, vehicle breakdowns, new orders, or cancellations. Vehicle routes need to be flexible and take into account changes to traffic and local conditions. Optimised routing systems also need problem solving capabilities that are based on practical experience and knowledge (e.g. machine learning). This adds complexity to the routing systems as they must continuously adapt to changing conditions to maintain efficiency. Often systems can be extremely complex and need to be simplified to operate rapidly.

Generally routing algorithms prioritise meeting delivery times. Any delay leads to dissatisfaction, poor reviews and potential loss of business. Delays or mistakes in delivery can lead to customer dissatisfaction, negative reviews, and loss of business. Sustainability can be part of customer satisfaction as many customers now value environmental sustainability and are prepared to adapt their schedules to reduce emissions from the food they eat. This can include using eco-friendly vehicles, optimising routes to reduce mileage, or grouping deliveries to minimise travel distances.

Many optimisation methods and algorithms are available. These algorithms aim to find the most efficient routes that satisfy all constraints and objectives while considering the dynamic nature of the problem. Advances in technologies such as global positioning system (GPS) tracking, real time traffic data and automated route planning have improved the efficiency of systems. There is much ongoing research in this area.

3.9 The labour market

All sectors are experiencing significant shortage of skilled labour across Europe and the UK[49]. Some of this has been exacerbated by the COVID-19 pandemic where workers returned to their home countries and have not been replaced in the labour market.

3.10 Increased use of renewables

Using of renewable energy to power transport vehicles is feasible and is being developed by several companies. For example, Sunswap have developed a TRU which uses roof mounted solar to provide clean energy to run the refrigeration system and minimise battery charging time. Sunswap have recently announced an agreement with international shipping and logistics company Det Forenede Dampskibs-Selskab (DFDS) to deploy a Sunswap transport refrigeration unit into their fleet in early 2022, following which an order for production units is expected to be confirmed. DFDS has launched a climate action plan to become carbon neutral by 2050[50].

Fraunhofer ISE are also developing PV modules that are both light and robust for on-roof installation (retrofit) and full-integration into the truck body[51]. They are also working on an energy forecasting model for trucks. Based on the vehicle load and the PV electricity produced along a route they will be able to predict the driving range, loading periods and electricity production.

3.11 High capacity vehicles

In Europe vehicles are constrained by weight and size limits. Being able to transport a greater mass of product in one consignment is generally more efficient. In Finland vehicles can be up to 5.5 m in length and 76 tonnes gross weight. In Australia that can consist of double or triple road trains of 53.5 m long and up to 125 tonnes[52]. Whether such large vehicles would be suitable for many European road may be an issue.

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[49] https://ec.europa.eu/commission/presscorner/detail/en/ip_23_5732

[50] https://www.sunswap.co.uk/

[51]https://www.ise.fraunhofer.de/en/press-media/press-releases/2020/lade-pv-project-begins-vehicle-integrated-pv-for-electrical-commercial-vehicles.html

[52] ITF (2018) “Towards Road Freight Decarbonisation Trends Measures and Policies”, ITF Policy Papers, OECD Publishing, Paris.

3.12 Increased use of robotics and automation

Although robotics and automation have many benefits, they are best suited to repetitive tasks and where tasks and products are consistent. Automation and robotics technologies offer several advantages in terms of efficiency, accuracy, and safety. Automated systems can efficiently track and manage inventories. Sensors can scan and rapidly identify products, record their locations, and update the inventory database. This reduces manual errors and ensures accurate stock control and streamlined supply chain management.

Autonomous or self-driving vehicles are under development. These can be used to deliver food and incorporate routing optimisation schemes as described above. Such vehicles can operate around the clock, improving overall efficiency and reducing labour costs. Robots can also automatically load and unload vehicles which reduces labour, can also reduce loading times and potentially also emissions.

Automation and robotics have considerable potential to streamline delivery of foods. This is an area which is developing but has potential to lead to more efficient and sustainable delivery operations.

3.13 Training and skills

All businesses are placing a greater emphasis on sustainable operational practices. This is an area where workers will need new and enhanced skills to adopt eco-friendly practices. As part of sustainability and also due to the impact of energy price increase there is likely to be greater emphasis on energy management. To overcome the need for training, automated diagnostic systems can be applied to detect potential issues and solutions. Systems can also schedule maintenance tasks and proactively reduce breakdowns and unplanned downtime. Better training on design, operation of equipment and operational practices which minimise energy use are likely to be valued more in the future.

3.14 Circular economy and food waste

The EU has developed a 'Circular economy action plan' which was adopted in March 2020. It is one of the main parts of the European Green Deal. The plan aims to make sustainable products the norm in the EU while halving municipal waste in Europe by 2030 (2018 baseline).

The plan impacts the entire life cycle of products and aims to encourage reduction in waste and circularity in the use of resources. Much of the initiative related to food is targeting food waste, water use and general sustainability of food distribution and consumption. Packaging is also targeted with the aim to increase use of recycled plastics and to use plastics more sustainably.

As part of this initiative the Commission is planning legislation on the right to repair products. The Sustainable Products Initiative will revise the Ecodesign Directive, and it is currently in the public consultation phase. The initiative aims to make products more durable, reusable, repairable, recyclable, and energy efficient as well as to provide end users with a practical means to self-repair their products or choose a third-party service provider instead of going through the manufacturer.

Previously EU initiatives have focused more on end-of-life, whereas there is now a shift in attention to the entire lifecycle of a product. Like the Ecodesign directive, the Sustainable Products Initiative will provide a general framework, and sector-specific legislation for different product categories. In addition, there is an intention to introduce an EU Digital Product Passport with information on components and their potential for recycling.

4 THE FOOD TRANSPORT ROADMAP

The focus of this report is to assess the technologies and strategies available to the food transport sector to reduce their carbon emissions. We have focused on road transport as the main form of transportation within the EU. This covers the emissions that they generate today and also how emissions moving forward to 2050 could be reduced to ultimately assess how a food transport vehicle could become zero carbon. During the work, 29 different technologies and strategies were reviewed in detail to assess their opportunities to reduce carbon. This covered technologies that could be applied to the refrigeration, vehicle body and operational practices.

5 TECHNOLOGIES/STRATEGIES

Energy saving technologies/strategies were initially identified and listed. In total, 29 technologies and strategies were reviewed (see Detailed technology/strategy reviews). Technologies/strategies were only included if they had the potential to reduce carbon emissions. A comprehensive review of each technology was carried out and any references listed. The reviews included published information, or any information obtained directly from manufacturers of the equipment. The reviews compared and contrasted available information (peer reviewed papers, conference papers, grey literature, manufacturers data, personal experience) to provide a critical assessment of the validity of the information. The proportion of GHG emissions that a technology could save and any constraints around the use/application of the technology were reported. Whether savings were scope 1 or 2 were assessed. In addition, the cost for application of the technology and the TRL were listed if available. If a technology was not currently available, the approximate time until it could be placed on the market was estimated (Table 6).

SCOPE 1 EMISSIONS

Scope 1 covers emissions from sources that an organisation owns or controls directly – for example from burning fuel.

SCOPE 2 EMISSIONS

Scope 2 are emissions that a company causes indirectly when the energy it purchases, and uses is produced.

Some technologies/strategies were direct retrofit options, but others would be more appropriately applied to a new vehicle. Information on each technology/strategy is noted in Table 7. Only options with a TRL of 8-9 are considered for full assessment as it is not possible to guess the impact that lower TRL technologies might have in the future. From the analysis it was clear that many of the 29 technologies and strategies had low TRL levels and were not ready for deployment.

Table 6. Review summary information included at the end of each review.

Information	Comments
Scope 1 emissions savings (% or another quantifiable metric)	Overall savings that the review indicated.
Quality of scope 1 emissions information	How robust is the available information?
Scope 2 emissions savings (% or another quantifiable metric)	Overall savings that the review indicated.
Quality of scope 2 emissions information	How robust is the available information?
TRL level	Marked as: TRL1-4 TRL5-7

Information	Comments
	TRL8-9 TRL 1 - basic principles observed TRL 2 – technology concept formulated TRL 3 – experimental proof of concept TRL 4 – technology validated in lab TRL 5 – technology validated in relevant environment TRL 6 – technology demonstrated in relevant environment TRL 7 – system prototype demonstration in operational environment TRL 8 – system complete and qualified TRL 9 – actual system proven in operational environment
Maintainability issues	Any relevant issues are listed.
Legislative concerns	Any relevant issues are listed.
Payback time (years)	Time to recover cost of technology. This is equal to the saving in electrical energy per year divided by the cost of the technology. It does not include other ongoing costs, e.g. maintenance, cost of finance etc.

Table 7. List of technologies/strategies assessed, when they can be applied and the type of emission saving.

Technology	TRL level	Where applied:			Carbon savings	
		Retrofit	New	Scope 1 - fuels[53]	Scope 1 - fugitive	Scope 2[53]
Fuels						
Biomethane	8-9	✓		✓		
Electrification (light commercial vehicles) vehicle	6-9		✓	✓		
Electrification (light commercial vehicles) refrigeration	6-9		✓	✓		
Electrification (MHCV) refrigeration	6-9		✓	✓		
Hydrogen	5-8		✓	✓		
PV panels	5-8		✓	✓		✓
Refrigerated body/box						
Aerogel	5		✓	✓		
Air distribution systems	7		✓	✓		
Controlled atmosphere	8-9	✓		✓		
Door protection	9	✓		✓		
External and internal surface characteristics	4		✓	✓		
Foaming agents /new insulation foams	7-9		✓	✓		
Surface coatings	6		✓	✓		

[53] Assuming compared to a diesel driven engine and refrigeration system.

Technology	TRL level	Where applied:			Carbon savings	
		Retrofit	New	Scope 1 - fuels[53]	Scope 1 - fugitive	Scope 2[53]
Ozone	5		✓	✓		
VIP Panels	7		✓	✓		
Refrigeration unit						
Absorption refrigeration system powered by exhaust gases	3-4		✓		✓	
Air cycle	4-5		✓		✓	
Compressor control	7-8		✓	✓		
Cryogenic systems (liquid nitrogen, liquid carbon dioxide)	8-9		✓		✓	
Natural refrigerants - carbon dioxide	5-7		✓		✓	
Natural refrigerants - hydrocarbons	6-8		✓		✓	
Natural refrigerants – vapour absorption refrigeration systems	3-4		✓		✓	
Thermal energy storage -PCM and eutectic plates	8-9		✓	✓	✓	
Thermal energy storage - sensible energy storage	4		✓	✓	✓	
Logistics						
Artificial intelligence (AI)	4-9	✓		✓		
Decentralised Ledger technologies and blockchains	4-9	✓		✓		
Innovative green logistic schemes	4-9	✓		✓		
Innovative logistic schemes (including multitemperature vehicles)	4-9	✓		✓		
Vehicle routing optimisation	4-9	✓		✓		

5.1 What can we learn from the reviews?

The technologies/strategies were initially assigned to the following groups to identify which would save the most carbon across a refrigerated vehicle:

Potential to save carbon:

Low (L): <25% potential saving

Medium (M): >25% and <70% saving

High (H): >70% saving

Payback time:

<1 year

1 to 3 years

3 to 5 years

>5 years

Neutral/limited information

Negative payback

Technologies and strategies were then divided into sectors of relevance (Figure 11). Those in:

- Category 1 have the highest carbon savings potential and shortest payback and so should be considered immediately,
- Category 2 have high carbon savings potential but will take longer to payback,
- Category 3 have less carbon saving potential but have short paybacks,
- Category 4 have lower carbon saving potential and are longer to provide paybacks.

Other technologies outside of these categories could also be considered but are likely to be of lower relevance.

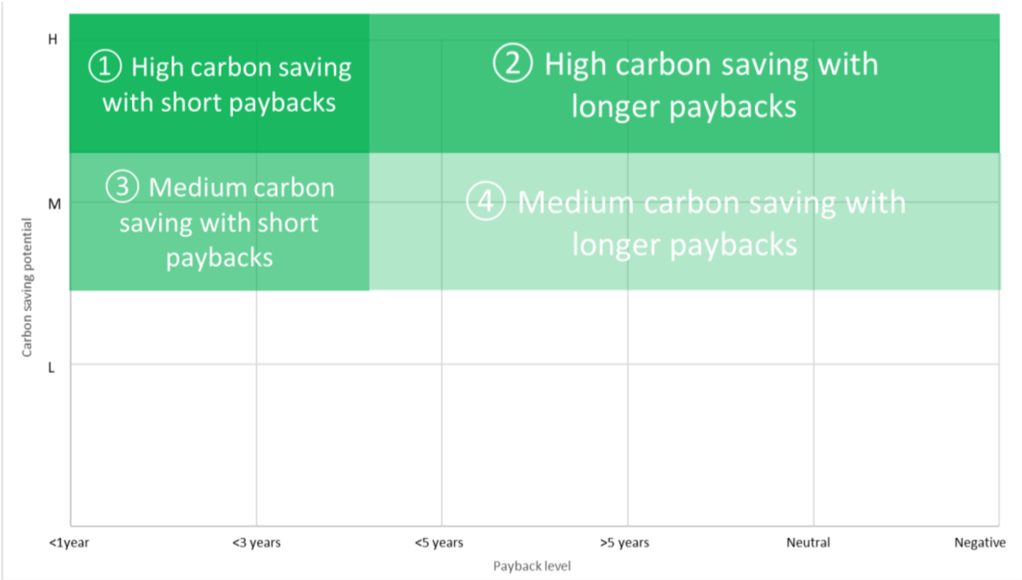


Figure 11. Potential carbon savings and payback sectors.

Technologies with a TRL of above 8 were assessed using the above methodology. Results are presented in Figure 12. It was clear that most of the reviewed technologies were not available today. Those that had a lower TRL were difficult to assess as there was very limited information on the of performance the technologies. It was therefore not possible to assess looking forward when the lower TRL technologies would be applied or their benefits.

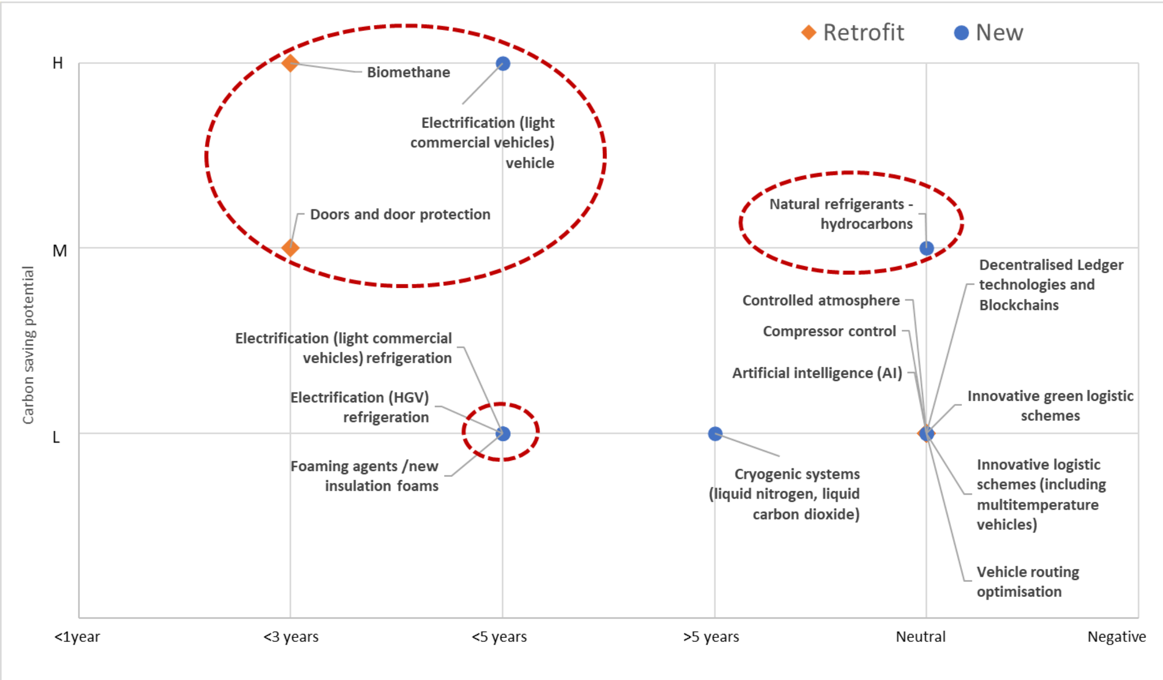


Figure 12. Transport technologies assessment.

6 WHAT STRATEGIES SHOULD WE APPLY TO GET TO ZERO CARBON IN THE TRANSPORT SECTOR?

6.1 Scenarios

6.1.1 Baseline

Modelling was caried out to assess energy use and emissions from 6 typical vehicle types in 6 European countries (UK, France, Lithuania, Norway, Italy, Poland). The missions applied to each vehicle are presented in Table 8.

THE VEHICLES WE MODELLED

6 vehicle types were modelled with different missions applied to each (Table 8):

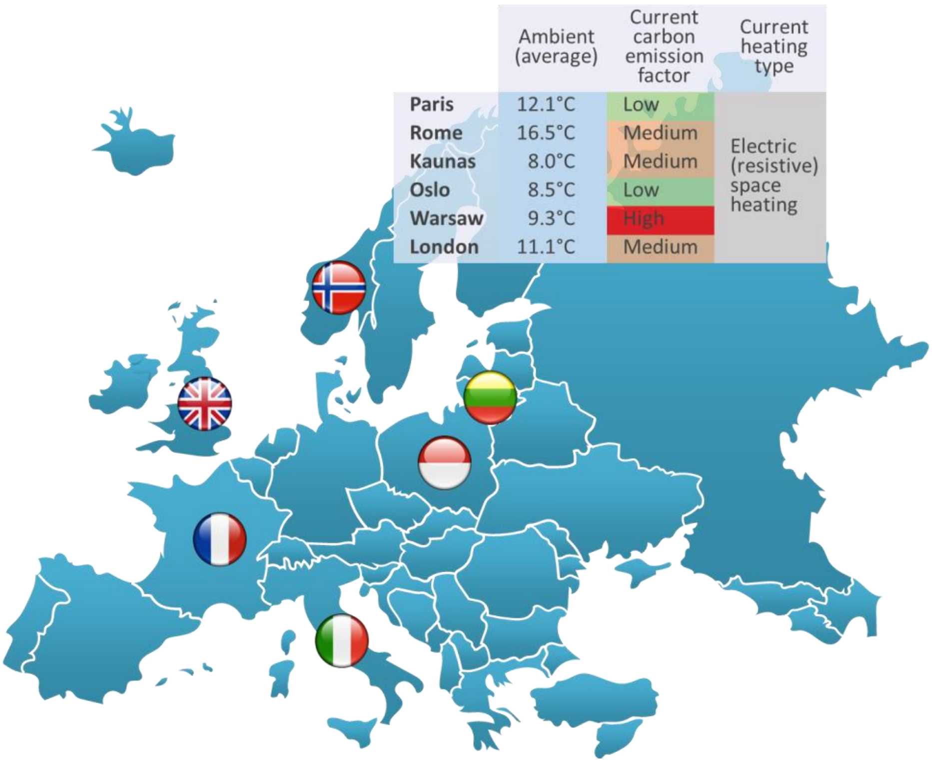
1. *Long haul medium temperature (MT) vehicle.*
2. *Long haul low temperature (LT) vehicle.*
3. *Regional MT transport vehicle.*
4. *Regional LT transport vehicle.*
5. *Last mile multi-temperature vehicle.*
6. *Last mile frozen transport vehicle with TES*

Table 8. Mission baselines for each vehicle type modelled.

	Long haul MT	Long haul LT	Regional transport MT	Regional transport LT	Last mile multi-temp	Last mile frozen TES
Vehicle						
Distance (km)	400	400	200	200	100	100
Speed (km/h)	83.1	83.1	74.2	74.2	18.9	18.9
Journey duration (h)	5.8	5.8	3.2	3.2	10.6	8.0
Stops	0	0	1	1.0	20	20

	Long haul MT	Long haul LT	Regional transport MT	Regional transport LT	Last mile multi-temp	Last mile frozen TES
Stops time (h)	n/a	n/a	0.5	0.5	0.1	0.1
Vehicle emission factor (gCO_2/km)	783.5	783.5	627	627	130	130
TRU						
Fuel	Diesel	Diesel	Diesel	Diesel	Diesel	Electricity
Refrigerant	R452A	R452A	R452A	R452A	R452A	R452A
Charge (kg)	6	6	5	5	2	6
GWP	2140	2140	2140	2140	2140	2140
TRU emission factor (gCO_2/kWh)	575	575	575	575	651	Dependant on location and time
Insulation k value (W/m^2 K) (15% better than the least stringent requirement of ATP agreement for the corresponding temperature class)	0.60	0.35	0.60	0.35	0.35	0.35

6.1.2 Global warming



The impact of climatic temperature changes due to global warming were modelled through applying an RCP 4.5 climate change scenario. This is described by the Intergovernmental Panel on Climate Change (IPCC) as a moderate scenario in which emissions peak around 2040 and then decline. Energy use and emissions in 2020 and 2050 were calculated for all vehicle missions and countries.

The grid emission factors for energy resources were applied forward to 2050. However, it was not possible to identify predicted electrical grid emission factors into the future for Norway or Italy and so it was only possible to show the emissions in 2020 for these countries (Figure 13). As can be seen, the grid intensity factors reach almost zero in Lithuania, the UK and France by 2050. No information on future grid intensities was available for Italy and Norway. However, Norway already has a very low grid intensity that is the lowest of the 6 countries considered. Poland has the highest intensity in 2020 and although it is predicted to reduces considerably it is still the highest of the 6 countries considered in 2040 (no data was available for later dates).

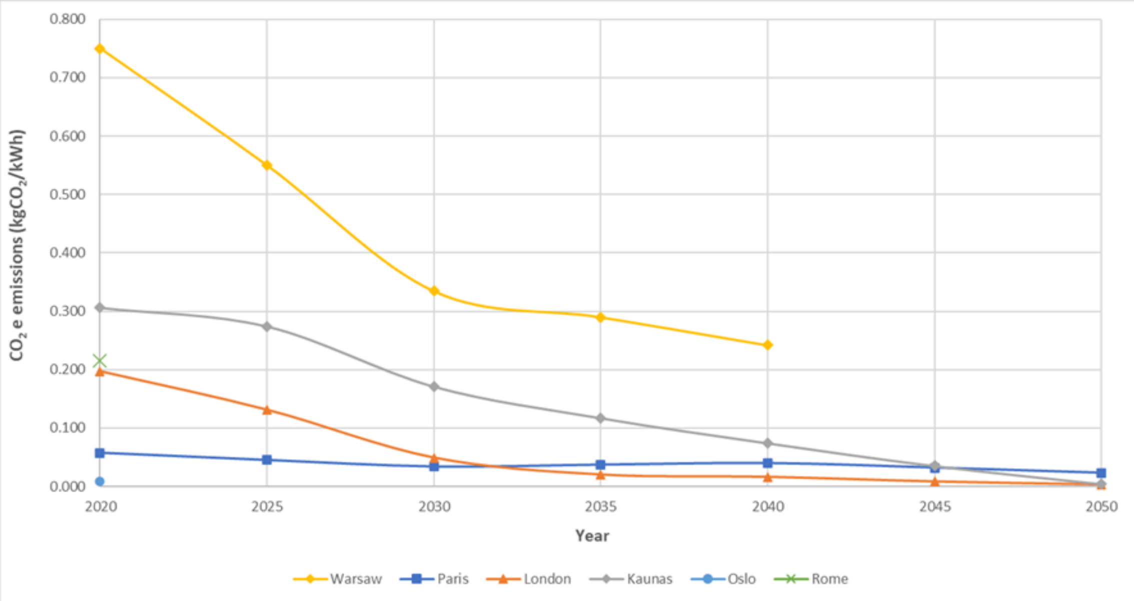


Figure 13. Grid electrical carbon conversion factors for the 6 countries studied (where available).

6.2 Application of technologies

The modelling in the baseline scenario was extended to include the technology options identified as being most suitable to reduce carbon with the best paybacks. Each technology was modelled alone to assess individual impact on energy and carbon emissions. The scenarios modelled were:

1. Adding door curtains on the TRU (60% infiltration reduction).
2. Better TRU insulation. The impact of better insulation (K=0.3 W/m^2 K) was applied to both chilled and frozen vehicles.
3. Electrification of the TRU.
4. R744 TRU.
5. R290 TRU.

Technologies were then combined as follows and energy and carbon emissions calculated:

5. Better door curtains and TRU insulation with a R744 TRU.
6. Better door curtains and TRU insulation with a R290 TRU.
7. Better door curtains and TRU insulation with electrified R744 TRU.
8. Better door curtains and TRU insulation with electrified R290 TRU.

6.3 Assumptions applied in the modelling

The modelling assumptions are presented in section 13 Modelling.

6.4 Accumulated carbon emissions

Predicted carbon emission savings can be used to calculate the cumulative reduction in emissions over time. Although there are ambitions to reduce carbon emissions to zero by 2050, this is a rather arbitrary target and the rate at which this is achieved is also important. The earlier that carbon emissions are reduced, the less overall emissions occur, which is more important than reaching zero carbon emissions by a fixed date. By applying the combined technologies, we calculated the total carbon savings from the different transport vehicle missions, that can be achieved from 2020 to 2050 and the impact of accelerating the move to low GHG emission technologies.

Other options can then be selected to assess impacts of when changes are made on accumulated carbon savings. For example:

- If nothing was done until 2025 and then technologies were applied (option 1)..
- If nothing was done until 2030 and then technologies were applied (option 2)..
- If nothing was done until 2035 and then technologies were applied (option 2)..

6.5 Results

6.5.1 Impact of climate change

Impact of climatic temperature change: Figure 14, Figure 15, Figure 16, Figure 17, Figure 18 and Figure 19 show the impact of climatic temperature change on emission from the 6 locations in 2020 and 2050. The graphs present information divided into TRU emissions, fugitive (leakage) emissions and driving emissions.

Overall differences between emissions in 2020 and 2050 were relatively small for the long haul and regional transport vehicles (less than 0.1%). This was because emissions from the TRU were a minor contributor to the overall emissions (less than 3% of the emissions were from the energy consumption of the TRU in long haul and regional transportation) and these are the only emissions affected by climate change in our model. For the last mile multi temperature vehicles the difference between 2020 and 2050 was 0.9-2.1% across all countries. For the last mile frozen TES where electricity was used to charge the TES, the emissions reduced by 2050 in all the countries.

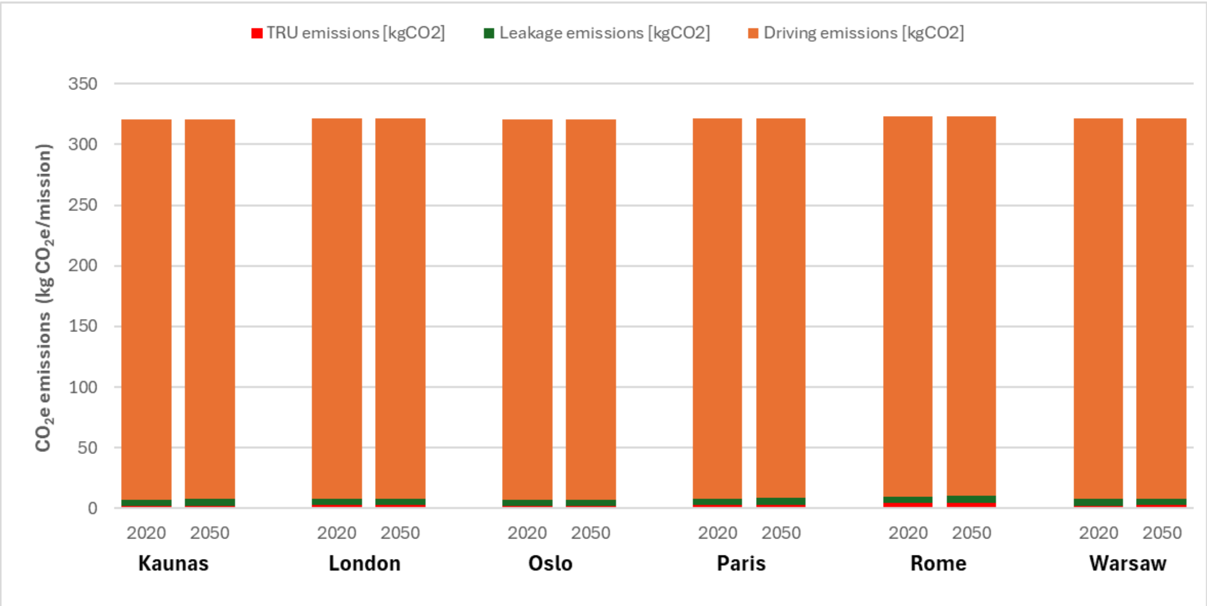


Figure 14. Impact of climatic temperature change between 2020 and 2050 (2040 for Warsaw) for the long-haul MT vehicle in the 6 locations studied.

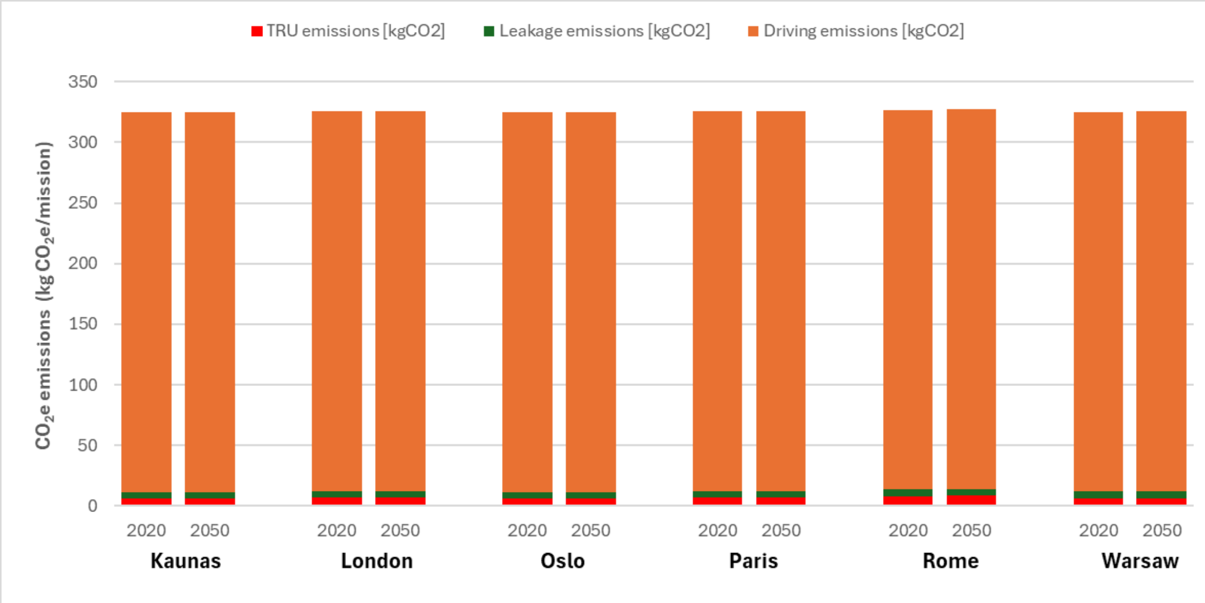


Figure 15. Impact of climatic temperature change between 2020 and 2050 (2040 for Warsaw) for the long-haul LT vehicle in the 6 locations studied.

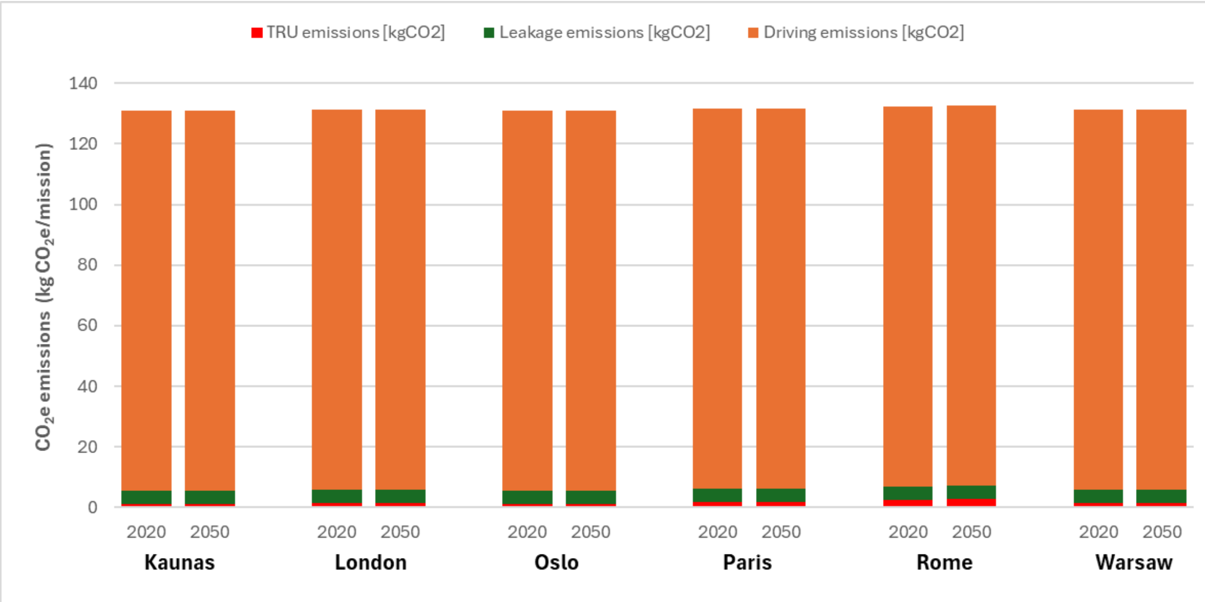


Figure 16. Impact of climatic temperature change between 2020 and 2050 (2040 for Warsaw) for the regional MT transport vehicle in the 6 locations studied.

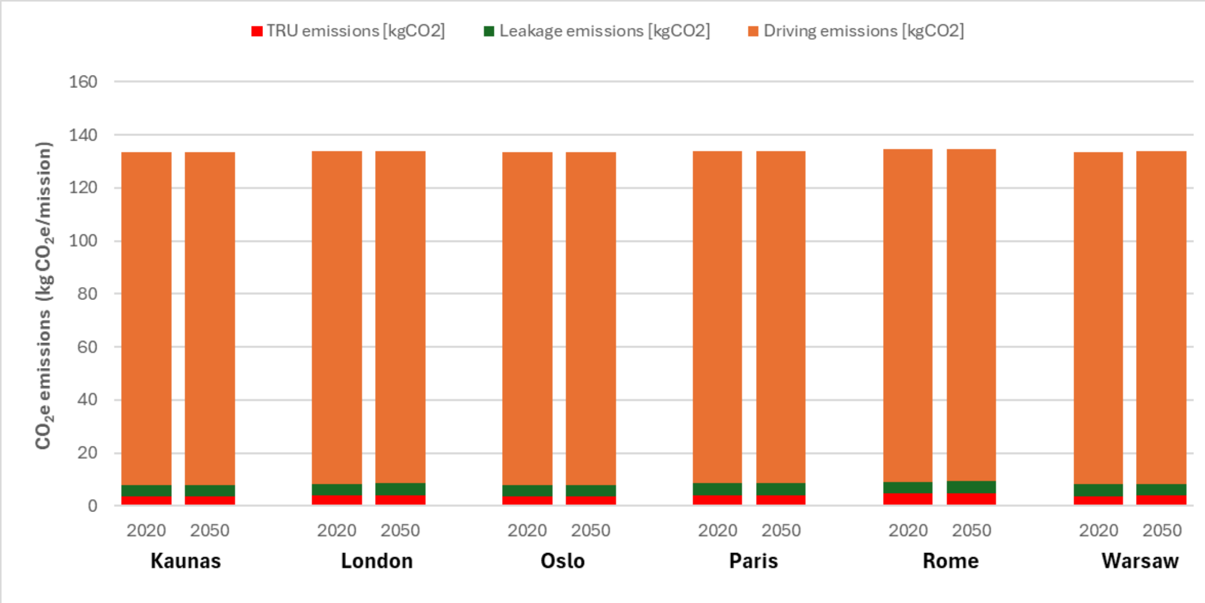


Figure 17. Impact of climatic temperature change between 2020 and 2050 (2040 for Warsaw) for the regional LT transport vehicle in the 6 locations studied.

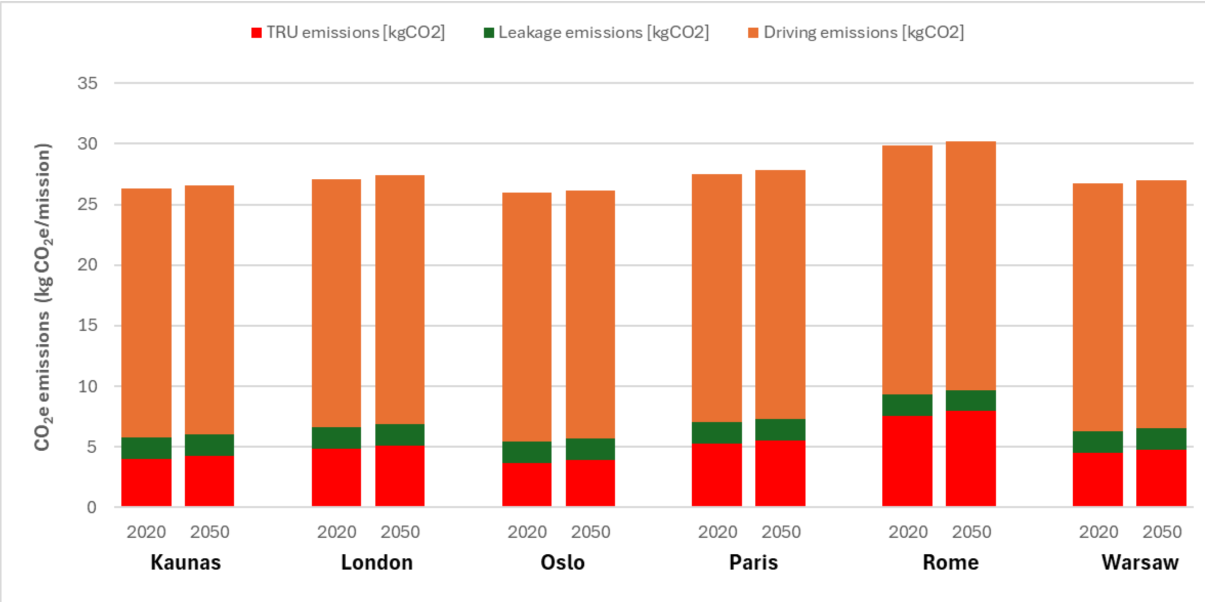


Figure 18. Impact of climatic temperature change between 2020 and 2050 (2040 for Warsaw) for the last mile multi temperature transport vehicle in the 6 locations studied.

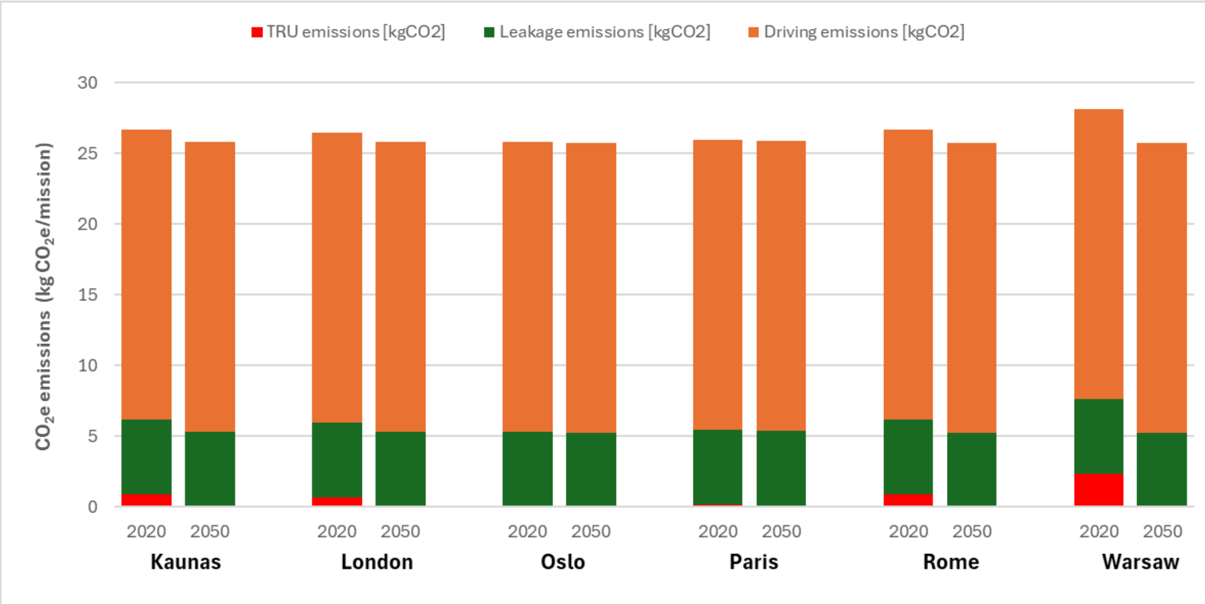


Figure 19. Impact of climatic temperature change between 2020 and 2050 (2040 for Warsaw) for last mile frozen transport vehicle with TES in the 6 locations studied.

6.5.2 Impact of applying technologies to the vehicle TRU

The selected scenarios were applied to the varied vehicle types and missions and the energy consumption and carbon emissions calculated. Only the energy and carbon emissions from the TRU are presented, as these technologies only impacted on the TRU (vehicle emission remained constant). The impact of electrification of the TRU are only presented in the carbon emission graphs as the energy consumption when a TRU is electrified was assumed to not change the kWh/mission figures. Figure 20, Figure 21, Figure 22, Figure 23, Figure 24 and Figure 25 present the energy consumption and Figure 26, Figure 27, Figure 28, Figure 29, Figure 30 and Figure 31 the carbon emissions. The energy used and emission from all vehicles, missions and countries is presented in Appendix 1.

Without application of technological interventions, the sector cannot decarbonise. The modelling demonstrated that significant reductions in carbon emissions could be achieved as follows:

Better door curtains on the TRU (60% infiltration reduction)

Curtains were shown to have no effect on long haul vehicles, and this was because there were no door openings in the long-haul mission. For last mile deliveries where there were many door openings, curtains reduced the TRU energy consumption by 29%.

Better TRU insulation (k=0.3)

Improved insulation had the greatest effect on long haul (MT), reducing the energy consumption by 27%. However, for last mile deliveries the reduction was only 1%. This was because all the heat load was through the insulation in long haul, whereas for last mile deliveries, a large proportion of the heat load was through the door. Insulation had a larger effect on MT than LT, as LT insulation in the baseline is closer to the improved insulation, which is the same for both LT and MT.

Electrification of the TRU

Electrification of the TRU had the greatest benefit where grid emission factors are low. The greatest reduction in emissions were for last mile in Paris with a 68% reduction. There was no benefit for the TES, as this was already running off grid electricity.

R744 or R290 TRU

Both the R744 and R290 TRUs were considered to have a higher COP than the baseline R452A system for both LT and MT (Figure 43 and Figure 44). Hence energy consumption for the TRU was lower in all circumstances compared to R452A. Most of the time the R290 systems had a higher COP than the R744 system. R744 only outperformed R290 at medium outdoor temperature, and at LT, this was very minimal. This meant that for all scenarios R290 gave the lowest energy consumption. In terms of carbon emissions R290 was lower than R744 in all scenarios except last mile multi-temp in Rome (29% reduction for R744 and 28% for R290).

Better door curtains and TRU insulation with a R744 or R290 TRU

When insulation and curtains were combined with a low GWP refrigeration system, the best savings were seen on last mile vehicles with an R290 refrigeration system, with a 39% reduction in emissions. The smallest reductions were seen on LT vehicles using R744 with savings of 8 to 11%.

Better door curtains and TRU insulation with electrified R744 or R290 TRU

More significant savings in carbon emissions occur when changing the TRU to R744 or R290 and using zero carbon energy to power it. For the last mile TES unit in Norway, a reduction in emissions of almost 100% was shown.

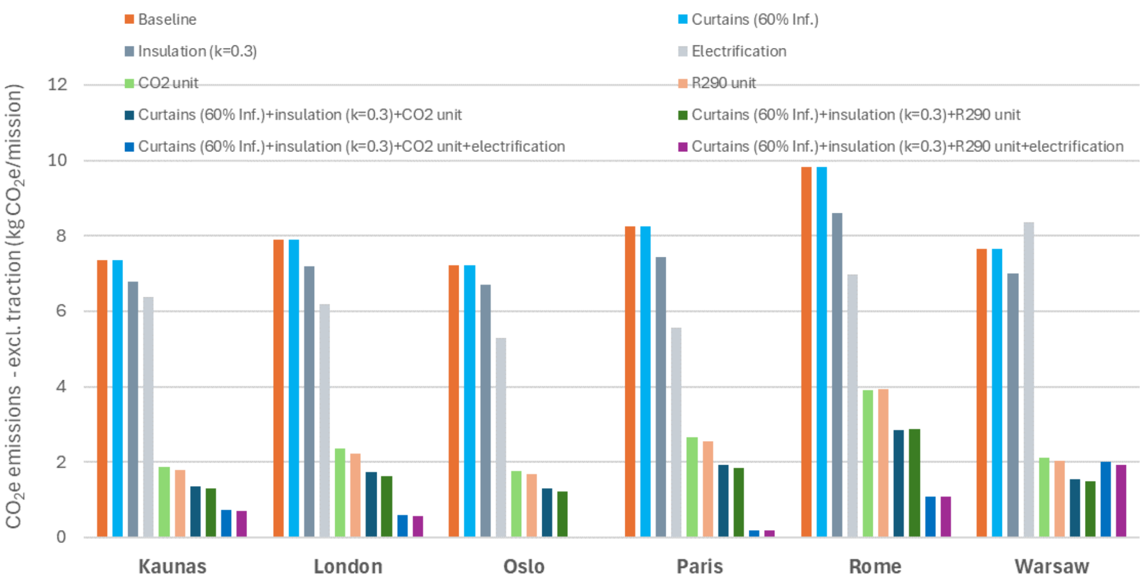


Figure 20. Impact on energy used when technologies were applied to the long-haul MT vehicle in the 6 locations studied.

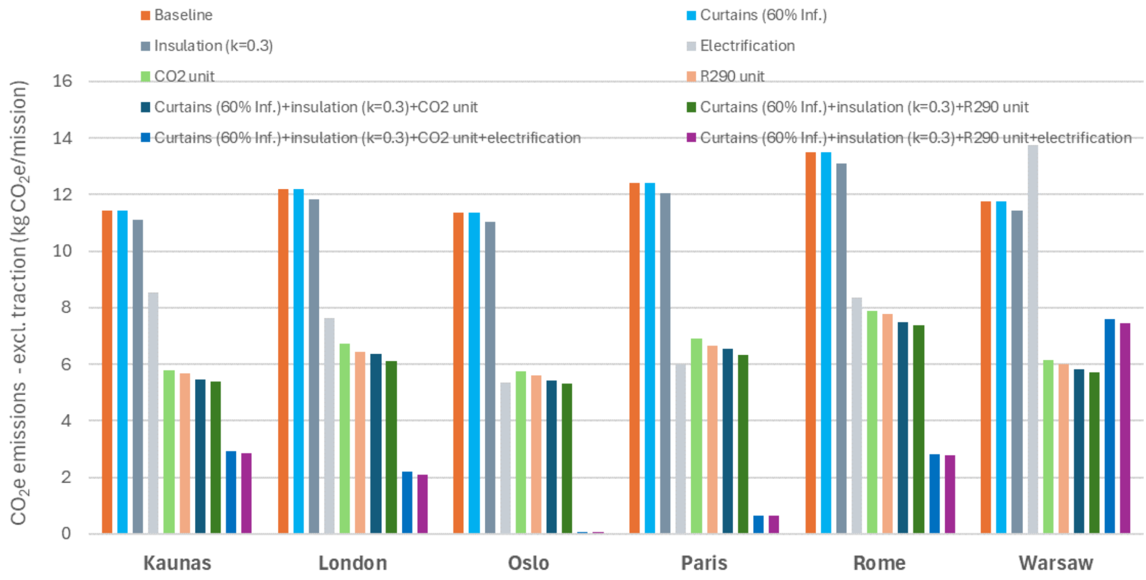


Figure 21. Impact on energy used when technologies were applied to the long-haul LT vehicle in the 6 locations studied.

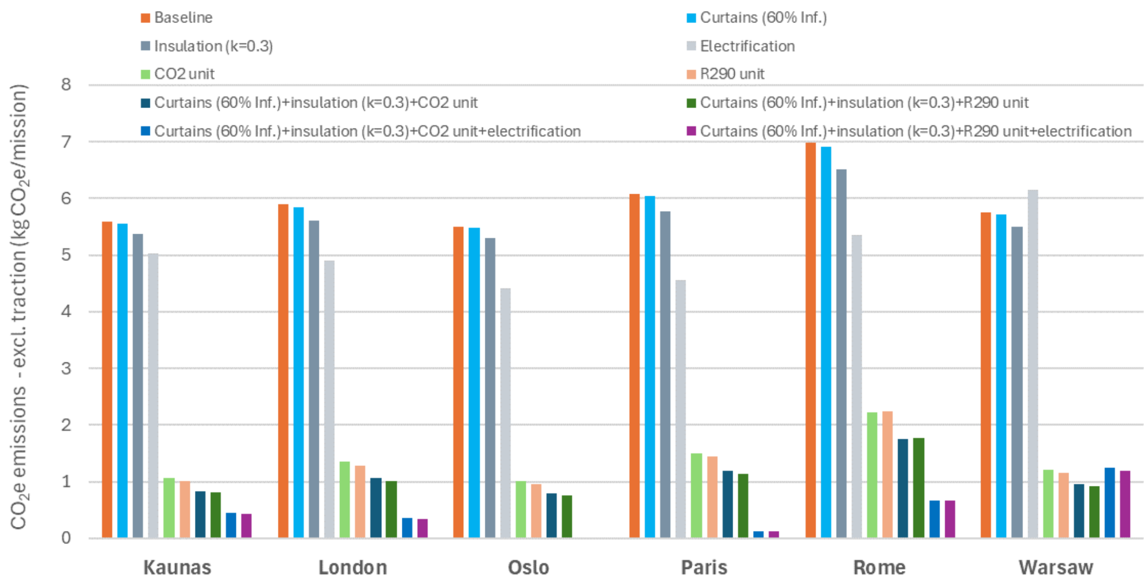


Figure 22. Impact on energy used when technologies were applied to the regional MT transport vehicle in the 6 locations studied.

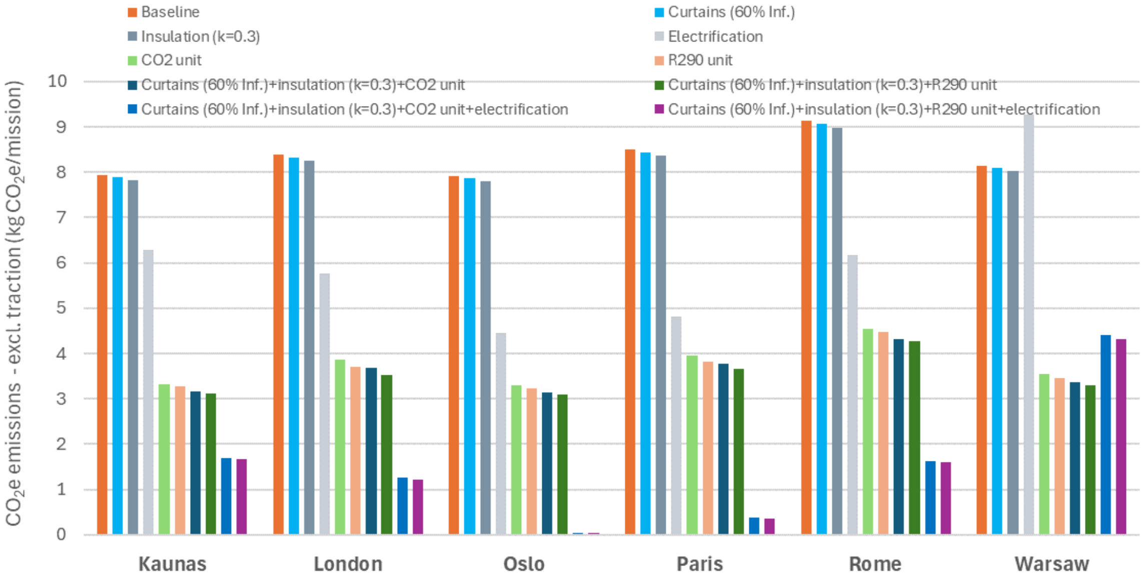


Figure 23. Impact on energy used when technologies were applied to the regional LT transport vehicle in the 6 locations studied.

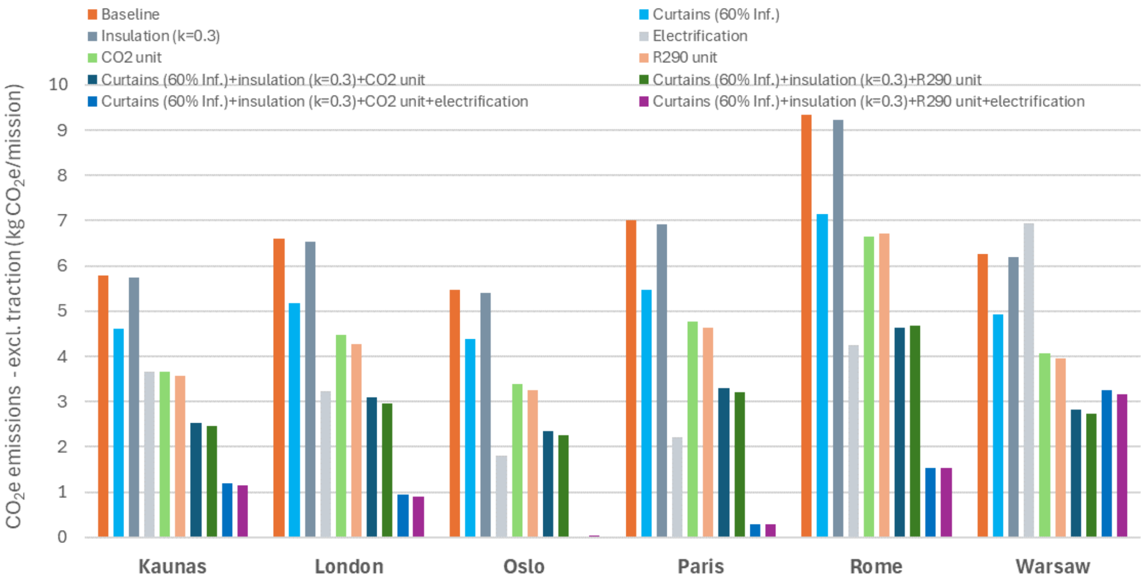


Figure 24. Impact on energy used when technologies were applied to the last mile multi temperature transport vehicle in the 6 locations studied.

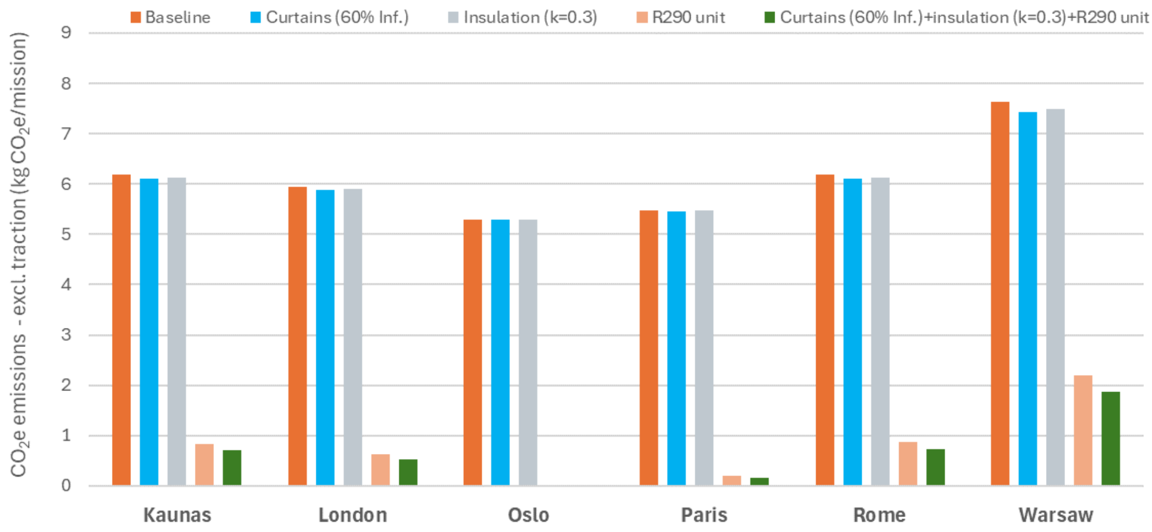


Figure 25. Impact on energy used when technologies were applied to the last mile frozen transport vehicle with TES in the 6 locations studied.

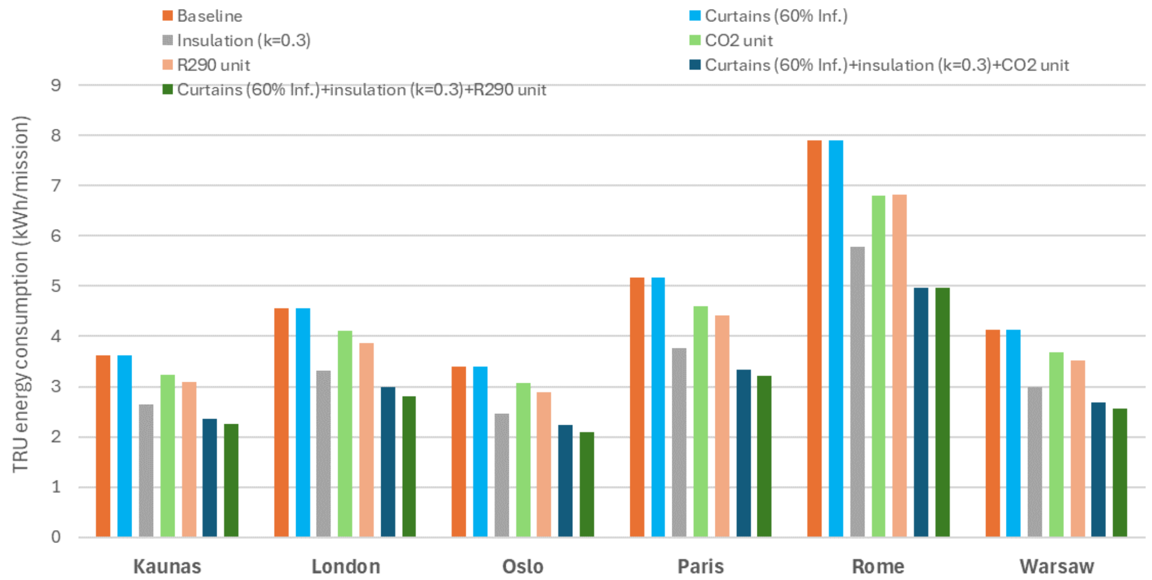


Figure 26. Impact on carbon emissions when technologies were applied to the long-haul MT vehicle in the 6 locations studied.

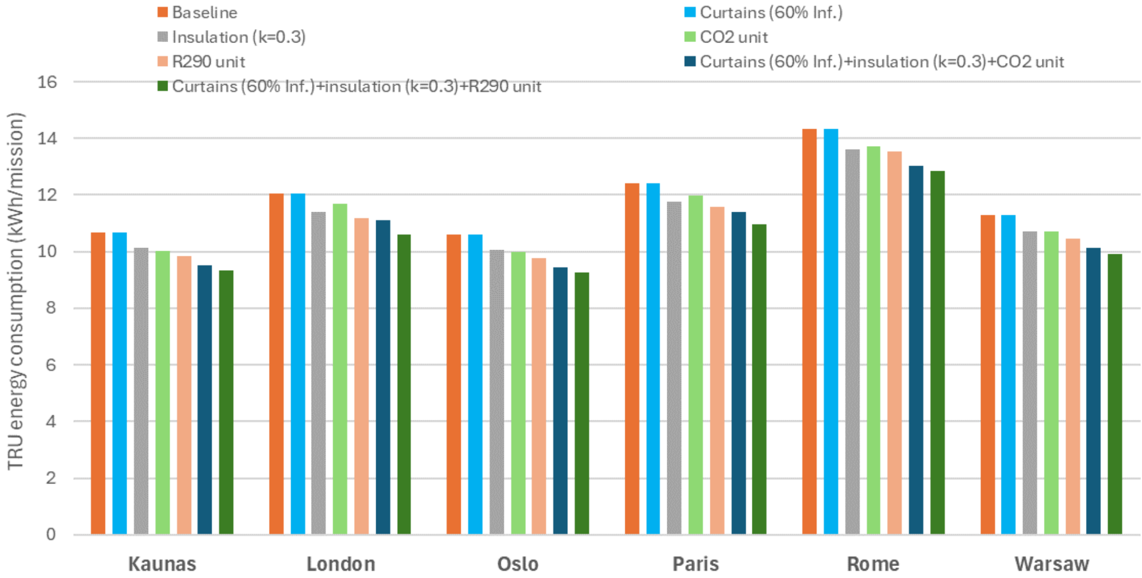


Figure 27. Impact on carbon emissions when technologies were applied to the long-haul LT vehicle in the 6 locations studied.

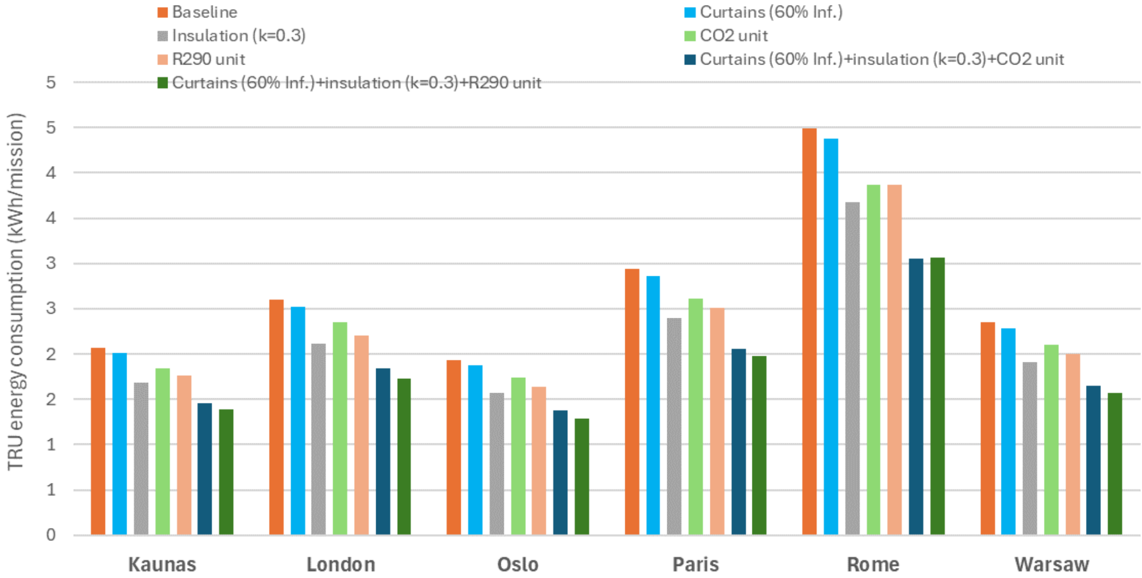


Figure 28. Impact on carbon emissions when technologies were applied to the regional MT transport vehicle in the 6 locations studied.

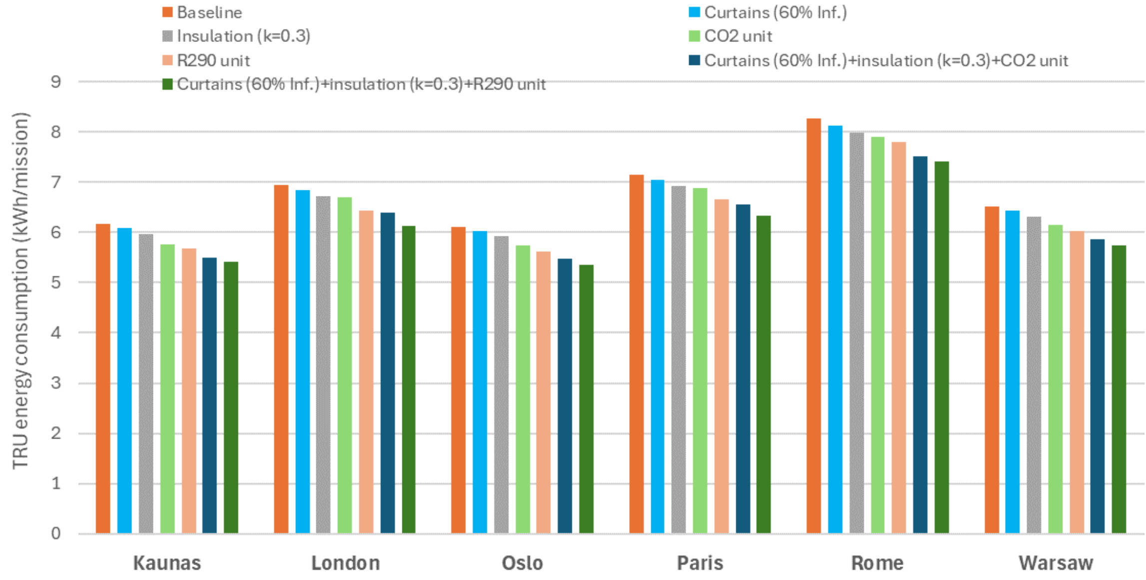


Figure 29. Impact on carbon emissions when technologies were applied to the regional LT transport vehicle in the 6 locations studied.

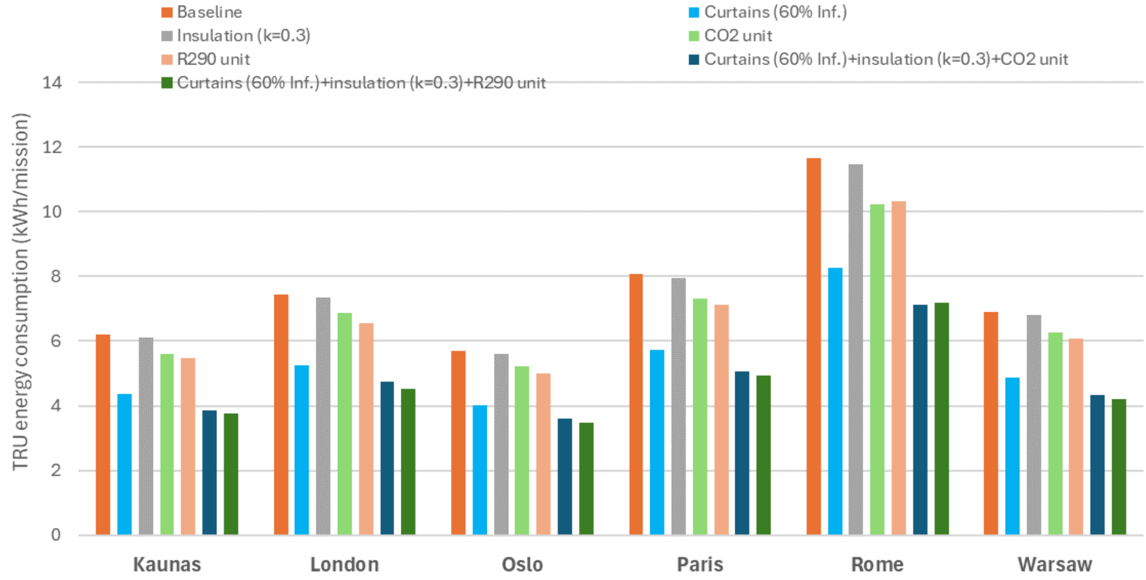


Figure 30. Impact on carbon emissions when technologies were applied to the last mile multi temperature transport vehicle in the 6 locations studied.

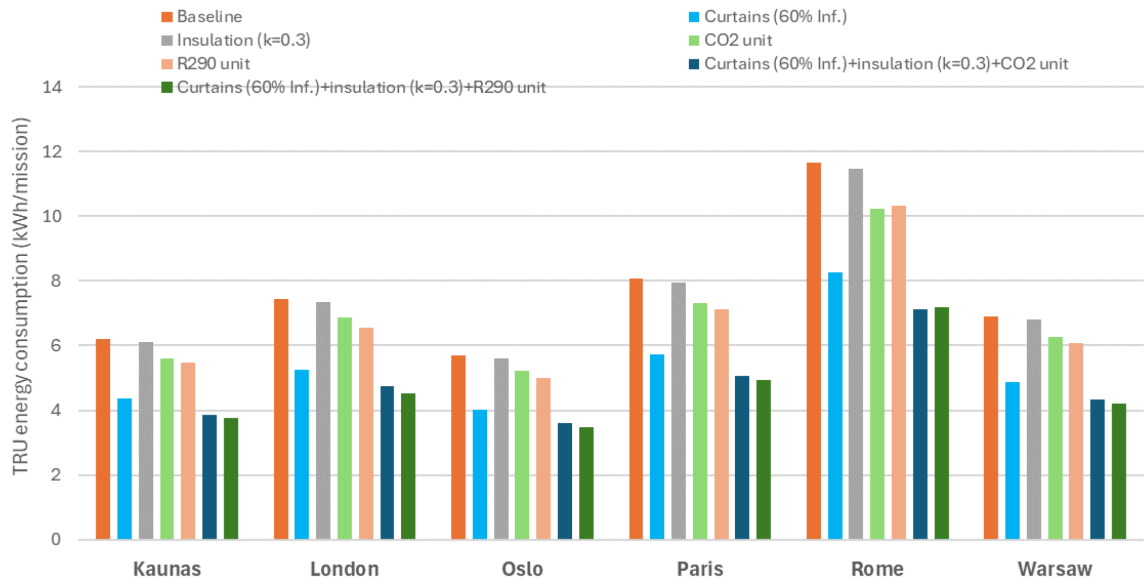


Figure 31. Impact on carbon emissions when technologies were applied to the last mile frozen transport vehicle with TES in the 6 locations studied.

6.5.3 How close to net zero (for the TRU) is possible if all technologies were applied immediately

The impact of applying strip curtains, better insulation, electrification and an alternative refrigerant TRU on carbon emissions in each of the 6 countries through to 2040/2050 was predicted (where data on future grid carbon factors was available). The impact of R744 and R290 TRUs were considered separately (Figure 32, Figure 33, Figure 34, Figure 35, Figure 36 and Figure 37).

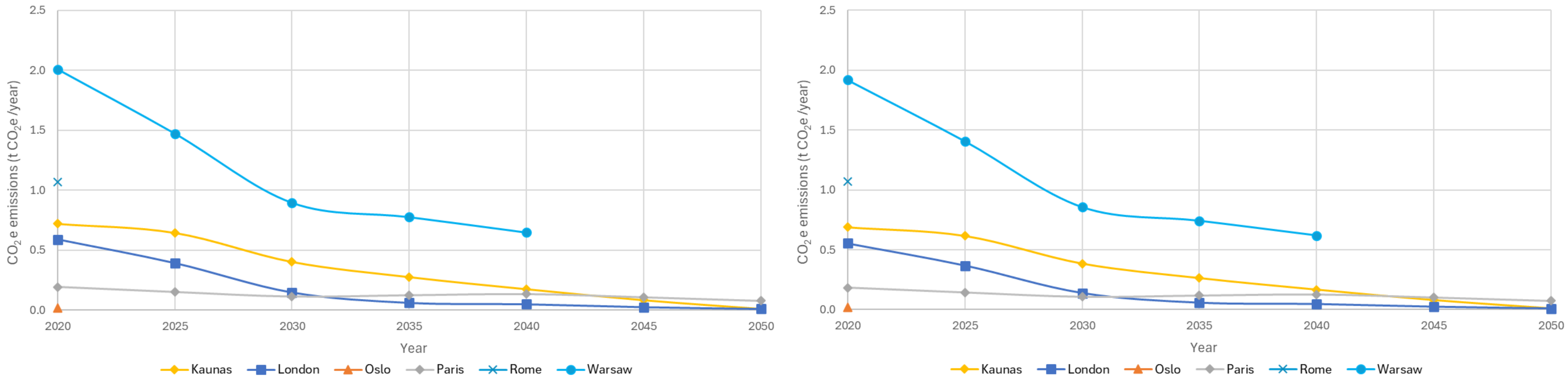


Figure 32. Carbon emissions through to 2050 (where available) when all technologies were applied to the long-haul MT vehicle in the 6 locations studied (R744 refrigeration system: left; R290 refrigeration system: right).

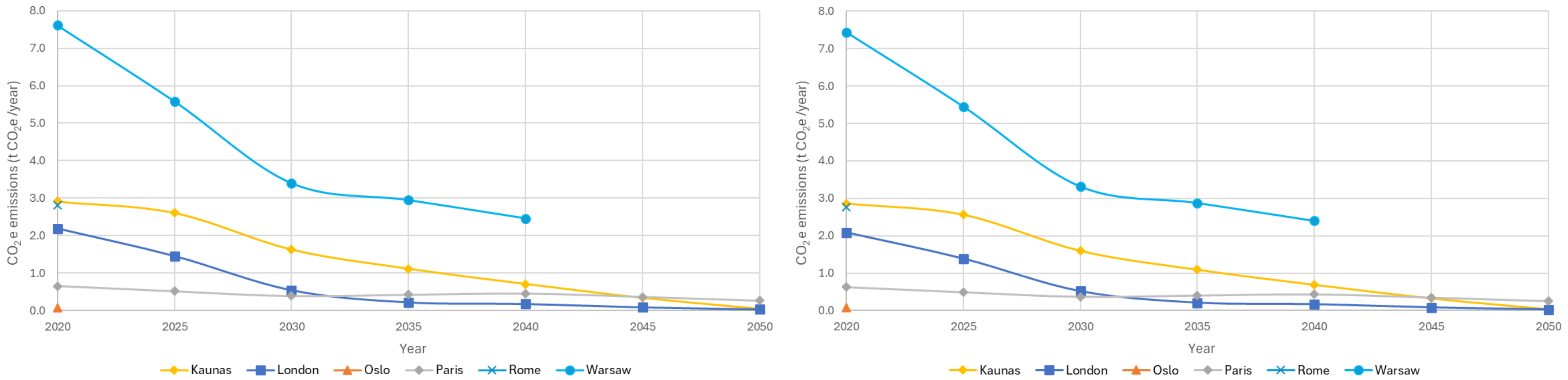


Figure 33. Carbon emissions through to 2050 (where available) when all technologies were applied to the long-haul LT vehicle in the 6 locations studied (R744 refrigeration system: left; R290 refrigeration system: right).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036588

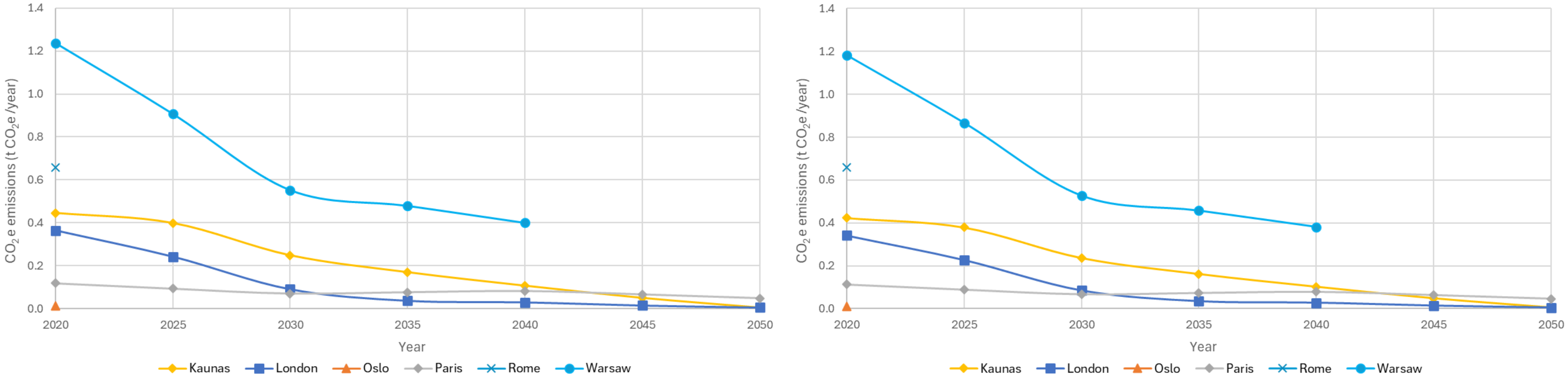


Figure 34. Carbon emissions through to 2050 (where available) when all technologies were applied to the regional MT transport vehicle in the 6 locations studied (R744 refrigeration system: left; R290 refrigeration system: right).

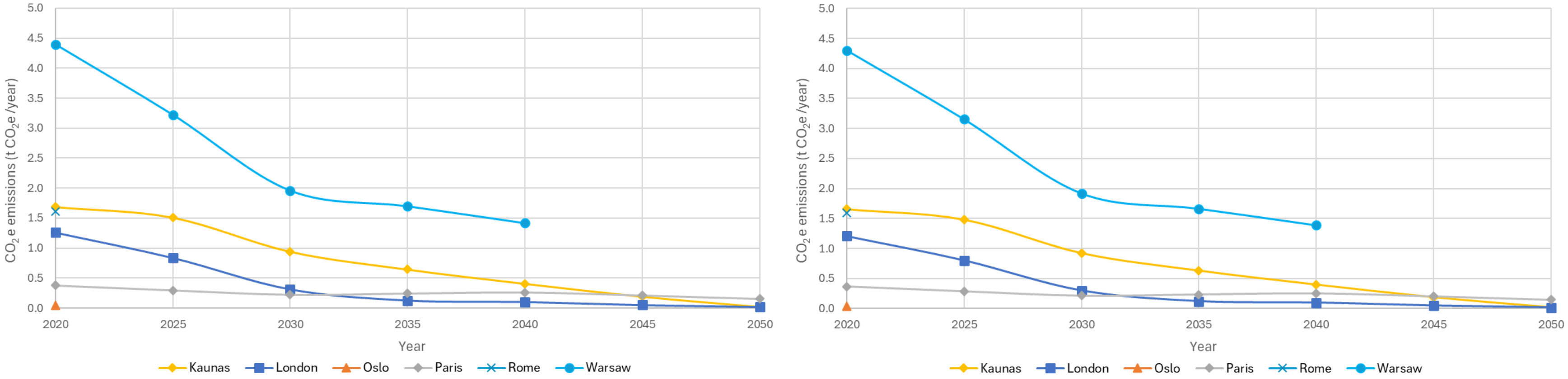


Figure 35. Carbon emissions through to 2050 (where available) when all technologies were applied to the regional LT transport vehicle in the 6 locations studied (R744 refrigeration system: left; R290 refrigeration system: right).

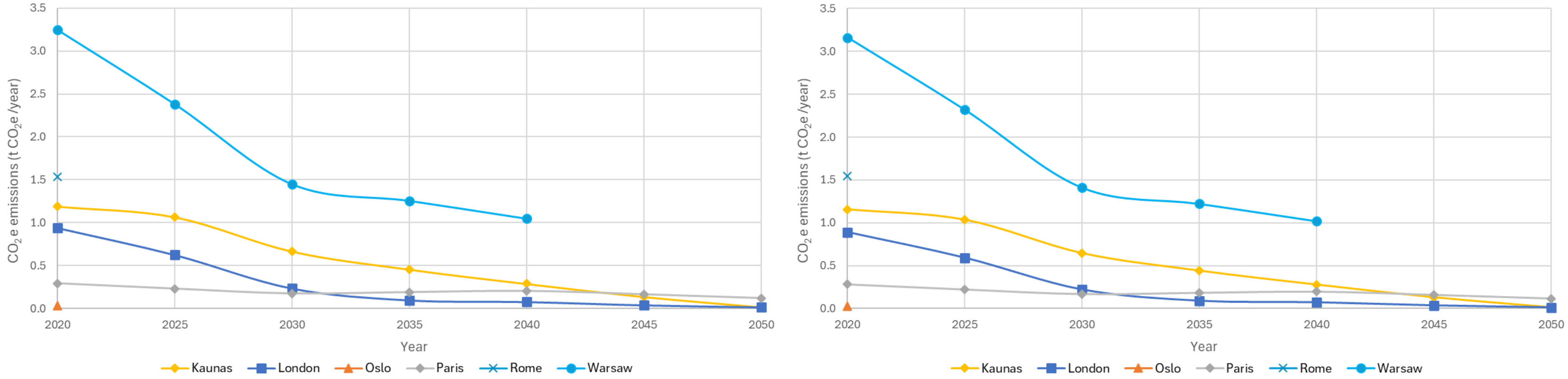


Figure 36. Carbon emissions through to 2050 (where available) when all technologies were applied to the last mile multi temperature transport vehicle in the 6 locations studied (R744 TRU: left; R290 TRU: right).

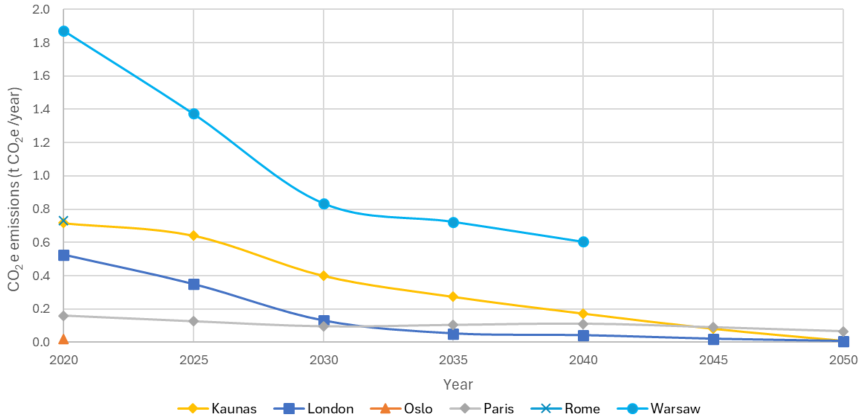


Figure 37. Carbon emissions through to 2050 (where available) when all technologies were applied to the last mile frozen transport vehicle with TES in the 6 locations studied (R290 refrigeration system, no R744 option is available).

6.5.4 Accumulated carbon emission savings

The accumulated carbon emitted between 2020 and 2050 when the technologies with the greatest carbon reduction potential (infiltration reduced, insulation improved, electrified R290 TRU) was applied was calculated for the 2 scenarios.

- Option 1: If nothing was done until 2025 and then technologies were applied.
- Option 2: If nothing was done until 2030 and then technologies were applied.
- Option 2: If nothing was done until 2035 and then technologies were applied.

Results are presented in Table 9 and Figure 38. The accumulated carbon savings were greatest in Kaunas and Warsaw. Accumulated savings were more from the LT vehicles as they used more energy. The earlier that technologies were applied the more accumulated savings were achieved. This demonstrates that it is imperative to apply technologies as quickly as possible and that delays have significant impacts on accumulated carbon emissions.

Table 9. Accumulated carbon emitted between 2020 and 2050 in Kaunas, London, Paris and Warsaw (for infiltration reduced, insulation improved, electrified R290 TRU).

	Kaunas (to 2050)	London (to 2050)	Paris (to 2050)	Warsaw (to 2040)	Option 1	Option 2	Option 3
Long haul MT	9.34	4.51	3.65	6.66	6.14	8.05	9.11
Long haul LT	38.81	17.03	12.50	25.78	23.43	31.81	36.65
Regional transport MT	5.75	2.78	2.25	4.10	3.78	4.96	5.61
Regional transport LT	22.49	9.84	7.22	14.92	13.56	18.42	21.23
Last mile multi-temp	15.70	7.27	5.62	10.95	9.92	13.21	15.08
Last mile frozen TES	9.73	4.29	3.19	6.49	5.92	8.01	9.21

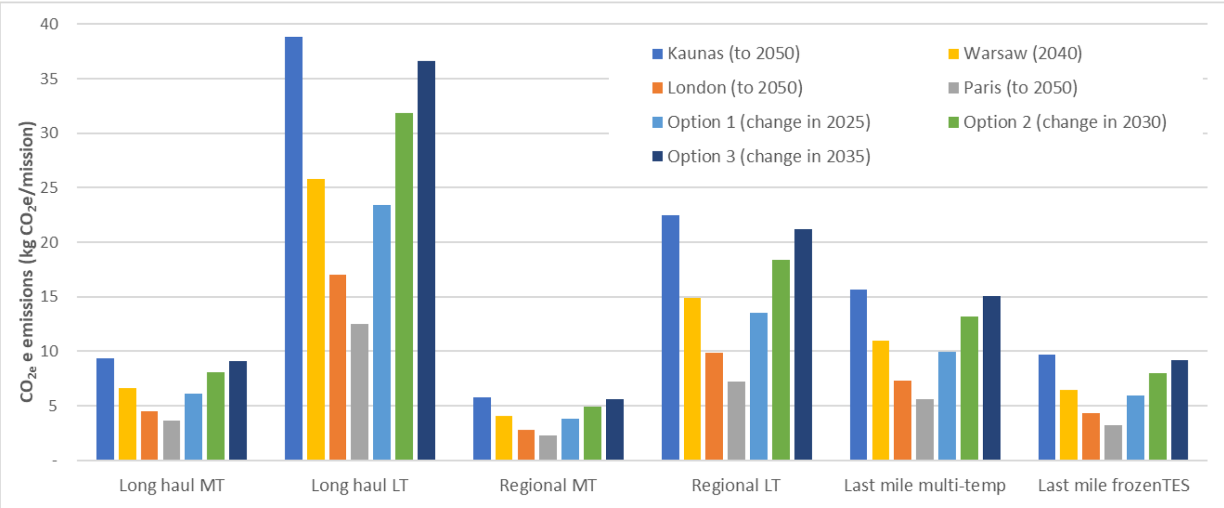


Figure 38. Accumulated carbon emitted between 2020 and 2050 for vehicle missions in Kaunas, London, Paris and Warsaw (for infiltration reduced, insulation improved, electrified R290 TRU).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036588

7 RECOMMENDATIONS

OUR RECOMMENDATIONS

- *Apply technological interventions as rapidly as possible to ensure cumulative carbon emissions are maximised.*
- *Electrification of the TRU and moving to a natural refrigerant have significant impact in all vehicles.*
- *Better insulation benefits long haul and regional vehicles more than last mile vehicles.*
- *Better door protection and recuing infiltration have more benefits for last mile delivery vehicles.*
- *To achieve significant carbon reductions a range of technologies need to be applied to the TRU.*
- *Interventions vary according to location, when they are applied and type of vehicle. Carbon emissions related to electrification are dependent on the electrical grid emissions factor in a country. Therefore, always consider individual situations.*

The modelling of the technological options across 6 vehicle missions in the 6 locations provided a direct comparison between the impact of each intervention in each location.

For the larger long haul and regional vehicles, the TRU was a relatively small part of the overall carbon emissions from the vehicles. However, this was not the case for the last mile vehicles where the TRU was responsible for 17-27% of the emissions.

Impacts of technologies on carbon savings varied according to the vehicle type and vehicle missions. Better insulation had far more impact on long haul and regional vehicles as heat gain was primarily through the insulation as there were no door openings. Local delivery vehicles benefitted more from better door curtains and reduced infiltration as they had regular stops to unload food. Changing to a low GWP natural refrigerant had benefits for all vehicles where the TRU had an operational refrigeration system on board. R290 TRUs performed slightly better in almost all countries and vehicle missions than R744 in the modelling scenarios.

Electrification of the TRU had significant impacts as the grid decarbonised in each country. In Lithuania and the UK, grid emissions are predicted to reach almost zero by 2050. France already has a low electrical grid carbon emission intensity, and this will not change dramatically through to 2050. Although we were unable to find how grid carbon intensity would change in the future in Norway the grid carbon intensity is already very low. There is no evidence that Norway will change the way they generate electricity and so it seems highly likely that the electrical grid emission factors carbon intensity in Norway will remain low moving forward. No official information on grid carbon intensity was available for Italy. The trend in Italy over the past 20 years has been for electrical grid carbon intensities to decrease and if this trend continues then Italy will also emit less carbon in 2050[54]. The country that stands out as not achieving the low grid carbon intensities as fast as other European countries is Poland. Although the grid is decarbonising in Poland it is still predicted to be at a relatively high level in 2040 (no data for 2050 could be identified for Poland).

Decarbonisation of the electrical grid will have a huge impact on carbon emissions from vehicles once they are fully (motive engine as well as TRU) electrified in most European counties. However, although decarbonisation is occurring rapidly the use of other technologies to reduce carbon are also essential, especially in the short term as the grid decarbonises. This also increased the accumulated carbon

[54] https://www.statista.com/statistics/1290244/carbon-intensity-power-sector-italy/

saved, as applying carbon saving technologies rapidly has significant impacts on accumulated carbon through to 2050.

Overall, one clear outcome from the modelling was that not all interventions had the same impact across the vehicles modelled and in the different countries evaluated. This was due to several factors which included the countries electrical grid carbon intensities and their rate of change over time and the different way in which the different vehicles were operated. It is therefore essential to assess each vehicle type individually to ascertain the most beneficial interventions.

To achieve near net zero carbon emission in vehicle TRUs will require a range of initiatives. It was clear from the modelling that it is important to act quickly to achieve the greatest cumulative carbon emissions and that applying low carbon interventions should be prioritised at the earliest opportunity. Making an assessment of the best technologies for each application is also important to maximise both energy and carbon savings.

Ultimately all the technologies and interventions we examined are available today and so the opportunity to reach near net zero carbon for transport vehicle TRUs exists and is feasible. The diagram below shows what we consider to be the priority areas for refrigerated vehicle manufacturers to focus on.

DETAILED TECHNOLOGY/STRATEGY REVIEWS

8 FUELS

8.1 Biomethane

Biogas converted to biomethane (through purification) can be readily used in natural gas-powered vehicles as another option to fossil natural gas. Using biomethane as transportation fuel results in low GHG emissions that make it a suitable source of renewable fuel. Biomethane turns out to be a great fit to replace fossil-based fuels in terms of environmental and economic considerations (Scarlat et al 2018]. Biomethane as a transport fuel provides a sustainable and readily available alternative for conventional transport fuels, representing a key solution in the transition towards a climate neutral economy (European Commission, 2020).

Biomethane can be used either in the form of Bio-CNG or Bio-LNG to serve as a transport fuel. Bio-CNG is the compressed gas form and Bio-LNG is the liquified form of biomethane. Bio-CNG and Bio-LNG can replace conventional CNG and LNG derived from natural gas without any need for infrastructure changes (Prussi et al., 2021). Both fuels can be produced either directly at the biomethane production plant (so called on-site production) or by extracting biomethane from the grid using Guarantees of Origin (GOs). When produced on-site, the Bio-CNG or Bio-LNG can be delivered to a filling station where it will be used as a transport fuel, or it can be transported via truck to be delivered to its final end-users. On-site production of Bio-CNG and Bio-LNG production is especially of interest in rural areas, where it can provide a green fuel at relatively low cost and without the need for transport via the gas grid.

Jensen et al., 2017 examined three biogas production scenarios in Denmark with a focus on commercial light and heavy-duty vehicle utilization, using three different technology assumptions for AD biogas production and assuming a 100% share for biomethane fuelled heavy-duty vehicles.

Pääkkönen et al. (2019) find that approximately half of the heavy-duty transport in Finland could be biomethane fuelled by 2030. The estimated production costs for biomethane (81–190 €/MWh) would be competitive with the current consumer diesel price (152 €/MWh). Utilizing the total biomethane potential in heavy-duty transport would furthermore decrease the respective carbon dioxide emissions by 50%.

The potential renewable resource of biomethane from food waste is shown to be equivalent to 2.8% of energy in transport in Ireland (Browne and Murphy, 2013). However, for this resource to be realised within the EU, source segregation of food waste must be affected. The organic fraction of municipal solid waste (OFMSW) which is dominated by food waste is problematic as it is putrescible; it contaminates recyclable material in combined waste collection systems and releases methane to the atmosphere when deposited in landfill sites.

Some countries plan to direct most of the biomethane production to be used for transportation-related applications (Estonia, 100%; Sweden, 83%, Finland, 100%, France, 34%, Italy, 100%, The Netherlands, 19%) (EBA, 2021).

Studies have shown that using biomethane as a vehicle fuel is greatly preferable to power generation without external heat recovery (Goulding and Power, 2013) and that biomethane also delivers greater environmental benefits than both biodiesel and first-generation bioethanol (Murphy et al., 2013; Patterson et al., 2011).

The current biomethane production costs are estimated to be on average 80 €/MWh. They can be divided into feedstock costs (16 €/MWh), CAPEX (32 €/MWh) and OPEX (32 €/MWh). It must be noted that during the past year, due to the increasing energy prices, OPEX, including feedstock costs, have increased. For 2050, the estimations range between 57 – 66 €/MWh (EBA, 2021).

Biomethane is a feasible energy resource that can meet sustainable production requirements. Researchers performed an economic analysis on biomethane plants, obtained from the organic fraction of municipal solid waste (OFMSW) varying from 100 to 500 m^3/h capacity, based on Net Present Value for two distinct policy scenarios in Italy: i. Certificate of Emission of Biofuel in Consumption (Baseline Policy Scenario) and ii. Tariff Premium (Alternative Policy Scenario). In addition, the Break-Even Point is calculated for the critical variables. The results show that the cost of biomethane production varies from 0.54 to 0.78 €/m^3 and the profitability changes depending on the policy scenario (D'Adamo et al., 2023).

Sustainable transport biofuels are already offering low carbon intensity mobility to the legacy fleet and will become more important in shipping and aviation in the future. Total GHG emissions - from biomass feedstock production, through feedstock conversion to biofuel, and to the latter's use in internal combustion engines (ICE)—are typically between 32% and 98% lower than those resulting from the use of fossil fuels such as gasoline, diesel, and natural gas (Ammenberg et al., 2021).

Scope 1 emissions savings (% or another quantifiable metric)	Up to 80%
Quality of scope 1 emissions information	Verified in the peer-reviewed environmental engineering literature
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	TRL 8-9
Maintainability issues	Similar to natural gas (CNG or LNG)
Legislative concerns	Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure
Payback time (years)	Dependent on solution 3-12 years

8.2 Electrification (light commercial vehicles)

There is a clear trend towards electrification of LCVs. According to Tsakalidis et al, 2020, total road CO_2 emissions could be decreased by 3% by a strong electrification of LCVs, which results from a 30% emission reduction for the LCV sector. According to the same authors, small eLCV are already competitive, while medium eLCV still show a slightly higher cost of ownership (1200-2300€ in 5 years). The authors suggest that incentives might solve this gap. If additional technologies such as regenerative braking are also applied authors such as Gustafson (2018) estimate paybacks can be a low as 2 years.

Klaungberga et al, 2016, analysed the German and Austrian market and found that in Germany the wholesale and retail trade sector together with transportation and storage and human health, are potentially early adopter of eLCVs. They also concluded that Austrian companies that participated to the study were able to conclude their activity within 100 km/day of electric transportation.

Minetto et al., 2023., evaluated the impact of electrification of LCVs in the European fleet and concluded that the reduction of primary energy associated to the natural refrigerant cooling units and the average reduction of CO_2 emissions factors due to electrification of the LCV refrigeration units (lead to an overall 43.0% reduction of annual CO_2 emissions linked to operation in the best-case scenario, compared to the baseline configuration where the compressor was connected to the traction motor. In addition, the complete electrification of LCVs units (TRU and main engine), resulted in a significant contribution to reduce localised pollution in urban areas and to comply with zero emission zones. Overall, in the best-case scenario, annual CO emissions can be reduced by 90.5%, NOx and THC emissions by 94.0% and PM emissions by 97.7%.

Scope 1 emissions savings (% or another quantifiable metric)	100%
Quality of scope 1 emissions information	High. Increasing of scope 2 emissions (in place of scope 1) leading to an overall saving of: 43% CO_2, 91% CO, 94% NOx and THC and 98% PM (savings of the TRU in LCV, multi-drop mission, natural refrigerant-CO_2-unit).
Scope 2 emissions savings (% or another quantifiable metric)	Increase
Quality of scope 2 emissions information	High
TRL level	TRL 6-9
Maintainability issues	No
Legislative concerns	None
Payback time (years)	<5 years

8.3 Hydrogen

Gaseous fuels with low life-cycle GHGs play a prominent role in the EUs decarbonisation plans. Renewable and low-GHG hydrogen are highlighted in the ambitious goals for a cross-sector hydrogen economy laid out in the European Commission's Hydrogen Strategy.

The suitability of hydrogen and fuel cells varies between transport modes and reflects the diverse nature of the transport sector, which spans land, sea and air, plus freight and passengers. Conventional internal combustion engines can be modified to run on pure hydrogen and could see early deployment as they are substantially cheaper than fuel cells. Hydrogen can be blended with natural gas or diesel in dual-fuel vehicles (Staffell et al., 2019). Certain operations in these fleets are intensively used and require long ranges, and some fleet owners and operators have found it cost-effective in regions where hydrogen stations exist to install fuel cell range extenders on light- and medium-duty trucks (IEA, 2019). While the theoretical potential is very large, actual deployment will depend very strongly on the interactions between vehicle costs, fuel costs and policies, as well as the cost of alternatives and evolving driving habits in different countries.

With many new applications of hydrogen, there is an increasing demand for technologies that produce hydrogen. Hydrogen production technologies differ regarding the state of development, the required feedstocks and resources, and also by the associated GHG emissions (Hren et al., 2023). Hydrogen could potentially play a significant role in the provision of electricity, heat, industry, transport and energy storage in a low-carbon emissions energy system if produced from renewable and waste material energy sources (Olabi et al., 2021). Hydrogen offers the potential for meeting global energy requirements with minimum pollution and is especially promising for balancing variable renewable energy, and emissions decarbonisation of hard-to-electrify sectors, such as heavy industry and heavy-duty transport. However, when comparing the supply chain of hydrogen as a whole, several critical aspects are identified, such as: The absence of value chains for clean hydrogen, the high cost of production, storage and transportation, the lack of international Standards, lack of storage and transport infrastructure (Tarhan et al., 2021), risks in investment, low efficiencies of mid-size and large-scale applications (Yue et al., 2021), heavy power requirements, safety concern and others.

The use of hydrogen as an energy carrier in the transportation sector holds great prospects in order to reduce CO_2 emissions and the dependency on fossil fuels. For a medium-sized, fuel cell powered car, only around 4 kg of H_2 would be needed to reach a driving range of 400 km (Adelhelm and de Jongh, 2011). However, due to the properties of hydrogen, the development of a suitable tank system is very challenging. The use of metal hydrides for the solid-state storage of hydrogen is promising mainly because they allow the storage of large amounts of hydrogen at low pressures in a small volume. In this process, hydrogen is bound to a metal hydride with moderate heat and pressure. The "hydrogenated" material can then be stored at ambient pressure and temperature without the risk of boil-off. To release hydrogen, the process is repeated with a different pressure and temperature range, enabling the extraction of hydrogen in its gaseous form. The hydrogen content of magnesium hydride is 7.7 wt% with a hydrogen density of 110 g/L, for example (i.e. a MgH_2 block of 52 kg and 36 L contains 4 kg of hydrogen). Storage of hydrogen is an important area for research, particularly when considering transportation as a major user, and the need for efficient energy storage for intermittent renewable power systems. Although compressed gas and liquid hydrogen storage systems have been used in vehicle demonstrations worldwide, the issues of safety, capacity and energy consumption have resulted in a broadening of the storage possibilities to include metal hydrides and carbon nanostructures (Desai et al., 2023; Sakintuna et al., 2007).

Hydrogen-powered trucks offer the promise of an attractive alternative to battery electric (BEV) trucks for tackling the challenge of decarbonizing heavy-duty and long-haul trucking. As the production cost of hydrogen decreases and the investment in relevant infrastructure grows, hydrogen fuel cells will emerge as a commercially viable green alternative that will outcompete fossil fuels (Hassan et al., 2023).

The first hydrogen fuel-cell electric vehicles are already being rolled out in Europe. The FresH2 solution was developed at the Rodez site, in France. It delivers the electrical energy necessary for the refrigerated transport units that equip semi-trailers for controlled atmosphere road transport. These are mainly used for the transport of perishable foodstuffs and medicines. FresH2 consists of a fuel cell powered by hydrogen tanks to which power electronics are added to convert the direct current supplied by the cell into the alternating current required by the refrigeration unit. Bosch-France's ambition with this innovation is to produce in the Rodez plant a competitive turnkey solution that can be integrated into all types of refrigerated trailers, including existing trailers (IIR, 2021).

Currently, the number of hydrogen-powered trucks is small, but is expected to increase rapidly through 2030. From the mid-2020s the vehicle offering will increase significantly, with at least 60,000 trucks expected to be in operation by 2030. Indeed, an EU-wide target of around 300 truck-suitable hydrogen refuelling stations by 2025, and at least 1,000 no later than 2030, should be set. Moreover, one hydrogen refuelling site should be available every 200 kilometre by 2030. A hydrogen refuelling station for trucks should have a daily capacity of at least six tonnes of H_2 with a minimum of two dispensers per stations (ACEA, 2021). Six truck-suitable hydrogen refuelling stations (350 bar) are in operation in Switzerland from 2021.

Hydrogen production

The water electrolysis method shows a net positive energy footprint (60.32 GJ/tH_2), suggesting that more energy is used than produced. Considering the operating environmental footprint of storage and transportation, gaseous hydrogen transported via a pipeline is a better alternative from an environmental point of view, and with a lower energy footprint (38 %–85%) than the other options, such as steam reforming of natural gas, biomass gasification, biogas steam and autothermal reforming, steam reforming of alcoholic waste, steam reforming of glycerol, AG2S process, water electrolysis, aluminium oxidation, dark fermentation and iron-based chemical looping. Storage and transport (without construction) would account for around 35.5% of the total GHG footprint of a hydrogen value chain (production, storage, transportation and losses) if liquefied and transported via road transport instead of a pipeline (Hren et al., 2023).

Refrigeration

Research of Segura et al. (2023) presents a turnkey solution of a hydrogen powered refrigeration system (HPRS) to be integrated into standard light trucks and vans for short-distance food transport and delivery. The proposed solution combines an air-cooled polymer electrolyte membrane fuel cell (PEMFC), a lithium-ion battery and low-weight pressurised hydrogen cylinders to minimise cost and increase autonomy and energy density. In addition, for its implementation and integration, all the acquisition, power and control electronics necessary for its correct management have been developed. Similarly, an energy management system (EMS) has been developed to ensure continuity and safety in the operation of the electrical system during the working day, while maximizing both the available output power and lifetime of the PEMFC. Experimental results on a real refrigerated light truck provide more than 4 h of autonomy in intensive intercity driving profiles, which can be increased, if necessary, by simply increasing the pressure of the stored hydrogen from the current 200 bar to whatever is required. The correct operation of the entire HPRS has been experimentally validated in terms of functionality, autonomy and safety; with fuel savings of more than 10% and more than 3650 kg of CO_2/year avoided (Segura et al., 2023).

Production costs for green hydrogen is currently around US$6/kg, with a price around $8-$10/kg at the pump. The production cost of hydrogen was $3.66/kg$H_2$ for the base year 2020 by chemical looping partial oxidation of methane (Anaya et al., 2023). However, decreases in fuel costs are expected, with renewable hydrogen costs projected to reach levels of $1.4-$2.3/ kg by 2030-2050 (Kim et al., 2021). This in turn is expected to generate a price at the pump between $3-$5/kg, creating room for heavy-duty hydrogen trucks to be cost competitive. In addition, fuel cell systems are lighter than batteries used in electric vehicles, so less fuel will be needed compared to BEV trucks delivering the same payload (Svensson et al., 2023). For the cost of storing compressed gaseous hydrogen (CGH_2) estimated by Teichmann et al. is 0.27 $ kgH_2 (Teichmann et al., 2012).

Scope 1 emissions savings (% or another quantifiable metric)	100%
Quality of scope 1 emissions information	High

Scope 2 emissions savings (% or another quantifiable metric)	Compared to diesel, all Scope 1 emissions are converted to Scope 2. Compared to BEV, it very much depends.
Quality of scope 2 emissions information	Diesel (high) BEV (low)
TRL level	TRL 5-8
Maintainability issues	Similar to natural gas (CNG or LNG)
Legislative concerns	Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure
Payback time (years)	n/a

8.4 PV panels

The application of solar photovoltaic (PV) technology in the transportation of food products involves various aspects such as environmental benefits, energy efficiency, economic viability, and improved food safety. Solar PV can be used to power refrigerated trucks, food trucks, trailers, and containerships. The potential for vehicle integrated PV technology on trucks has been estimated in the EU at 90 GW (Kutter et al., 2021). Solar PV can help to improve food safety by maintaining the temperature of refrigerated vehicles and containers. This is important because food spoilage is a major problem in the food supply chain (Hammond et al., 2015). There are several different technologies that can be used to integrate solar PV into food transportation systems. These include rooftop solar, trailer-mounted solar, solar-powered charging stations.

Solar panels can be installed on the roofs of refrigerated trucks, trailers, and containerships. This is a simple and effective way to add solar power to these vehicles. Solar PV technology can be integrated into electric vehicles (EVs) to charge their batteries and extend their driving range. Solar panels can be installed on the roof or body of an EV, capturing sunlight and converting it into electricity. This solar energy can then be used to power the vehicle's electric motor, reducing the reliance on grid electricity and decreasing the carbon footprint of transportation. Depending on the size of the van or truck, it is possible to install from 4 to 34 m^2 of PV panels. Most of the common vapor compression refrigeration systems employed in refrigerated trailers are directly driven by Diesel engines ranging in power from 9 to 30 kW (Bagheri et al., 2017). These diesel engines are run anywhere from 1000 hours to 7200 hours per year depending on type of operation (EPRI, 2010).

Some applications of PV panels installed directly on-board of the vehicles have been investigated as auxiliary power source for propulsion (Abdelhamid et al., 2016; Fathabadi 2018; Bhargav and Kaushik, 2019). The expected annual solar yield for the Renault Master E-Tech utility van in Stockholm would be within the range of 1825 kWh and 10216 kWh for a Tesla Semi tractor unit with an attached trailer, operated in Seville. These yields would translate to an annual solar range equivalent to 6637 km and 8173 km, respectively. The vehicle integrated PV system can cover significant shares of the energy demand of the vehicle assuming German average annual mileage for each vehicle type: up to 35% in case of Renault Master E-Tech and up to 9% for long-haul trucks (Kutter et al., 2021).

Refrigerated transport requires additional fuel for refrigeration other than for traction. Photovoltaic panels on the vehicle rooftop, a battery bank, and a power conversion system can replace the diesel engine driving the transport refrigerated unit. Batteries allow for the storage of solar energy and the use of it for refrigeration at night or when the vehicle is not in direct sunlight. In long-haul deliveries, vehicles cross zones with different climate conditions, which affect both refrigeration requirements and photovoltaic energy conversion. Mandatory driver's breaks and rest also affect delivery timing and energy consumption (Meneghetti et al., 2021). When the delivery tour embraces long travel distances, the vehicle can cross different climate zones, facing different outdoor temperatures and solar irradiance. Therefore, an optimization model for system sizing should not only be multiperiod, in order to take into account daily and seasonality variation of climate conditions, but also multizone. It should also be considered that the configuration of the return journey to the depot can affect the feasibility of the PV system. If the vehicle is empty and travels with refrigeration off, then the PV energy generated during the whole return journey can be used to charge the battery. Otherwise, when a complementary business is introduced in order to exploit a full truck load, the PV system should counterbalance refrigeration requirements even when coming back to the depot, but in this case avoided fuel costs and GHG emissions for the diesel-driven transport refrigerated units can be maximised (Meneghetti et al., 2021).

Solar PV in food transport refrigeration was developed by The Sustainable Energy Research Group from University of Southampton. The world's first solar powered refrigeration unit installed on a working articulated vehicle for Sainsbury's Supermarkets Ltd (Bahaj and James, 2002; Bahaj 2000). Power for the refrigeration unit is generated by photovoltaic panels mounted on the trailer's roof. An on-board battery stores the excess power for use by the refrigeration system during the hours of darkness. The team demonstrated that, by improving the trailer's insulation and evaporator design, the solar-powered refrigeration unit used considerably less energy than a standard diesel-driven unit. It enables the trailer to keep operating throughout the year.

The Iveco manufacturer (Cold Car, 2015) placed PV panels on the roof of truck and implemented a fresh (0°C) system, based on a CO_2 single stage compressor. The world's first solar powered hybrid truck tested on public roads was by Scania in Sweden. They claim that the hybrid lorry covered by solar panels are capable of providing up to 10000 kilometres of range annually in Spain, and a driving range of up to 5000 kilometres per year in Sweden (Cuthbertson, 2023).

In addition to solar-powered EVs, solar PV technology can be utilised to power charging stations for electric vehicles. Solar panels can be installed on the roofs of charging stations, generating electricity to charge EVs parked nearby. This approach not only reduces the demand for grid electricity but also provides a sustainable and decentralised charging infrastructure, especially in remote areas where grid connectivity may be limited. Bessa and Matos, (2012) investigated the use of EVs in the process of integrating distribution networks with PV. Furthermore, the study indicates that throughout the day, when solar radiation is at its greatest, solar electricity may be easily stored in EV batteries for future use. EVs might be charged during the day in parking lots located within offices, so that the EVs may be completely re-charged during working times, allowing the solar-to-vehicle (SV2) method to be realised (Varun et al., 2023). In their current state mounted on vehicle, PV cannot generate the amount of energy needed to fully power electric cars or trucks. Since cars spend most of their time in open air parked or while driving, placing PV cells on car roofs is beneficial to apply part consumable electricity or help charge electric batteries.

The yearly yield by solar irradiation in terms of charging cost savings to the initial cost of the system was compared. It was found, that the vehicle integrated PV system can be profitable in Freiburg and Seville assuming a 10-year lifetime. In Stockholm the vehicle integrated PV system is only profitable within 10 years if the system cost reaches 1.0 €/Wp and below. The combination of low irradiation and cheap electricity is responsible for longer payback times of the vehicle integrated PV system in the investigated scenarios in Sweden. For Germany, although the vehicle integrated PV yield is lower on commercial vehicles, it is only slightly less profitable than in Spain due to the higher electricity price.

Payback times below 5 years in Germany and Spain are realistic (Kutter et al., 2021). The PV panels represents 49% of total investment cost, while the battery and power conversion system are 32% and 19%, respectively. Switching the transport refrigerated units power system from fossil to the renewable-driven energy also leads to fuel savings for traction due to a lighter configuration of the vehicle, which allows lower weight-related consumption. Furthermore, a decrease in total transport refrigerated units maintenance cost can be estimated for the PV-driven transport refrigerated unit, with a reported value of EUR 0,30 per operating hour. At current costs, the payback period is approximately 4,6 years, without taking into account additional savings for alternative battery exploitation in winter and spring. Double increase in battery capacity the payback period increases to 7,08 years (Meneghetti et al., 2021). Despite the system shows a quite long payback period at current costs (around 6 years), forecasts on the next 10 years agree on a drastic reduction of PV system cost components, which can lead to a payback period lower than 2 years in the best scenario (Meneghetti et al., 2021a).

Increasing the penetration of renewables into the refrigerated transport can be a viable solution to increase sustainability of cold chains (Meneghetti et al., 2021). Using compressors equipped with electrical motors to be ready for fully electric or hybrid vehicle, eventually supported by integral PV systems (Rossetti et al., 2022). Fuel consumption is the main emission and emits at least 70–80% of the total GHG emissions (Li, 2017). Since no energy supply comes from the grid, GHG emissions from fossil fuel combustion are entirely eliminated when the diesel fuel engine is replaced by the PV panels and battery for powering the refrigeration unit. About 2055 $kgCO_2e$ per vehicle (having 2.8 kWp and 12 kWh battery) can be saved yearly, when taking a well-to-wheel emission factor for diesel of 3.2 $kgCO_2e/L$ (Otten et al., 2015). By replacing the diesel fuel required by the transport refrigerated units with the energy generated by the PV panels and the battery recharge from the grid, it is possible to decrease GHG emissions by 89 %. About 9572 $kgCO_2e/yr$ for a single vehicle can be saved, when taking an emission factor well-to-wheel for diesel of 3.2 $kgCO_2e/l$ and an Italian carbon intensity for electricity generation of 0.259 $kgCO_2e/kWh$ (Meneghetti et al., 2021a).

Scope 1 emissions savings (% or another quantifiable metric)	70-90 %
Quality of scope 1 emissions information	Low
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	TRL5-8
Maintainability issues	No specific requirements
Legislative concerns	No concerns
Payback time (years)	3 to 12 years

9 REFRIGERATED BODY/BOX

9.1 Aerogel

Aerogels are synthetic, porous, t substances with very low density and thermal conductivity (Meliță et al., 2019 and Berardi, 2019) making them potentially useful as insulation materials. Thermal conductivities of aerogel board have been reported as 15-17 mW/(m·K) (Adl-Zarrabi, 2020).

Aerogels have seen most use applied to building insulation (e.g. Adl-Zarrabi and Johansson, 2020, Baetens et al 2011, Berardi 2019, Jelle et al 2015, Koebel et al 2012, Meliță and Croitoru 2019, Orsini et al 2020 and Shatat et al 2015 among others). Aerogel-based blankets, where aerogel is coupled with a fibrous matrix, have been used in buildings for both internal and external insulation of the walls since the early 2000s (Adl-Zarrabi and Johansson, 2020). Case studies showed that aerogel blankets can be installed in up to five layers (50 mm) to increase effectiveness. When used as a retrofit solution 35 mm of aerogel has the same insulating effect as 82 mm of PU. The cost of retrofitting aerogel is 45% higher than the average of other types of insulation (Orsini et al, 2020).

Aerogel has been studied as a filler material in Vacuum Insulated Panels (Liang et al 2017).

Aerogels are of concern as a source of health issues. They can be a mechanical irritant to the eyes, skin, respiratory tract, and digestive system. Small aerogel particles can potentially cause silicosis and so forth when inhaled and can induce dryness of the skin, eyes, and mucous membranes (Thapliyal and Singh 2014).

Scope 1 emissions savings (% or another quantifiable metric)	By reducing k-value of truck body, diesel emissions could be reduced.
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	By reducing K-value of truck body, diesel emissions could be reduced.
Quality of scope 2 emissions information	No information
TRL level	TRL 5
Maintainability issues	Fragility, robustness.
Legislative concerns	Health issues.
Payback time (years)	Unknown for transport applications.

9.2 Air distribution systems

During transport, foods are usually stored in refrigerated containers or vehicles. Maintaining an even temperature throughout the cargo is essential in order to preserve the quality, safety and shelf life of the perishable food load. Within the refrigerated space, the temperature level and its homogeneity are directly governed by airflow patterns. The design of the air-distribution system should allow these airflows to compensate heat fluxes exchanged through the insulated walls or generated by the products (Moureh et al., 2009). This should also result in a more energy-efficient operation of refrigeration units for transport, reducing cooling cycles. However, the fans that generate the airflow are also major energy consumers in any refrigerated storage application. Shorter cooling times may require higher airflow rates, and actually increase the energy consumption due to the fan operation. This energy consumption is directly proportional to the pressure drop over the heat exchanger, in the air distribution system and across the cargo, the generated volumetric airflow rate, the fan power efficiency and the time the fans are operating. Pressure drop and volume rate are determined by the working point of the fan pressure curve, determined again by the pressure drops in the refrigerated system. Usually, the higher the pressure drop, the lower the flow rate of the fan, while the fan power efficiency typically has an optimum at a certain flow rate. Reducing the air flow resistance (pressure drop) will therefore not necessarily reduce energy consumption. Lower pressure drops will increase the flow rate, but may decrease the fan efficiency, and as a result increase the total fan electric power need and savings then depend purely on reducing fan operation time. It may then be smarter to reduce the rotation speed of the fans to deliver the same flow rate at lower pressure drop and at the same fan efficiency: this is where significant fan energy savings can be made when optimizing air distribution (Defraeye et al., 2015).

Smale et al. (2006) reviewed the application of computational fluid dynamics (CFD) and other numerical modelling techniques to the prediction of airflow in refrigerated food applications including cool stores, transport equipment and retail display cabinets. The authors concluded that the application of airflow modelling techniques to food refrigeration systems provides an opportunity to develop improved understanding of the underlying phenomena, to reduce ventilation and temperature heterogeneity and increase the efficiency and effectiveness of refrigeration systems. Ben Taher et al. (2022) reviewed energy efficiency measures for refrigerated transport, for the purposes of maintaining transportable food at the required temperature and ensuring the temperature uniformity in the container. In particular, they highlighted key aspects related to the temperature-controlled transport described in the literature including airflow patterns and air change rates. On the aspect of optimizing the air distribution systems in refrigerated transport, Hui et al. (2008) attempted to determine the effect of different accessories on air distribution in refrigerated semi-trailers transporting fresh horticultural produce. Air temperature data were gathered from mixed loads; including fruits, vegetables, cut flowers, and nuts, transported in 20 trailers equipped either with frame or solid bulkheads, and flat or ducted floors. Some trailers were also equipped with an air-delivery duct to improve air circulation at the rear and sides of the load. However, the airflow patterns varied so greatly for trailers with similar conditions that no conclusive statement could be made about which set of accessories could better improve air distribution and energy consumption. Senguttuvan et al. (2021) investigated the airflow and heat transfer characteristics in a conventional refrigerated container (CRC), and an improved refrigerated container (IRC) loaded with cargoes by CFD modelling of the airflow in the system considering the refrigeration unit and the cargoes in the container as porous media. The IRC design was changed to enhance the airflow in the refrigerated container by modifying the aerodynamic design of the refrigeration unit (Senguttuvan et al., 2020). Results showed that the heat transfer and the temperature homogeneity of the cargoes in IRC were significantly improved due to the enhanced airflow by the improved design of the refrigeration unit in IRC. The works did not consider the effects on energy consumption. Jiang et al. (2020) used a validated CFD model to study the effects of adding internal air guide structures inside a refrigerated container with a bottom-up airflow system (including a T-bar floor) packed with cherry tomatoes on the distribution of temperature. The air gaps in the refrigerated container caused a large amount of cold air to be lost, resulting in poor cooling performance. Three baffles were added to block the air gaps and guide the airflow into the stack. Compared with the standard refrigerated container, the airflow inside the improved refrigerated container was more uniform, and the vertical velocity through pallets was increased by 12% to 247%, depending on the position of pallet in the container. The temperature distribution inside the stack of the improved refrigerated container was more uniform and was maintained within ± 1 °C. The temperature rise due to fruit respiration was reduced by 13% to 51%, compared to a container without the air guides. The results showed that the distribution of air flow and temperature was greatly improved by adding the three baffles. In addition, the performance in the improved refrigerated container for different fruits and vegetables showed that the proposed structures have wide applicability across different food products. In order to provide accurate guidance, further experimental studies on the improved refrigerated container were suggested. Again in this work, energy consumption was not considered. Moureh and Flick (2009) reported the numerical and experimental characterization of airflow within a semi-trailer enclosure loaded with pallets and a top-down airflow system. The performance of ventilation and temperature homogeneity were characterised with and without supply air duct systems. Both configurations are extensively used in refrigerated transport. The numerical modelling of airflow was performed using CFD. Numerical and experimental results clearly showed the importance of air ducts in decreasing temperature differences throughout the cargo. The results showed a high degree of ventilation heterogeneity inside the pallets without air ducts. Without air ducts, the heat transfer coefficients indicated that products located near the outlet can suffer of over-chilling while the last pallets at the rear were subjected to overheating. The use of air ducts contributed significantly to a more even distribution throughout the container by improving air supplying towards the rear, whilst reducing airflow intensity at the front. Full-scale temperature measurements obtained within the load in a truck using air ducts providing two inlet sections located at the front and close to the rear part of the container, clearly showed appropriate temperature of products in these areas. On the contrary, high temperature levels in the intermediate part of the container were observed. The authors concluded there is a need for air ducts with more inlet sections in order to better homogenise ventilation throughout the whole container with top-down airflow systems. Another ceiling air duct configuration was used by Han et al. (2016) to maintain uniformity of the cargo and reduce cooling time during transportation, in a top-down airflow system with packed potatoes on pallets. The results showed that the additional air conduit inside the compartment should significantly improve the spatial uniformity of the temperature inside the cargo area. The results of the simulation were consistent with experiments. The resulting spatial variation in temperature was ∼1 °C. Kayansayan et al. (2017) evaluated different injection slot widths of the refrigeration unit in a top-down airflow refrigerated truck to determine optimal cooling characteristics at different air supply rates and for different truck lengths, but this work was conducted on an empty truck. Referring to temperature distribution effectiveness, the container with an aspect ratio of 3.33 at half-span injection showed the highest effectiveness for the range of Reynolds numbers studied. Results from the analysis of air ventilation indicated that for long trucks and low air velocity, the ventilation effectiveness was less than unity and the velocities were close to zero in almost half of the container.

On the aspect of optimising the air distribution by improved packaging design that reduce pressure drops through the cargo, more efforts have been reported. Berry et al. (2022) reviewed the existing science and practices used to design the common corrugated paperboard packaging systems. They investigated the main interactions and challenges affecting package design decisions. Every unit operation exposes the packaged produce to different environmental and physical conditions and treatments, which impose different performance requirements on the packaging. Furthermore, each cold chain is uniquely designed to accommodate the respective fruit type and circumstances. The optimal design of a carton is thus dependent on the specific cold chain it is operating in. A multi-criteria decision analysis was put forward as a novel method to better interpret integrated performance evaluations, which uses multiple evaluations to holistically assess all relevant packaging functionalities (cooling, mechanical, logistical and cost). Getahun et al. (2017a) developed and validated a CFD model of airflow and produce cooling inside a fully loaded refrigerated shipping container with a bottom-up airflow distribution system. The detailed structure of the T-bar floor of the reefer and resistance to airflow of wooden pallets were included in the model. The absence of vent-holes on the bottom face of the packaging box caused non-uniform airflow and a highly heterogeneous cooling. These results demonstrated the importance of packaging design that take into account the airflow path inside reefers. In Getahun et al. (2017b), the cooling performance of commonly used package designs used for handling apple was investigated. The effects of vertical flow resistance on the rate and uniformity of cooling were further investigated. Adding vent-holes (3.5% vent area) on the bottom face of the package reduced vertical airflow resistance and reduced the seven-eighth cooling time by 37% compared to a package with no bottom vent-holes. Impacts of temperature uniformity are mainly on quality aspects and remaining shelf life of the food, thereby affecting food losses and waste.

To gain more insight into the thermal heterogeneity and the associated differences in quality evolution for large ensembles of packed fruit, the temperature–time history of individual fruit using CFD and fruit quality evolution using kinetic rate law models can be combined (Wu and Defraeye, 2018; Wu et al., 2019b). To achieve a more comprehensive analysis of the impact of modified packaging, Wu et al. (2019a) proposed a novel computational method, by combining life cycle assessment with virtual cold chains. This holistic approach allowed, first, to track the thermal history of the cooling process and fruit quality decay of each single fruit in an entire pallet throughout the cold chain, using CFD. Second, the carbon footprint of the supply chain was quantified. This method enriched life cycle assessment with more customised input data from multiphysics modelling, and at the same time assesses food quality evolution throughout the supply chain. Significant differences between ventilated carton designs (63 g CO_2e/kg) were identified, namely, 10% of the environmental impact of the entire supply chain. By combining climate impact with the predicted quality retention, this method will help retailers to choose the most optimal package design and cold chain scenario to make their food supply chains more sustainable.

On a final aspect related to the use of airflow during transport, Ben Taher et al. (2021) proposed the use of air curtains that can be employed to optimise the energy consumption and cooling time when opening the truck door, considering different loading scenarios (empty, partially truckload, and almost fully truckload). The use of this device could lead to savings up to 25.3% of the cooling energy consumption.

Scope 1 emissions savings (% or another quantifiable metric)	Difficult to assess: adapting air distribution will affect fan net power, fan efficiency and fan operation time. Changing air distribution will affect all of these and combined they may reduce or increase energy consumption One LCA study (Wu et al., 2019a) claimed differences of up to 63 g CO_2-eq/kg by adapting different vented packaging in the cold chain, e.g., 10% of the total chain impact. The largest impact of the packaging is however related to differences in fruit packing density, thereby affecting the per kg emission
Quality of scope 1 emissions information	No data in literature
Scope 2 emissions savings (% or another quantifiable metric)	None.
Quality of scope 2 emissions information	High
TRL level	TRL 7

Maintainability issues	n/a
Legislative concerns	n/a
Payback time (years)	No information

9.3 Controlled atmosphere

Atmospheric manipulation for the protection of stored bulk or packaged food products dates back to a century (Ben-Yehoshua, S. et al., 2005) when it was showed that low O_2 and high CO_2 atmospheres inhibited the respiration climacteric and were beneficial for the long-term storage of apples. Initially, modified atmospheres (MA) or controlled atmospheres (CA) were used as an alternative to conventional chemical fumigants for controlling insect pests and rodents attacking stored grain, oilseeds, processed commodities, and some packaged foods. These atmospheres have also manifested protection against fungal growth and improved product keeping properties and quality. Although the initial applications were confined to changing the proportion of O_2 and CO_2 in the atmosphere surrounding the product (the balance being N_2 gas, and the humidity varying between 20% RH to over 90% depending on the crop) the potential for combining MA with refrigeration was soon recognised to be the solution for sea-freight transport of fresh fruits. It was also demonstrated that the physiological and biochemical basis of the longer freshness effects was not simply a reduction in respiration, but also an inhibition of the production and action of ethylene (Thompson, 2010) which gave rise to the widespread use of controlled atmospheres for the bulk transport of fruits, vegetables and also flowers.

MA is used as a general term, including all cases in which the composition of gases in the treatment enclosure have been modified to create conditions favourable to the extension of keeping properties. MA containers have the appropriate mixture injected into the sealed container at the beginning of the journey with no subsequent control, which means that the atmosphere is constantly changing during transport due to respiration and leakage. In a CA setting, atmospheric composition within the enclosure is controlled or maintained at a level to compensate the aspiration of the crop or produce. For meat and other products of animal origin, the specific application MAP or modified atmosphere packaging is used, with the specific term Active packaging where the gas composition within the pack is somehow regulated.

The system used to generate the atmosphere in a container fall into three categories (Thompson, 2010):

1. The gases that are required to control the atmosphere are carried with the container in either a liquid or solid form. This involves injecting N_2 into the container to reduce the level of O_2, often with some enhancement of CO_2. It was claimed that such a system could carry cooled produce for 21 days compared with an earlier model, using N_2 injection only, which could be used only on journeys not exceeding 1 week. The gases were carried in the compressed liquid form in steel cylinders at the front of the container, with access from the outside.
2. Membrane technology used to generate the gases by separation. Such containers use ventilation to control O_2 levels and a molecular sieve to control CO_2.
3. The gases are generated in the container and recycled with pressure absorption and swing absorption technology. The molecular sieve would also absorb ethylene and had two distinct circuits, which were switched at predetermined intervals so that while one circuit was absorbing the other was being regenerated. The regeneration of the molecular sieve beds

could be achieved when they were warmed to 100°C to drive off the CO_2 and ethylene. This system of regeneration is referred to as 'temperature swing', where the gases are absorbed at low temperature and released at high temperature. Regeneration can also be achieved by reducing the pressure around the molecular sieve, which is called 'pressure swing'. During the regeneration cycle the trapped gases are usually ventilated to the outside, but they can be directed back into the container if this is required. The levels of gas, temperature and humidity within the container are all controlled by a computer, which is an integral part of the container.

Container CA systems may be equipped with additional auxiliary equipment to compensate leakage losses or to control specific components:

- Oxygen addition and CO_2 injection may be necessary if the losses are greater than the respiration supply. To add O_2, air from outside the container is allowed to enter by opening a control valve for a short period. CO_2 can be supplemented from gas cylinders.
- Humidity injection system: To increase the relative humidity within the container, an atomised spray of water is injected, as required, into the main airflow.
- Ethylene can be removed from the container using an absorption bed, which contains activated alumina or magnesium sulphate. Alternatively, 1-methylcyclopropene (1-MCP) gas is used which is an extremely effective inhibitor of ethylene action (Watkins 2008), also as in powdered cyclodextrin-bound formulation (Daly and Kourelis, 2000).

The principal way of preserving fruits and vegetables in storage or during long-distance transport is by refrigeration. Controlled atmosphere and modified atmosphere packaging are considered supplements to increase or enhance the effect of refrigeration, standard refrigeration units are therefore integral components of CA installations. Without proper control of storage temperature, the benefits of MAP may be lost. Higher temperatures also inevitably lead to less dissolved CO_2 in the product and consequently loss of inhibitory effect, which may result in higher microbial and enzymatic activity, and uncertainties concerning the microbial safety, as food-borne pathogens might be present in the product. Contemporary gas analytical and control technologies permit the use of CA for transport purposes at a range of sizes, from quasi-static applications built into sea-freight 20' or 40' containers to mobile trailers.

The relationship between CA storage and temperature has been shown to be complex. At 10°C, for example, CA storage could increase the storage life of apples compared with those stored in air, while at 15°C their storage life was the same in both gas storage and air. However, the opposite effect was shown by Ogata et al. (1975). They found that CA storage of okra at 1°C did not increase their storage life compared with storage in air, but at 12°C CA storage increased their postharvest life. This suggests that CA transport of certain crops may benefit from higher temperatures, resulting in energy saving due to less cooling needed.

For animal meat, legislative maximum temperatures apply for transport which gives a maximum transportation air temperature of 6°C for transports up to 30 hours and 3°C for transports up to 60 hours (Regulation (EC) 853/2004). This limits the applicability of CA transport, as the potential energy saving on refrigeration is minimal. Some bacteria, like non-proteolytic C. botulinum in MA packaged fresh fishery products represents a potential risk for several reasons (Sivertsvik, 2002), as the inhibition of the normal aerobic spoilage bacteria by MA reduces bacterial competition that may permit non-proteolytic C. botulinum growth and toxin production during prolonged refrigerated or temperature abuse storage; and products contaminated with C. botulinum and packaged under MA may become toxic and yet remain acceptable with respect to odour and appearance to the consumer.

The use of CA transport has been demonstrated to be beneficial in extending the shelf life of crops and produce in the literature of the last decades. If CA is applied and maintained correctly together with temperature, the combination of these processes can reduce the amount of product wastage from deterioration and spoilage in the food cold chain, during storage and transport. However, once refrigeration is in place, no significantly lower energy use in combination with CA could be demonstrated and CA of lower value products will probably not be a viable technique compared to conventional chilling due to the extra costs of equipment needed for maintaining the CA conditions during transport. For short-haul and distribution traffic, every opening of the doors would break the CA conditions, such system would be prohibitively expensive. Nevertheless, CA transport remains a viable option for the overseas and long-haul transportation of temperature-sensitive leafy vegetables and tropical fruits. This is particularly true for fruits where the use of ethylene removal or inhibition with 1-MCP gas makes it the preferred choice.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	No information relating to transport applications.
Quality of scope 2 emissions information	No information.
TRL level	TRL 8
Maintainability issues	Limited life-time of CA containers
Legislative concerns	Health issues (atmosphere deprived of oxygen)
Payback time (years)	Strongly product dependent but several years

9.4 Door protection

According to Rai et al (2019) warm air infiltration during door openings of refrigerated delivery trucks can account for approximately 34% of the overall refrigeration load, with this share estimated to be higher for longer and/or more frequent door openings.

A simple method of door protection which has been commonly used in the cold storage industry is the suspension of flexible PVC strips inside the door, to provide a barrier to airflow when the door opens. This technology can also be used on refrigerated transport vehicles. They are inconvenient to use as they impede loading and unloading. For this reason, even when they are fitted on the vehicle they are not always utilised by the drivers (Rai, 2019).

An alternative to the strip curtain is the air curtain, which requires energy to drive one or more fans, but which does not block vision or impede traffic. Most air curtains studies are related to cold storage rooms (see Cold storage Roadmap). However, Rai et al (2019), found that an air curtain at optimum velocity (3.1 m/s in this study) can help reduce the energy consumption by almost 48% for a refrigerated truck body. Tso et al (2002) found that using an air curtain can have energy savings up to 40 and 11%, respectively, compared to the cases without an air curtain and using plastic strip curtain. Le Blanc found that air curtains in most cases reduced air infiltration (up to 40%). However, at high ambient temperatures (> 40°C), the air curtain was less effective than plastic strip curtains since it entrains more heat into the cold environment near the bottom of the door.

For loading bay doors which open to the outside ambient to allow vehicles to back onto them, it is common to have rubber flaps or soft, compressible seals or cushions around the openings. These require frequent checking and maintenance to avoid damage and resultant leaks. Inflatable versions of the seals allow more flexibility to cover varying gaps due to different vehicle sizes and can function better than normal flap protection. For example, Escriva et al 2020 found that inflatable seals reduced the energy related to infiltration by up to 88% compared with simple flap operation in cold warehouses in Spain).

Scope 1 emissions savings (% or another quantifiable metric)	Up to 48% energy savings reported
Quality of scope 1 emissions information	High
Scope 2 emissions savings (% or another quantifiable metric)	Up to 48% energy savings reported
Quality of scope 2 emissions information	High
TRL level	TRL 8-9
Maintainability issues	No issues
Legislative concerns	No impact
Payback time (years)	No information

9.5 External and internal surface characteristics

External and internal surfaces play a crucial role in the thermal performance of insulated vehicles due to their impact on heat transfer mechanisms. Key factors of the surface characteristics (except conductive heat transfers) influence the thermal losses primarily by radiative and convective heat transfer. From the measurement of 20 feet (Twenty-foot Equivalent Units, TEU) refrigerated containers, the overall mean rate of energy consumption is around 3.6 kW per TEU (Wild, 2009). Another study by Fitzgerald et al. (2011) assumed the mean energy consumption rate of the Refrigerated container to be 2.7 kW/TEU and indicated potential variations of around 60% due to various factors. Average sun-shade difference for outdoor temperature reaches more than 7 °C and so, walls exposed to sun radiation show clearly differentiated thermal patterns compared to shaded ones (Rodríguez-Bermejo et al., 2007).

Budiyanto and Shinoda (2018) have conducted a thermal study of a container for international transport. The authors collected environmental parameters, i.e., solar radiation, surface temperature, and air temperature on a white painted test container in Japan in August, with an internal temperature setpoint of +1 °C. They concluded that the direct effect of solar radiation on the container surface causes the temperature penetration of the container wall and increases the amount of energy consumption. The maximum solar radiation of about 700 W/m² causes the surface temperature to reach up to 35 °C (at the ambient temperature of 19 °C), and the maximum power consumption to reach 7.5 kW/h during noon. However, the average power consumption for the rainy condition decreased only to 7.3 kW/h with the average solar radiation of about 150 W/m² during noon. This suggests a relatively minor contribution of the radiative thermal load of a structure from the heating by external radiation such as the sun, versus other losses like convection and air infiltration into the enclosure.

The colours of outdoor structures, including buildings, vehicles and transport containers, are typically chosen for functional or aesthetic reasons. With the exception of bare, polished metals, the appearance of a surface to the eye is not a good guide to emissivity's near room temperature. For example, white paint absorbs very little visible light. However, at an infrared wavelength of 10 µm, white paint absorbs light very well, and has a high emissivity. With a chosen colour, however, one still may control the radiative thermal load for heating or cooling purposes. Li et al. (2018) provided a comprehensive calculation of the tunable range of radiative thermal load for all colours. The range exceeds 680 W/m² for all colours (white) and can be as high as 866 W/m² (gray), resulting from effects of metamerism, infrared solar absorption and radiative cooling. They have also demonstrated experimentally that two photonic structures with the same pink colour can have their temperatures differ by 47.6°C under sunlight.

Radiative cooling technology utilises the atmospheric transparency window (8–13 mm) to passively dissipate heat from Earth into outer space (3 K). This technology has attracted interest for passive building cooling and passive refrigeration in arid regions. Chen et al. (2016) have theoretically shown that ultra-large temperature reduction for as much as 60°C from ambient is achievable by using a selective thermal emitter and by eliminating parasitic thermal load. They have experimentally demonstrated a temperature reduction of 37°C from the ambient air temperature through a 24-h day–night cycle, with a maximal reduction of 42°C that occurs when the experimental set-up enclosing the emitter is exposed to peak solar irradiance.

Radiative cooling technology is not yet commercialised for scalability reasons and as the materials used are too costly for this purpose. Nevertheless, the colour and the condition of a surface affects its absorptivity and reflectivity. Dark-coloured surfaces in general absorb more radiation in the solar spectrum and emit more thermal radiation than light-coloured surfaces; om the other hand the effect of solar heating is much bigger than night sky cooling. Therefore, increasing emissivity for increased night sky cooling, will also increase daytime heating, therefore giving an overall inferior performance.

Scope 1 emissions savings (% or another quantifiable metric)	3%
Quality of scope 1 emissions information	1 peer review publication.
Scope 2 emissions savings (% or another quantifiable metric)	No information relating to transport applications.
Quality of scope 2 emissions information	No information.
TRL level	TRL 4
Maintainability issues	Applicability in heavy duty applications. Paint would need to be kept clean and undamaged.
Legislative concerns	None known.

Payback time (years)	Unknown for transport applications.

9.6 Foaming agents /new insulation foams

An important step in improving the energy efficiency and thus reducing carbon emissions of refrigerated transportation vehicles is to reduce the heat loads which the refrigeration system must handle. As such, the choice of proper insulation materials is critical to reduce the heat loads associated with transmission losses through the walls, roof and floor of the insulated box. Furthermore, proper insulation leads to better temperature stability of the foodstuff payload. The typical measure of a insulations performance is by use of the overall heat transfer coefficient (K), and according to the ATP agreement the upper limits are either 0.70 or 0.40 W/m^{2}K depending on insulation class (normal or heavy, i.e., chilled or frozen transport) (United Nations, 2022). Historically, CFCs and HCFCs were used as foaming agents because they possessed many of the properties that made up for an ideal blowing agent but are obviously not currently suitable due to environmental concerns. For rigid expanded polystyrene (XPS), rigid polyurethane (PUR) and flexible PUR foams, natural blowing agents such as CO_2 or pentane have been proven successful (Hasse et al., 2012). With respect to improving the K-value, one approach is to increase wall thicknesses, but due to ATP regulations the practical thickness limit is 0.1 m (i.e., 50 mm each side) so that pallets can fit inside (Evans, 2008). The K-value is also subject to ageing, due to e.g. outside air/moisture infiltration into the foam material, and data shows a typical deterioration of 3-5% per year (Tassou et al., 2009). Some notable examples of initiatives to reduce the heat load if insulated boxes are the used include eutectic plates and use of PCM in walls, while vacuum-insulated panels (VIP) have been investigated as replacement for the traditional insulating foams in use (Maiorino et al., 2021). Uwa et al. (2019) investigated composite insulation of polypropylene (PP) and nanoclay and found that compared to pure PP, thermal conductivity was reduced from 0.293 to 0.123 W/mK, significantly improving the insulation capacity.

Scope 1 emissions savings (% or another quantifiable metric)	Foaming agents: according to GWP-scale of selected agent. Insulation: No direct reference found
Quality of scope 1 emissions information	No information
Scope 2 emissions savings (% or another quantifiable metric)	No information
Quality of scope 2 emissions information	No information
TRL level	TRL 7-9
Maintainability issues	Insulation typically deteriorates due to ageing
Legislative concerns	Selected materials should obviously be graded food safe
Payback time (years)	No information

9.7 Surface coatings

Ensuring food safety is paramount during chilled transport as one cannot absolutely rely on the temperature control alone owing to the delicate balance between the limited capacity of the refrigerating equipment and the unavoidable heat losses due to the door openings. While occasional and short-term peaks in the vehicle temperature are not a food safety issue in frozen transport due to the heat capacity of the frozen products, temperature variation is a source of concern in chilled transportation. Chilled areas are susceptible to moisture buildup, which can create an environment conducive to bacterial growth. Condensation on the interior walls and around door seals allow the harbouring of pathogens, spoilage bacteria and moulds and sanitation is difficult because of the complex shape and joints in the insulation cover. Coatings help mitigate this risk by providing a barrier against heat loss, condensation and by preventing the accumulation of bacteria on surfaces.

Antibacterial coatings inhibit the growth and proliferation of bacteria on surfaces. In chilled storage areas, where temperatures favour bacterial growth, these coatings help maintain a hygienic environment and extend the shelf life of stored products. Examples of antibacterial coatings suitable for use in chilled storage areas include:

Silver-Based Coatings: silver ions have well-known antibacterial properties and are often incorporated into coatings to inhibit bacterial growth. Quaternary Ammonium Compounds (QACs) are a class of chemicals commonly used as disinfectants and sanitisers. They can also be formulated into coatings to provide antibacterial properties to surfaces in chilled storage areas. QAC-based coatings are effective against a wide range of bacteria and are often used in food processing and storage facilities. Copper-Based Coatings and high-copper alloys including brass and bronze have been re-discovered owing to their inherent antimicrobial properties over stainless steel and food grade plastics, as it effectively kills or inhibit the growth of bacteria on surfaces. Copper plates tolerate well the high moisture level, and can be made to endure the extreme variations in the temperature including heat expansion and shrinkage and the mechanical movement of the insulated enclosure. Copper-based coatings, including copper-infused paints and coatings, are foreseen to be increasingly used in chilled storage facilities to help control bacterial contamination.

Polymeric coatings containing antimicrobial additives, such as antimicrobial nanoparticles or organic antimicrobial agents, are formulated to provide long-lasting antibacterial protection to surfaces. These coatings can be applied to walls, ceilings, and other surfaces in chilled storage areas to prevent bacterial growth and maintain cleanliness. Photocatalytic Coatings: Photocatalytic coatings contain nanoparticles, such as titanium dioxide (TiO2), which, when exposed to light, produce reactive oxygen species that can kill bacteria and inhibit their growth. Photocatalytic coatings can be applied to surfaces in chilled storage areas to provide continuous antibacterial protection under light exposure.

Antibacterial coatings of vehicles help to reduce the risk cross-contamination during transport by inhibiting the microbial growth on surfaces. This is particularly important in chilled transport where the temperature may occasionally rise over the safe limit during loading and unloading, and condensation is frequently present on the insulated walls.

The insulation of the vehicle enclosure may be further improved by using Thermal Barrier Coatings (TBCs) that insulate directly on the metal sheet. Thermal barrier coatings feature a ceramic topcoat which provides thermal insulation in the form of a low thermal conductivity ceramic structure. Such ceramic microspheres, made of calcinated α-Al_2O_3 hollow spheres (diameter 14…50 µm, wall thickness 4…8 µm) have reduced the thermal conductivity of acrylic and polyvinyl paints from about 1.6 W/m^2K down to about 0.25 W/m^2K at 3% dosage and to about 0.12 W/m^2K at 8% dosage (Velciu et al., 2013) on typical paint thicknesses of 250±50 µm.

Whereas Thermal Barrier Coatings alone do not considerably contribute to the energy loss of the vehicle enclosure, they do somewhat delay the instantaneous formation of condensation on the internal wall. This gives a tolerance against microbial growth, or, in combination with antibacterial coatings, a better protection against biofilm formation on the surfaces.

Scope 1 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 1 emissions information	n/a
Scope 2 emissions savings (% or another quantifiable metric)	No information relating to transport applications.
Quality of scope 2 emissions information	No information.
TRL level	TRL 6
Maintainability issues	Fragility, robustness.
Legislative concerns	Legal/health issues of certain antimicrobial coatings.
Payback time (years)	Unknown for transport applications.

9.8 Ozone

Ozone is a powerful disinfectant and antimicrobial agent, widely used in the healthcare and food industries. It works by disrupting the cell walls and membranes of microorganisms, including bacteria, moulds and yeast. This oxidative effect leads to the inactivation of pathogens and spoilage microorganisms, helping to disinfect surfaces as well as to extend the shelf life of perishable goods.

The primary advantage of ozone treatment is the non-residual feature of the process (Brodowska et al., 2018). Ozone treatment is considered as a cost-effective and eco-friendly food processing technology.

By using ozone in combination with chilled transport, savings on the cooling can be achieved through improving the hygiene and better efficiency of the in-vehicle evaporators and/or by affording higher transport temperatures during the transport of produce and delaying the quality deterioration by airspace ozonisation.

1. Surface Decontamination

Aqueous ozone solutions are used in practice for water disinfection and purification. Ozonated water can be used for cleaning vehicle interior surface and equipment. CIP washing of food processing equipment and drains with ozone-containing water is now common practice (Prabha et al., 2015). This has been adapted to the cleaning and sanitation of vehicle interior and cooling equipment (evaporators) which operate at near 0°C temperature and experience moisture condensation which gives rise to the growth and biofilm formation of psychrophilic foodborne pathogens Staphylococcus aureus (Wu and Su, 2014; Bolton et al., 1988; Mead and Adams, 1986; Archer et al., 2011) and Listeria monocytogenes. In particular, Listeria has the ability to grow at temperatures as low as 0 °C which permits multiplication not only in refrigerated foods but surfaces too and is a constant contamination source in the droplets from the chiller evaporator biofilm, through aerosols. Even though a survey (Evans et al, 2003) reported no Listeria species from 336 environmental samples taken, 25% of sites examined had more than 105 colony-forming units per cm² which indicates the routine maintenance were not effective at maintaining low levels of bacteria on evaporators, also potential pathogens such as Aeromonas or Yersinia spp. could colonise this environment as they also grow at low temperature.

Biofilm formation on the evaporator surfaces can also lead to biofouling which drastically reduces the evaporator's cooling capacity by reducing both the heat transfer coefficient and the restricting air flow through its lamellae which, unlike ice, cannot be easily removed. The best strategy to eradicate bacterial biofilms is to prevent biofilm formation. In most cases, especially for vehicles, it is neither possible nor cost-effective to sterilise all environment, therefore, other measures must be taken to decrease the population of harmful bacteria and biofilms. This can be done by carrying out regular cleaning and disinfection so that cells do not attach firmly (reversibly) to contact surfaces.

The effect of ozone on the inactivation of foodborne bacteria biofilms by aqueous ozone in 0.5 ppm concentration was demonstrated (Marino et al., 2018) for biofilms treated in dynamic conditions, 5.47 ± 0.27, and 5.33 ± 0.18 Log CFU/cm² for S. aureus and L. monocytogenes biofilms. Ozonated water is particularly suitable for the daily sanitation protocols at the end of the day or during process downtime. The same authors have also investigated the use of gaseous ozone, at low concentrations (up to 0.2 ppm) estimated inactivation of 2.01–2.46 Log CFU/cm² were obtained after 60 min, while at 20 ppm concentration a complete inactivation (<10 CFU/cm²) of L. monocytogenes and 4.72 Log CFU/cm² reduction of S. aureus was achieved. Gaseous ozone might be used for the treatment of confined spaces for longer times (e.g., overnight) and in the absence of personnel, to allow an eco-friendly control of microbial biofilms and consequently reduce the risk of pathogen contamination and biofouling of chillers.

2. Ozone in vehicle airspace

The use of ozone in modified atmosphere transport involves employing ozone gas to extend the shelf life of perishable goods during transportation and storage. When ozone is introduced into the modified atmosphere, it can help to reduce the microbial burden on the surfaces of fruits, vegetables, and other perishables, reducing the risk of microbial growth during transportation and storage. Utilisation of the properties makes ozone eminently suitable for increasing the storage life of perishables foods in refrigerated premises (Prabha et al., 2015).

Liew and Prange (1994) have demonstrated the effects of ozone and storage temperature on carrots and two postharvest moulds – Botrytis cinerea and Sclerotinia sclerotiorum. A 50% reduction of daily growth rates of both fungi at 16°C and 0.06 ppm ozone concentration indicated that ozone was fungistatic, but at the expense of fading of the roots. Similar studies with Botrytis cinerea on peaches by Palou et al. (2002) with 0.3 ppm ozone atmosphere storage at 5°C; for strawberries by Nadas et al. (2003) storage for 3 days at 2°C with 1.5 ppm ozone and transferred to room temperature; and Perez et al. (1999) storage for 3 days at 2°C and 0.35 ppm, then 4 days at 20°C. Ozone treated fruits showed less weight loss than the non-treated samples after cold storage - probably, ozone treatment reduced water loss through transpiration of the fruit, but this effect disappeared when the fruit was returned to ambient air (Karaca and Velioglu, 2007).

From the studies it is estimated that 0.5 ppm ozone in the atmosphere exhibits a fungistatic effect comparable to a +2°C decrease in storage temperature, while a concentration of 1.0 ppm has a comparable effect to a +5°C temperature increase over a period of 3-4 days. Therefore, ozonation of the airspace in transport vehicles emerges as the most reasonable option for trans-continent transports, especially when precise temperature control of the produce cannot be guaranteed.

The residual ozone concentration is influenced by temperature; increasing the storage temperature would increase the amount of ozone required to maintain a specific residual concentration. Therefore,

maintaining a constant residual ozone concentration over a storage period will require adjustments in the amount of ozone supplied. It is important to use ozone judiciously, as excessive concentrations may have negative effects on the quality of some products and could pose safety concerns.

In practice, ozone treatment systems have few basic components: the gas (air or pure oxygen), an ozone generator, an electric power source, and an ozone analyser. Generally, in corona-discharge type generators dry air or pure oxygen are used as an oxygen source for conversion into ozone. Pure oxygen from cylinders is preferred, as for air, it is essential to dry it to very low (−65°C) dew point to increase ozone treatment effectiveness and prevent the formation of nitrogen oxides. Ozone generators are lightweight, affordable devices that can connect directly to the vehicle's electrical supply and draw very little additional power on top of the power requirements of the cooling unit. Ozone adjustment can be made with an automated gas control system to maintain gas concentrations, such as the ozone application and measurement systems frequently used by environmental and pollution measurements.

Monitoring and controlling ozone levels, as well as considering the specific requirements of different types of products, are crucial aspects of successful microbial control using ozone in modified atmosphere transport. At the same time, it is economic as the investment and operational cost of the equipment are on an acceptable level in relation to the cost of chilled transport vehicles.

Scope 1 emissions savings (% or another quantifiable metric)	Technology permits a tolerance to temperature increase of +2…+5°C during transport.
Quality of scope 1 emissions information	Not quantified.
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	TRL 5
Maintainability issues	Additional electricity supply required for the control and ozone generator circuits. Potential issues with elastomers and seals.
Legislative concerns	Health issues.
Payback time (years)	Unknown for transport applications.

9.9 Vacuum insulated (VIP) Panels

For a refrigerated appliance which spends the majority of its time with doors closed, one of the principal ways of reducing heat gains is to improve the insulation. Increasing the thickness of conventional insulation such as polyurethane (PU) can achieve this, but this reduces the useful net volume inside the appliance. Advanced insulation such as VIPs can be used instead, to offer better resistance to heat transfer with the same or even lower thickness. Reducing the heat gain has a corresponding reduction in the energy consumption of the refrigeration compressor.

VIPs consist of an open cell foam slab enclosed in a barrier film (Brown et al, 2007). A high vacuum is achieved within the enclosure, maintained by the impermeability of the barrier film and by the presence of a gas absorber (or getter) within the enclosure. The foam slab maintains the physical dimensions of the panel, supporting the barrier film, reduces convection by the remaining gas molecules and the radiant heat transfer across the panel. The getter absorbs water vapour, atmospheric gasses and gasses emitted by the slab during the life of the panel to maintain the vacuum. Various materials have been studied and used for the filling of VIPs, including glass fibre (Chen et al 2015), fumed silica/hollow glass microsphere (Li et el 2016), and also aerogel (Liang et al 2017).

The thermal conductivity of VIPs is around one fifth of that of a typical PU foam insulation panel. VIPs typically have a thermal conductivity of around 3 mW/m.K (measured at the centre of a panel). However, the film material does influence the conductivity of the panel as a whole and 5 mW/m.K would be more typical when considering the complete panel. Therefore, for a given thickness of wall, the heat gain through the walls could be reduced by as much as 80%. The impact of thermal bridging at the edges of VIPs has been reported by various authors, including Isaia et al 2015 and Lorenzati et al 2016.

According to Simões et al (2021), to achieve an overall U-value (a measure of heat transfer resistance) of 0.24 W/m2K would require an encapsulated VIP thickness of 40 mm and to achieve a U-value of 0.12 W/m2K would require 75 mm. The equivalent thicknesses of Expanded Polystyrene (EPS) would be 127 and 272 mm respectively.

VIPs are however unsurprisingly more expensive than PU and similar panels. For example, Simões et al (2021) reported the cost of VIPs as 3000 €/m^3, with an installation cost of 62.5 €/m^2 and a service life of 25 years. For EPS the comparative figures were 120 €/m^3, 50 €/m^2, and 25 years.

Compared with simpler PU and similar panels, the robustness of VIPs can be of concern in applications where they might be punctured or otherwise damaged. Protective measures to avoid damage are often used, such as sandwiching between metal or plastic, or embedding the VIPs in PU foam (e.g. Hammond and Evans 2014).

The most widely reported application for VIPs is overwhelmingly in building insulation, both domestic and commercial (publications are numerous, but see for example Baetens et al 2010, Adl-Zarrabi and Johansson 2020, Kalnaes et al 2014, Kucukpinar et al 2015, Shatat et al 2015 and many others).

Use for refrigerated applications incudes domestic refrigerators, professional refrigerators and freezers, cold storage rooms and other cold chain equipment, including shipping containers, cool boxes and road transport. Bansal et al (2011) reviewed several studies with VIPs in domestic refrigerators. In one study, energy savings of up to 20.4% were achieved in comparison with 1990s technology insulation, depending upon such factors as the area covered, the resistivity of the panels, edge losses, etc. while other studies achieved 25% performance improvements.

Hammond and Evans (2014) installed VIPs in refrigerator walls and foamed round them with PU. This yielded 86% of the expected benefit compared with a full VIP coverage (which was not physically possible in the refrigerator carcase). The potential energy savings and payback times were also calculated for a domestic refrigerator-freezer, a professional service refrigerator, a professional service freezer (both upright models) and a retail display chest freezer. Payback for the professional freezer was the best at 1.4 years while the professional refrigerator was 4.7 years. Energy savings were for the best payback options were 5.7 kWh/yr (refrigerator) and 19.1 kWh/yr (freezer). Energy savings were between 32 to 60% depending on the way the VIPs were applied. Further work by Hammond and

Marques (2014) on a different professional cabinet design with drawers modelled and tested the use of VIPs. Energy savings of between 12.4% (refrigerator) and 12.5% (freezer) were found with paybacks of 7.6 and 3.1 years for the fridge and freezer respectively.

Verma and Singh (2020) reported that VIPs should achieve approximately a 20% energy saving in domestic refrigerators compared to standard PU. They assessed the benefits of 3 types of VIP (fumed silica VIP, glass fibre VIP, alternate core VIP) against PU. The fumed silica VIP provided the lowest energy consumption (19.6% less than PU foam) but added weight to the appliance (addition of 2.48 kg). The payback time for the fumed silica was 3.2 years. Verma and Singh (2019) also reviewed performance of VIPs in other cold chain equipment.

Thiessen et al 2018 applied 8mm thick VIP inside the cavity of a domestic refrigerator and found that 56 % coverage of the internal surface area achieved a reduction of 21 % in the energy consumption.

The study and use of VIPs is less common for transport applications, possibly due to robustness and installation issues, as well as cost. As reviewed by Dong et al 2023, one study used numerical simulation to study use of vacuum insulation board in refrigerated truck walls and concluded that the overall heat transmission into the refrigerator truck using VIPs was 56.1 % of that of an ordinary refrigerator truck. Another used VIP panels to form the structure of the refrigerated compartment. Without VIPs the maximum temperature in the compartment reached 6°C, with a regional temperature variance of 10 °C. With an 87% VIP coverage, most of the temperatures in the compartment were lower than -1°C, and the maximum regional temperature difference was 6 °C.

Issaro 2022 submitted a PhD thesis on the application of VIPs to chilled and frozen refrigerated road transport containers and the potential for energy saving. The best fuel saving for the various configurations of chilled trucks was 11.25%, and for frozen trucks it was 16.99%.

Verma and Singh 2019 assessed the impact of the thinner walls made possible by VIPs in transport reefers. PU foam normally used for insulating the walls of reefer trucks was said to provide a U-value of 0.38 $W/m^2.K$. If the walls were instead VIP insulated, the thickness required to provide the same U-value would be 21.1 mm, which would increase the internal volume by about 3%. The authors presented the impact as an example of 1030 tonnes of food transported in reefer trucks, each weighing 5 tonnes with a holding capacity of 10 tonnes. With PU containers, this would require 103 journeys, but if the trucks were VIP insulated, each could carry 10.3 tonnes and the total would require only 100 journeys. This is equivalent to a 3% saving in the typical reefer truck consumption of 20 gallons of fuel per day travelling 200 kms, responsible for emissions of 5.1 tonnes of CO_2 per month.

This analysis did not include the difference in weight of the PU and VIP options. It was suggested that PU thickness would be 92.1mm to provide the required U-value compared to 21.1mm for VIPs, with only the vertical sides and ends being changed to VIPs. With a typical density of 80 kg/m^3 for PU and 200 kg/m^3 for VIPs, the total weight of the insulation for the PU option would be approximately 1133 kg, while the VIP option would be 898 kg (approximately 80% of the original PU weight). This could offer further scope for fuel savings.

A passive transport container insulated with VIPs and using PCMs to maintain temperature was reported by Fricke et el 2008. The container was claimed to maintain a temperature of -18°C for 4 days or stay within a temperature span of +2 to +8°C for 9 days.

In a transport-related application, cool boxes used for delivery and storage of perishable foods, Kan et al 2022 reported several studies that found that VIPs could considerably extend the maintained periods at acceptable temperatures. Any associated impact on energy use during such delivery was not included.

Scope 1 emissions savings (% or another quantifiable metric)	Heat transmission into VIP insulated refrigerated truck 56.1% that of PU truck (Dong et al 2023). Use of thinner VIP panels would save 3% of refrigerated vehicle fuel (Verma et al 2019). Fuel savings of up to 11.25% for chilled food transport, and 16.99% for frozen (Issaro 2022).
Quality of scope 1 emissions information	Medium
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	TRL 7
Maintainability issues	Potential issues with robustness of the VIPs
Legislative concerns	None
Payback time (years)	No data for transport applications

10 REFRIGERATION UNIT

10.1 Absorption refrigeration system powered by exhaust gas heat

Vapour Absorption Refrigeration Systems VARS have been proposed with working fluids NH_3-H_2O in road transport, to recover the exhaust heat of the thermal traction engine to cool the insulated box of trailers and trucks; Venkataraman et al., 2021 offer a comprehensive review of previous studies presented in the literature, encompassing both experimental and modelling work. Operating conditions of the traction engine highly impact on both available heat and temperature level, then different back up options are proposed in the literature, like the use of a burner to provide further supply when needed (Koheler et al. 1997) and a by-pass in case of excess heat availability. COP was calculated as 0.27, with the proposal of improvements to increase it by 25%.

Horuz, 1998, also offered an additional fuel burner for stand-by periods and eutectic plates as TES for handling excess heat.

The heat recovery from the engine might impact of the efficiency of the engine itself: for the specific analysed case, Horuz 1999 estimated 2% penalisation in the motor efficiency.

Challenges related to the heat availability and temperature, impact on motor efficiency, corrosion issues, optimal design, size and weight of components still need a lot of research. It is however worth reminding that the trend towards electrical/hybrid traction will reduce opportunities for such systems. At the same time, the combination with fuel cell might open new scenarios for the future, as illustrated in Venkataraman et al., 2020. After reviewing the literature, the Authors however concluded that the integration of fuel cells with VARS would need an exceptional research and development effort for both heat recovery, integration and compact and light system design, but it would finally drive towards vehicle efficiency, emission and noise reduction, including of course the use of natural working fluid (NWF).

Scope 1 emissions savings (% or another quantifiable metric)	No direct quantification of savings available COP 0.25-0.30
Quality of scope 1 emissions information	Good
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	TRL3-4
Maintainability issues	n/a
Legislative concerns	None
Payback time (years)	n/a

10.2 Air cycle

Air cycle refrigeration is based on the reverse Brayton or reverse Joule cycle (reviewed by Shuailing et al 2023). It is a gas rather than a vapour cycle, hence the gas does not change phase during the cycle. The Brayton cycle is less efficient than vapour compression cycles primarily as heat transfer is sensible not latent and the efficiency of the expansion and compression components (typically turbomachinery) is low (Giannetti and Milazzo 2014, Spence et al 1997). One of the ways of improving the efficiency of air cycle is to use the work carried out in expansion to further compress the air on the high-pressure side, lowering the overall energy input for a given expansion pressure ratio. This can be done by mounting the compressor and turbo expander on a common rigid shaft in an arrangement known as a bootstrap system. A further efficiency improvement is to use a recuperative heat exchanger to pre-cool the air into the turbine with the cold air returning from the cooling apparatus. An advantage of air cycle compared with vapour compression is that it can cope better with off-design operation (Park et al 2012).

Air cycle does however use air as the working fluid which presents no detrimental emissions due to leakage, unlike vapour compression systems based on commercial refrigerants (e.g. Shuailing et al 2023). Comparisons with such systems are however difficult, as leakage rates vary considerably depending on application and installation quality.

Air cycle is currently dominant in the air conditioning and cabin pressurisation of modern aircraft (Rogers, 1994), where size, weight, reliability and a plentiful supply of compressed air outweigh energy efficiency concerns. Air cycle railway carriage air conditioning systems have also been developed for Germany's ICE-3 high-speed train, where the robustness and low maintenance requirements contributed to lower life cycle costs than conventional vapour compression systems.

Air cycle refrigeration has been investigated for a number of other applications. These include low temperature freezing of products such as shrimp (Biglia et al 2017, Hou and Zhang, 2009), combined cooking and cooling of products such as beef burgers (Foster et al 2011), various food processing applications including replacement of liquid nitrogen freezing (Pelsoci and Bond, 2001), air conditioning and desalination on ships (Hou et al., 2008), supermarket refrigerating and ventilated air conditioning (Elsayed et al., 2006), cold storage warehouse cooling and dehumidification (Elsayed et al 2008) and cooling for food road transport (Spence et al., 2004 and 2005).

For transport, Tassou et al 2009 included air cycle in a review of technologies which could reduce energy consumption. This was based mainly on Spence et al 2004 and 2005, who reported on the design, construction and testing of an air cycle demonstrator plant for refrigerated road transport, with the aim of to achieving an equivalent refrigeration capacity, specified as 12 kW in a 0°C trailer and 7.2 kW in a -20°C trailer, both at 30°C ambient. The demonstrator unit used commercially available components, including the diesel engine prime mover and air circulation fans of the existing vapour compression system. Standard exhaust turbocharger components were selected for the two compressor stages and the turbine.

The fuel consumption of the air cycle plant was found to be approximately 200% higher than for the vapour compression system when trying to meet full loads but was estimated to be only 80% more at part load. The poor performance was attributed mainly to the constrictions on components (turbomachinery and heat exchangers).

The authors extrapolated the performance to a plant using optimal components using a mathematical model, which predicted a COP of 0.53 at -20°C and 7.8 kW refrigeration capacity. This was only 7% lower than the corresponding COP for a vapour compression system. It was speculated that under part-load conditions, which represent a large proportion of long-haul operations, the optimised air cycle would maintain full load COP and require lower driving power than the vapour compression system.

Scope 1 emissions savings (% or another quantifiable metric)	Leakage of air presents no emissions problem, but quantifying the benefit compared to leakage of GHG refrigerants is difficult due to variable leakage. For road transport applications, a laboratory scope system (with non-ideal, off the shelf components) used more fuel than vapour compression. It was however estimated using mathematical modelling that an optimised system at part load might use less fuel than vapour compression
Quality of scope 1 emissions information	Low
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	TRL 4-5
Maintainability issues	No particular issues
Legislative concerns	None

Payback time (years)	Likely to be more costly than conventional alternatives

10.3 Compressor control

The connection between the cooling unit and the power line coming from the vehicle engine can have a relevant impact on the overall efficiency of the refrigeration system.

In the baseline configuration, widely spread in Light Commercial Vehicles, the cooling unit's compressor is directly driven by the vehicle engine by means of a belt, while the vehicle main alternator powers the heat exchangers fans. In this configuration the rotational speed of the cooling unit's compressor, during ON periods, is strictly tied to the vehicle engine rotational speed, meaning that the cooling capacity provided by the unit and the actual cooling demand of the insulated box are not necessarily coincident.

If an alternator converts the mechanical power coming from the vehicle engine to the electrical power needed to feed both the cooling unit's compressor and the heat exchangers fans, the compressor rotational speed and the vehicle engine rotational speed are decoupled. With such an arrangement, a variable speed control of the compressor is allowed, leading to a consequent optimization of the cooling unit's performance according to the actual cooling demand of the insulated box.

A further improvement is in place when the mechanical energy coming from the vehicle engine is converted to electrical energy by an alternator and it is stored inside a battery, which then feeds the unit's compressor and the heat exchangers fans. In this configuration the power production by the vehicle engine and the power supply to the cooling unit are decoupled: the vehicle engine additional power production depends only on the charge level of the battery, which must be kept in conditions to provide the required power to the cooling unit. Such a solution allows both the optimization of the cooling unit's performance, matching the cooling demand of the insulated box and the unit's cooling capacity, and the optimization of the vehicle engine fuel consumption and pollutant emissions. In fact, the presence of the battery allows to keep the engine OFF during the pre-cooling activity which precedes the delivery mission and during long pauses and to perform a StartandStop management of the engine during the urban drive, switching off the engine when the vehicle is still but ensuring the necessary power supply to the cooling unit, if needed.

Fabris et al., 2022, analysed the impact of the three different configurations when applied to a Light Commercial Vehicle under a multidrop delivery mission.

Fabris et al, 2022, demonstrated that, in their analysed case, the implementation of the battery to store the energy produced by the engine and to allow a StartandStop management of the engine can lead to a 11.1 % reduction of the fuel consumption, a 24.0 % reduction of the CO emissions, a 1.1 % reduction of the NOx emissions, a 25.0 % reduction of the THC emissions and a 16.6 % reduction of the PM emissions compared with the use of a direct belt connection between the engine shaft and the cooling unit.

Artuso et al, 2019, assessed the degradation of the overall mission COP related to the duty cycle. The use of an inverter driven electrical compressor can offer an opportunity to increase the average COP. Minetto et. al, 2023, evaluated the impact of the use on an inverter to reduce cycling losses of the refrigerating unit of a Medium Heavy Commercial Vehicle, assessing 24% reduction in energy demand. However, the benefit is highly dependent on the unit sizing, as it derives from reduction in cycling losses. Therefore, it represents a good opportunity for long-distance vehicles, as the refrigerating unit needs to guarantee a fast pull down but means that it will be oversized under steady state conditions (long travels with closed doors)

Scope 1 emissions savings (% or another quantifiable metric)	11% CO_2, 24% CO, 1% NOx, 25% THC and 17% PM (Light Commercial Vehicle, multi-drop mission, 0°C application) 24% CO_2 (Medium-Heavy commercial vehicle, long distance, -20°C application)
Quality of scope 1 emissions information	Fair
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	TRL 7-8
Maintainability issues	No
Legislative concerns	None
Payback time (years)	No information

10.4 Cryogenic systems (liquid nitrogen, liquid carbon dioxide)

Within the usage of cryogenic technologies for transport refrigeration is liquid nitrogen (LN_2) and liquid carbon dioxide (LCO_2) and liquid hydrogen (LH_2) used as working fluids. In direct systems, the cryogenic fluid is evaporated within the refrigerated space, whereas an indirect system utilises a heat exchanger inside the refrigerated space. Due to the replacement of air inside the refrigerated space, the direct system requires additional oxygen level control (Tassou and Rai, 2017). (Kehinde, Raji, Ngonda, and Kanyarusoke, 2022) (Kehinde, Raji, Ngonda, and Kanyarusoke, 2022).

Rai and Tassou (2017) compared a diesel-powered vapour compression transport refrigeration system with an indirect LN_2 and LCO_2 system. The authors conclude that for the assumptions made, the emissions were found to be similar. (Rai and Tassou, 2017). The authors state that the differences are too small to draw definitive conclusions. Since the major emissions from cryogenic units are due to the production, emission saving can be achieved by improvements to the production of cryogenic fluids (Tassou and Rai, 2017).

According to Rai and Tassou (2017), the required mass of fuel for diesel driven refrigeration systems is much smaller compared to that of cryogenic fluid for the same distribution trip (Tassou and Rai, 2017). Thereby, diesel powered units can cover longer trips at the same tank size (Tassou and Rai, 2017).

Cryogenic cooling systems emit very low noise and can achieve a rapid temperature pull-down of the refrigerated space. Therefore, cryogenic systems are combined with vapor compression systems for long journey operations. (Kehinde, Raji, Ngonda and Kanyarusoke, 2022).

Clean Cold Power UK Ltd is developing a system that utilises first the evaporation enthalpy of the cryogenic fluid and then powers a vapour compression system by a Dearman engine through the expansion of the cryogenic fluid. According to the liquid air energy network, there is a high potential for emission saving by the introduction of such a system, but recent numbers could not be found. (Atkins, Garner, Cooper, and Owen, 2014).

Scope 1 emissions savings (% or another quantifiable metric)	Emissions found to be similar. (Tassou and Rai, 2017)
Quality of scope 1 emissions information	Medium
Scope 2 emissions savings (% or another quantifiable metric)	No information
Quality of scope 2 emissions information	No information
TRL level	TRL 8-9 (for LN_2 and LCO_2) Kehinde, Raji, Ngonda, and Kanyarusoke, 2022)
Maintainability issues	No information
Legislative concerns	Future legislation could implement restrictions to particulate and NOx emissions, increasing the economic attractiveness (Tassou and Rai, 2017). Potential safety issues due to oxygen depletion.
Payback time (years)	At a par compared to conventional TRUs, but the infrastructure and installation costs are higher. (Tassou and Rai, 2017)

10.5 Natural refrigerants

10.5.1 Carbon dioxide

The first CO_2 unit for road transport dates back to 1997, when Kohler et al developed an electrically supplied prototype with about 4 kW capacity at -20°C box temperature. The design included an internal heat exchanger and specific effort was dedicated to the optimisation of the compressor, considering that at the time CO_2 technology still lacked key components. The Authors demonstrated the improvement in capacity using Internal Heat Exchanger (IHX), while no impact on COP was registered at 30°C ambient. Further calculation (Sonnekalb, 2000) showed a 20% reduction in the Total Equivalent Warming Impact (TEWI) with respect to an equivalent R404A unit.

Finckh et al., 2016, summarised their experience, i.e. presented the manufacturer's point of view, when dealing with natural working fluids in transport refrigeration. Research and development on CO_2 unit for trailers and containers started in 2005 and focused on a two-stage unit with economiser. In 2020, a field test for fresh products was performed in Germany; ATP tests at -20/30°C and 0°C/30°C showed a 10/20% COP reduction with respect to HFCs and encouraged to further optimisation of intercooler and gas cooler. Kujak and Schultz (2018) dedicated further effort to the analysis of the two-stage circuit run on R744 and still found a performance gap with the reference R452A unit. They identified compressor optimisation and use of improved cycles, such as ejectors, as the keys to increase the performance of the trailer unit.

The interest of the market in CO_2 units is demonstrated by many field experiences: multi-temperature trailers equipped with R744 units, based on a previous design for intermodal containers, have started to run in Europe and USA (Carrier, 2017a) under various field trials. Of course, the availability of components for small system, developed for stationary refrigeration, may push the development much faster than it happened for stationary systems, where many years were required.

Artuso et al., 2020, presented a R744 refrigerating system designed to serve an insulated body and operating in subcritical or transcritical mode, depending on the outdoor conditions. The unit has the possibility to work accordingly to a traditional back pressure and Low-Pressure Receiver (LPR) design or to use a fixed geometry two-phase ejector to recover part of the expansion work, according to the experience gained in stationary refrigeration. The novelty of the design lies in the adoption of an auxiliary evaporator in the line between the ejector outlet nozzle and the low-pressure receiver. The operation of the refrigerating system using three different configurations is simulated for an internal cargo space temperature of -2°C and an external environment temperature varying between 10 °C and 45 °C. The ejector configuration overperformed the traditional back pressure configuration by + 13.8% at ambient 42°C. On the other hand, as the ejector gave advantage when ambient temperature was above 26 °C, the use of an ejector in combination with an auxiliary evaporator was able to operate more efficiently than the traditional configuration for all the ambient temperatures below 42 °C. Thus, the operation according to this configuration could effectively extend the operating range of the two-phase ejector to lower ambient temperatures. The system proposed by Artuso et al., 2020, was also dynamically simulated by Fabris et al., 2021, during a long-range delivery mission of temperature-controlled goods, implementing an automatic control to include or exclude the auxiliary evaporator depending on the external ambient temperature, which was variating along the day. The system, employed in a mean summer day in hot European climatic conditions (average daily temperature equal to 31.5°C), presented an average mission COP of 1.60.

Minetto et al., 2023, calculated the COP of a 0°C and -20°C CO_2 unit, based on a simple transcritical cycle, showing a better COP with respect to a market-available R134a unit throughout the analysed outdoor temperature. Despite the implemented LT CO_2 unit featured a single compression, single expansion cycle, which is not the preferred option for LT application, it performed similarly to the R134a unit at outdoor temperature above 20°C. It is however widely recognised that modifications (two stage compression with intercooling, split cycle, use of ejector, etc) to the simple compression cycle can significantly improve its COP under LT operations.

Fabris et al, 2024, compared the performance of a R744 unit, equipped with ejector and auxiliary evaporator, with a R134a one, applied to the same LCV and performing a multi-drop delivery mission in Athens. The R744 unit overperformed the R134a, displaying +27.5% improvement in the annual COP. However, the increased weight of the R744 unit resulted in significantly higher emissions associated with fuel consumption, leading to +9.3% higher fuel related emissions for the R744 unit (to transport the higher weight) with respect to fuel related emissions for the R134a unit. However, when considering total emissions (operations, leakages, production and dismission of unit), the R744 system ended in 31.9 % reduction in the lifetime CO_2 equivalent emissions with respect to the R134a system. Further developments are ongoing to significantly reduce the weight of the CO_2 unit.

To meet increasing demand for multitemperature vehicles, the lay-out proposed by Artuso et al., 2020, was further upgraded to serve a multi-temperature vehicle, with a low temperature compartment (-20°C) and a fresh compartment (0°C), according to an arrangement typical of last mile delivery. The challenge lies in avoiding two-stage compressor by taking advantage of pressure lifts provided by two-phase ejectors. Different lay outs have been proposed, such as in Fabris et al., 2023.

The underlying goal is to demonstrate the feasibility and competitiveness of CO_2 units for transport refrigeration, while using compressors equipped with electrical motors to be ready for fully electric or hybrid vehicle, eventually supported by integral photovoltaic (PV) systems (Rossetti et al., 2022).

CO_2 units were also successfully used to freeze eutectic plates (Micheletto and Rosso, 2004). The eutectic material was frozen by direct expansion of CO_2 through copper serpentines, significantly reducing the freezing time with respect to the reference R507 unit. A huge effort was done at the time to optimise the two-stage semi-hermetic compressor.

The same manufacturer (Cold Car, 2015) later worked on a fresh (0°C) system, based on a CO_2 single stage compressor; the truck was also equipped with PV panels.

Scope 1 emissions savings (% or another quantifiable metric)	27.5% COP improvement on a yearly basis (referred to R134a) at 0°C internal temperature for multi-drop delivery in Athens. (Fabris et al. 2024) 100% GHG emissions related to refrigerant leakage. 31.9% life-based emissions savings (operations, leakages, production and dismission of unit)
Quality of scope 1 emissions information	Good
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	TRL5-7
Maintainability issues	No specific requirements. Trained maintenance staff recommended.
Legislative concerns	No concerns
Payback time (years)	No available data

10.5.2 Hydrocarbons

The use of hydrocarbons (HCs) is generally limited by their flammability, especially when safety is in general terms a major issue, like in sea transport, or when dangerous boundaries may occur like in road/rail transport through tunnels. It is however more and more recognised that flammability is not necessarily an issue when proper risk assessment is performed, and proper maintenance procedures are in place. A lot of effort is taking place at standardisation level to regulate the use of flammables, namely HCs; this approach is a necessary step. Manufacturers of refrigerating systems for land transport or intermodal containers are actually needing such regulations to realistically evaluate HC alternatives, which are widely known to be better performing than HFCs, while maintaining a very similar circuit layout, as demonstrated in small stationary applications for a long time. Details about risk assessment for road transport with R290 are given, amongst others, in König and Enkemann, 2013.

Colbourne et al., 2017, studied the possibility of using propane in transport refrigeration systems, comparing the use of R290 and of R404A in terms of environmental impact. The Authors demonstrated that the COP of the R290 system is 15-25% higher in MT applications (0°C) and 10-30% higher in LT applications (-20 °C) compared to the corresponding R404A system. The authors suggested that the R290-based system could achieve a significant reduction in the indirect emissions linked to the cooling unit power supply (−16% diesel fuel consumption) and generate only 34% of the overall global warming emissions with respect to the R404A system.

In addition to theoretical studies, there are different examples of successful implementation of R290 units in refrigerated trucks. In South Africa (Wilson et al., 2015; Ramaube and Huan, 2019; Kivevele, 2022), starting from an early financed project at the beginning of 2010s, R290 has been used to replace R404A in the refrigeration unit of a truck. Performance mapping at both 0°C and -20°C box temperature, at the extreme ambient condition of 50°C, resulted in more than 25% COP increase, as reported by the Authors. While a full risk assessment was performed, the total R290 charge was reduced to 20% of the initial R404A charge by reducing the internal volume of the system.

Recently, a new electrically driven transport refrigeration unit using employing R1270 (propene) and CO_2 as operating fluids has been developed and tested in the field (Cop et al., 2023). In the cooling unit, R1270 is used as the primary fluid performing a vapour compression cycle placed completely outside of the insulated box, while CO_2 is used as the secondary fluid, to allow the delivery of the cooling effect inside the insulated box while preventing any possible formation of flammable mixtures due to leakage of hydrocarbon in the storage space. In addition, accord to the manufacturer, the refrigerant charge of R1270 can be reduced by more than 90 percent compared to conventional solutions.

A similar solution, consisting in a self-contained R290 unit with a secondary loop, was also presented for electric light commercial electric vehicles, displaying the potential of zero emission option when the vehicle battery is charged by photovoltaic (Haroldsen, 2023).

Scope 1 emissions savings (% or another quantifiable metric)	-66% GHG emissions with respect to R404A unit +15-25% COP improvement (referred to R404A) at 0°C internal temperature, +10-30% COP increase (referred to R404A) at -20°C internal temperature
Quality of scope 1 emissions information	Good
Scope 2 emissions savings (% or another quantifiable metric)	n/a
Quality of scope 2 emissions information	n/a
TRL level	TRL6-8
Maintainability issues	Flammable refrigerant. Trained maintenance staff recommended
Legislative concerns	No concerns/ EN standard nearly available (EN 17893)
Payback time (years)	No available data

10.6 Thermal energy storage

10.6.1 PCM and eutectic plates

Thermal energy storage (TES) offers several advantages that contribute to increased efficiency, flexibility, and cost-effectiveness. Thermal energy can be stored as sensible, latent, or chemical heat. A latent heat storage consists of a phase change material (PCM). It is much more compact than sensible storage and the technology is available for many different temperature levels and applications. A purpose of utilising a PCM for heat storage is to decouple supply and demand (Selvnes et al, 2021).

PCMs can be classified based on different measures, and one is their chemical composition, where the three main categories are organic (both paraffin and non-paraffin substances), inorganic (metallic and hydrated salts) and eutectics (a combination of at least two different materials; organic or inorganic). It is crucial to select the suitable PCM materials to guarantee the efficiency and dependability of the thermal energy storage system and it depends on factors such as the operating temperature range, heat transfer rate, conductivity, latent heat capacity, reversibility and thermal stability (Umate, Sawarkar, 2024)

Calati et al (2022) reviewed PCMs for refrigerated transport in the cold chain, where two main different approaches were identified: Enhancement of insulation wall by PCMs (including eutectic plates) or application of PCMs in the refrigeration unit. There were two main objectives of adding PCMs to the walls. The first was reducing the peak heat load and the heat transferred into the refrigerated space, or as a cold source at the carriage targeted temperature. The use of eutectic plates mounted on the ceiling of an empty compartment gave the best results in terms of preventing air infiltration, but the presence of cargo disrupted these recirculation zones, allowing hot air to enter more easily, resulting in higher food temperatures. However, as the load decreases during transport, the ceiling mounted cold plate configuration becomes more effective, similar to the empty compartment scenario. The effect of the relative humidity on the cold compartment should be considered. The second was to use the PCM as a cooling source, which would be charged when the vehicle is stationary in the depot. This method allows for considerable local emissions reductions compared to having a refrigeration system in the vehicle and the possibility to change from fossil fuels to renewable sources. Additional studies to find the best systems are suggested, especially focusing on the charging and discharging phases. There were only a few studies covering economic advantages, but savings of up to 80-90% were indicated. This was due to a flexible electricity price where the charging process is completed during the off-peak period (assuming a COP of the refrigerating unit of 1.5).

Scope 1 emissions savings (% or another quantifiable metric)	No information on reduction of leakage of refrigerants, but if the method of changing from a refrigeration system in the vehicle to a PCM-based system which is charged by a stationary refrigeration system (with natural refrigerants) there is a 100% reduction in the direct emissions of the refrigerant leakage
Quality of scope 1 emissions information	No information
Scope 2 emissions savings (% or another quantifiable metric)	Increase as diesel emissions move the electric emissions.
Quality of scope 2 emissions information	Very large variation in the energy reduction potential in the articles that Calati et al (2022) reviewed.

TRL level	TRL 8-9. Eutectic plates are the most mature alternative, they have already found application in the market
Maintainability issues	The effect of the relative humidity on the cold compartment should be considered
Legislative concerns	Selecting a PCM that is not harmful for the food if leaking, or ensuring that the PCM will not be in contact with the food
Payback time (years)	Top performing systems: 2 years (Calati et al, 2022)

10.6.2 Sensible energy storage

The Colruyt Group has developed a concept for transportation of fresh products without requiring refrigerated trucks (Colruyt Group, 2021). A 'smart cool box' is the heart of the concept, which has an outer shell made of black expanded polypropylene (EPP). Expanded polystyrene (EPS) is lighter and has better insulation properties, but EPP provides a stronger structure, resistant against impacts etc. Inside the box there are slots for inserting so-called cooling plates. These are stainless steel plates containing a mixture of water and graphite. The graphite increases the conductivity of the water by a factor of 3. For frozen applications, a salt solution is applied to achieve the desired freezing point. There is also room for lining the box (between the EPP and cooling plates) with vacuum insulated panels (VIP) to maintain stable temperature for longer periods.

The concept of the cooling box is based on sensible energy storage. A sensible storage means that the heat is stored by increasing (or decreasing) the temperature of a medium, such as water, air, oil, sand or rocks (Dincer and Rosen, 2011). The cooling plates are 'charged' by contact cooling, and as such requires a refrigeration system with capabilities of low temperatures (-30°C or less) to provide an efficient charging process. The concept is applied at a distribution centre in Londerzeel, where plate charging is automated, i.e., a 'used' plates are put on a modular belt leading them through a process of drying, visual inspection and charging (freezing).

Scope 1 emissions savings (% or another quantifiable metric)	No information, but the concept can enable a shift from refrigerated to regular transportation vehicles
Quality of scope 1 emissions information	No information
Scope 2 emissions savings (% or another quantifiable metric)	No information
Quality of scope 2 emissions information	No information
TRL level	TRL 7
Maintainability issues	No information
Legislative concerns	No information
Payback time (years)	No information

11 LOGISTICS

11.1 Innovative green logistic schemes

11.1.1 A Brief introduction to Innovative / Green Logistics

Logistics. It is the part of supply chain management that deals with the efficient flow of goods and services from the origin to the customers. Logistics, especially transport, contributes significantly to environmental impact, with the emission of greenhouse gases. For instance, the logistics sector accounted for 25%-27% of the EU-28's total greenhouse gas emissions in years 2014-2017 (Dragan et al, 2016; Jacobs, 2020).

This led to the introduction of the concept of *green logistics*, in which the use of innovative schemes and technologies allows the reduction of the overall impact.

Logistics Performance Index (LPI). In 2007 the World Bank introduced the LPI to measure the competitiveness of an entire nation's companies using a score from 0 to 5 [3]. This score is obtained through both quantitative and qualitative measurements of six parameters which are finally assigned a score between 0 and 5. These parameters are:

- Customs: the efficiency of customs processes.
- Infrastructure: quality of both transport and information technology infrastructures.
- Ease of organizing competitive shipments.
- Quality of logistics shipping and customs brokerage services.
- Tracking and Tracing.
- Timeliness: the timely arrival of goods.

The LPI index is relevant for green logistics as there are several studies (see Magazzino et al, 2021 and Sikder et al, 2022 for two surveys) that demonstrate that a high LPI corresponds to a low emission of greenhouse gases in general and of CO_2 in particular.

11.1.2 Reduction of GHG Emissions

As regards reducing greenhouse gas emissions and having sustainable logistics, a set of good practices must be adopted. Wadawadigi (2022) reports a comprehensive set of these good practices:

1. Gather data to measure GHG levels and pinpoint where emissions come from.
2. Connect with supply chain partners and intercompany carbon data exchange.
3. Build compliance into processes with both internal policies and national/international regulations.
4. Improve capacity management, i.e. maximizing the capacity utilization of delivery vehicles and sophisticated route planning capabilities.
5. Tackle the last mile delivery challenge, i.e. the demand for small delivery quantities, singular orders, and locally dispersed delivery locations.
6. Track everything.
7. Embrace the circular economy.

As emerges from this list, the major innovations in the field of logistics involve, among others, the use of various innovative information technologies, in particular Artificial Intelligence (AI), Internet of Things (IoT), and Distributed Ledger Technologies (DLTs).

In particular, *IoT and cloud computing* are relevant to items 1, 2, and 6 of the previous list. Thanks to these technologies it is possible to collect data in the field and share them with supply chain partners.

AI and *Operational Research* (OR) are relevant to points 4 and 5. It is in fact thanks to this type of algorithms that it is possible to optimise transport, in particular capacity both over long distances and on the so-called last mile. In fact, it is estimated (Jacobs, 2020) that 30% of transports are (partly) empty runs due to demand imbalances, time constraints or insufficient planning. By optimizing capacity, according to some estimates, it could save between 3% and 7% of fuel consumption and up to 25% for small transporters (last mile) (e.g. see Draganet al (2016); Jacobs (2020); The Word Bank (2023); Magazzino et al (2021); Sikder et al (2022); Wadawadigi (2022); Harrirand Sari-Triqui (2022)). In particular, for the last mile, optimization techniques can take into account that multitemperature vehicles can be used to transport different goods at the same time and therefore contributing to increasing the overall capacity.

DLTs are relevant to points 3 and 6. In fact, DLTs offer immutable and secure registers where you can record what has been traced. Furthermore, smart contracts, technology associated with DLTs, offer tools to force process compliance with policies and regulations.

11.1.3 Estimate of CO_2 emissions reduction by type of IT

The information technologies that can be used to implement innovative logistics schemes, as seen above, are numerous.

It should also be noted that, when any information technology is used, this involves energy consumption and the consequent emission of greenhouse gases. The evaluation of these emissions can be found in technology reviews on AI, IoT, and DLT.

The challenge therefore consists in using these technologies to achieve a reduction in emissions greater than the emissions introduced by the ITs themselves.

There are therefore some works that try to estimate the reduction in emissions using these technologies. Table 1 reports some of these results. First, note the great variability in these estimates. This obviously depends on the specific implementations used. But this variability also depends on the level of development of the countries, in fact countries with a high income (consequently a high LPI) obtain greater reductions in emissions (about double) (Luo et al, 2022; Magazzino et al, 2021).

Furthermore, it should be noted that for the DLTs it was not possible to find a reliable estimate. Indeed, some works claimed that blockchain technology can bring around 30% extra reduction of emissions for the next decade (e.g., see Bin et al, 2022). Unfortunately, as Samet et al. pointed out too (Samet et al, 2023), no research study in the literature was found to quantify the impact of blockchain technology adoption on the decarbonization pathways in the logistics sector.

Scope 1 emissions savings (% or another quantifiable metric)	2.5%-55% (Luo et al, 2022; Ding et al, 2023; Ding et al, 2023; Efimova and Saini, 2023; Gui-e and Jian-Guo, 2020; Chung, 2021; Degot et al, 2021)
Quality of scope 1 emissions information	Not applicable
Scope 2 emissions savings (% or another quantifiable metric)	Using ITs introduce additional scope 2 emissions
Quality of scope 2 emissions information	It depends in which country Its are locate

TRL level	TRL 4-9
Maintainability issues	No particular issues
Legislative concerns	The European Commission pays attention to transport themes (European Commission, 2024)
Payback time (years)	Not available

11.2 Artificial intelligence (AI)

AI can be used to manage quantities that are correlated with emissions (for example the distance traveled in each trip, the number of trips, stops for refueling, the load of each vehicle, etc.). In particular, AI can be used both to make predictions and to optimise these quantities.

Routing, scheduling, planning are all problems that can benefit from the use of AI techniques.

11.2.1 A Brief introduction to Artificial Intelligence

Artificial intelligence (AI) is the discipline that studies computer systems capable of emulating some of human cognitive abilities. These abilities include reasoning, learning, perception, natural language recognition, understanding context, problem solving, and adapting to new situations.

A specific area of *Machine Learning* (ML). ML focuses on building models that can learn from data. This can include pattern recognition, predicting future outcomes, and adapting to new information.

Artificial Neural Networks (ANN) are one of the ML paradigms that have been receiving attention in recent years. This paradigm is inspired by the structure and functioning of the human brain. ANNs are often used for deep learning tasks.

In *Deep Learning* (DL), the features to be used by the ANN are not selected by the human operator, but are learned by the network itself. It is precisely to carry out this task that deep neural networks are made up of different layers of nodes (Figure 39).

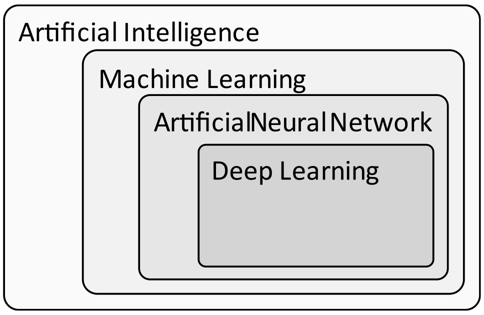


Figure 39. The relationship between AI, ML, and DL.

Focusing on machine learning in general and deep learning in particular, it must be remembered that the system, before being deployed and used, must be prepared. Training consists of collecting and pre-processing data, selecting features (in case deep training is not used), and then moving on to the actual training, the evaluation of the model and the tuning of hyperparameters. It should therefore not be surprising that in terms of computational and therefore energy resources required, the preparatory phase of the model is the most expensive one. Consequently, it is also the phase that has the highest emission of greenhouse gases.

11.2.2 Available systems on market

Before reviewing the different systems on the market, it is necessary to make a premise: AI is used transversally along the entire food chain (Transport, Retail, Catering, Storage, Domestic, Processing), therefore the technological review is valid for all the sectors.

The ML platforms on the market can be divided into two categories: pre-trained systems and systems to be trained.

1. **Pre-trained models** are models that some companies or research centers have already trained and are ready to be used. They have the advantage of not requiring users to train them (and therefore the energy impact for users is lower) but they have the disadvantage of being trained with datasets that are not specific to the problem that users need to solve. It is no coincidence that most of these models are usually pre-trained to detect natural language processing, coding, and computer vision problems. As far as we know, up-to-now there are no pre-trained models to solve problems related to the food supply chain.
2. **To be trained models** are models available on different platforms that need to be trained with datasets provided by users. Once the training and tuning of the hyperparameters is finished, these models can be deployed and used. They have the disadvantage of requiring training and tuning, therefore a greater need for computational and energy resources. They have the advantage of being able to be trained to solve the user's specific problem.

11.2.3 Energy consumption for pre-trained models

Regarding *pre-trained models*, it is difficult to find data relating to energy consumption, as the consumption of such models depends on several factors: the type of hardware used, whether the hardware is on-premise or in a remote data centre, whether the hardware is located in an air-conditioned room or not, the climatic conditions in which it operates, etc. Recently, however, some studies have been done to estimate the energy consumption of such models. The data reported here mainly refer to the estimates proposed by Desislavov et al (2023) and to a lesser extent to the results obtained by de Vries [2].
The energy consumption for pre-trained models is reported in Table 10. For each model, Table 10 reports the energy consumption in the worst and the best case, i.e. using an unoptimised processor or an optimised one (see Dessislavov et al, 2023). Please notice that the first row of the table reports the energy consumption for a query with the Google search engine. This data serves as a baseline.

Table 10. Energy consumption for most relevant DL pre-trained models

Domain	Model	Joule per Inference		Reference
		(WORST)	(BEST)	
Any	Standard Google search		1,000	de Vries, A. (2023)
Vision	AlexNet	0.2191	0.0045	Desislavov, R., Martínez-Plumed, F., and Hernández-Orallo, J. (2023)
	ZFNet-b	0.7654	0.0159	Ditto
	VGG-19	6.071	0.126	Ditto
	Densenet-201	1.3395	0.0278	Ditto
	Xception	2.5926	0.0538	Ditto
	MobileNet	0.1759	0.0037	Ditto
	ShuffleNet x1.0 (g=8)	0.0432	0.0009	Ditto
	MobileNetV2 1.4	0.1821	0.0038	Ditto

Domain	Model	Joule per Inference		Reference
		(WORST)	(BEST)	
	ShuffleNetV2 x1.0	0.0463	0.001	Ditto
	NoisyStudent-B7	11.4198	0.2371	Ditto
	ResNeSt-269	24.0432	0.4991	Ditto
	EfficientNetV2-L	16.358	0.3396	Ditto
Text	ELMo	4.0123	0.0711	Ditto
	BERT Large	12.1914	0.2162	Ditto
	Megatron	2,777.7778	49.253	Ditto
	ALBERT-xxl	385.8025	6.8407	Ditto
	Theseus 6/768	1.7438	0.0309	Ditto
	Microsoft T-NLG	5,555.5556	98.506	Ditto
	ELECTRA Large	12.1914	0.2162	Ditto
	MobileBERT	0.8272	0.0147	Ditto
	GPT-3	114,197.5309	2,024.8454	Ditto
	SqueezeBERT	1.1451	0.0203	Ditto
	BLOOM (Hugging Face)		14,400.00	de Vries, A. (2023)

11.2.4 Energy consumption for models to be trained

Regarding the energy consumption of the *models to be trained*, here the situation becomes even more complex. In fact, as mentioned before, the preparatory phase involves the completion of several steps and for each step there are numerous alternatives. On the other hand, within the ENOUGH project, this seems to be the way to follow, given that, as also emerges from Table 10, there are no pre-trained AIs specific for the food supply chain.

Therefore, going in this direction it is necessary to analyse which options can lead to a reduction in greenhouse gas emissions. A recent study (Patterson et al, 2022) focuses precisely on this aspect and proposes four best practices, the so-called *4Ms best practices*: model, machine, mechanization, and map.

1. **Model**: Selecting efficient ML models that deliver equivalent or even better result quality can reduce the calculation by factors of ~1.3-5-10.
2. **Machine**: Using processors optimised for ML training, such as tensor processing units (TPU) and recent GPUs (e.g., V100 and A100), compared to general-purpose processors, can improve performance/watt by factors ~2 –5.
3. **Mechanization**: Computing in the cloud rather than on-premises improves the energy efficiency of data centres, reducing energy costs by a factor of 1.4–2 (cloud providers use data centres designed for energy efficiency).
4. **Map**: Placing data centres in locations with the cleanest energy and where climate conditions are favourable can reduce the carbon footprint by factors of 5-10. This is also why a solution in the cloud rather than on-premises may be recommended (the use of zero-carbon clouds, such as Meta and Google, further reduces the footprint).

Model. As there are no models for the food industry already available on the market, it is necessary to review the scientific literature on the subject. A recent review has been proposed by Esmaeily et al (2023). From this review it emerges that there are different types of models that are used in the context of food industry in general and food supply chains in particular. In most cases, more traditional

ML models such as Support Vector Machine (SVM), Random Forrest (RF), Multi Layer Perception (MLP) are used. Obviously, DL is also finding application in this sector, in this case the most used models are Convolutional Neural Networks (CNN). Unfortunately, none of these models are optimised for energy consumption. Recently, however, a new type of more promising models based on so-called attention mechanisms have been proposed, in particular **Transformer** models (Esmaeily et al, 2023). These models have the characteristic of having high accuracy despite not containing recurrent units (unlike Recurrent Neural Networks - RNN). This translates into less training time and therefore less energy consumption. For example, Large Language Models, used by GPT-3 and BLOOM among others, are based on Transformer models.

Machine. The energy *efficiency of a processor unit* is measured in *FLOPS/Watt*, where FLOPS stands for Floating Point Operations per Second. The new generation of GPUs (Graphics Processing Units) and the very new TPUs (available on Google cloud) improve this efficiency considerably.

As regards TPUs, being processing units available exclusively on the Google cloud, the only data available is that provided by Google itself. According to their sources the efficiency improves by about 2-3 times compared to other specialised processing units and the CO_2e emissions are reduced up to 20 times (Jouppi et al, 2023).

However, as regards the energy efficiency of GPUs, Table 2 reports a comparison between some of the most popular GPUs, including the most recent ones. The data reported in Table 11 were taken from the recent study by Desislavov et al (2023). Please notice that the first row of the table reports a GPU produced in 2010, all the other GPUs were produced in the last five years.

Table 11. Energy efficiency of the most popular GPUs (Dessislavov, 2023).

OPTIMISED	GPU	TYPE	GFLOPS/WATT
No	GeForce GTX 580	Desktop	6.48
	Tesla V100	Server	52.33
	Tesla T4	Server	115.71
	GeForce RTX 2080	Desktop	46.84
	GeForce RTX 2080 Ti	Desktop	53.8
	Nvidia Titan RTX	Desktop	58.25
	GeForce RTX 3080	Desktop	93.13
	GeForce RTX 3090	Desktop	101.71
For CNN	Tesla V100	Server	119.03
	Tesla T4	Server	312.15
	A100 (TF32)	Server	68.52
	A100 (Mixed)	Server	130.88
For RNN	Tesla V100	Server	138.13
	Tesla T4	Server	365.46
	A100 (TF32)	Server	139.64
	A100 (Mixed)	Server	183.23

Mechanization and **Map**. As for the last two best practices, they mean that one needs to select a cloud service provider that can guarantee a reduced carbon footprint. This means on the one hand a provider that uses efficient processing units (see previous point) and on the other that has an efficient data centre.

The efficiency of a data centre is measured in terms of Power Usage Effectiveness (*PUE*).

$$PUE = \frac{P_T}{P_{IT}}$$

where P_T is the total power absorbed by the data center and P_{IT} is that used only by the IT equipment. The carbon footprint is directly proportional to the *PUE*, so the closer this ratio is to 1, the lower the carbon footprint of the data centre. Table 12 reports the average *PUE* of the main cloud providers as reported by Brown (2023).

Table 12. PUE of the main cloud providers (updated at May 2023) (Brown, 2023).

Company Name	PUE	Source
OVHcloud	1.09	https://www.ovhcloud.com/en/about-us/our-responsibility/environment/pue/
Microsoft Azure	1.12	https://docs.microsoft.com/en-us/azure/architecture/topics/green-datacenter-design/power-efficiency
Google Cloud Platform	1.12	https://cloud.google.com/sustainability/data-centers#data-center-power-usage-effectiveness-pue
Amazon Web Services	1.2	https://aws.amazon.com/about-aws/sustainability/data-centers/
Oracle Cloud Infrastructure	1.2	https://www.oracle.com/corporate/citizenship/sustainability/reporting/data-center.html
Tencent Cloud	1.2	https://intl.cloud.tencent.com/document/product/213/1370
Salesforce	1.22	https://www.salesforce.com/company/sustainability/data-centers/
Alibaba Cloud	1.21	https://www.alibabacloud.com/help/doc-detail/54736.htm
Dataqube	1.35	https://www.dataqube.global/
IBM Cloud	1.45	https://www.ibm.com/cloud/data-centers

11.2.5 GHG emission reduction using AI in Logistics

When AI technologies are adopted in a production or logistics process, there is obviously additional energy consumption due to the use of these technologies. Consequently, the use of these technologies produces indirect emissions.

The advantage in using these technologies lies in the fact that AI allows the optimization of the process and therefore the overall energy consumption and GHG emissions of the entire process should decrease.

Therefore, after reporting the consumption and emissions introduced by the adoption of specific technologies in the previous tables, Table 4 reports the overall GHG emissions savings adopting AI technologies trained on cloud providers.

It should be noted that real data on emission reductions are not available but can only be estimated.

Scope 1 emissions savings (% or another quantifiable metric)	2.5%-13%. Using AI techniques mainly allows saving on overall scope 1 emissions (Gui-e, et al, 2020; Chung, 2021; Degot et al, 2021 (for example the distance travelled in each trip, the number of trips, stops for refuelling, the load of each vehicle, etc.)
Quality of scope 1 emissions information	Not applicable
Scope 2 emissions savings (% or another quantifiable metric)	Using AI techniques introduce additional scope 2 emissions

Quality of scope 2 emissions information	It depends in which country the datacentre is located and what is the datacentre PUE
TRL level	TRL 4-9
Maintainability issues	No particular issues
Legislative concerns	EU AI Act (under approval (European Parliament, 2023)
Payback time (years)	Not available

11.3 Decentralised ledger technologies and blockchains

Distributed Ledger Technologies (DLTs) are a broad category of technologies that enable the recording and sharing of data across a distributed network of nodes. In a DLT, data is recorded in a distributed, replicated, synchronised, and shared manner among network participants, without the need for a central controlling authority and consequently without a single point of failure.

In general, this type of system requires a peer-to-peer architecture and a consensus algorithm to allow the ledger to be replicated between the nodes of the system called validator nodes (if the consensus algorithm used is the proof-of- work nodes are called "miners").

Typically, DLT ledgers are designed to be immutable. Immutability refers to the fact that once data has been recorded on the DLT, it is virtually impossible to modify or delete it.

The main advantage of this type of architecture is that each node records in its own copy of the ledger the transactions that have been approved by the majority of nodes. This proves to be particularly useful in all those scenarios where there are independent, autonomous actors and often with conflicting interests, i.e. those scenarios where there is no mutual trust.

The consensus algorithm and the high number of nodes (the higher the better) make negligible the probability that a number of dishonest nodes will be able to impose their decisions.

The blockchain is a specific form of DLT based on the adoption of a specific data structure to represent the ledger: the blockchain. The blockchain is a list (or chain) of blocks where each block (a sort of “page” of the ledger) is connected to the previous block by means of a cryptographic primitive, called hash, and the transactions to be reported in the block (on the ledger page) are grouped in structures called Merkle trees.

Blockchains are commonly associated with cryptocurrencies, such as Bitcoin and Ethereum, but have broader applications, including supply chain traceability.

1. A Premise

Before reviewing the different systems on the market, it is necessary to make a premise: DLTs are used transversally along the entire food chain (Transport, Retail, Catering, Storage, Domestic, Processing), therefore the technological review is valid for all the sectors.

2. Available systems on market

The DLTs on the market can be divided into two categories: permissionless and permissioned.

1. **Permissionless DLTs** are distributed ledgers where anyone can become a validator node, without needing to obtain permission from someone, these nodes usually receive a reward for

keeping a copy of the ledger and the work of validating transactions. So, each client has to pay a fee when submitting a transaction. These solutions are considered very secure and decentralised (suitable in contexts without mutual trust). They usually have scalability and power consumption issues.

2. **Permissioned DLTs**, on the other hand, have an authority or a consortium of authorities that must authorise requests to join the community of validators. Validator nodes usually do not receive any reward for their work and therefore transactions are generally free. These solutions are considered not very decentralised. Therefore, a greater level of trust is required in the validator nodes or in the authority that grants them permissions. They are considered very scalable and their energy impact is low.

11.3.1 Energy consumption for permissionless DLTs

The energy consumption for public (permionless) DLTs is shown in Table 13.

Table 13. Energy consumption for most relevant DLTs with their respective CO_2 emissions (Yehia Ibrahim Alzoubi and Alok Mishra, 2023).

DLT	Power consumption/year (MWh)	CO_2 emission/year (t)	Power (Wh/Tx)	Consensus	Website
Bitcoin	143,630,000.00	86,790,000.00	648,860.00	PoW	https://bitcoin.org/
Cardano	631.91	290.04	51.59	PoS	https://cardano.org/
Tezos	128.94	53.79	41.45	PoS	https://tezos.com/
Chia	190.00	__	23.00	PoST	https://www.chia.net/
Polkadot	70.25	32.24	17.42	PoS	https://polkadot.network/
Ripple	474.00	400.00	7.9	XRP	https://ripple.com/
Ethereum	2045.68	684.12	6.29	PoS	https://ethereum.org/en/
Flow	715.00	__	6.03	PoS	https://flow.com/
Avalanche	718.15	268.11	4.76	PoS	https:// www.avax.network/
Bitgreen	86.18	__	1.21	zk-SNARK	https://bitgreen.org/
Hedera	__	__	0.17	Hashgraph	https://hedera.com/
Solana	3012.97	1382.96	0.51	PoH, PoS	https://solana.com/
IOTA	6,000.00	__	0.111	Tangle	www.iota.org/
Polygon	107.18	49.2	0.103	PoS	https://polygon.technology/
Tron	162,867.85	69.47	0.07	DPoS	https://tron.network/
Stellar	481.00	173.00	0.22	FBA	https://stellar.org/
Algorand	4160.83	1909.82	0.008	PoS	https://algorand.com/
Fantom	8.2	__	0.000028	Lachesis	https://fantom.foundation/

11.3.2 Energy consumption for permissioned DLTs

The energy consumption and equivalent CO_2 emission for permissioned DLTs is more difficult to calculate, as each organization/consortium implements its own platform and consumption strongly depends on this (how many validation nodes there are, which hardware it is used, and so on). Just to have an idea, Hyperledger Fabric (one of the most popular platforms to deploy permissioned DLTs) has an average power consumption per transaction and per node equal to 0.00001852 Wh/Tx.

Table 14 reports the power consumption per transaction of Hyperledger Fabric compared with the most popular public DLTs.

Table 14. Energy consumption: a comparison between permissionless (white cells) and permissioned (grey cells) DLTs

DLT	Power (Wh/Tx Nodes)
Bitcoin [2]	0.6488600000
Hedera	0.0058620690
Avalanche	0.0047600000
Stellar	0.0044000000
Solana	0.0005100000
Cardano	0.0000396846
Ethereum	0.0000314700
Hyperledger Fabric	0.0000185200
Algorand	0.0000036364
Fantom	0.0000005600

11.3.3 GHG emission reduction using DLTs in Logistics

When DLTs are adopted in a production or logistics process, there is obviously additional energy consumption due to the use of these technologies. Consequently, the use of these technologies produces indirect emissions.

The advantage in using these technologies lies in the fact that DLTs allow the optimization of the process and therefore the overall energy consumption and GHG emissions of the entire process should decrease.

Therefore, after reporting the additional emissions Table 3 reports the overall GHG emissions savings adopting green public DLTs. It should be noted that for the DLTs it was not possible to find a reliable estimate. Indeed, some works claimed that blockchain technology can bring around 30% extra reduction of emissions for the next decade (Bin et al., 2022)). Unfortunately, as Samet et al. (2023) pointed out too, no research study in the literature was found to quantify the impact of blockchain technology adoption on the decarbonization pathways in the logistics sector.

Scope 1 emissions savings (% or another quantifiable metric)	Not available. However, using DLTs mainly allows saving on overall scope 1 emissions (Bin et al, 2022; Samet et al, 2023)
Quality of scope 1 emissions information	Not applicable
Scope 2 emissions savings (% or another quantifiable metric)	Using DLTs introduce additional scope 2 emissions. However green DLTs allow saving up 99.99% (e.g. using Ethereum instead of Bitcoinn)
Quality of scope 2 emissions information	Public blockchains have miners all around the world, so the quality should be considered low
TRL level	TRL 4-9

Maintainability issues	No particular issues
Legislative concerns	The European Commission aims to use innovations in DLTs to fight climate change (European Commission, 2022) and has launched he European Regulatory Sandbox for Blockchain (European Commission, 2023)
Payback time (year	Not available

11.4 Innovative logistic schemes (including multitemperature vehicles)

11.4.1 A Brief introduction to Internet of Things

The *Internet of Things* (IoT) refers to the extension of the Internet to the world of concrete objects and places, which acquire their own digital identity so that they can communicate with other objects in the network and be able to provide services to users.

In other words, this means that there are things (e.g. sensors, actuators, smart devices, etc.) that produce and receive data in order to communicate with other things and provide services to remote users. These objects reach the network via a gateway (see Figure 40).

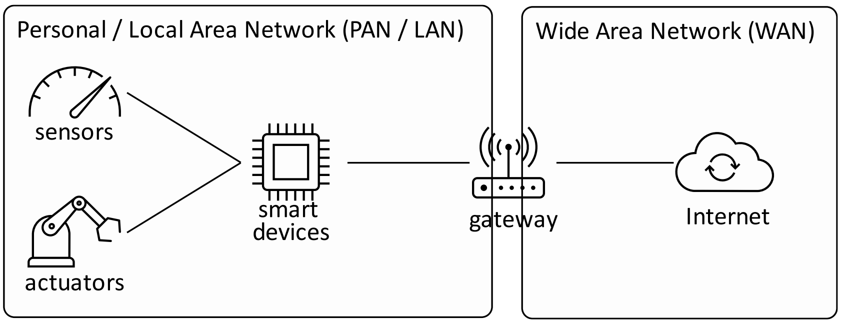


Figure 40. An architecture of an IoT system.

Therefore IoT-enabling technologies for the food supply chain include sensors and actuators, smart device processors, and networking protocols. In this review, we focus on wireless sensor networks (WSNs) as they are the most used and the most critical from the energy consumption perspective. Regarding processors, we focus on low-power processors. Regarding protocols, it should be noticed that they must act at the level of personal area networks (PAN), local networks (LAN), and wide area networks (WAN). On the one hand, specific protocols have been defined for the IoT that allow the various devices within the range of a personal/local network to communicate with each other and with the gateway. These protocols typically act at the physical and data connection levels and can be used as an alternative to traditional protocols (e.g. Wi-Fi). On the other hand, there are specific protocols that act at the highest levels of the protocol stack that can be used as an alternative to traditional protocols (e.g. HTTP). A synoptic view of the IoT protocol stack and that of the traditional web is shown in Figure 41.

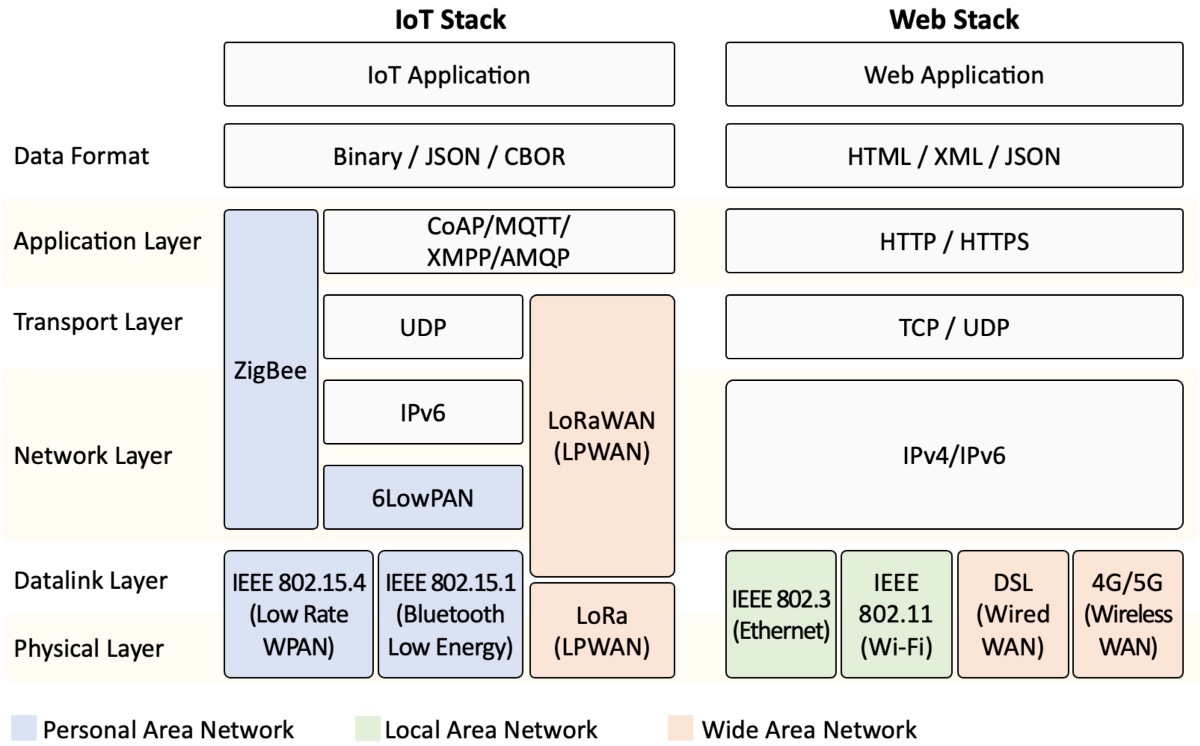


Figure 41. IoT protocol stack vs. web protocol stack.

11.4.2 Available technologies on market and the related energy consumption

Before reviewing the different systems on the market, it is necessary to make a premise: IoT is used transversally along the entire food chain (Transport, Retail, Catering, Storage, Domestic, Processing), therefore the technological review is valid for all the sectors.

Wireless Sensor Network. There are several solutions to reduce the energy consumption of a wireless sensor network. Alsgarif et al (2023) reported an updated and fairly comprehensive review of techniques for reducing energy consumption. Table 15 reports a summary of these techniques with their respective advantages and disadvantages.

Table 15. A summary of energy-saving estimates for different green WSNs techniques (Alsharif et al, 2023).

WSNs techniques.	Energy-efficient technique	Energy savings	Advantages	Disadvantages
Radio optimization Techniques	*Transmission power control*: Dynamic adjustment of transmission power to minimise energy consumption.	Up to 50%	- Reducing energy consumption and prolonging network lifetime. -Improving network scalability and coverage - Improving network reliability by reducing interference and packet loss. - Adapting to changes in	- Increasing complexity and overhead of network protocols. - Potentially increasing end-to-end latency and reducing throughput. - Depending on the specific algorithm used, it may require additional hardware or computational resources.

WSNs techniques.	Energy-efficient technique	Energy savings	Advantages	Disadvantages
			network topology and environmental conditions	
	Cooperation between wireless sensors: Collaborative data processing, routing, and sharing among neighbouring sensors.	Up to 80%	- Reducing redundancy and improving data accuracy. - Enhancing security and fault tolerance.	- Depending on the specific algorithm used, it may require additional hardware or and computational resources. - Depending on the application, it may require additional communication overhead or latency.
	Spatial diversity: Using multiple antennas to transmit the same signal from different locations, which can reduce the transmission power required to achieve the same level of communication performance.	20–50%	- Increased energy efficiency and network lifetime. - Improved network coverage and reliability. - Reduced interference and signal fading.	- Requires additional hardware to implement. - Can increase network complexity. - May lead to higher deployment costs.
	Modulation optimization: Adjusts modulation scheme based on channel conditions and node distances.	Up to 60%	- Increased energy efficiency. - Improved data transmission rates.	- Complex algorithm design. - Sophisticated hardware. - Susceptible to interference.
Sleep/Wake-up techniques	*Topology control:* Adjusting the transmission range; nodes can avoid unnecessary communication.	15–60%	- Extends network lifetime. - Balances energy usage. - Reduces congestion.	- Increased complexity and overhead. - May impact network performance.
	Duty cycling: Whan a sensor is put into sleep mode (“duty cycle”) the node does not transmit or receive data, and its radio is turned off.	30–50%	- Easy to implement. - Longer network lifetime.	- Reduced network throughput. - Increased latency. - Reduced network coverage.

WSNs techniques.	Energy-efficient technique	Energy savings	Advantages	Disadvantages
Energy harvesting techniques	Solar	70–90%	- Renewable energy. - Widely available. - Can be used in remote areas.	- Dependent on weather conditions (sunlight). - High initial cost.
	Wind	10–20%	- Renewable energy. - Can be used in remote areas.	- Dependent on wind speed. - High initial cost.
	Kinetic	20–40%	- Can be integrated with human activity. - Low initial cost.	- Limited availability of kinetic energy sources.
	Thermoelectric	5–10%	- Low-maintenance. - No moving parts.	- Low energy conversion efficiency and limited availability of heat sources.
	Electromagnetic	5–10%	- Can harvest energy from various sources. - Low-maintenance.	- Limited availability of electromagnetic energy sources.
Architecture and Routing protocols	Cluster architecture	20–40%	- Reduces energy consumption of nodes.	- Decrease network scalability.
	Multipath routing	20–30%	- Increases network lifetime and reliability.	- Requires extra resources and overhead.
	Relay node placement	30–50%	- Extends network coverage - Reduces energy consumption.	- Increases network complexity and maintenance costs.
Data Reduction Techniques	Aggregation	20–80%	- Reduces communication traffic.	- Increases data latency and processing overhead.
	Adaptive sampling	30–60%	- Reduces unnecessary data transmission.	- Requires extra resources and overhead.
	Compression	50–90%	- Reduces data size and energy consumption.	- Requires extra resources and processing overhead.
	Network coding	30–70%	- Increases data reliability - Reduces energy consumption.	- Increase computational complexity.

Processors. The energy consumption of smart devices depends on several factors. One of the main elements is the type of processor used. The energy consumption of a processor must obviously be related to the number (millions) of operations per second (MOPS) that the processor can perform. For this reason, rather than total energy consumption, it is important to measure efficiency, i.e. MOPS/mW. There are many processors for the IoT, the efficiency of some of the most recent are reported in Table 16, as reported by Alsharif et al (2023).

Table 16. Overview of recent processors that are both energy-efficient and ultra-low-power. Alsharif et al, 2023).

	Number of cores	Data format	Technology	Best perf. (MOPS)	Energy eff. (MOPS/ mW)
MSP430	1	16-bit	CMOS	25	64.5
ReiSC	1	32-bit	CMOS	57.5	68.6
TMS320C64x	1	32-bit VLIW	CMOS	662	4.5
FRISBEE	1	32-bit VLIW	FD-SOI	2600	16
ARM CortexM3	64	32-bit	CMOS	1600	3.9
OpenRISC	4	32-bit	FD-SOI	3300	193

Protocols. A similar discussion can be made for protocols. Also, in this case the evaluation of energy consumption must be related to characteristics such as the bit rate and the distance that can be covered. There are several studies that have addressed this issue. Some recent works on this topic are those of Alsharif et al (2023), Fraga-Lamas et al (2021), Aslan and Aslan (2023), and Schaefer et al (2013)]. Table 17 reports the power consumption for the most popular protocols for IoT compared with more traditional protocols.

Table 17. Overview of recent processors that are both energy-efficient and ultra-low-power (Alsharif et al (2023), Fraga-Lamas et al (2021), Aslan and Aslan (2023)).

Protocol	Frequency	Distance	Data Rate	Power Consumption
Bluetooth 5 LE	2.4 GHz	50-150 m	1360 kbit/s	1–20 mW, Low power and rechargeable (days to weeks)
ZigBee	2.4 GHz	10-100 m	250 kbit/s	100–500 µW (Fraga-Lamas et al, 2021), batteries last months to years up to 6.63 mW 4. (Schaefer et al, 2013)
6LoWPAN	2.4 GHz	10-100 m	250 kbit/s	up to 11.4 mW (Schaefer et al, 2013)
Sigfox	868–902 MHz	- 30-50 km in the countryside - 3-10 km in the city center	100 kbit/s	Battery lasts 10 years sending 1 message, <10 years sending 6 messages
LoRaWAN	2.4 GHz	2-5 km, 15 km	0.25–50 kbit/s	Long battery life, it lasts > 10 years
Wi-Fi (IEEE 802.11b/g/n/ac)	2.4–5 GHz	<150 m	up to 433 Mbit/s (one stream)	High power consumption, rechargeable (hours)
Wi-Fi HaLow (IEEE 802.11ah)	868–915 MHz	<1 km	100 kbit/s per channel	1 mW
4G	450MHz - 3.8GHz	Entire cellular area	200 kbit/s–1 Gbit/s	600-1200 mW
5G	450 MHz - 6 GHz 24.25 GHz - 52.6 GHz	Entire cellular area	100 Mbit/s (avg.) 20 Gbit/s (peak)	up to 1500 mW

11.4.3 GHG emission reduction using IoT in Logistics

When IoT technologies are adopted in a production or logistics process, there is obviously additional energy consumption due to the use of these technologies. Consequently, the use of these technologies produces indirect emissions.

The advantage in using these technologies lies in the fact that IoT enables the optimization of the process and therefore the overall energy consumption and GHG emissions of the entire process should decrease.

Therefore, after reporting the consumption and emissions introduced by the adoption of specific technologies in the previous tables, Table 4 reports the overall GHG emissions savings adopting IoT technologies and the scope 2 emissions savings adopting green IoT technologies.

It should be noted that real data on emission reductions are not available but can only be estimated.

Scope 1 emissions savings (% or another quantifiable metric)	2.5%-13%. Using IoT techniques mainly allows saving on overall scope 1 emissions (Luo et al, 2022; Ding et al, 2023; Efimova and Saini, 2023)
Quality of scope 1 emissions information	Not applicable.
Scope 2 emissions savings (% or another quantifiable metric)	Using IoT techniques introduce additional scope 2 emissions, but using green IoT techniques, one can save 5%-90% emissions
Quality of scope 2 emissions information	It depends in which country the datacentre is located and what is the datacentre PUE
TRL level	TRL 4-9
Maintainability issues	No particular issues
Legislative concerns	The EU actively cooperates with industry, organisations and academia to unleash the potential of IoT (European Commission,2023)
Payback time (years)	Not available

11.5 Vehicle routing optimisation

11.5.1 A Brief introduction to Vehicle Routing Problem

Mathematical Programming (MP) is part of operations research and deals with optimization problems, i.e. finding the best solution from a set of feasible alternatives. A MP problem have the following general form:

$$\begin{array}{lrl} \max/\min & f(\mathbf{x}) & \mathbf{x} = (x_1, x_2, \dots, x_n) \\ & g_j(\mathbf{x}) \le 0 & j = 1,2,\dots,m \\ & h_k(\mathbf{x}) = 0 & k = 1,2,\dots,p. \\ & x_i \in X_i & i = 1,2,\dots,n. \end{array} \qquad (1)$$

where $f(\mathbf{x})$ is the objective function (i.e. the function to optimise), x_i are the decision variables, X_i the related variable domains, $g_j(\mathbf{x})$ and $h_k(\mathbf{x})$ the variable constraints.

Depending on the form taken by the objective function and constraints, MP problems can specialise in problems of

- *Linear Programming* (LP), when variables are real, objective functions and constraints are linear;
- *Integer Programming* (IP), when variables are integer; it specialises in *Integer Linear Programming* (ILP) when objective functions and constraints are linear;
- *Mixed Integer Programming* (MIP), when some variables are integer, others are real; it specialises in *Mixed Integer Linear Programming* (MILP) when objective functions and constraints are linear;
- *Combinatorial Optimisation*, when variables are discrete; it specialises in *Binary Programming*, when variables are binary.

A generalization of problem (1) can be considered the *multi-objective optimization problem* (MOP), a kind of problem that involves optimizing multiple (often conflicting) objectives simultaneously.

The **Vehicle Routing Problem** (VRP) is a combinatorial optimization problem that involves determining the most efficient way to deliver goods or provide services to a set of locations using a fleet of vehicles. The objective is to minimise the total cost, which may include factors such as travel distance, time, or vehicle-related expenses, while satisfying various constraints.

The **Green Vehicle Routing Problem** (G-VRP) is a variant of the classical VRP that takes into account environmental considerations, i.e. minimizing the environmental impact associated with the transportation of goods or provision of services. The primary objective of the Green VRP is to optimise routes and schedules for a fleet of vehicles in a way that reduces fuel consumption, GHG emissions, or other negative environmental effects.

11.5.2 Mathematical Programming Solving Methods

In mathematical programming, various solving methods and approaches are used to find optimal solutions. These solving methods and algorithms depend on the optimization problems. Relevant solving methods for green transportation and green VRP can be grouped in the following types:

- *Exact Methods*. They employ systematic search strategies that explore the solution space exhaustively. They guarantee optimal solutions, subject to computational limits. Some examples: Simplex, branch-and-cut, dynamic programming.
- *Heuristic Methods*. Problem-specific methods designed for specific types of problems. They do not guarantee optimal solutions. Some examples: greedy algorithms, nearest-neighbour search, random search.
- *Metaheuristic Methods*. Higher-level strategies that guide the search process in the solution space. They can be applied to a wide range of problems. They do not guarantee optimal solutions. Some examples: genetic algorithms, simulated annealing, tabu search, and particle swarm optimization.
- *Decomposition methods*. They are designed to address large-scale optimization problems by breaking them down into smaller, more manageable subproblems. Some examples: column generation, route splitting, Benders decomposition.

11.5.3 Reduction of GHG Emissions in transportation

Reducing GHG emissions in transportation can be studied as an optimization problem. This means defining mathematical programming models that consider routings, resource locations, and inventory planning.

Routings. This problem can be formulated as a green VRP. This problem has received particular attention in the literature and there are several models and methods that have been proposed. A good review of such works can be found in some recent systematic reviews (Mor and Speranza, 2023, Endler et al, 2023; Gu et al, 2023)

Table 18 reports some of the most significant works as reported by Endler et al (2023).

Table 18. Methods and algorithms for Green VRP (Endler et al, 2023).

Problem Class	Methods / Algorithms	References
VRP with fuel consumption and carbon emission	**Exact** (*Tabu Search*) combined with **Decomposition Method** (Route Splitting)	Zhang, J., Zhao, Y., Xue, W., and Li, J. (2015)
Electric Fleet Size and Mix VRP with Time Window and Recharging Stations (E-FSMFTW)	**Exact** (*Branch-and-price*) **Heuristics** (*Adaptive Large Neighbourhood Search, Random kernel search*)	Hiermann, G., Puchinger, J., Ropke, S., and Hartl, R. F. (2016). Bruglieri, M., Paolucci, M., and Pisacane, O. (2023)
Battery swap station location-routing problem with capacitated electric vehicles	**Heuristics** (*Adaptive Variable Neighbourhood Search*)	Hof, J., Schneider, M., and Goeke, D. (2017)
VRP with intermediate stop (VRPIS)	**Heuristics** (*Adaptive Variable Neighbourhood Search*)	Schneider, M., Stenger, A., and Hof, J. (2015)
Hybrid VRP	MILP formulation **Heuristics** (*Large Neighbourhood Search*)	Mancini, S. (2017)
Two-echelon time-constrained VRP in linehaul-delivery systems (2E-TVRP) considering CO_2 emissions	**Heuristics** (*Clarke and Wright algorithm*)	Li, H., Yuan, J., Lv, T., and Chang, X. (2016)
Fuel emissions optimization in VRP with time-varying speeds	**Exact** (*Tabu Search*) combined with **Decomposition Method** (*Column generation*)	Qian, J., and Eglese, R. (2016)
Alternative fuel VRP	**Heuristics** (*Multi-space sampling*)	Montoya, A., Guéret, C., Mendoza, J. E., and Villegas, J. G. (2016)
CO_2 emissions VRP	**Metaheuristics** (*genetic algorithm with block recombination approach*)	Tiwari, A., and Chang, P. C. (2015)
Heterogeneous Green vehicle routing and scheduling problem with time-varying traffic congestion	MIP formulation **Heuristics** (*Iterated Neighbourhood Search*)	Xiao, Y., and Konak, A. (2016)
Asymmetric capacitated VRP	MILP	Leggieri, V., and Haouari, M. (2018)

Furthermore, within the food supply chain, the case of the transport of multiple commodities is of particular importance, especially in the presence of incompatible commodities. In the latter case, means of transport with multiple compartments are required. It should be noticed that vehicles with multiple temperatures fall into this category. This specific problem received a great attention too. A brief review of some significant works in the field is reported in Table 19.

Table 19. Methods and algorithms for VRP with multiple commodities (Gu et al, 2023).

Problem Class	Problem Subclass	Methods / algorithms	References for food supply chain
Incompatible commodities	Multi-compartment VRP (*Multi-temperature vehicles are included here*)	**Heuristics** (*construction heuristics, local search operators, large neighbourhood search*) **Metaheuristics** (*memetic algorithms, population-based algorithm*), **Exact** (*branch-and-price, branch-and-cut, branch-and-price-and-cut*)	Chen, J., Dan, B., and Shi, J. (2020) Wang, X., Liang, Y., Tang, X., and Jiang, X. (2023).
	Multi-trip VRP	**Heuristics** (*iterated local search*)	Battarra, M., Monaci, M., and Vigo, D. (2009)
Compatible commodities	Indivisible commodities	**Decomposition Method** (*Column generation*) **Exact** (*dynamic programming, branch-and-cut, branch-price-and-cut*), **Heuristic**s (*Adaptive Large Neighbourhood Search*)	Gu, W., Cattaruzza, D., Ogier, M., and Semet, F. (2019)
	Multiple origins and destinations	**Metaheuristics approaches** (*population algorithm based on randomised tabu thresholding*)	
	Commodities with heterogeneous features	**Decomposition Method** (*Column generation*) **Exact** (*branch-price-and-cut, branch-and-cut*)	Paradiso, R., Dabia, S., Dullaert, W., and Gromicho, J. (2022). Paredes-Belmar, G., Marianov, V., Bronfman, A., Obreque, C., and Lüer-Villagra, A. (2016) Paredes-Belmar, G., Montero, E., Lüer-Villagra, A., Marianov, V., and Araya-Sassi, C. (2022).

Resource Location. This problem is generally addressed as a special case of a multi-objective optimization problem. An updated review of works dealing with this problem is provided by Fan et al [23]. Table 20 reports a summary of this review.

Table 20. Methods and algorithms for Resource Location Optimization (Fan et al, 2023).

Problem class	Methods / algorithms	References
Multi-objective Integer Programming	Exact and Heuristics (LINGO Mixed Integer Solver)	Chaabane, A., Ramudhin, A., and Paquet, M. (2012)
Multi-objective Possibilistic Programming	Decomposition Method (Benders decomposition) Heuristics (local branching)	Pishvaee, M. S., Razmi, J., and Torabi, S. A. (2014)
Multi-objective Programming	Multi-objective evolutionary algorithm (metaheuristics)	Harris, I., Mumford, C. L., and Naim, M. M. (2014)
GVRP with resource location	Metaheuristics (Whale optimization algorithm)	Dewi, S. K., and Utama, D. M. (2021)
Multi-objective Programming	Metaheuristics (Genetic algorithm)	Fatemi-Anaraki, S., Mokhtarzadeh, M., Rabbani, M., and Abdolhamidi, D. (2022) Wolff, S., Seidenfus, M., Brönner, M., and Lienkamp, M. (2021)

Inventory planning. This problem has also been addressed in some works, as reported in the review by Fan et al. Few of these are shown in Table 21.

Table 21. Methods and algorithms for Inventory Planning Optimization (Fan et al, 2023).

Problem class	Methods / algorithms	References
Economic order quantity (EOQ)	Exact	Konur, D., and Schaefer, B. (2014).
Newsvendor model	Exact	Arıkan, E., and Jammernegg, W. (2014).

11.5.4 GHG emission reduction using VRP

When VRP optimization algorithms are adopted in a logistics process, there is obviously additional energy consumption due to the use of these technologies. Consequently, the use of these technologies produces indirect emissions.

The advantage in using these technologies lies in the fact that VRP algorithms allow the optimization of the process and therefore the overall energy consumption and GHG emissions of the entire process should decrease.

Therefore, Table 5 reports the overall GHG emissions savings adopting optimization technologies.

It should be noted that real data on emission reductions are not available but can only be estimated.

Scope 1 emissions savings (% or another quantifiable metric)	2.5%-13%. Using optimization techniques mainly allows saving on overall scope 1 emissions (Chung, 2021)
Quality of scope 1 emissions information	Not applicable.
Scope 2 emissions savings (% or another quantifiable metric)	Using optimization techniques introduce additional scope 2 emissions
Quality of scope 2 emissions information	It depends in which country the server where the algorithm run is
TRL level	TRL 4-9
Maintainability issues	No particular issues
Legislative concerns	None
Payback time (years)	Not available

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13 MODELLING

The primary objective of the simulation was to assess the emissions associated with the truck and the refrigeration units under various scenarios, each chosen to represent different links in the cold chain.

Calculations were performed to determine a yearly average performance for six locations in Europe: Kaunas, London, Oslo, Paris, Rome, and Warsaw.

The first section of this section presents the details of the numerical model, including descriptions of the main components involved in the simulation and their interrelations. The second section details the scenarios considered and the corresponding inputs to the model.

13.1 Numerical modelling

Refrigerated trucks have been modelled using a quasi-steady-state approach to account for the main thermal loads on the isothermal box and the performance maps of the refrigeration unit cooling the box. Emissions caused by the powertrain system have been quantified based on literature data.

The programming environment used to estimate energy consumption and emissions was MATLAB [Mathworks, 2022]. The following flowchart provides a schematic view of the overall computational scheme (Figure 42).

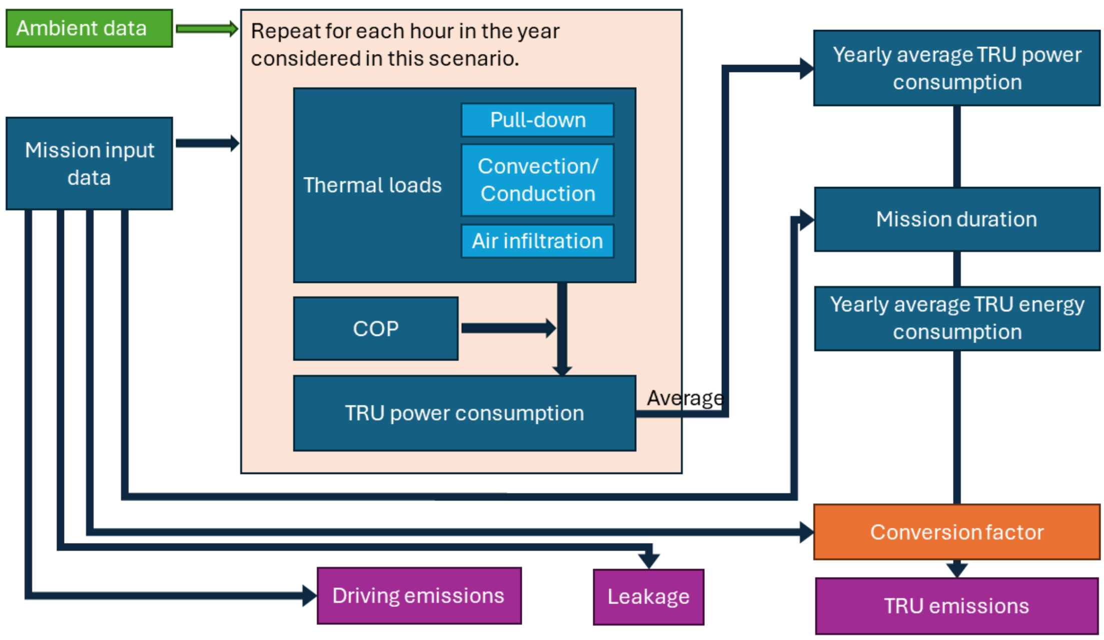

Figure 42. Schematic view of the overall computational scheme.

Initially, all boundaries specifying the type of transport and truck involved, as well as the annual ambient data relative to the considered location, are uploaded. The thermal loads and the refrigeration unit's performance (COP) lead to the estimation of the hourly average power consumption. This value is then averaged over the year, and considering the mission duration, leads to the yearly average mission energy consumption. The type and technology used to power the refrigeration unit define the energy conversion factor, which is used to convert the energy demand into the associated emissions.

Data from the refrigeration unit (charge and refrigerant) are used to estimate the leakage rate, which is then converted to equivalent CO_2 emissions by applying the GWP of the refrigerant.

The driving distance and the truck type allow for the estimation of driving emissions.

The main subsystems included in the model are:

- The refrigeration box body and thermal loads
- The transport refrigeration unit (TRU)
- Power supply for the TRU
- Vehicle powertrain emissions characterization

Each of these elements will be discussed in the following sections.

13.1.1 Isothermal box and thermal loads

The thermal loads of the truck were modeled considering three main components: the pulldown energy required to lower the box temperature to the operational set-point from an initial stationary condition; the power needed to counteract heat infiltration through the closed box walls; and the heat loads resulting from external air infiltrations during unloading operations.

The pulldown energy was estimated based on the experimental characterization reported by Artuso et al. [Artuso et al, 2019]. The stationary equilibrium temperature was assumed to be the average ambient temperature for the given day and location, while the operational equilibrium condition was considered the average between the ambient temperature and the set-point used for the internal air temperature.

Conduction-convection heat infiltration was modeled according to the global heat transfer coefficient (K), as defined in the ATP agreement [UNECE, 2022].

Air infiltrations were estimated using a simplified correlation derived from the experimental data reported by Lafaye de Micheaux et al. (2015). The mass flow entering the refrigerated box was first calculated as a function of the door opening time. The thermal load associated with this hot air infiltration was then evaluated, considering both the latent and sensible heat required to cool the humid ambient air to the operational set-point temperature inside the box.

Solar radiation was not included in the model, as previous studies demonstrated that this factor is significant only if long stops are considered [Artuso et al, 2019]. In fact, when the truck is in motion, the external convection between the box's outer surface and the ambient air is sufficient to maintain the surface temperature close to the ambient level.

13.1.2 Transport Refrigeration Unit (TRU)

The Transport Refrigeration Unit (TRU) is characterised by its Coefficient of Performance (COP) curve. The performance of both conventional and R290 systems was modeled based on the experimental data reported by Colbourne et al. [Colbourne et al., 2017]. Each system employs a simple vapor compression cycle with a thermostatic expansion valve.

Due to the lack of open literature on the remaining systems (R744 units and Eutectic systems), COP curves were derived from dedicated numerical simulations. Dynamic lumped element models were developed within the commercial software environment of Simcenter Amesim [Siemens, 2024] for this purpose. Each component was modeled according to the specifications provided by the manufacturer. Further details about the modeling approach can be found in Fabris et al. [Fabris, 2021].

13.1.2.1 R744 MT and LT units

For low-temperature applications, a two-stage compressor with a low-pressure receiver and a back-pressure valve was utilised. A similar system, employing a single-stage compressor and including an ejector, was used for medium-temperature applications. When the ambient temperature exceeds

20°C, the ejector allows to recover a portion of the expansion losses. Conversely, when the ambient temperature falls below 20°C, the system reverts to a single-stage cycle with back pressure and a flooded evaporator (Figure 43 and Figure 44).

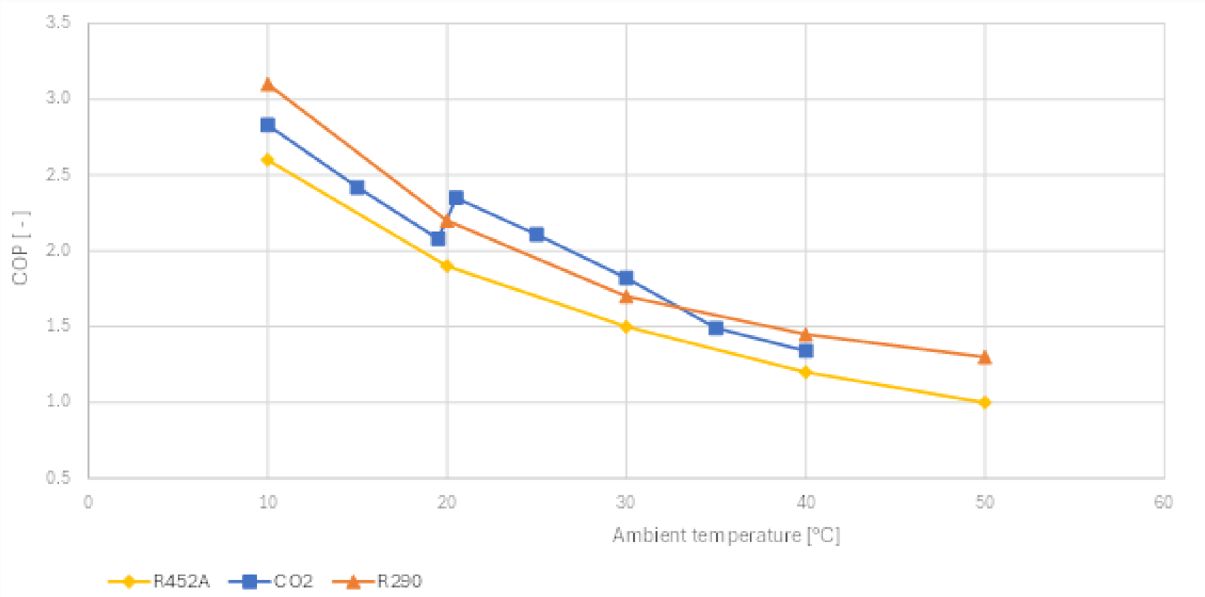

Figure 43. Medium temperature (0°C) COP.

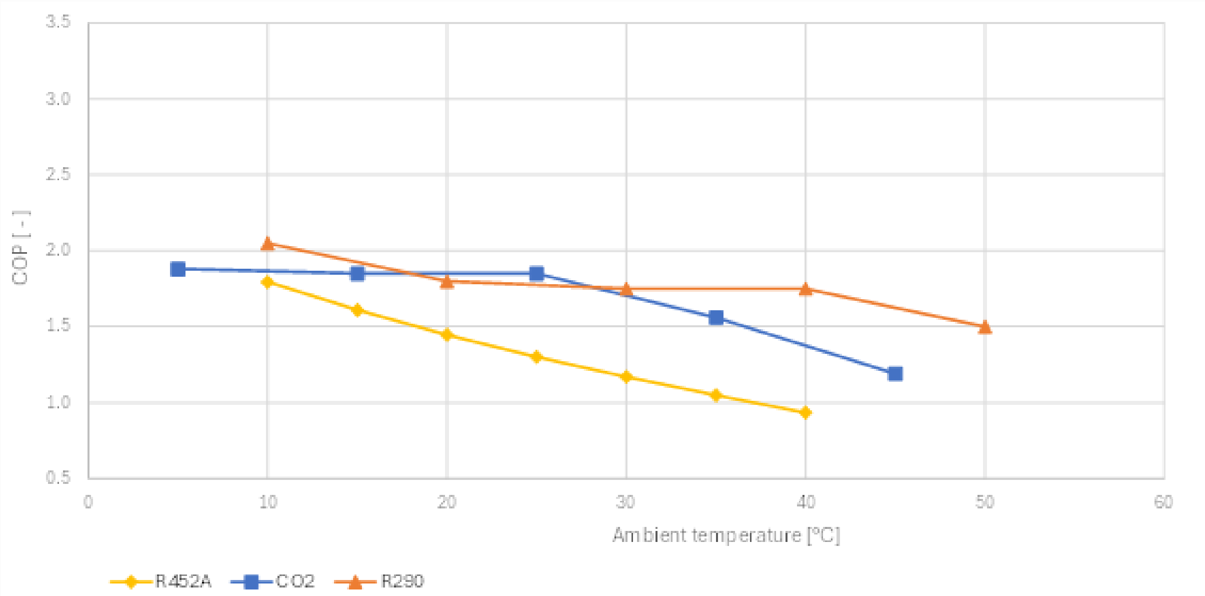

Figure 44. Low temperature (-20) COP.

13.1.2.2 Stationary refrigeration units for eutectic systems

The baseline unit was modeled as a single-compression simple cycle with a thermostatic expansion valve. The low-pressure side of the cycle is achieved by connecting the stationary unit to the refrigeration loop integrated into the eutectic plates. In this setup, the refrigerant evaporates, removing heat from the plates until the phase change material is subcooled (Figure 45).

In this instance, the natural refrigerant solution is an R290 stationary unit, modeled after its synthetic counterpart. Charge minimization is a critical objective in designing R290 systems to mitigate the risks associated with flammability. Therefore, the direct expansion of the refrigerant in the plates is not considered. Instead, a secondary loop that pumps liquid CO_2 is implemented. This system is described and characterised in Fabris et al. [Fabris et al., 2024].

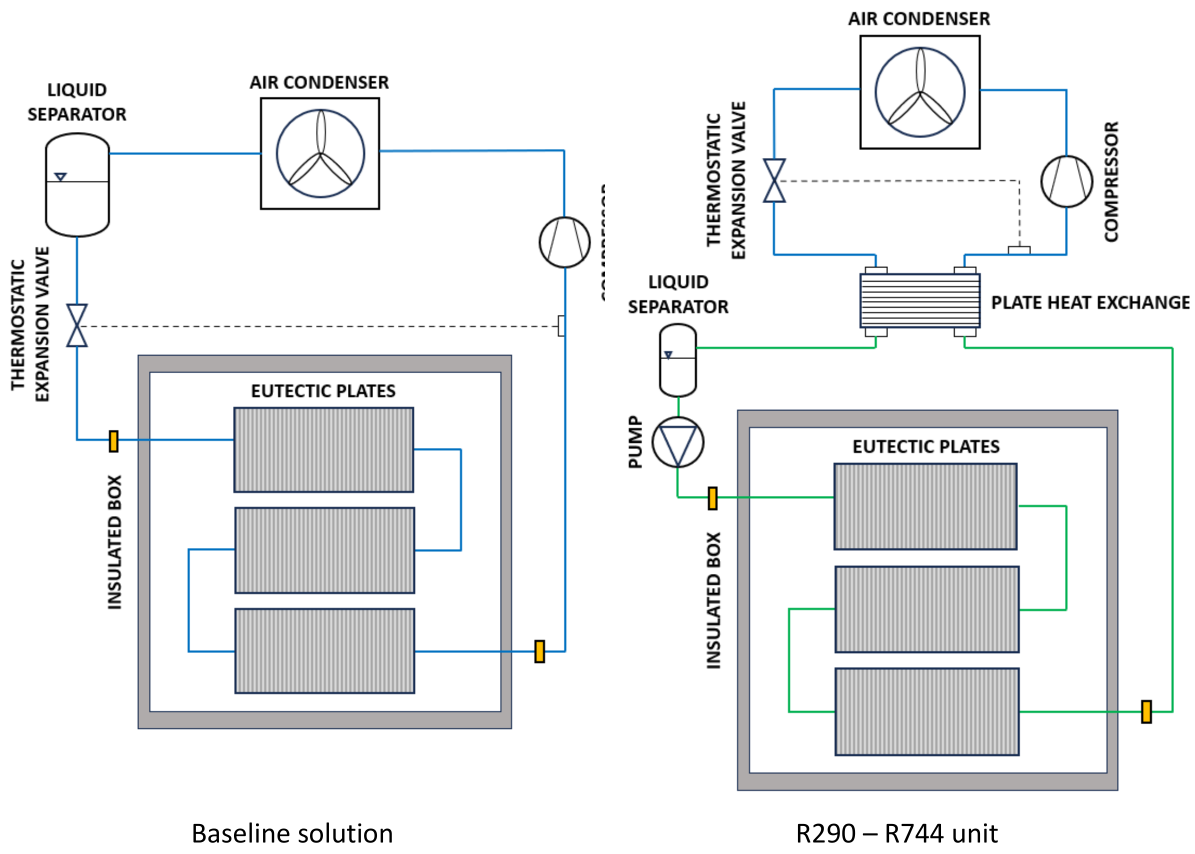

Figure 45. Refrigeration units for eutectic systems.

The charging process of a eutectic system, starting from a resting condition, is a dynamic phenomenon. The evaporation temperature of the refrigerant changes over time in response to the eutectic material's temperature, affecting the COP. Initially, the Thermal Energy Storage (TES) temperature decreases steadily from the ambient temperature to the phase change temperature. Then, the TES temperature varies slightly, due to the glide during solidification. Once full solidification has occurred, the temperature drops again as the eutectic material becomes subcooled (Figure 46).

For this reason, the COP of eutectic system units is expressed in terms of energy, considering the

$$COP = \frac{\int Q}{\int P_c + P_f}$$

Where:

- Q is the cooling power;
- P_c is the compressor power consumption
- P_f is the fan electrical consumption

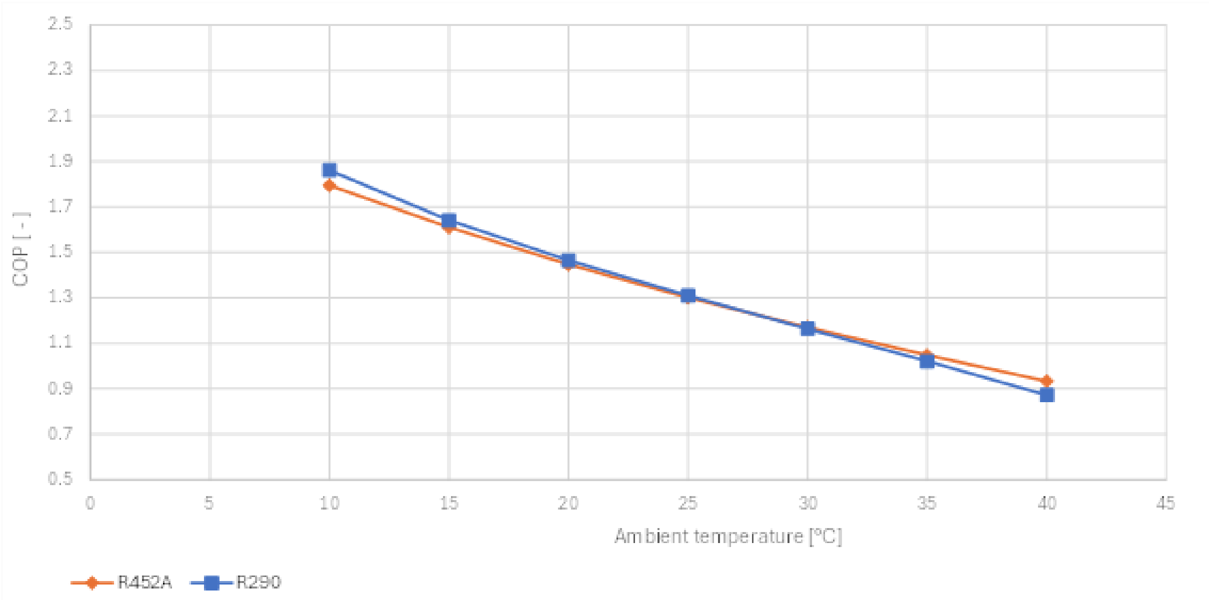

Figure 46. Eutectic cooling.

13.1.2.3 Partialisation losses

To account for partialisation losses in the TRU a penalising factor is applied based on the equation reported in EN 14825, which accounts for the performance degradation of fixed capacity units under partial loads:

$$COP_{PL} = COP_{DC}\left(1 - C_d(1 - C_R)\right)$$

where:

- COP_{PL} is the Coefficient Of Performance resulting from partialisation;
- COP_{DC} is the nominal Coefficient Of Performance at declared capacity;
- C_R is the capacity ratio, i.e. the ratio between the cooling request and the declared capacity
- C_d is the degradation coefficient.

Based on numerical simulations of both synthetic and R744 systems, degradation coefficients were set to 0.25 for frozen applications and 0.15 for chilled applications.

In the case of eutectic systems, where the unit runs continuously at full power until the solidification of the eutectic plates is complete, partialisation losses are not relevant.

13.1.3 Power Supply of the TRU

To convert the energy consumption of the TRU into emissions, it is necessary to define the nature of the energy products and the technology used for each truck type.

13.1.3.1 Vapor compression cycle TRU in Light Commercial Vehicles.

In the baseline solution, the TRU is powered by the vehicle's main engine via a belt connection in the engine compartment. The carbon conversion factor was set to 651 g/kWh according to Grigoratos et al.

When the unit is powered by batteries, the carbon conversion factor is assumed to be equal to the grid consumption conversion factor of the respective country. It is important to note that the additional mass represented by the batteries has been neglected in this scenario. Therefore, the results should be considered a best-case scenario, assuming the electrification of the TRU does not change the overall mass of the vehicle.

The impact on the powertrain power request and the reduction of the truck load capacity should be included in the model for a more detailed quantification.

13.1.3.2 Vapor compression cycle TRU in Medium and Heavy Commercial Vehicles, including trailers and semitrailers.

In this case, the unit is typically powered by a dedicated diesel engine. The carbon conversion factor was estimated based on the Stage V classification for non-road mobile machinery (NRMM) and set to 575 g/kWh [Desouza et al., 2020].

13.1.3.3 Eutectics Light Commercial Vehicles

The charging of the TES system is performed before the missions start, and the stationary refrigeration unit is powered by the electrical grid. The grid consumption conversion factor for each considered country was used to account for the indirect emissions associated with the consumed energy.

Since the refrigeration unit operates before the mission begins, a slight modification of the algorithm is considered for this unit, as presented in Figure 47. The thermal loads are evaluated during working hours (in this case, 8:00 – 22:00), while the COP is computed as the average during the night hours (19:00 – 7:00). The annual average energy consumption is then obtained as the average of the daily energy consumption.

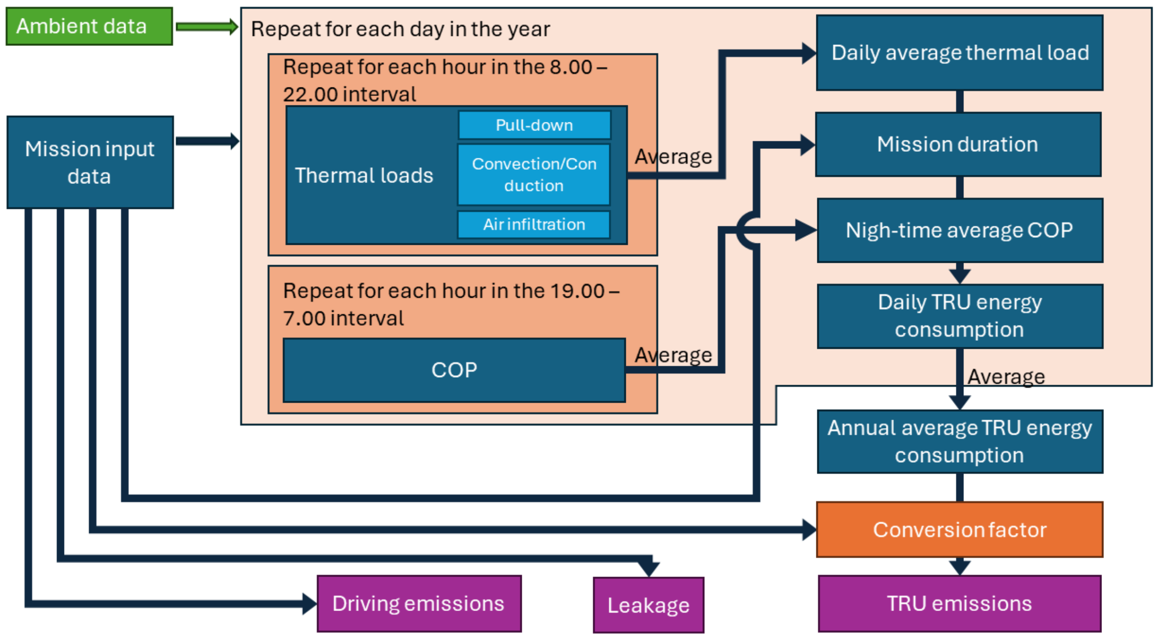

Figure 47. Charging of the TES system.

13.1.4 Vehicle Powertrain emissions

Emissions were estimated using data available in literature or regulations as follow.

13.1.4.1 Ligh Commercial Vehicle

For Light Commercial Vehicles, the emissions factor of 205 gCO_2/km was used, in agreement with the fleet-wide equivalent WLTP target for the 2021-2024 period, defined in the last amendment (28/03/2023) of the EU regulation 2019/631.

13.1.4.2 Heavy Commercial vehicles and road tractors

Heavy Commercial Vehicles and Road Tractors' emissions factors were set according to the ICCT 2021 baseline data [Ragon and Rodríguez, 2021]. These values have been defined as average emissions from all trucks registered by all manufacturers in the period 01/07/2019 - 30/06/2020, divided by groups and subgroups.

For this study, the subgroup 4-RD (Rigid Truck, 4x2 wheels for regional delivery) and 5-LH (Tractor, 4x2 wheels for long haul) were used respectively for regional transport and long-haul scenarios. Emissions factors for these subgroups are 627 and 783.5 gCO_2/km, respectively.

13.1.4.3 Leakage quantification

The leakage rate is typically expressed as a percentage of the system's charge that is lost over a specified time period. For TRUs, leakages can be estimated at 15% of the system's charge per year.

Leakages have been assessed by considering one mission to represent a day's activity. Therefore, for each mission, $15\%/365 = 0.4\%$ of the TRU's charge was considered to be released into the atmosphere. The Global Warming Potential (GWP) of the refrigerant was used to convert this impact into an equivalent mass of carbon dioxide.

13.2 Boundary conditions and simulation scenarios

13.2.1 Ambient data

The ambient data (temperature and relative humidity) for 2020 and 2050 have been used. The 2020 data set has been downloaded from the Energy Plus database (https://energyplus.net/), while the 2050 data set has been estimated based on the 2020 data set, considering an average increment in temperature of 0.7°C.

13.2.2 Missions

Six different scenarios have been taken into account to represent different stages of the food chain. Each scenario is defined by the same set of parameters, which specify all the boundaries requested by the model other than the ambient data (which are uploaded independently). Here are the input parameters, divided by categories:

13.2.3 Vehicle and driving data.

The truck type (semitrailer, heavy truck, light truck) is defined in agreement with the identified scenario, as well as the number and duration of the deliveries, and the mission length.

The average mission velocity has been derived from the WLTP Class 3a cycle average velocities, including stops (here defined as stops due to road crossings, traffic lights, or traffic jams) velocities in different phases (Table 22).

Table 22. Average mission velocity.

Phase	Average velocity including stops [km/h] (Class 3a, v_{max}<120 km/h)
Urban (Low 3)	18.9
Sub Urban (Medium 3-1)	39.3
Rural (High 3-1)	56.4
Highway (Extra-High 3)	92.0

In particular, long-haul missions were represented considering ¾ of the distance to be travelled at highway speed and ¼ at rural (average) speed. Regional transport was assumed to be an average between rural and highway conditions. For the last mile, the urban speed was used.

The mission duration, which is used to define the TRU operating time, is defined by the following equation:

$$t_{TRU} = \frac{L}{v_m} + n_s\, t_s + t_p$$

where:

L is the mission length;

v_m is the average velocity;

n_s, t_s are the number and the duration of the delivery stops;

t_p is the parking time, assumed to be 0 if the mission can be concluded in less than four hours or one hour for longer mission, to consider that drivers have the obligation to stops at least one hour after four hours of driving.

For each mission, an interval was defined to identify the portion of the day considered relevant for the specified scenario. Only the hours within these limits were accounted for when computing the thermal load on the refrigerated box, contributing to the yearly performance.

13.2.4 Isothermal box and TRU

The isothermal box dimensions were defined for each truck type considered. The main parameters are reported in Table 23.

Table 23. Isothermal box dimensions.

Truck Type	L [m]	H [m]	B [m]	Si [m^2]	Vi [m^3]
Light truck (with on-board refrigeration unit)	3.1	2.2	2.1	35.9	14.3
Light truck (eutectic)	3.2	1.5	2.1	29.3	10.1
Heavy Truck	9	2.2	2.5	95.6	49.2
Semitrailer	13	2.2	2.5	133.2	71.5

The operating temperature was assumed according to the scenario being described, considering 0°C for chilled goods and -20°C for frozen goods.

Reference value for k was assumed to be 10%-15% better than the minimum requirement of ATP agreement for the corresponding temperature class, thus k = 0.60 W m^{-2} K^{-1} for chilled applications and k = 0.35 W m^{-2} K^{-1} for frozen applications.

The operating temperature and the refrigerant fluids were then used to upload the proper COP curve for each case, among those presented earlier. The declared capacity of the unit was chosen to be representative of the market and depends on the truck type and the temperature class, as shown in Table 24.

Table 24. Declared capacity of trucks.

	Declared Capacity [kW]	
Truck Type	**Chilled (0°C)**	**Frozen (-20°C)**
Light truck (with on-board refrigeration unit)	3.8	2.2
Light truck (eutectic)	/	/
Heavy truck	8.6	4.7
Semitrailer	10.0	5.7

13.2.5 List of considered scenarios.

Table 25reports all the data characterising each of the six considered scenarios.

Table 25. Six scenarios considered.

Description	Long haul		Regional transport		Last mile delivery	
Number	1	2	3	4	5	6
Temperature	0°C	-20°C	0°C	-20°C	0°C / -20°C	-20°C
Truck Type	Semitrailer	Semitrailer	Heavy truck	Heavy truck	Light truck (multi-temp TRU)	Light truck (eutectic)
Distance [km]	400	400	200	200	150	100
Speed [km/h]	83.1	83.1	74.2	74.2	18.9	18.9
Deliveries [-]	0	0	1	1	20	20
Deliveries duration [min]	/	/	30	30	5	5
Relevant hours	0.00 - 24.00	0.00 - 24.00	0.00- 24.00	0.00 - 24.00	8.00 – 22.00	8.00 – 22.00

13.3 Bibliography for modelling

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14 APPENDIX 1

Scenario	Metric	Long haul MT					
		Kaunas	London	Oslo	Paris	Rome	Warsaw
Baseline	kWh/mission	3.63	4.55	3.40	5.17	7.90	4.13
	$kgCO_2e$/mission	7.36	7.90	7.23	8.25	9.82	7.65
Better door curtains on the TRU (60% infiltration reduction)	kWh/mission	3.63	4.55	3.40	5.17	7.90	4.13
	% change	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	$kgCO_2e$/mission	7.36	7.90	7.23	8.25	9.82	7.65
	% change	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Better TRU insulation	kWh/mission	2.64	3.31	2.47	3.76	5.77	3.00
	% change	27.3%	27.4%	27.4%	27.2%	27.0%	27.3%
	$kgCO_2e$/mission	6.79	7.18	6.70	7.44	8.60	7.00
	% change	7.7%	9.1%	7.4%	9.8%	12.5%	8.5%
Electrification of the TRU	kWh/mission	3.63	4.55	3.40	5.17	7.90	4.13
	% change	0%	0%	0%	0%	0%	0%
	$kgCO_2e$/mission	6.39	6.17	5.30	5.57	6.98	8.37
	% change	13.3%	21.8%	26.6%	32.4%	29.0%	-9.4%
R744 TRU	kWh/mission	3.24	4.12	3.07	4.60	6.80	3.68
	% change	10.8%	9.6%	9.6%	11.0%	14.0%	10.8%
	$kgCO_2e$/mission	1.86	2.37	1.77	2.65	3.91	2.12
	% change	74.7%	70.0%	75.5%	67.9%	60.2%	72.3%
R290 TRU	kWh/mission	3.09	3.87	2.89	4.41	6.81	3.52
	% change	14.7%	15.0%	14.9%	14.6%	13.8%	14.6%
	$kgCO_2e$/mission	1.79	2.23	1.67	2.54	3.92	2.03
	% change	75.7%	71.7%	76.9%	69.2%	60.1%	73.4%
Better door curtains and TRU insulation with a R744 TRU	kWh/mission	2.36	2.99	2.23	3.35	4.97	2.68
	% change	35.1%	34.3%	34.3%	35.2%	37.2%	35.1%
	$kgCO_2e$/mission	1.36	1.72	1.29	1.93	2.86	1.54
	% change	81.6%	78.2%	82.2%	76.6%	70.9%	79.8%
Better door curtains and TRU insulation with a R290 TRU	kWh/mission	2.25	2.81	2.10	3.21	4.97	2.56
	% change	38.0%	38.3%	38.2%	37.9%	37.1%	38.0%
	$kgCO_2e$/mission	1.30	1.62	1.21	1.85	2.87	1.48
	% change	82.3%	79.4%	83.2%	77.5%	70.8%	80.7%
Better door curtains, better TRU insulation, electrification, R744 TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	0.72	0.59	0.02	0.19	1.07	2.01
	% change	90.2%	92.5%	99.7%	97.6%	89.1%	73.7%
Better door curtains, better TRU insulation, electrification, R290 TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	0.70	0.56	0.02	0.19	1.08	1.93
	% change	90.6%	92.9%	99.7%	97.7%	89.0%	74.8%

Scenario	Metric	Long haul LT					
		Kaunas	London	Oslo	Paris	Rome	Warsaw
Baseline	kWh/mission	10.68	12.04	10.60	12.41	14.32	11.29
	$kgCO_2e$/mission	11.42	12.20	11.37	12.41	13.51	11.77
Better door curtains on the TRU (60% infiltration reduction)	kWh/mission	10.68	12.04	10.60	12.41	14.32	11.29
	% change	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	$kgCO_2e$/mission	11.42	12.20	11.37	12.41	13.51	11.77
	% change	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Better TRU insulation	kWh/mission	10.12	11.42	10.04	11.77	13.60	10.70
	% change	5.2%	5.2%	5.3%	5.2%	5.0%	5.2%
	$kgCO_2e$/mission	11.10	11.84	11.05	12.05	13.10	11.43
	% change	2.8%	2.9%	2.8%	3.0%	3.1%	2.9%
Electrification of the TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	8.55	7.65	5.36	5.99	8.36	13.75
	% change	25.2%	37.3%	52.9%	51.8%	38.2%	-16.8%
R744 TRU	kWh/mission	10.03	11.70	9.97	11.99	13.72	10.70
	% change	6.1%	2.9%	5.9%	3.4%	4.2%	5.3%
	$kgCO_2e$/mission	5.77	6.73	5.74	6.90	7.89	6.15
	% change	49.5%	44.9%	49.5%	44.4%	41.6%	47.7%
R290 TRU	kWh/mission	9.86	11.18	9.77	11.57	13.52	10.45
	% change	7.7%	7.2%	7.9%	6.8%	5.6%	7.4%
	$kgCO_2e$/mission	5.68	6.44	5.62	6.66	7.78	6.02
	% change	50.3%	47.3%	50.6%	46.3%	42.4%	48.9%
Better door curtains and TRU insulation with a R744 TRU	kWh/mission	9.52	11.10	9.46	11.38	13.04	10.15
	% change	10.9%	7.8%	10.8%	8.3%	8.9%	10.1%
	$kgCO_2e$/mission	5.47	6.38	5.44	6.55	7.50	5.84
	% change	52.1%	47.7%	52.2%	47.3%	44.5%	50.4%
Better door curtains and TRU insulation with a R290 TRU	kWh/mission	9.35	10.60	9.26	10.98	12.85	9.91
	% change	12.5%	11.9%	12.7%	11.5%	10.3%	12.2%
	$kgCO_2e$/mission	5.38	6.10	5.33	6.32	7.40	5.71
	% change	52.9%	50.0%	53.1%	49.1%	45.3%	51.5%
Better door curtains, better TRU insulation, electrification, R744 TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	2.91	2.19	0.08	0.65	2.81	7.61
	% change	74.5%	82.1%	99.3%	94.7%	79.2%	35.3%
Better door curtains, better TRU insulation, electrification, R290 TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	2.87	2.10	0.08	0.64	2.77	7.44
	% change	74.9%	82.8%	99.3%	94.9%	79.5%	36.8%

Scenario	Metric	Regional transport MT					
		Kaunas	London	Oslo	Paris	Rome	Warsaw
Baseline	kWh/mission	2.07	2.60	1.93	2.94	4.50	2.35
	$kgCO_2e$/mission	5.59	5.89	5.51	6.09	6.98	5.75
Better door curtains on the TRU (60% infiltration reduction)	kWh/mission	2.01	2.53	1.88	2.86	4.38	2.29
	% change	2.7%	2.7%	2.6%	2.6%	2.6%	2.7%
	$kgCO_2e$/mission	5.55	5.85	5.48	6.04	6.91	5.71
	% change	0.6%	0.7%	0.5%	0.7%	1.0%	0.6%
Better TRU insulation	kWh/mission	1.68	2.11	1.57	2.39	3.67	1.91
	% change	18.6%	18.7%	18.7%	18.6%	18.3%	18.6%
	$kgCO_2e$/mission	5.36	5.61	5.30	5.77	6.51	5.50
	% change	4.0%	4.7%	3.8%	5.2%	6.8%	4.4%
Electrification of the TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	5.03	4.91	4.41	4.57	5.36	6.16
	% change	10.0%	16.7%	19.9%	25.0%	23.2%	-7.2%
R744 TRU	kWh/mission	1.85	2.35	1.75	2.62	3.87	2.10
	% change	10.7%	9.5%	9.5%	10.9%	14.0%	10.7%
	$kgCO_2e$/mission	1.06	1.35	1.01	1.51	2.23	1.21
	% change	81.0%	77.0%	81.7%	75.2%	68.1%	79.0%
R290 TRU	kWh/mission	1.76	2.20	1.64	2.51	3.87	2.00
	% change	14.8%	15.1%	14.9%	14.6%	13.9%	14.7%
	$kgCO_2e$/mission	1.02	1.27	0.95	1.45	2.23	1.16
	% change	81.8%	78.4%	82.8%	76.2%	68.0%	79.8%
Better door curtains and TRU insulation with a R744 TRU	kWh/mission	1.45	1.85	1.37	2.06	3.06	1.65
	% change	29.7%	28.8%	28.8%	29.8%	32.0%	29.7%
	$kgCO_2e$/mission	0.84	1.06	0.79	1.19	1.76	0.95
	% change	85.0%	81.9%	85.6%	80.5%	74.8%	83.5%
Better door curtains and TRU insulation with a R290 TRU	kWh/mission	1.39	1.73	1.29	1.98	3.06	1.58
	% change	33.0%	33.2%	33.1%	32.8%	32.0%	32.9%
	$kgCO_2e$/mission	0.80	1.00	0.75	1.14	1.77	0.91
	% change	85.6%	83.0%	86.4%	81.2%	74.7%	84.1%
Better door curtains, better TRU insulation, electrification, R744 TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	0.45	0.37	0.01	0.12	0.66	1.24
	% change	92.0%	93.8%	99.8%	98.0%	90.6%	78.4%
Better door curtains, better TRU insulation, electrification, R290 TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	0.43	0.35	0.02	0.12	0.66	1.19
	% change	92.3%	94.1%	99.7%	98.0%	90.5%	79.3%

Scenario	Metric	Regional transport LT					
		Kaunas	London	Oslo	Paris	Rome	Warsaw
Baseline	kWh/mission	6.17	6.94	6.12	7.15	8.26	6.52
	$kgCO_2e$/mission	7.95	8.39	7.91	8.51	9.15	8.14
Better door curtains on the TRU (60% infiltration reduction)	kWh/mission	6.08	6.84	6.03	7.04	8.13	6.42
	% change	1.4%	1.4%	1.3%	1.4%	1.6%	1.4%
	$kgCO_2e$/mission	7.90	8.33	7.87	8.45	9.07	8.09
	% change	0.6%	0.7%	0.6%	0.7%	0.8%	0.7%
Better TRU insulation	kWh/mission	5.97	6.71	5.91	6.91	7.98	6.30
	% change	3.3%	3.2%	3.3%	3.3%	3.4%	3.3%
	$kgCO_2e$/mission	7.83	8.26	7.80	8.37	8.99	8.02
	% change	1.5%	1.5%	1.5%	1.6%	1.8%	1.5%
Electrification of the TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	6.29	5.76	4.45	4.81	6.17	9.28
	% change	20.9%	31.3%	43.8%	43.5%	32.5%	-14.0%
R744 TRU	kWh/mission	5.77	6.71	5.73	6.88	7.90	6.15
	% change	6.5%	3.3%	6.3%	3.8%	4.4%	5.6%
	$kgCO_2e$/mission	3.32	3.86	3.30	3.96	4.54	3.54
	% change	58.2%	54.0%	58.3%	53.5%	50.3%	56.6%
R290 TRU	kWh/mission	5.68	6.43	5.62	6.65	7.79	6.02
	% change	7.9%	7.3%	8.1%	6.9%	5.6%	7.6%
	$kgCO_2e$/mission	3.27	3.70	3.24	3.83	4.49	3.47
	% change	58.8%	55.9%	59.1%	55.0%	50.9%	57.4%
Better door curtains and TRU insulation with a R744 TRU	kWh/mission	5.50	6.40	5.47	6.56	7.50	5.86
	% change	10.8%	7.7%	10.6%	8.2%	9.1%	10.0%
	$kgCO_2e$/mission	3.17	3.68	3.15	3.77	4.32	3.37
	% change	60.2%	56.1%	60.2%	55.6%	52.8%	58.6%
Better door curtains and TRU insulation with a R290 TRU	kWh/mission	5.41	6.13	5.36	6.34	7.41	5.74
	% change	12.3%	11.6%	12.3%	11.3%	10.3%	11.9%
	$kgCO_2e$/mission	3.12	3.53	3.09	3.65	4.26	3.31
	% change	60.7%	57.9%	61.0%	57.1%	53.4%	59.4%
Better door curtains, better TRU insulation, electrification, R744 TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	1.69	1.26	0.05	0.38	1.62	4.40
	% change	78.8%	84.9%	99.4%	95.6%	82.3%	46.0%
Better door curtains, better TRU insulation, electrification, R290 TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	1.66	1.21	0.05	0.37	1.60	4.31
	% change	79.1%	85.5%	99.4%	95.7%	82.5%	47.1%

Scenario	Metric	Last mile multi-temp					
		Kaunas	London	Oslo	Paris	Rome	Warsaw
Baseline	kWh/mission	6.21	7.44	5.69	8.06	11.64	6.91
	$kgCO_2e$/mission	5.80	6.60	5.46	7.01	9.34	6.26
Better door curtains on the TRU (60% infiltration reduction)	kWh/mission	4.38	5.26	4.03	5.71	8.27	4.88
	% change	29.4%	29.4%	29.2%	29.1%	28.9%	29.4%
	$kgCO_2e$/mission	4.61	5.18	4.38	5.48	7.14	4.94
	% change	20.5%	21.5%	19.8%	21.8%	23.5%	21.1%
Better TRU insulation	kWh/mission	6.12	7.34	5.61	7.95	11.47	6.81
	% change	1.4%	1.5%	1.5%	1.5%	1.4%	1.4%
	$kgCO_2e$/mission	5.74	6.53	5.41	6.93	9.23	6.19
	% change	1.0%	1.1%	1.0%	1.1%	1.1%	1.0%
Electrification of the TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	3.66	3.23	1.80	2.22	4.26	6.94
	% change	36.9%	51.2%	67.0%	68.3%	54.4%	-10.9%
R744 TRU	kWh/mission	5.61	6.88	5.22	7.31	10.23	6.26
	% change	9.7%	7.6%	8.3%	9.3%	12.1%	9.4%
	$kgCO_2e$/mission	3.65	4.48	3.40	4.76	6.66	4.08
	% change	37.0%	32.2%	37.8%	32.1%	28.7%	34.8%
R290 TRU	kWh/mission	5.47	6.55	5.01	7.11	10.32	6.09
	% change	11.9%	12.1%	12.0%	11.8%	11.3%	11.9%
	$kgCO_2e$/mission	3.56	4.26	3.26	4.63	6.72	3.97
	% change	38.6%	35.4%	40.3%	33.9%	28.0%	36.6%
Better door curtains and TRU insulation with a R744 TRU	kWh/mission	3.87	4.75	3.61	5.07	7.12	4.33
	% change	37.6%	36.1%	36.5%	37.1%	38.8%	37.3%
	$kgCO_2e$/mission	2.52	3.10	2.35	3.30	4.63	2.82
	% change	56.5%	53.1%	56.9%	52.9%	50.4%	54.9%
Better door curtains and TRU insulation with a R290 TRU	kWh/mission	3.78	4.53	3.47	4.93	7.18	4.21
	% change	39.1%	39.2%	39.0%	38.8%	38.3%	39.0%
	$kgCO_2e$/mission	2.46	2.95	2.26	3.21	4.68	2.75
	% change	57.5%	55.3%	58.6%	54.1%	49.9%	56.1%
Better door curtains, better TRU insulation, electrification, R744 TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	1.19	0.94	0.03	0.29	1.53	3.25
	% change	79.5%	85.8%	99.5%	95.8%	83.6%	48.1%
Better door curtains, better TRU insulation, electrification, R290 TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	1.16	0.89	0.03	0.29	1.55	3.16
	% change	80.0%	86.5%	99.4%	95.9%	83.4%	49.5%

Scenario	Metric	Last mile frozen TES					
		Kaunas	London	Oslo	Paris	Rome	Warsaw
Baseline	kWh/mission	2.96	3.36	2.90	3.50	4.22	3.15
	$kgCO_2e$/mission	6.18	5.94	5.30	5.48	6.18	7.64
Better door curtains on the TRU (60% infiltration reduction)	kWh/mission	2.71	3.07	2.66	3.20	3.84	2.88
	% change	8.5%	8.6%	8.3%	8.6%	9.1%	8.6%
	$kgCO_2e$/mission	6.11	5.88	5.30	5.46	6.10	7.44
	% change	1.3%	1.0%	0.0%	0.3%	1.3%	2.7%
Better TRU insulation	kWh/mission	2.79	3.16	2.73	3.30	3.98	2.96
	% change	5.9%	5.9%	6.0%	5.9%	5.8%	5.9%
	$kgCO_2e$/mission	6.13	5.90	5.30	5.47	6.13	7.50
	% change	0.9%	0.7%	0.0%	0.2%	0.9%	1.8%
Electrification of the TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	6.18	5.94	5.30	5.48	6.18	7.64
	% change	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R744 TRU	kWh/mission	2.96	3.36	2.90	3.50	4.22	3.15
	% change	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	$kgCO_2e$/mission	6.18	5.94	5.30	5.48	6.18	7.64
	% change	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
R290 TRU	kWh/mission	2.74	3.12	2.68	3.28	4.00	2.92
	% change	7.5%	7.1%	7.6%	6.5%	5.3%	7.3%
	$kgCO_2e$/mission	0.84	0.62	0.02	0.19	0.86	2.19
	% change	86.4%	89.6%	99.5%	96.5%	86.1%	71.3%
Better door curtains and TRU insulation with a R744 TRU	kWh/mission	2.53	2.87	2.49	2.99	3.59	2.69
	% change	14.5%	14.5%	14.2%	14.5%	14.9%	14.5%
	$kgCO_2e$/mission	6.05	5.84	5.30	5.45	6.05	7.30
	% change	2.1%	1.6%	0.1%	0.5%	2.2%	4.5%
Better door curtains and TRU insulation with a R290 TRU	kWh/mission	2.34	2.67	2.30	2.80	3.40	2.50
	% change	20.9%	20.5%	20.7%	20.1%	19.4%	20.7%
	$kgCO_2e$/mission	0.72	0.53	0.02	0.16	0.73	1.88
	% change	88.4%	91.1%	99.6%	97.0%	88.1%	75.5%
Better door curtains, better TRU insulation, electrification, R744 TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	6.05	5.84	5.30	5.45	6.05	7.30
	% change	2.1%	1.6%	0.1%	0.5%	2.2%	4.5%
Better door curtains, better TRU insulation, electrification, R290 TRU	kWh/mission	n/a	n/a	n/a	n/a	n/a	n/a
	% change	n/a	n/a	n/a	n/a	n/a	n/a
	$kgCO_2e$/mission	0.72	0.53	0.02	0.16	0.73	1.88
	% change	88.4%	91.1%	99.6%	97.0%	88.1%	75.5%

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