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Towards sustainability of road refrigerated transport in the food chain

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ABSTRACT

The global road transport refrigeration fleet serving the food chain is estimated in 3.4 million vehicles; the sector is constantly growing and new habits, like online shopping and consequent short distance delivery, are spreading. The emissions of the sector were estimated in about 50 Mt CO2eq in 2021, being the largest part due to diesel motors. It is commonly agreed that around 20% of the vehicle emissions are to be ascribed to the refrigeration unit consumption. However, the entire traction sector is facing new challenges to meet environmental targets. At the same time, working fluids for vapour compression cycles are undergoing a tough revision process, which mainly targets GHG emissions reduction but at the same time concerns related to other environmental impacts on human health and ecosystems are gaining attention. In this paper, technological solutions to reduce the overall environmental impact of road refrigeration transport are considered and exemplified.

Keywords: Transport Refrigeration, Emissions, Natural Working Fluids, GHG, Sustainability

1. INTRODUCTION

According to IIR, 2021, 70% of the food for human consumption requires refrigeration at a certain point of its life; a wider cold chain is a recognised method to contribute to the challenge of providing sufficient and safe nutrition to the growing population. On the other hand, the present cold chain equipment is responsible for a large share of the global emissions, which is estimated in 4% (including emissions from food loss and waste related to lack of refrigeration) by FAO, 2022. IIR, 2021 calculates that an “improved” cold chain, i.e. extended and better performing, would allow a 50% reduction in its emissions. Transport refrigeration is a key link in the cold chain, which occurs several times along the product life and is crucial for its integrity. According to IIR, the global refrigerated fleet in 2021 consisted in 3.4 M vehicles and, based on their assumptions, the related global emissions were about 50 Mt CO2eq, representing nearly 25% of the total cold chain emissions.

To meet the general cold chain sustainability goals (UNEP, 2022) and specifically the call for neutral or positive environmental impact of the food chain, as required by the European Farm to Fork Strategy, it is relevant to analyse each component of the refrigeration equipment (box and unit), contributing to the emissions and to evaluate improvement strategies.

The reduction of the thermal load is strictly related to the insulation of the box, which is described by the overall heat transfer coefficient, taking into consideration distributed and localised heat transfer: in this manuscript, the ATP (UNECE, 2022) definition as well as the reference values for Normal and Heavy Insulated boxes are considered. Boundary conditions (outdoor temperature and humidity, solar radiation, indoor setpoint) and overall mass impact on pulldown energy, which must be performed at empty box; boundary conditions, mission profile (long distance drive, delivery mission, etc) and goods thermal capacity (and respiration load, if the case) define the operation loads. Good practice, as presented in section 3, contributes to the overall energy demand.

In the case of mechanically refrigerated equipment, for a given thermal load, the refrigerating unit efficiency defines the actual energy demand; it is therefore relevant to act on the unit efficiency to reduce the consumption. Despite COP data are normally not widely and openly available from manufacturers, the literature shows that COP values are poorer than in stationary refrigeration (Artuso et al, 2019a; Wu et al, 2013).

Fabris et al., 2022, show that decoupling the refrigerating unit from the driveline and the control of the cooling unit's compressor rotational speed can lead to a 26 % increase of the mission COP and a 39.3 % increase of the mission unit's Duty Cycle. Artuso et al, 2019a, assess 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. In addition, refrigerated vehicles present a real chance of implementing solar panels on top of the roof, to support the refrigerating unit thus reducing the net demand from the vehicle or the electrical grid. This solution is more and more promoted in the market. Rossetti et al, 2022, demonstrate that the solar panels can provide from 65% to 112% of the annual energy consumed by the cooling unit, depending on the time the truck is under direct sunlight, if Athens climate is assumed.

It is worth reminding that the reduction of energy demand from the vehicle or the grid is a straightforward way to reduce the CO2 emissions, while dedicated evaluations based on motor map is required to estimate the other gases (CO, THC, NOx) and PM emissions, which have also an additional impact on localised pollution. Fabris et al, 2022, show that, for their analysed case, implementation of a battery to store the energy produced by the engine and to allow a Start&Stop management determines 11.1 % reduction of the fuel consumption and 24.0 %, 1.1%, 25%, 16.6% reduction of the CO, NOx, THC and PM emissions respectively in comparison with a direct belt connection between the engine shaft and the cooling unit.

Finally, emission reduction can be addressed by acting on refrigerant use. Synthetic refrigerants either have a high GWP or pose concerns in terms of P-FAS production. International agreements and local regulations are establishing stricter limits to their use. Natural refrigerants then represent the long term environmental sustainable solution as well as a reliable investment, considering that refrigerated vehicles have typically a 10-15 year long life (Tassou et al., 2009; Wu et al., 2013, Li, 2017). In the last years, a relevant number of scientific and technical publications have demonstrated that natural refrigerants, in particular HCs and CO2, can overcome the performance of synthetics also in transport refrigeration. Colbourne et al. (2017), demonstrate 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 and that the R290 system resulted in -16% diesel consumption and -66% emissions. Fabris et al, 2023, use a dynamic model to compare the energy performance of a R134a vs CO2 unit in the South European Climate and show that the seasonal COP of the CO2 unit is 27% better than the R134a one.

In this paper, a methodology to calculate the emissions of the actual European road transport refrigeration fleet is proposed and used to evaluate the reference emissions and compare them to an "improved" fleet, where the above anticipated strategies are implemented. The adopted improvements are representative of high TRL technologies which are rather available or close to become ready for the market and consequently have real chances of fast implementation.

2. EVALUATION OF THE EMISSIONS OF THE EUROPEAN FLEET

2.1. Methodology

2.1.1. The fleet

The annual quantity of transported goods for each European country is evaluated according to the road freight transport data by country published by Eurostat (Eurostat, 2023), considering the category "Food products, beverages and tobacco". Data regarding the ATP registered number of vehicles available from national reports related to Italy (OITAF, 2022) and France (Cavalier, 2021) were used to define a correspondence between ATP vehicles number and the mass-distance (t-km) reported by Eurostat. On the basis of this correlation, the number of refrigerated vehicles and the sub-division between Light Commercial Vehicles (LCVs) and Medium and Heavy Commercial Vehicles (MHCVs) has been estimated as a function of mass-distance data of each country.

Based on the data available in reports regarding the food market sales in Europe (Statista Research Department, 2023; Expert Market Research, 2023), the share of refrigerated vehicles transporting chilled products at MT conditions (0°C) is assumed to be equal to 65%, while the remaining 35% of refrigerated vehicles is assumed to transport frozen food at LT conditions (-20°C).

The average dimensions of the insulated box are assumed to be equal to 2.2 m x 2.1 m x 3.2 m (external surface area equal to 36.8 m^2) for LCVs and to 2.2 m x 2.5 m x 9 m (external surface area equal to 95.6 m^2) for MHCVs.

2.1.2. The climatic conditions and delivery mission definition

Three main climatic zones (Mediterranean, temperate and cold) are identified according to the European Environment Agency (EEA, 2012). Each Country is assigned to one or two of the three climatic zones (Li and Zidorn, 2022). The annual hourly climatic conditions (temperature, relative humidity, solar radiation) of each of the three climatic zones are obtained from the EnergyPlus online database (EnergyPlus, 2023), considering Athens, Strasbourg and Helsinki as representatives.

For the evaluation of the annual energy consumption of refrigeration units, repetitions of the same delivery mission, 8 hours/day (from 09:00 to 17:00), 5 days/week for 50 weeks (Li, 2017) all year long and different climatic conditions of each working day are assumed.

2.1.3. The thermal loads

Pulldown, convection/conduction heat flux through the box walls and ambient air infiltrations are considered as thermal loads.

The pulldown of the insulated body is characterized by a thermal capacity evaluated as a function of the external surface and of the experimental data reported by Artuso et al., 2019b. The pulldown corresponds to the energy required to cool down the box from the daily averaged ambient temperature to the average box temperature, which is the mean between the ambient temperature and the internal set-point temperature (0°C for MT, -20°C for LT).

The convection/conduction heat through the box walls is computed using the global heat transfer coefficient of the box and the difference between the ambient temperature and the set point temperature. The infiltration heat load is linked to external air entering the box during mission door openings. The mass of external air (characterized by temperature and relative humidity) infiltrating inside the insulated box for a single door opening is modelled according to Lafaye de Micheaux et al. (2015). Since LCVs are commonly used for multi-drop short-distance delivery missions in urban environment while MHCVs are commonly used for long-distance deliveries characterized by a lower number of products drops, 16 and 4 door openings are considered for LCVs and MHCVs, respectively, for each mission day. The door opening time is assumed to be equal to 1 minute for chilled products transport and 30 seconds for frozen products transport.

2.1.4. The refrigeration units

In this study, the effects of the implementation of sustainable and efficient solutions in the refrigerated transport sector are evaluated, to quantify the possible GHG and pollutant emissions savings linked to the employment of natural refrigerants and alternative energy sources in transport refrigeration on a European scenario.

As representative of the baseline road transport refrigeration sector, a simple vapor compression refrigeration unit is considered, employing R134a as refrigerant for Medium-Temperature (MT, 0°C) applications and R452A as refrigerant for Low-Temperature (LT, -25°C) applications. Its schematic is presented in Figure 1. In both cases a thermostatic expansion valve (EV) enforces a fixed superheat equal to 10 K at the outlet of the evaporator.

As an efficient alternative to the synthetic refrigerant cooling units, natural fluid based units are considered, to skip transition solution and offer a long-term option. Specifically, a simple transcritical R744 unit for both the MT and the LT units is considered in this study. The R744 unit operational schematic is presented in Figure 2 entailing a simple back-pressure operation.

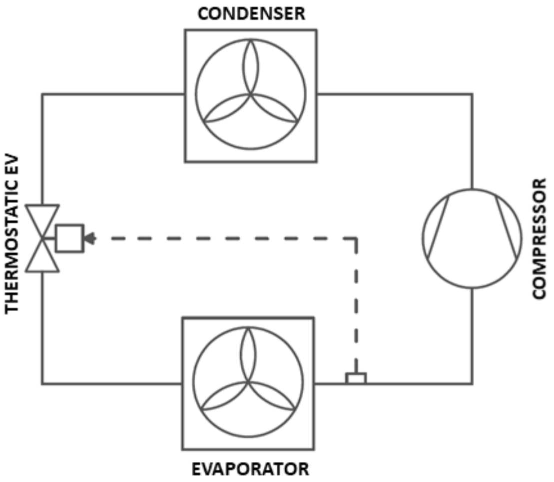


Figure 1 – Synthetic refrigerant (R134a for MT, R452A for LT) unit operational schematic.

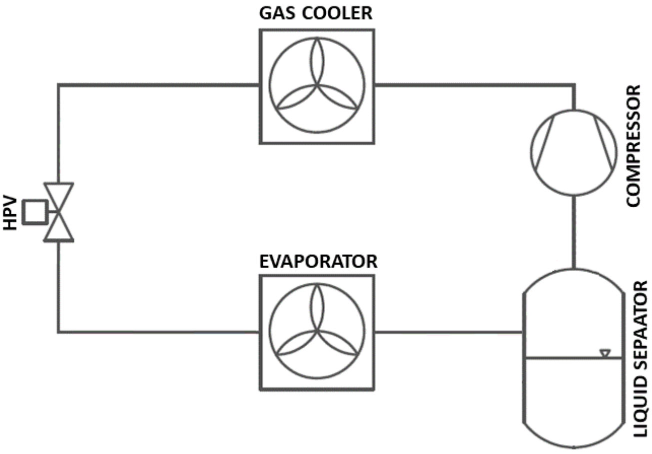


Figure 2 – Natural refrigerant (R744 for both MT unit and LT) unit operational schematic.

The rated cooling power of the cooling units (referred to operation with ambient temperature equal to 30°C), based on units available in the market (Daikin, 2022), is reported in Table 1.

Table 1 – Rated cooling power [W] of the cooling units as a function of temperature level and vehicle category, for ambient temperature equal to 30°C.

	LCV	**MHCV**
MT (0°C)	3800	8600
LT (-20°C)	2020	4700

A dynamic numerical model of the cooling units is developed using the commercial multi-physics software Simcenter Amesim 2021.2. The numerical approach of the software is based on the discretization of real components in lumped parameters elements, connected to describe the entire system. Each element is described by nonlinear time-dependent differential equations involving the state variables. Equations are then assembled in a system of differential equations, according to the elements connection. A detailed description of the dynamic numerical modelling approach can be found in Fabris et al. (2021). The numerical model is used to evaluate the steady-state COP of the synthetic refrigerant units (MT unit with R134a, LT unit with R452A) and of the natural refrigerant units (both MT and LT with R744) for different ambient temperature conditions and, in addition, to determine the degradation of the steady-state COP during ON/OFF operation according to different duty cycle values, as a function of the external ambient temperature. Both the COP mapping and the degradation factor accounting for duty cycle value will be used to model the system overall performances.

2.1.5. Energy consumption of the refrigeration unit

For each working hour, the duty cycle of the cooling units is evaluated as the ratio between the actual cooling demand of the insulated box (corresponding to the total thermal load as results of pulldown load, convection heat and infiltration heat due to door openings) and the cooling capacity of the cooling unit (evaluated as the cooling effect which could be provided by the cooling unit in steady-state operation, for the specific ambient temperature). The steady state COP is firstly computed as a function of the ambient temperature. This value is then reduced by the degradation factor due to intermittent operation as function of the duty cycle and of the ambient temperature.

The energy required to run the cooling unit is computed based on the cooling demand and the COP for each working hour. Considering the sum of each working hour, the total annual energy consumed by a single cooling unit and, consequently, the annual energy consumed by the entire fleet of refrigerated vehicles in Europe, according to the three different climatic zones, temperature levels (MT, LT) and type of vehicle (LCV, MHCV) are computed.

2.1.6. GHG and other emissions

Different possibilities to supply the cooling unit compressor are considered: a direct connection to the vehicle prime engine (assumed to be a EURO VI diesel engine) through a belt; a separate dedicated Non-Road Mobile Machinery (NRMM) diesel engine, grid electricity, stored in a battery pack. The equivalent CO_2 and main pollutant emissions linked to each of the above-mentioned scenarios are reported in Table 2.

Table 2 – Equivalent CO_2 and main pollutant emissions [g/kWh] for energy generation. *: emissions for the electrical grid are expressed in terms of Volatile Organic Compound instead of Total Hydrocarbons.

	CO_2	**CO**	**NO_x + THC**	**PM**
Vehicle engine (EURO VI)	651 (Grigoratos et al, 2019)	0.88 (Grigoratos et al, 2019)	0.45 (Grigoratos et al, 2019)	0.01 (Grigoratos et al, 2019)
Dedicated engine (NRMM)	575 (Desouza et al., 2020)	6.60 (ICCT, 2016)	7.50 (ICCT, 2016)	0.40 (ICCT, 2016)
Electrical grid	238 (EEA, 2022)	0.09 (ISPRA, 2020)	0.30 * (ISPRA, 2020)	0.00 (ISPRA, 2020)

In addition to the equivalent CO_2 emissions related to the cooling unit energy consumption, the direct equivalent CO_2 emissions linked to the leakage of refrigerant during the units life cycle is also considered. An annual leakage rate during operation equal to 10-37% (Tassou et al., 2009), 10-25% (Li, 2017), 5-25% (Wu et al., 2022) of the total charge is reported in literature. An average annual leakage rate equal to 15% is assumed in this study. The Global Warming Potential (GWP) of R134a, R452A and R744 refrigerants are 1530, 2140 and 1 $kg_{CO2,eq}/kg_{refrig}$, respectively (IPCC, 2021). The cooling units are assumed to be charged with 2 kg of refrigerant for the LCVs synthetic refrigerant units (Tassou et al., 2009) and 5 kg for the MHCVs synthetic refrigerant units (Tassou et al., 2009). Previous studies in literature report that, for equivalent cooling capacity systems, R744 units charge would be 1.3-2.3 times the charge of the synthetic refrigerant ones (Karampour and Sawalha, 2018; Aprea et al., 2012; Rossi et al., 2021). A R744-HFC charge ratio equal to 2.3 $kg_{R744}/kg_{syntethic}$ is then conservatively assumed.

2.1.7. Baseline and future scenarios

Different scenarios, accounting for the current baseline and for the possible improvements characterizing the future European road transport refrigeration fleet are considered. The baseline scenario, representative of current technology, assumes synthetic refrigerant cooling units (R134a for MT, R452A for LT) and global heat transfer coefficients of the insulated box respecting the limits set by the ATP agreement by 10% and 5%

for MT and LT respectively (0.63 W m^{-2} K^{-1} for MT, 0.38 W m^{-2} K^{-1} for LT). For LCVs, a belt-driven cooling unit is considered, while for MHCVs a dedicated engine (NRMM) is in place. Transmission losses are neglected.

Different scenarios are then considered assuming the cumulative implementation of more sustainable solutions. Firstly, the the insulation of the box is improved by assuming that the MT boxes achieve the insulation level of LT boxes (global heat transfer coefficient of 0.38 W m^{-2} K^{-1} for both MT and LT). Secondly, properly sized natural refrigerant cooling units (R744 for both MT and LT) are implemented. This step includes also the electrification of the cooling units, assuming LCVs ones are powered on battery packs and MHCVs ones can be powered by the traction engine by electrical transmission. Finally, the widespread use of variable speed compressors to limit cycling losses is considered.

The integration of photovoltaic (PV) panels is then evaluated as further improvement to reduce the unit energy draw from an external source. PV panels efficiency is 20% and PV panels surface is equal to 90% of the insulated box roof area. The hourly global horizontal radiation data are used for the three climatic zones to evaluate the annual energy produced from the solar source. Solar energy production is limited to the working hours.

2.2. NUMERICAL RESULTS

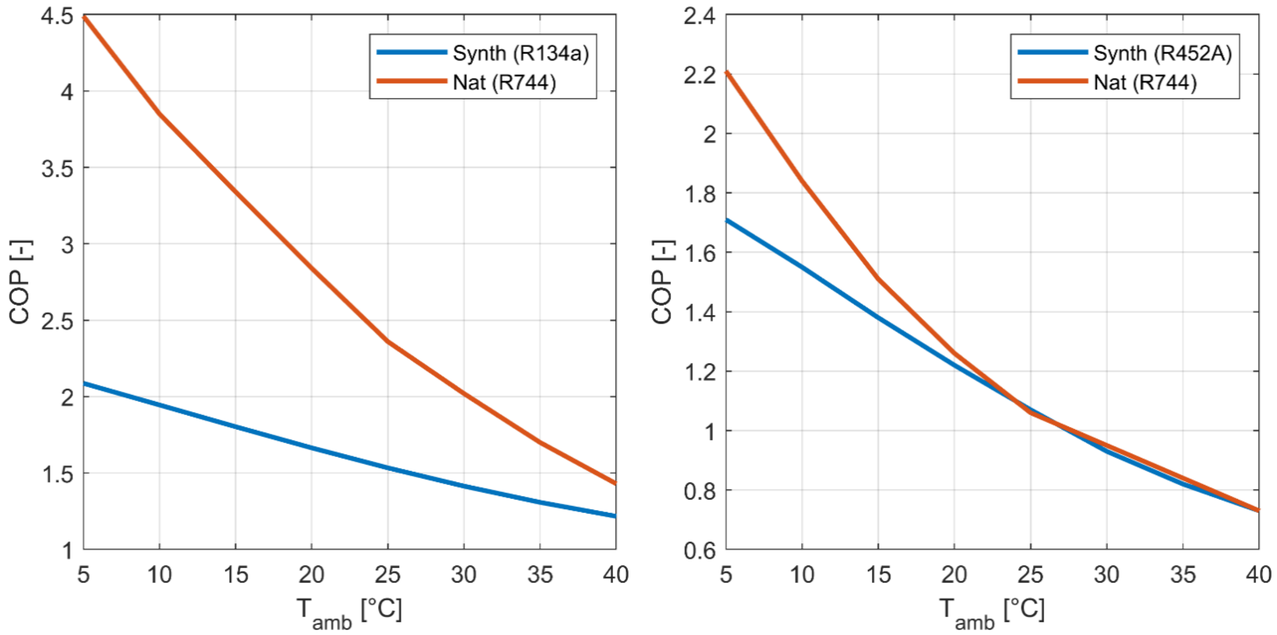
Firstly, the European road transport refrigeration fleet composition has been estimated. Based on pre-pandemic data referred to the European road freight transport in 2019, a total number of 1,677,490 total refrigerated vehicles are estimated to be circulating in Europe for temperature-controlled transport of perishable goods.

Considering the refrigerated vehicles number by country and the climatic conditions of each country, the number of temperature-controlled vehicles by climatic zone and vehicle category (LCVs or MHCVs) is computed. For the country assigned to more than one climatic zone (Li and Zidorn, 2022) the respective fleet is divided evenly between the relevant climatic zones. Results are reported in Table 3.

Table 3 – Number of refrigerated vehicles [-] circulating in Europe by climatic zone and vehicle category.

	LCVs	**MHCVs**
Mediterranean	161,248	243,300
Temperate	659,396	569,005
Cold	21,580	22,961
TOTAL	842,224	835,266

The steady-state performance of the refrigeration units considered in this study has been assessed through numerical simulations. The steady-state COP of the transport refrigeration units employing synthetic and natural refrigerants are presented in Figure 3. Figures 3a and 3b report the steady-state COP of the MT and LT cooling units, respectively, designed to provide cooling effect at an internal air temperature of 0°C (MT) and -20°C (LT), as a function of the ambient temperature.



(a) (b)

Figure 3 -Cooling units steady-state COP as a function of ambient temperature: (a) MT units (internal temperature equal to 0°C); (b) LT units (internal temperature equal to -20°C).

According to the evaluation of the hourly performance following the approach described in the previous section, the annual energy consumed by the entire fleet of refrigerated vehicles in Europe is computed for the baseline scenario, representative of the sector in its status, and in three other scenarios, representative of the progressive implementation of more sustainable and efficient solutions in the future. The complete description of each of the four considered scenarios is provided in Table 4, where the improvement compared to the previous scenario is highlighted in red.

Table 4 – Different scenarios considered to evaluate the primary energy consumption and the emissions of current and future European road refrigerated transport sector.

	Scenario 1: **Synthetic refrigerant (baseline)**	**Scenario 2:** **Improved insulation**	**Scenario 3:** **Improved insulation + Improved units**	**Scenario 4:** **Improved insulation + Improved units + Compressor control**
Insulated box global heat transfer coefficient	MT: 0.63 W m^{-2} K^{-1} LT: 0.38 W m^{-2} K^{-1}	**MT: 0.38 W m^{-2} K^{-1}** LT: 0.38 W m^{-2} K^{-1}	MT: 0.38 W m^{-2} K^{-1} LT: 0.38 W m^{-2} K^{-1}	MT: 0.38 W m^{-2} K^{-1} LT: 0.38 W m^{-2} K^{-1}
Primary energy source	LCVs: vehicle diesel engine (EURO VI) MHCVs: dedicated engine (NRMM)	LCVs: vehicle diesel engine (EURO VI) MHCVs: dedicated engine (NRMM)	**LCVs: electricity from grid** **MHCVs: vehicle diesel engine (EURO VI)**	LCVs: electricity from grid MHCVs: vehicle diesel engine (EURO VI)
Refrigeration unit	MT: R134a unit LT: R452A unit	MT: R134a unit LT: R452A unit	**MT: R744 unit** **LT: R744 unit**	MT: R744 unit LT: R744 unit
Compressor control	Thermostat (ON/OFF operation)	Thermostat (ON/OFF operation)	Thermostat (ON/OFF operation)	**Inverter with 50% - 100% regulation capacity**

The resulting annual primary energy consumption of the European road refrigerated transport fleet, classified by temperature level (MT or LT) and vehicle class (LCVs or MHCVs), is reported in Table 5 and in Figure 4. The implementation of insulated boxes with a better global heat transfer coefficient for the whole fleet, of better performing refrigeration units and of a control on the compressor speed results in a reduction of annual primary energy consumption equal to 8.5%, 15.3% and 5.0%, respectively, leading to an overall 28.8% reduction in the best-case scenario compared to the baseline reference scenario.

Table 5 – Annual energy draw [TWh] to be provided from an external source for the operation of the cooling units of European refrigerated transport sector in different scenarios.

	Synthetic refrigerant (baseline)	Improved insulation	Improved insulation + Natural refrigerant	Improved insulation + Natural refrigerant + Compressor control
LCV MT	825	741	450	433
MHCV MT	1023	794	637	484
LCV LT	683	683	635	620
MHCV LT	1142	1142	1077	1077
TOTAL	3673	3360 (-8.5%)	2799 (-23.8%)	2614 (-28.8%)

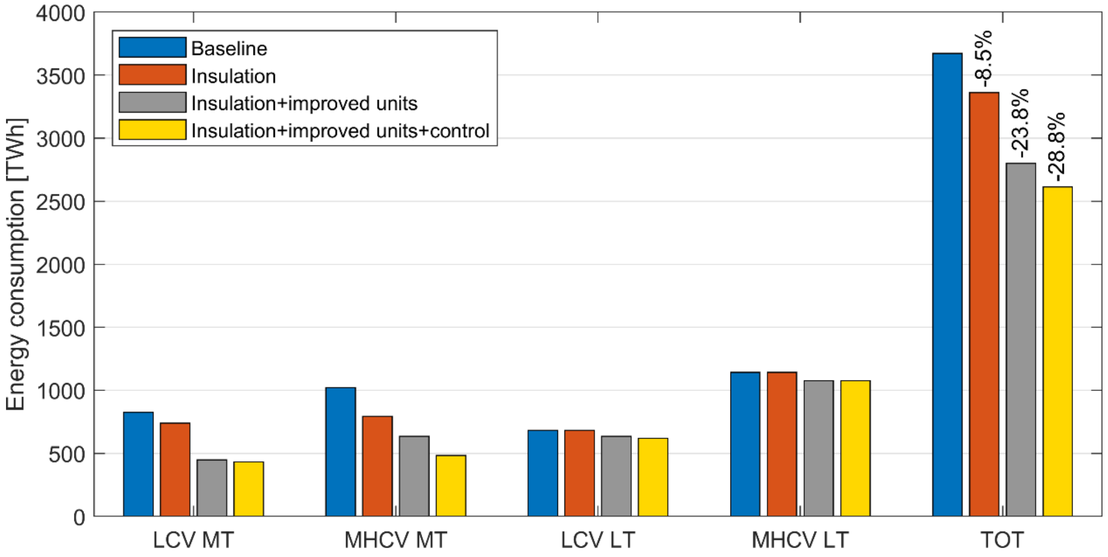
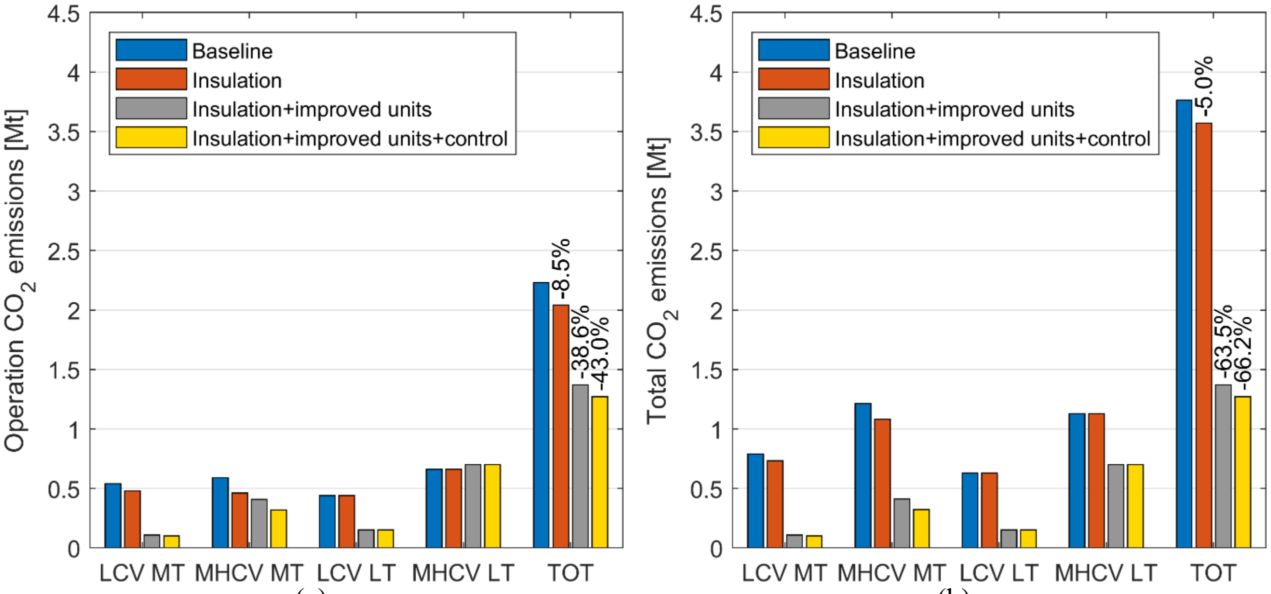


Figure 4 - Annual primary energy consumption for the operation of European road refrigerated transport sector in different scenarios.

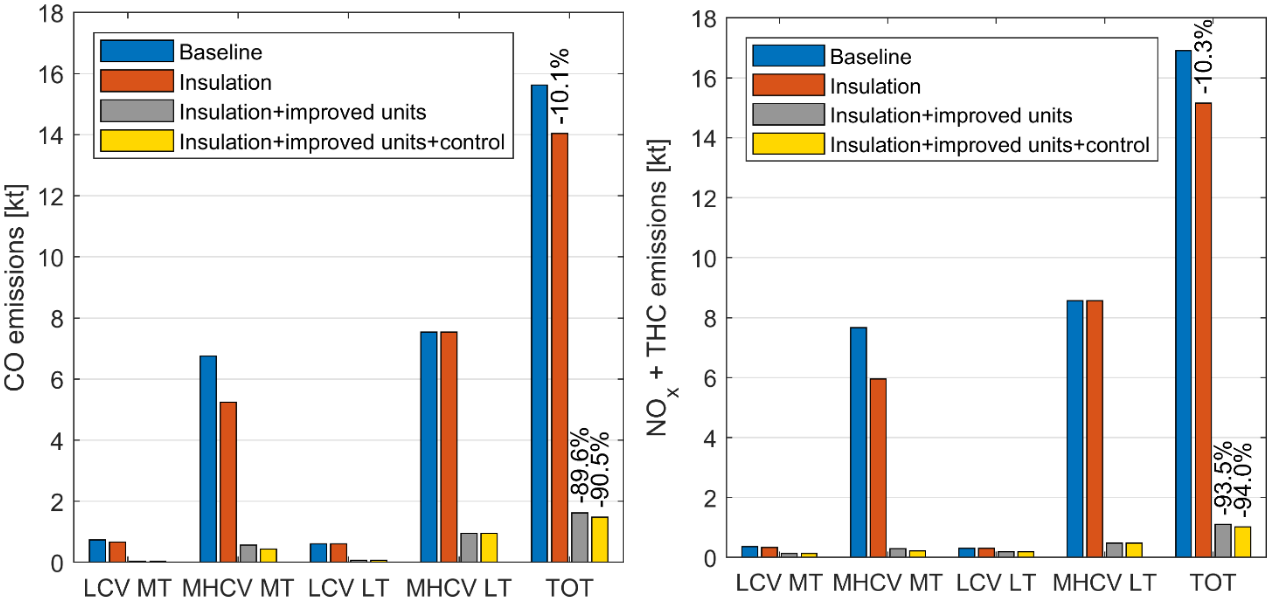
To evaluate the related GHG emissions, the annual CO_2 emissions linked to the operation of the cooling unit (calculated according to the specific source of primary energy for each considered scenario) and the total annual CO_2 emissions linked to both the operation and the refrigerant leakage are reported in Figure 5. According to the CO_2 emission factors in Table 2, the switch from a dedicated diesel engine to the vehicle primary engine as the energy source for the cooling units in MHCVs might seem counterproductive; however, this switch is justified by the massive reduction in the emission factor of other pollutants, having a significant impact on local pollution and on health of humans and environment, as it will be discussed further below. Nevertheless, 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 LCVs units (see Table 2) lead to an overall 43.0% reduction of annual CO_2 emissions linked to operation in the best-case scenario, compared to the baseline. The positive impact of natural refrigerant units is even more significant including the direct emissions due to refrigerant leakage, leading to an overall 66.2% reduction of total annual CO_2 emissions.



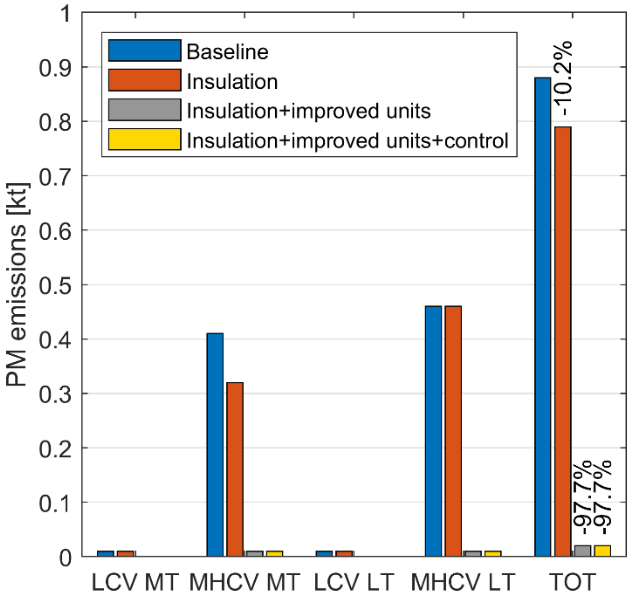
(a) (b)

Figure 5 - Annual CO₂ emissions of the European road refrigerated transport sector in different scenarios: (a) CO₂ emissions only related to cooling units operation; (b) CO₂ emissions related to both cooling units operation and refrigerant leakages.

As above mentioned, emissions of non-direct GHG pollutants related to primary energy consumption must be taken into consideration as well, as they have a significant impact on human and environmental health. Therefore, the annual emissions of the main pollutants (carbon monoxide, CO, nitrogen oxides and total hydrocarbon, NO_x + THC, particulate matter, PM) are reported in Figure 6. As already discussed, NRMM are characterized by very high pollutant emissions, and consequently the greatest part of pollutant emissions reduction is linked to the switch to a more efficient primary energy source for MHCVs. Nevertheless, the complete electrification of LCVs units, employed mostly in short-distance deliveries, can be considered as a significant contribution to reduce localized 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%.



(a) (b)



(c)

Figure 6 – Annual pollutant emissions for the operation of European road refrigerated transport sector in different scenarios: (a) CO; (b) NO_x + THC; (c) PM.

In addition to the possible improvements described in Table 4, the contribution of the integration of PV panels to exploit the solar source to produce energy, store it in battery packs and then supply it to the cooling unit, consequently reducing the unit energy draw from an external source, is also evaluated.

The actual contribution of the PV panels, considering the different temperature levels and the vehicle classes composition of the European fleet, is presented in Figure 7, in which the annual CO_2 emissions of the best-case scenario described in Table 4 (improved box insulation, improved cooling units, compressor control) are compared to the annual CO_2 emissions in case the PV panels production is used to reduce the primary energy request of the cooling unit.

As the solar production is influenced by shading, by the truck actual working hours and by the fact that the actual usage of this energy can be limited by the shift between energy demand and consumption and the size of the storage device used (Rossetti et al., 2022), the impact on GHG emission is reported also considering fraction (25%, 50%) of the energy produced under the refence conditions stated in Section 2.1.7.

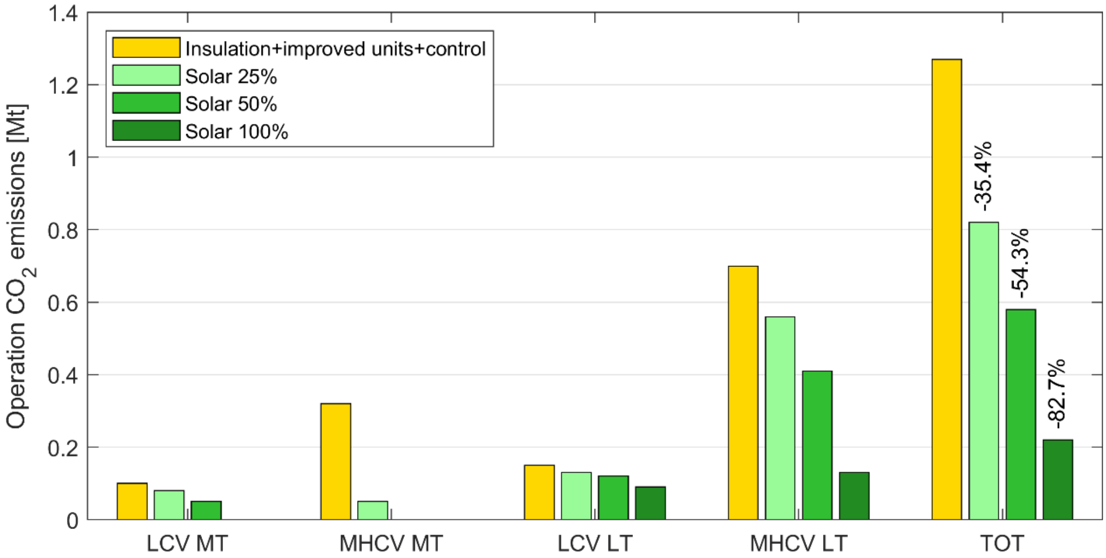


Figure 7 - Annual CO_2 emissions for the operation of European road refrigerated transport sector with different contributions of solar energy production

As expected, the PV panels contribution is substantial in case of MT applications where the ratio between available roof surface and energy demand is higher than in the case of LT applications. This is particularly true for MHCVs where the 50% of the available energy is enough to cover the annual energy demand. High improvements can be seen also in the MT LCVs and LT MHCVs. Overall, the annual CO_2 emissions of the European road refrigerated transport fleet can be reduced by 35.4%, 54.3% and 82.7% in case of 25%, 50% and 100% exploitation of the maximum possible production of solar energy, respectively, in respect of the best technological scenario discussed previously.

As the solar energy availability and the thermal loads are implicitly related to the climatic condition (hotter climates have on average more solar radiation than colder areas), it is interesting to segment the impact of the PV panels on the European refrigerated fleet also in terms of the three reference climatic zones, as reported in Figure 8.

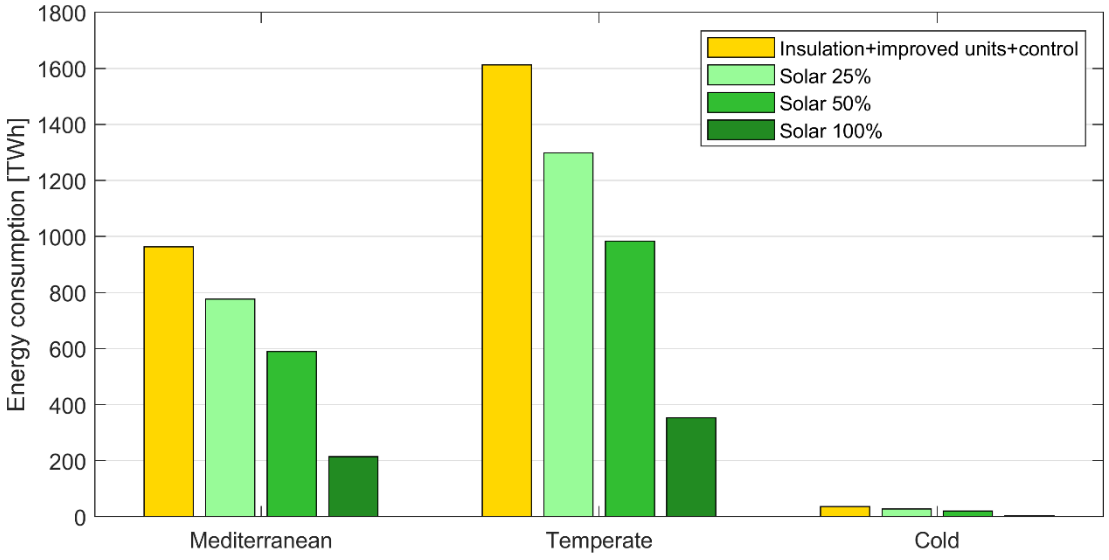


Figure 8 – Comparison between the annual primary energy consumption and the energy produced by PV panels in different scenarios and by climatic zone.

The model results demonstrate that thanks to the natural relation between thermal loads and the solar radiation, solar energy can be a valuable aid under all the considered climatic condition in relative terms: GHG emissions can be reduced up to 78% in hot and mild climates and 90% in cold climates. Therefore, in terms of energy balance, the adoption of solar panel on the truck roofs appears to be a viable solution under most of the climatic conditions. Nevertheless, economic and LCA analysis should be carried out to demonstrate the sustainability of this solution and to define the precise border of application of this technology in terms of truck size, operational scenarios (daily, nocturnal or mixed), set-point temperature and possible integration with the vehicle in case of hybrid or electrified vehicles.

3. GOOD PRACTICE

Best practice in system maintenance, operation and in logistic can help in reducing energy consumption and related emissions.

Devin and Cavalier, 2020 summarized a list of best practices in maintenance and operations to reduce the overall load and the energy consumption of refrigerated trucks, some of them impacting during operations (adjustment of setpoints according to the type of goods, respect of loading limits, proper maintenance of the box and the refrigerating unit, etc), some others directly dealing with loading (pre-cooling of the bodies before loading), unloading and deliveries (use of air curtains or plastic strips, switch off of the refrigerating unit when doors are open, etc).

The benefit quantification is however challenging, as it often implies overlapping effects, and it needs to consider the overall quality of the perishable goods.

Tso et al, 2002 experimentally investigated the effects of strip curtains and air curtains applied to the later door on the energy consumption of a 2.84 m insulated box in a refrigerated truck under high temperature and humidity ambient conditions (29°C-47°C). Within their analysis, they also considered the possibility of switching on and off the refrigerating unit when door was open, as well as the impact of the internal load (empty or half load). They concluded that the infiltration load can be reduced by 40% at 29°C when using air curtain, however they did not account for the energy to maintain it. They also remarked that air curtains generally work better that plastic strips, quantified in 11% less infiltration load.

Rai et al., 2019 and Tso et al, 2019 numerically evaluated the effects of air curtain key parameters (jet velocity, nozzle width and jet angle) on the overall performance of the air curtains, mainly evaluating the internal temperature distribution. They concluded that if the parameters are correctly tailored, the inner temperature increase can be maintained within 3°C.

Best practice in maintenance and operations has a lot to do with maintenance staff and drivers' engagement and encompass non-technological aspects, as behaviour and organisational barriers; therefore, proper measures need to be taken to assure full implementation of energy saving procedures.

Logistic is also regarded as a key to reduce refrigerated transport emissions. Logistic of the cold chain represents a multiobjective optimisation problem, where time, cost of fuel and transport operations, cargo quality and customer satisfaction may be considered as the key parameters. While optimisation numerical model are presented in the literature (Li and Li, 2023; Wang et al., 2020), IoT and AI are assuming increasing importance to implement energy saving logistic models and to increase the transparency of the chain.

4. CONCLUSIONS AND FURTHER STEPS TOWARDS SUSTAINABILITY

This manuscript has considered some possibilities to decrease the environmental impact of the transport refrigeration sectors and presented a methodology to emission figures for the European fleet.

The implementation of more efficient solutions (such as better box insulation, natural refrigerant units, more sustainable energy sources and improved unit control) can lead to a reduction of the annual energy draw of the European fleet up to 28.8%, of total CO2 emissions up to 66.2% and of other pollutants up to more than 90%. Solar power can significantly contribute to the annual energy balance of the European fleet.

As for mechanically refrigerated units, the way to natural refrigerants has not been yet fully identified. Interesting solutions, like HC systems and secondary loops are coming to the market. For example, recently a new electrically driven transport refrigeration unit using R1270 in the vapour compression cycle and CO2 as secondary fluid (Cooling Post, 2022) has been presented to the market by a German manufacturer. Following stationary refrigeration experience, it is likely that different solutions according to temperature application and unit size might find their market niche. Refrigerated devices, like cryogenic and eutectic solutions, have also a potential especially in electric vehicles; they allow for avoiding any localised pollution and are therefore suited for last mile delivery.

Transport refrigeration equipment must comply with tough space and weight constraints, assure reliability and easy maintenance all over the world, withstand accelerations and vibrations and operate properly under extremely variable outdoor conditions and cargo types.

More detailed analysis, like LCA methodology, can highlight weak points and suggest proper actions: Fabris et al, 2023, suggested that refrigerating weight reduction by dedicated lightweight components application is a key factor to further decrease the total lifetime CO2 equivalent emissions of the analysed R744 unit, which was already 26% less emitting than the baseline R134a unit.

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