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OVERVIEW ON TASK 6.5

1 GENERAL SUMMARY

This final report on demonstrators related to transport includes a description of the technological solutions, implementation methodology, results, and deviations.

Transport is one of the most critical links of the supply chain, occurring at many stages. The relevance of short distance transport and home delivery has been increasing over the last years due to growing urbanization, the outbreak of COVID pandemic, and a general increase of online grocery shopping, leading to a spreading of home delivery services also in areas where traditional shopping was still the predominating way. This sector is affected by specific problems, such as pollution in city centres and noise emission, but at the same time efficiency and long-term sustainability of refrigeration systems employed on vehicles to preserve the products cold chain represents a critical challenge.

The focus of the ENOUGH project was to contribute to the EU Farm to Fork Strategy by identifying technological, financial and political solutions to achieve climate neutrality of the European food supply chain. To contribute to this overall goal, the demonstration of innovative and sustainable technologies in each link of the cold chain, including the temperature-controlled sector, was a key activity of ENOUGH.

Therefore, efforts were dedicated to demonstrate sustainable solutions for refrigerated transport through the employment of natural refrigerants, the elimination of fossil fuels, the inclusion of renewable energy sources such as solar energy, the integration of thermal energy storage and the development of high efficiency cooling systems.

The demonstrators included in Task 6.5 are the following:

- Demo 7: “Fresh and Green Delivery”.
- Demo 8: “TES Last Mile Delivery”.

The partners CNR, SUT, ENEX and ELETICA, thanks to their experience in refrigeration systems design, development and control, demonstrated the best technologies to achieve climate neutrality of short distance refrigerated transport. Specific advanced components were developed as part of the demonstrator activities or carefully selected on the market in order to optimize the proposed systems. Proper KPIs, such as energy consumption and emission rates, were identified and evaluated numerically and experimentally.

2 RECOMMENDATIONS

The demonstrators involved in Task 6.5 have been focusing on the development of mobile, compact, efficient, and environmentally friendly solutions for road refrigerated transport. Key points which emerged from the demonstrators’ activities are the following:

- The use of CO_2 in a vapour compression cycle and the application of propane to TES in low temperature transported boxes, demonstrated within this Task, show that environmentally sustainable and high-efficiency refrigeration systems for road temperature-controlled transportation are already viable, as both demonstrators are characterized by a final TRL of 8.
- The refrigerated transport CO_2 unit architecture developed for Demo 7 could potentially be suitable even for stationary refrigeration units with medium/small size, leading to potential cost savings and ease of use thanks to the simplicity of its schematic.

- The results obtained in Demo 8 can contribute to the acceptance of hydrocarbons as a viable option in the transport refrigeration sector. These systems, in fact, have high potential as reliable and sustainable solution in many applications in refrigerated transport, but their development and adoption are currently limited due to the sector's lack of familiarity with them.
- The use of natural refrigerants and the overall development of natural refrigerants-based solutions in refrigerated transport is still marginal, especially compared to other sectors of refrigeration. However, the F-Gas Regulation and potential future policies limiting the use of synthetic refrigerants should be considered as motivating factors towards the development of long-term sustainable solutions in transport refrigeration.
- The solutions proposed in the transport demonstrators are also ready to comply with the foreseeable future characteristics of related sectors. For example, road mobility is moving towards a complete electrification: refrigeration technologies which avoid any use of fossil fuels and integrate renewable energy exploitation will align with such boundaries while contributing at the same time to the overall goal of achieving climate neutrality in food industry.
- Overall, compactness, light weight and efficiency are key factors in transport refrigeration applications. Current market, especially for CO_2 refrigeration units, presents limited options in terms of small-scale components, as larger application fields (i.e. commercial and industrial applications) represent the vast majority of market share. Dedicated components design would result in further significant performance improvements.

3 DESCRIPTION OF THE SECTOR

Within the cold chain, transport operations are a key link to ensure preservation of perishable goods at adequate temperature level. It is reported that around 31% of food supply chain includes refrigerated transportation (Bagheri et al., 2017). In latest years, the sector experienced a significant growth, as recent studies reported that the transport refrigeration sector will grow by 2.5% per year by 2030 (Oko-Recherche et al., 2011). The International Institute of Refrigeration reported that the global refrigerated fleet in 2021 consisted of 3.4 millions of vehicles and, according to the assumptions of that study, the related global emissions were about 50 $Mt_{CO2,eq}$, representing nearly 25% of the total cold chain emissions (IIR, 2021). Based on a Top-Down methodology, the ENOUGH project estimated the transport sector to be the third most emitting element in the food chain (after food production and manufacturing), accounting for the 15% of the whole chain. Another recent study estimated that the European road refrigerated fleet consumes more than 3500 GWh of primary energy on annual basis (Minetto et al., 2023a).

Most mobile cooling systems operate based on the vapour compression cycle, which enables continuous operation as long as a mechanical or electrical energy source is available. The configuration of refrigeration circuits can vary substantially depending on the specific application and associated storage requirements. Compared to stationary systems, mobile units must comply with stricter constraints regarding space and weight, enhanced reliability demands (particularly when maintenance access is limited for extended periods), and the use of standardized components that are globally available. Furthermore, they must be designed to withstand more severe environmental conditions, necessitating dedicated mechanical solutions. During operation, these systems are frequently subjected to accelerations, vibrations, and abrupt or extreme climatic variations. These constraints, together with the necessity of transporting different types of goods, make the design of transport refrigeration systems particularly challenging. Road transport is crucial for short and medium distances. The type of vehicle depends on the distance, and it varies from light commercial vehicles to long trailers and semi-trailers. The primary energy source employed by the refrigeration unit is usually either the vehicle internal combustion engine (for light-medium commercial vehicles) or a dedicated diesel engine (for heavy commercial vehicles or semi-trailers).

The refrigerants employed in current transport refrigeration units are predominantly synthetics (HFCs and, more recently, HFOs). While R404A and R134a have been the preferred refrigerants in the last years, because of F-gas phase down, retrofitting fluids like R452A, R449A and R442A have been identified. Recent studies reported that, in 2015, 94.6% of new road refrigerated transport equipment in France was employing R404A as the refrigerant, while in 2022 94.5% of new equipment was based on the use of R452A (Cavalier et al., 2023). R404A is almost no more used in new equipment (0.2% in 2022), but old units employing it are still considerably present in the national fleet (81.0% of the total refrigerant mass employed in temperature-controlled transport in 2022).

Throughout a 10 years life, the leakage rate of a refrigerated truck can be as high as 165% of the initial charge, with a yearly leakage rate ranging from 10 to 37% of the charge (Minetto et al., 2023b). This raises the critical issue linked to synthetic operating fluids: in fact, HFCs are characterized by a high Global Warming Potential (GWP), while HFOs could be potentially responsible for the release of PFAS in the environment, causing harmful effects on nature and human health.

Overall, the main challenge characterizing current road refrigerated transport sector is the simultaneous achievement of an increase of energy efficiency of the refrigeration units and a reduction of their carbon footprint, including both direct and indirect emissions.

4 DESCRIPTION OF THE TECHNICAL SOLUTIONS

To face the efficiency and sustainability challenges presented above, different technical solutions have been developed and integrated for the transport demonstrators.

Firstly, in Demo 7 the complete elimination of fossil fuels usage for short-range refrigerated transport was targeted. For small vehicles, in fact, electrification of both the vehicle propulsion and refrigeration system are commercially available and do not represent a challenge by its own. Vehicle batteries are dedicated to the power the powertrain and accessory systems, while a dedicated battery pack is used to power the refrigeration unit. Photovoltaic panels are integrated on the roof of the vehicle insulated body to contribute to extend the system autonomy while keeping the battery pack to a minimum size, to save space and weight.

Another approach to remove fossil fuels in last-mile delivery has been identified in Demo 8 with the employment of a passive cooling system during the driving missions by integrating a cold Thermal Energy Storage (TES) system in the insulated boxes used to carry the perishable products. This allows to utilize a stationary refrigeration unit when the vehicle is parked in the depot, before leaving for delivery missions, to cool down and eventually freeze a phase-change material contained in the insulated boxes. The same material will then maintain the temperature inside the box at the desired level for the whole duration of the delivery mission by progressively melting at a constant temperature, specific for the chosen material. Such a system also fits with the use of electric vehicles, as no energy is drained from the vehicle during deliveries. Furthermore, this solution allows to employ non-specialized vehicles, since the products are loaded into a transportable insulated box, improving the flexibility of transport operations by allowing simultaneous transportation of non-refrigerated and refrigerated products (potentially also at different temperature levels).

Moreover, the exclusive employment of natural working fluids in the cooling units was adopted, to avoid negative and harmful effects on the environment or on human health linked to refrigerant leakages. CO_2 (R744) and propane (R290) were identified for Demo 7 and Demo 8, respectively, as safe, suitable and sustainable operating fluids for the cooling systems developed in the demonstrator activities.

Finally, the employment of advanced components, optimized system schematics and control strategies allowed to achieve cooling systems characterized by high efficiency under different operating conditions, to outperform baseline traditional refrigeration systems employed in temperature-controlled road transport sector.

4.1 Definition of KPIs and benchmarks

The KPIs identified for transport demonstrators are listed below.

- Primary energy saving
- Emissions reduction
- Pollutant reduction in urban areas
- Energy saving due to renewable energy integration

The benchmark considered to evaluate these KPIs consists of standard vapor compression systems, with synthetic refrigerants, representative of baseline solutions currently employed in refrigerated transport sector, for the same application type of Demo 7 and Demo 8, respectively, according to the table below.

Table 1: Baseline technologies.

	Refrigerant	Nominal evaporation temperature	Nominal cooling power (30°C)	Refrigerant charge	Energy source
DEMO 7 baseline	R452A	-10 °C	3.8 kW	2.0 kg	Diesel
DEMO 8 baseline	R452A	-33 °C	0.6 kW	2.5 kg	Grid electricity

PRESENTATION OF DEMONSTRATORS

5 DEMO 7 – FRESH AND GREEN DELIVERY

5.1 Description

The objective of the "Fresh and Green Delivery" demonstrator (Figure 1) was to propose an energy efficient, environmentally sustainable and effective solution to reduce the carbon footprint of road refrigerated transport by integrating a cooling unit based on natural refrigerants (CO_2) and solar panels to minimise GHGs emissions of a medium-sized van dedicated to short distance delivery of fresh food products. The use of a natural refrigerant prevents the emissions related to the lifecycle of synthetic refrigerants. The CO_2 refrigeration unit includes advanced solutions, such as a specifically developed ejector, and optimized components to increase the overall performance of the system, lowering the energy request to preserve the transported food. Integration of rooftop photovoltaic panels further reduces the draw of primary energy of the system thanks to the produced electricity during the day.

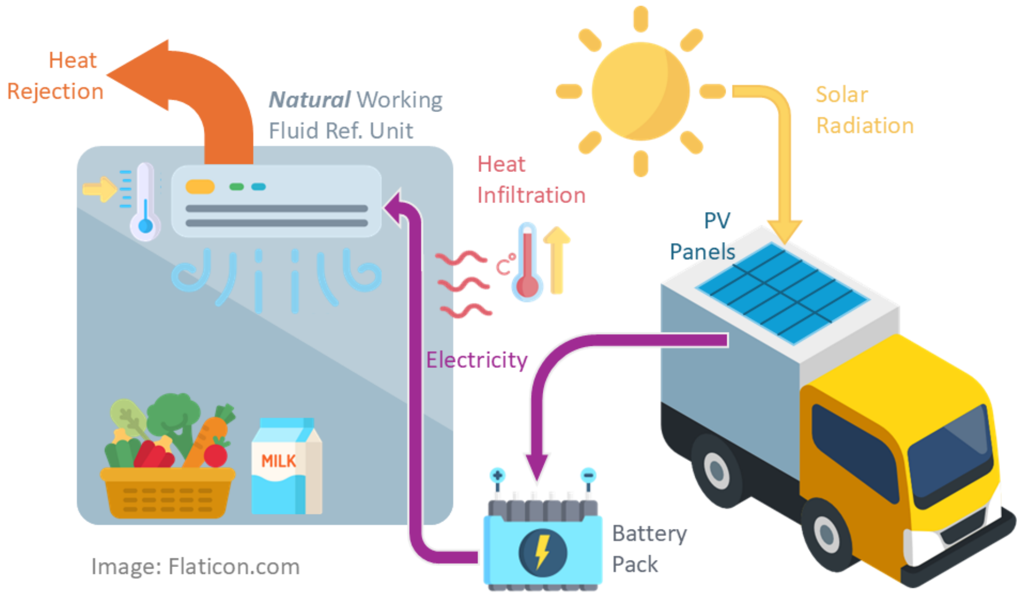


Figure 1. Simplified schematic of the structure of Demo 7 "Fresh and Green Delivery".

Compared to the main solutions of today's market, this demonstrator aims at completely removing the use of fossil fuels during temperature-controlled transport operations by employing an electric vehicle and additional photovoltaic panels, to contribute to the overall energy balance of the vehicle, and to use only natural refrigerants, replacing synthetic fluids and avoiding direct emissions due to their accidental leakage in the atmosphere.

The initial TRL of the demonstrator was equal to 6 at the project beginning and it is expected to become equal to 8 at the end of the project, by testing the natural refrigerant unit attached to the insulated body and then connected to the finalised vehicle.

5.2 Application methodology and assessment

The demonstrator activities started with the experimental assessment of the thermal and energy performance of a first CO_2 unit prototype in laboratory environment. At the same time, two advanced components (ejectors) were specifically designed and developed for the mobile application, and then experimentally tested in relevant operating conditions. A numerical model of a multi-temperature cooling unit, based on the implementation of the ejectors, was built and used to simulate the system performance. Afterwards, the system schematic was optimized for single-temperature applications, selecting efficient and compact components available in the market, and numerical simulations were used to assess the energy performance and the carbon footprint of the mobile refrigeration unit.

Design and experimental evaluation of stationary CO_2 unit prototype

As a first step in the evaluation of the optimal solution for refrigerated vehicles application, a stationary prototype of CO_2 cooling unit was installed in the laboratory (Figure 2) to be utilized as test bench to experimentally evaluate the effect of different configurations and operating conditions on the system performance. In this installation, different configurations can be employed by including or excluding an ejector or an auxiliary evaporator to enhance the performance in specific operating conditions.

Figure 2. First stationary prototype of CO_2 unit installed in the lab.

The gas cooler and the evaporators of the refrigeration unit are placed in two separate insulated chambers, in which the air temperature can be controlled to experimentally test the unit under the desired operating conditions: different ambient temperature conditions can be achieved by controlling the air temperature at the gas cooler (in the hot room) and different temperatures for perishable goods preservation can be achieved by controlling the air temperature at the evaporators (in the cold room).

Several thermocouples are placed at key points of the refrigeration system, to assess the thermodynamic cycle and the air and tubes temperatures. Pressure transducers are used to measure the pressure levels in six points of the refrigeration circuit, and three Coriolis mass flow meters are used to measure the total mass flow rate elaborated by the compressor and by the ejector. The electrical power consumption of the unit is measured by integrating high frequency acquisition of current-voltage signal on each phase. All parameters were logged with a frequency of 1 Hz.

Design and experimental test of MT and LT ejectors

Based on the design cooling capacities of the refrigeration unit (4.5 kW of MT refrigeration, at 0°C, for fresh products; 1.0 kW of LT refrigeration, at -20°C, for frozen products), two ejectors (MT and LT) were specifically designed and developed with the objective of enhancing the unit performance at high ambient temperature and allowing a single-compression cycle with two different temperature levels in separate compartments of the refrigerated vehicle. The components geometrical characteristics were optimized employing numerical algorithms. A series of 2-D CFD-based numerical simulations were carried out to numerically assess the performance of the ejectors under various operating conditions and the performance maps of the ejectors were then obtained through interpolation of the numerical results.

Figure 3. Ejectors specifically designed and developed for the demonstrator.

The ejectors (Figure 3) were manufactured and experimentally tested on a dedicated laboratory test rig. Dedicated temperature and pressure sensors were mounted approximately 10 cm from the ejector ports to monitor the ejector operating conditions. Coriolis mass flow meters were employed to measure the motive and suction mass flow rates. The parameters are logged with a frequency of one sample every five seconds. For each operating condition, data were measured for 10 minutes and then averaged to determine the steady-state performance in those specific conditions.

Numerical evaluation of cooling unit performance

A dynamic numerical model of the refrigeration system was developed using a commercial multi-physics simulation platform. The modelling approach is based on lumped parameters, whereby actual components are discretized into interconnected elements to represent the overall system architecture. Each element is described by a set of nonlinear, time-dependent differential equations governing the state variables. These equations are assembled into a global system of differential equations, which is then numerically integrated over time to reproduce the transient behaviour of the system.

The geometrical and performance characteristics of the refrigeration unit components implemented in the numerical model were based on real dimensions and on performance data declared by the manufacturers. The ejectors performance was modelled through implementation of the performance maps obtained from the CFD numerical simulations of the ejectors into the physical model of the cooling unit. The dynamic control of the refrigeration system operation was included in the numerical model through development of PI controllers setting the optimal gas cooler pressure as a function of ambient temperature.

Cooling unit optimization for mobile application

The MT section of the multi-temperature CO_2 unit was selected for the final development, manufacturing and installation of the field demonstrator on the light commercial vehicle (Figure 4). This allowed to comply with multiple challenges linked to the realization of the multi-temperature schematic of the cooling unit, including the limit of operability of the LT cycle for ambient temperatures above 35°C due to the compressor envelope constraints and the significant weight of key components such as the semi-hermetic piston compressor causing additional energy consumption of the vehicle while driving.

A light-weight scroll compressor was selected to replace the semi-hermetic piston compressor, reducing by approximately 60 kg the total weight of the unit and allowing at the same time to significantly simplify the unit control strategy by replacing an expensive electrical expansion valve with a fixed mechanical valve. Moreover, the wide range of rotational speed which characterize the scroll compressor allows a complete control of the CO_2 cycle parameters both with and without the employment of the ejector.

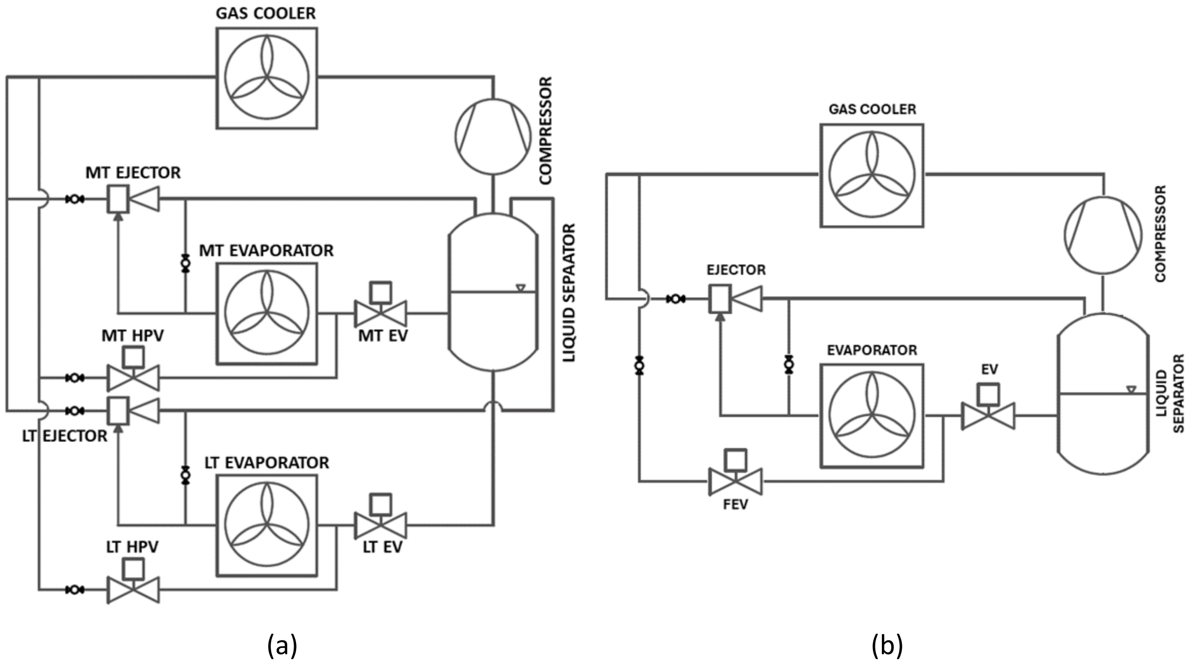


Figure 4. CO_2 unit schematic: a) initial multi-temperature schematic; b) MT single-temperature schematic selected for development.

The numerical model of the MT unit was then used to evaluate different refrigeration unit configurations and heat exchangers size, to identify the best trade-off between COP and unit weight, with the overall goal of minimizing the global carbon footprint.

5.3 Results

Design and experimental evaluation of stationary CO_2 unit prototype

To assess the performance of the CO_2 stationary unit installed in the lab, experimental tests were performed both in its simplest configuration (back-pressure configuration) and in ejector configuration. Experiments were performed for different values of the refrigerated space temperature T_{int} (-5°C ,0°C and 5°C) and ambient temperature T_{amb} (varying between 20°C and 40°C, with a step of 5°C). Experiments with ejector configuration were not conducted for low ambient temperature values. Results for T_{int} = 0°C are presented in Figure 5. Experimental results show that the ejector configuration can significantly enhance the system performance at high ambient temperatures, achieving an increase of the COP up to +22.1% and of the cooling capacity up to +26.0% for ambient temperature of approximately 40°C. Results also confirm the expected operating range of the ejector mode: in fact, for ambient temperature below 30°C the ejector cycle does not provide significant improvement over the simple cycle.

Moreover, to compare the performance of the CO_2 unit to the performance of baseline transport refrigeration units currently available in the market, data from prior studies available in literature, referring to a R404A unit (Colbourne et al., 2017) and to a R410A unit (Wu et al., 2013), characterized by very similar performance, have been compared to the experimental results of the R744 unit. At 20°C, the CO2 system in back-pressure configuration demonstrates an average performance improvement of +14.4% compared to the baseline systems, while at 40°C the improvements, employing the ejector configuration, are equal to +16.8%.

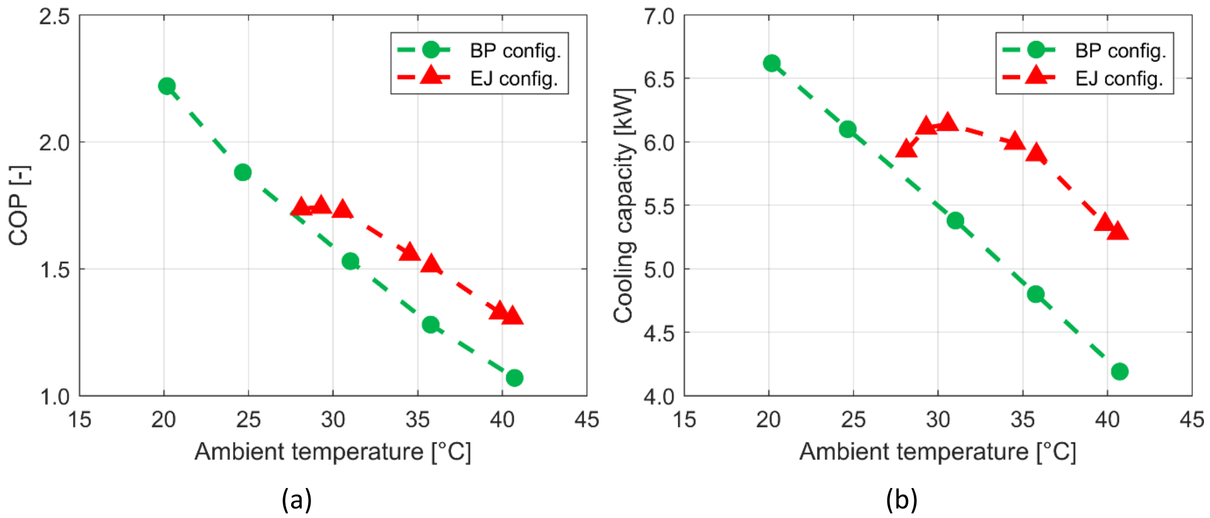


Figure 5. Experimental results of stationary CO_2 unit in back-pressure (BP) and ejector (EJ) configurations, for T_{int} = 0°C: a) COP; b) cooling power.

Design and experimental test of MT and LT ejectors

The MT and LT ejectors were experimentally tested in different operating conditions. Approximately 70 different operating points were acquired during the experimental campaign. For the LT ejector, the maximum of the recorded efficiency reaches approximately 25% and corresponds to a mass entrainment ratio (MER) of 0.5 (ejector efficiency and MER definitions can be found in Elbel and Hrnjak, 2008). These values were established as a preliminary goal at the beginning of both the ejector and the system modelling. For the MT ejector, the maximum recorded efficiency reached approximately 20% with the corresponding MER of 0.3, slightly lower than the desired MER defined in the design phase. Two sets of operating points are shown in Figure 6.

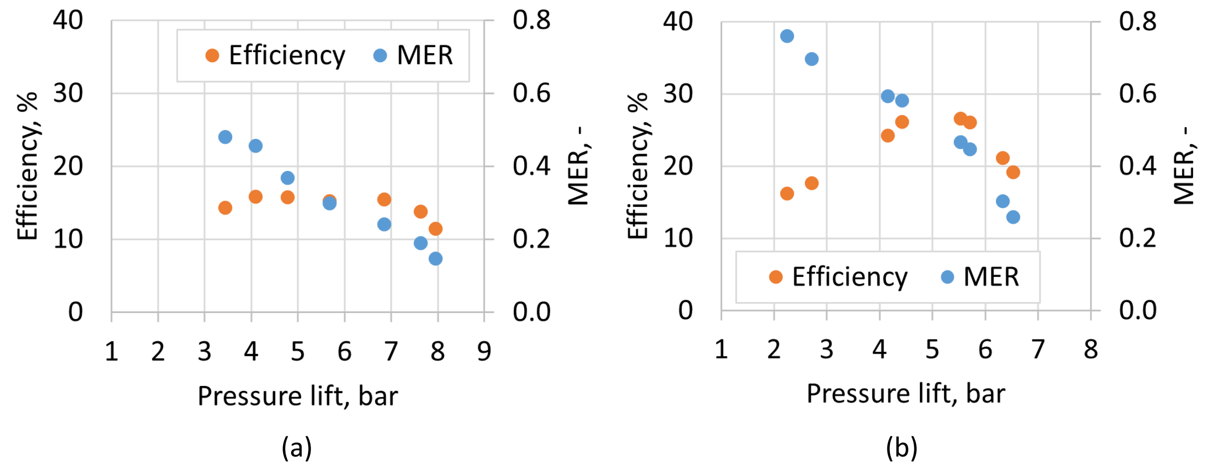


Figure 6. Experimental results of CO_2 ejectors with p_{motive} = 86.0 bar: a) MT ejector with $p_{suction}$ = 26.0 bar; b) LT ejector with with $p_{suction}$ = 22.5 bar.

The size of the MT and LT ejectors developed within the demonstrator activities was the most challenging requirement for their design and realization. In fact, the smallest CO_2 ejectors available in current market are developed for systems that offer at least 15 kW of cooling capacity and are characterised by throat diameters of approximately 1 mm. For this application, the MT and LT ejectors were characterised by a throat diameter of 0.95 mm and 0.46 mm, respectively, and the experimental tests confirmed their ability to satisfy the design cooling capacities of approximately 4.5 kW for MT and 1.0 kW for LT.

Numerical evaluation of multi-temperature cooling unit performance

Firstly, numerical simulations of the MT side of the CO_2 unit were performed to assess the annual performance of the unit and compare it to a reference R134a unit, representative of units currently employed in refrigerated transport. Simulations highlighted that the employment of the CO_2 unit in a urban delivery mission scenario, instead of the baseline R134a unit, can lead to an increase of the average mission COP (defined as the ratio between the total cooling energy provided by the unit and the total energy consumption over the delivery mission entire duration) equal to +27.5% on a yearly basis.

Considering the total carbon footprint of the two units over their life cycle, the R744 unit, compared to the R134a unit, presented lower equivalent emissions linked to operation (-15.2%) thanks to its higher annual COP, but higher equivalent emissions linked to the additional fuel consumption to carry the cooling unit weight on the vehicle, underscoring that, from a life cycle sustainability perspective, significant reductions in the carbon footprint of transport refrigeration units can be achieved by carefully selecting materials and designing components to reduce the weight of the cooling unit. Nevertheless, the high GWP of R134a leads to significant direct emissions due to leakages, resulting in a 31.9% reduction of the total lifetime carbon emissions of the R744 unit, considering both direct and indirect emissions.

Secondly, numerical simulations of the multi-temperature CO_2 unit were performed to assess at first the steady-state performance of the system under different environmental temperature conditions both in MT and LT operation, and then to evaluate the dynamic response of the system during a pull-down from equilibrium with the external environment to the MT and LT temperature set-points.

Simulation results showed that, at design ambient temperature of 30°C, the use of ejector cycle leads to a COP increase, compared to the back-pressure cycle, equal to 25.8% for MT operation and equal to 42.0% for LT operation. Nevertheless, the back-pressure cycle allows a significantly higher flexibility in the range of cooling power production compared to the ejector cycle, which can be useful during pulldown or part-load operation. The dynamic simulations highlighted that, during a pulldown from thermal equilibrium with the environment at 30°C, the system, operating in ejector configuration, takes around 23 minutes to reach the MT set-point temperature (0°C) inside the MT compartment and around 40 minutes to reach the LT set-point temperature (-20°C) inside the LT compartment of the refrigerated vehicle.

Cooling unit optimization for mobile application

For the final prototype development within the demonstrator activities and the mobile installation on the vehicle, the MT section of the multi-temperature CO_2 unit was selected.

Following the above-mentioned numerical results highlighting the crucial influence of weight reduction in transport refrigeration applications, an optimization of the refrigeration unit scheme and components was carried out, resulting in a reduction in size, weight and complexity of the control logic. Numerical simulations allowed to quantify the improvement in the performance of the optimized unit compared to the preliminary schematic in an increase in COP between 22.2% and 6.2%, for ambient temperature variable between 20°C and 40°C, respectively. Furthermore, the simulations allowed to estimate that the increase in COP, combined with the reduction in weight of the new scheme, can lead to a total reduction in emissions during annual operation of between -30.0% in cold climates (Helsinki) and -15.5% in hot climates (Phoenix).

The numerical simulations allowed also to evaluate the influence of different evaporator sizes on the overall annual carbon footprint of the unit. Results showed that an undersized evaporator leads to an increase of the total carbon emissions for all (cold, temperate and hot) climates, ranging between +6.2 and +6.9%. In fact, a smaller and lighter evaporator can reduce the emissions linked to vehicle driving, but the significant deterioration of the unit performance strongly increases the emissions linked to the unit operation, leading to a worse overall result. On the other hand, the effect of an oversized and heavier evaporator depends on the climatic conditions: +1.0% in cold climates, -1.5% in hot climates. The numerical results were useful to identify the correct evaporator size to be used in the final prototype, which has been manufactured and is under commissioning in the manufacturer laboratories, and it is shown in Figure 7.

Figure 7. Final prototype of the R744 transport refrigeration unit.

Publications

The following publications provide more in-depth information to the system, the experimental tests and the numerical analysis.

Journal papers

- Fabris, F., Pardiñas, Á. Á., Marinetti, S., Rossetti, A., Hafner, A., Minetto, S. (2023). A novel R744 multi-temperature cycle for refrigerated transport applications with low-temperature ejector: experimental ejector characterization and thermodynamic cycle assessment. International Journal of Refrigeration, 152, 26-35. https://doi.org/10.1016/j.ijrefrig.2023.05.003
- Fabris, F., Fabrizio, M., Marinetti, S., Rossetti, A., Minetto, S. (2024). Evaluation of the carbon footprint of HFC and natural refrigerant transport refrigeration units from a life-cycle perspective. International Journal of Refrigeration, 159, 17-27. https://doi.org/10.1016/j.ijrefrig.2023.12.018
- Fabris, F., Bodys, J., Marinetti, S., Minetto, S., Smolka, J., Rossetti, A. (2024). Numerical modelling of a single-compression multi-temperature ejector-supported R744 refrigeration unit for last mile delivery. International Journal of Refrigeration of Refrigeration, 160, 65-75. https://doi.org/10.1016/j.ijrefrig.2024.01.014

- Bodys, J., Palacz, M., Haida, M., Fabris, F., Rossetti, A., Smolka, J. (2025). Numerical and experimental assessment of the CO2 ejector for small scale refrigeration system for mobile/automotive applications. International Journal of Refrigeration. (*SUBMITTED*).
- Fabris, F., Shah, W., Minetto, S., Marinetti, S., Rossetti, A. (2025). Numerical assessment of the influence of a R744 cooling unit design and components on the overall carbon footprint of a light refrigerated vehicle. International Journal of Refrigeration. *(SUBMITTED).*

Conference presentations

- Fabris, F., Pardiñas, Á. Á., Marinetti, S., Rossetti, A., Hafner, A., Minetto, S. (2022). Experimental evaluation of the performance of an ejector for a single compression multi-temperature CO2 refrigeration unit. 15th IIR Gustav Lorentzen Conference on Natural Refrigerants, 13-15 June 2022, Trondheim, Norway. https://doi.org/10.18462/iir.gl2022.0098
- Fabris, F., Fabrizio, M., Marinetti, S., Rossetti, A., Minetto, S. (2023). Comparison of the environmental impact of HFC and natural refrigerant transport refrigeration units from a life-cycle perspective. 10th IIR Conference on Ammonia and CO2 Refrigeration Technologies, 27-29 April 2023, Ohrid, R. Macedonia. https://doi.org/10.18462/iir.nh3-co2.2023.0033
- Fabris, F., Bodys, J., Marinetti, S., Minetto, S., Smolka, J., Rossetti, A. (2023). Dynamic numerical modelling of a single stage dual temperature R744 ejector-supported refrigeration unit for last mile delivery. 26th International Congress of Refrigeration, 21-25 August 2023, Paris, France. https://doi.org/10.18462/iir.icr.2023.0810
- Fabris, F., Shah, W., Minetto, S., Marinetti, S., Rossetti, A. (2024). Effects of a R744 cooling unit design on the overall energy performance of a refrigerated vehicle. 16th IIR Gustav Lorentzen Conference on Natural Refrigerants, 11-14 August 2024, College Park, USA. https://doi.org/10.5281/zenodo.13985743

5.4 Impacts

The demonstrator focused on developing a compact, efficient and sustainable solution to help the road refrigerated transport sector to achieve climate neutrality by avoiding any use of fossil fuels, integrating renewable energy sources and eliminating synthetic refrigerants in vapor compression systems.

Compared to the main technology employed in the refrigerated transport sector, the use of an electric vehicle allows to use only grid electricity as a primary energy source for temperature-controlled logistics operations, resulting in an improvement of the overall carbon emission factor of the vehicle, a reduction of localized pollution and the integration of solar panels placed on the vehicle roof, which contribute to the energy requirement of the cooling unit, mitigating its impact on the vehicle driving autonomy.

Moreover, the employment of the natural refrigerant (CO_2) cooling unit leads to the double advantage of granting a high system efficiency during operation, thanks to advanced components (such as a specifically developed ejector) and a control strategy optimization, and negligible emissions due to refrigerant leakages. CO_2 is also an inherently safe gas as it is non-toxic and non-flammable.

A quantitative assessment of the primary energy saving and of the emissions reduction derived by the implementation of the solution developed in Demo 7 in various European climatic conditions is reported in Section 7.

5.5 Business potential

Electric mobility will replace fossil fuels for passenger cars and light commercial vehicles in the foreseeable future, especially in densely populated areas where local emission should be avoided to improve air quality. Moreover, synthetic refrigerants are soon going to be phased down due to environmental reasons. The solution developed in this demonstrator highlights that an electricity-based system, with further integration of solar renewable energy production, and employment of natural refrigerants can achieve competitive performance with limited environmental impact.

Environmentally conscious logistics firms are already exploring hybrid/electric truck fleets. Logistics companies focused on further reduce their carbon footprint could be the primary customers for this solution, followed by supermarkets and food distribution networks requiring sustainable local delivery solutions. The implementation by the market major players of a R744 cooling unit on light commercial vehicles might promote components manufacturers to develop products (compressors, ejectors) optimized for this kind of application, further increasing the potential for performance enhancement and reducing investment costs for the users.

6 DEMO 8 – TES LAST MILE DELIVERY

6.1 Description

The post-COVID era has witnessed a significant increase in new services related to e-commerce and last-mile delivery of perishable goods, which need to be delivered in urban areas and at the right temperature levels to preserve their quality and cold chain. Consequently, there has been a growing interest in the application of thermal energy storage (TES) solutions in transport refrigeration, which can help in enhancing efficiency, flexibility, and compactness of temperature-controlled last-mile delivery.

Within this context, the “TES Last Mile Delivery” demonstrator (Figure 8) aims to improve the environmental sustainability of last-mile deliveries through the use of TES inside insulated boxes used for the transport of frozen products. The TES is cooled before departure for delivery missions by a stationary cooling unit that uses natural refrigerants (propane) and uses latent/sensible heat to maintain the correct temperature range inside the isothermal boxes. This solution avoids the presence of an active refrigeration unit installed directly on the vehicle, saving mass and materials. Furthermore, as the insulated box and the TES system are not part of the truck, but instead a transported object, this solution can be coupled to non-specialized vehicles, allowing greater flexibility in fleet and logistics management: the truck can be loaded with one or more boxes according to the goods and temperature levels needed for the transport, and this arrangement can change at each use. On the other side, as the box is not linked to a predefined vehicle, different missions can be performed using different vehicles to better match routing and loading capacity. Since the refrigeration unit is powered by the electrical grid, this solution guarantees lower greenhouse gas (GHG) emissions compared to traditional fossil-fuel engine powered active refrigeration units installed on the vehicle. Furthermore, it contributes to reduce localized emissions and noise pollution in urban areas.

The thermal energy storage is achieved by means of a eutectic solution of inorganic salts, characterized by a nominal phase change temperature of -33°C, contained in eutectic plates fixed to the internal walls of the isothermal box. Thanks to this solution, the eutectic box is characterized by an autonomy of more than 12 hours: with an ambient temperature of 30°C, the internal temperature is constantly kept below the threshold of -20°C without the need for an active refrigeration system, therefore without the supply of electrical energy from outside.

Eutectic plates systems are an established technology and represent the most mature TES based solution in cold chain transport applications, as the ATP agreement (“Agreement on the international carriage of perishable foodstuffs and on the special equipment to be used for such carriage”, United Nations, 2024) by the United Nations already regulates their use in the industry. However, despite being identified as a valid alternative to traditional vapor compression units, especially for short distance or when a daily use is planned, eutectic plates still represent a marginal fraction (less than 5%) of transport refrigeration market (Fertel et al., 2023). In addition, only synthetic refrigerants are currently employed to freeze the eutectic plates before deliveries.

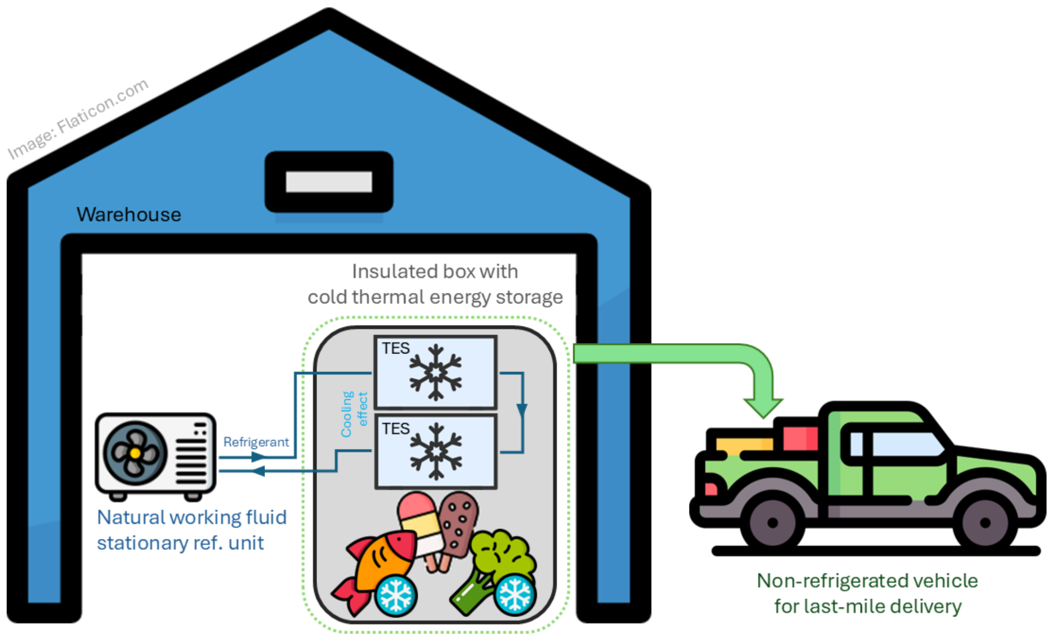


Figure 8. Simplified schematic of the structure of Demo 8 "TES Last Mile Delivery".

Compared to the main solutions of today's market, this demonstrator aims at using only natural refrigerants for the pulldown operations of the eutectic plates and an innovative geometry for the TES containers, leading to a simultaneous increase of the energy efficiency during operation and to a significant decrease of the carbon footprint of the whole solution over its lifetime, thanks to the elimination of high GWP working fluids.

The initial TRL of the demonstrator was equal to 5 and it is expected to become equal to 8 at the end of the project, with the natural refrigerant cooling unit installed and tested in conditions comparable to real daily delivery missions conditions.

6.2 Application methodology and assessment

The demonstrator activities started with the experimental assessment of the thermal and energy performance of the solution which is currently employed and which is meant to be replaced by the novel solution proposed by this demonstrator. Then, a numerical model was developed and validated against the experimental data. The model was then used to numerically evaluate the performance of the proposed solution under the same operating conditions.

Experimental test of baseline solution

The baseline R452A system has been experimentally tested to assess its thermodynamic and energy performance under nominal operating conditions. In particular, the experimental test is based on the ATP test procedure defined for eutectic plates equipment, as described in Annex 1 of the ATP (United Nations, 2024).

The environmental temperature is maintained equal to 30°C for the entire duration of the test. Once the mean inside temperature of the insulated box and the temperature of the eutectic plates are in equilibrium with the environmental temperature, the doors are closed, and the cooling unit is turned on. The insulated box is kept closed with the cooling unit in operation at full capacity for 24 hours, to freeze the PCM contained inside the eutectic tubes. After 24 hours, the cooling unit is turned off. The objective of the test is to assess how long the mean temperature inside the insulated box stays below the threshold temperature of -20 °C, after switching off the cooling unit.

Several thermocouples are placed in key points of the refrigeration system, to assess the thermodynamic cycle and the air and tubes temperatures. The temperature values are logged with a frequency of one sample per minute. The main electrical parameters (power consumption, voltage, current, frequency and power factor) are logged through a high precision multimeter, with a frequency of one sample every two minutes.

The test was conducted firstly on the insulated box equipped with eutectic plates, which is shown in Figure 9. The R452A cooling unit is visible on the top left part of the insulated box roof. Then, the thermal energy storage structure was changed from eutectic plates to eutectic tubes (shown in Figure 10). Eutectic tubes offer an alternative solution to eutectic plates and present some functional advantages. Firstly, in eutectic tubes the refrigerant pipe is external to the aluminium case containing the inorganic salts solution, allowing to handle potential higher pressures of the refrigerant and to achieve a quicker temperature decrease inside the box during pulldown. Secondly, thanks to their modular design and structure, eutectic tubes can be stacked together in case of higher thermal loads. Lastly, the aluminium case containing the eutectic salts solution can be easily opened, allowing in-house filling and potential swaps of the solution according to the temperature levels required for the correct preservation and transport of different products.

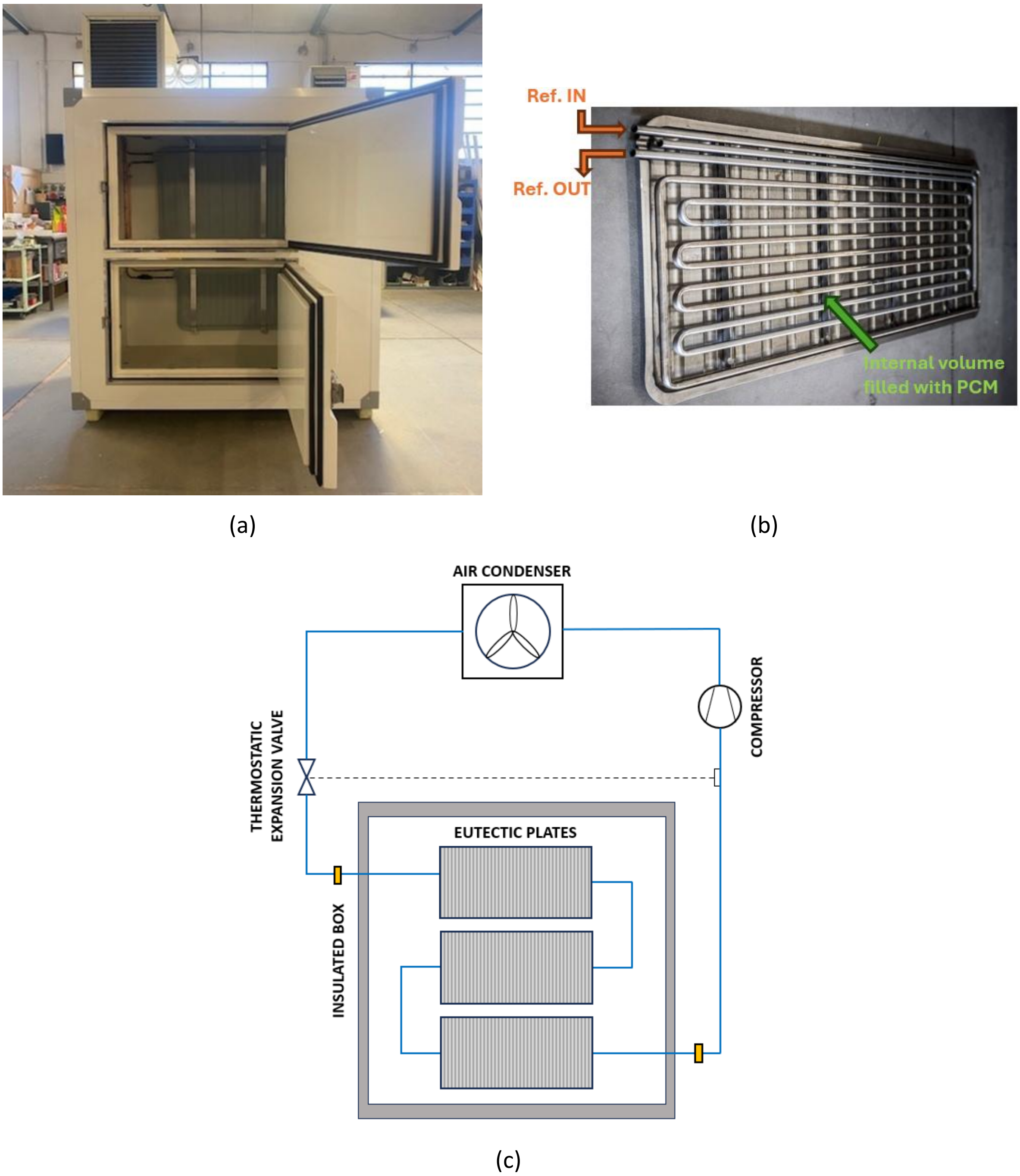
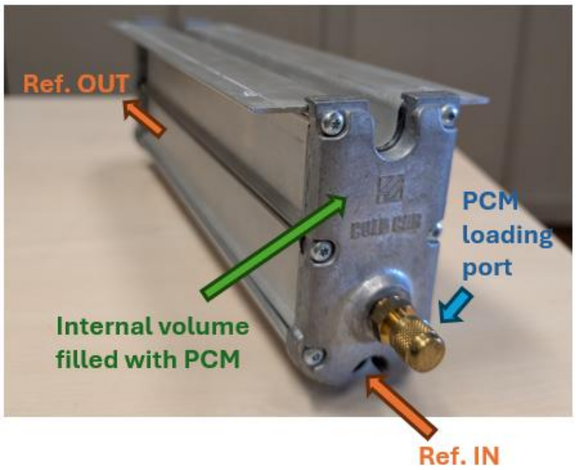
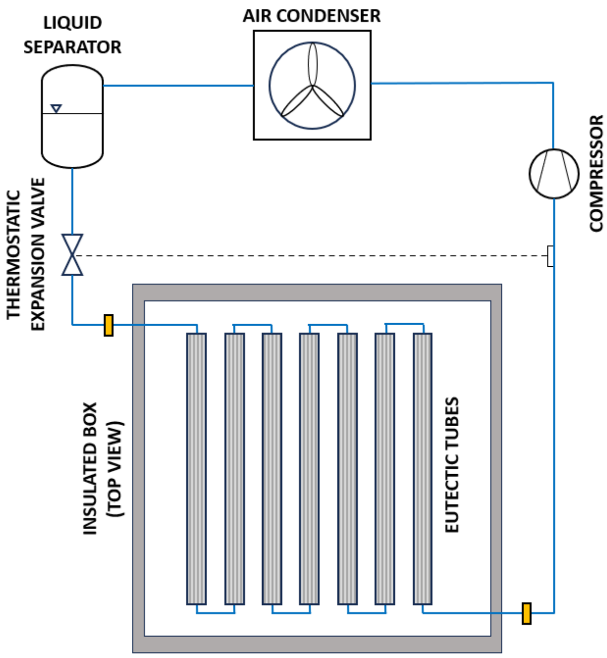


Figure 9. Insulated box equipped with eutectic plates: a) complete system; b) internal structure of the eutectic plate; c) refrigeration cycle schematic.

(a)



(b)



(c)

Figure 10. Insulated box equipped with eutectic tubes: a) eutectic tubes installed inside the box; b) portion of eutectic tube; c) refrigeration cycle schematic.

During the test campaign, the eutectic salts solutions employed as TES was maintained the same for both eutectic plates and tubes. However, the total quantity of material changed (72 kg for the eutectic plates solution, 36 kg for the eutectic tubes solution), leading to a TES capacity of approximately half of the baseline solution with plates. This was done to allow quicker pulldown operations, while still maintaining an autonomy which can cover a standard working day (around eight hours).

Numerical evaluation of natural refrigerant cooling unit

A dynamic numerical model of the refrigeration system was built using a commercial multi-physics software. The model employs a lumped-parameters approach, wherein real components are discretized into interconnected elements to represent the entire system. Each element is governed by nonlinear time-dependent differential equations that define the state variables. These equations are assembled into a system of differential equations, which is subsequently integrated over time to simulate the system's dynamic behaviour.

The numerical model has proved to be able to describe the behaviour of the cooling unit under different operating conditions. The dynamic numerical model was validated against the experimental data collected during the tests on the baseline system. For validation, the measured and simulated air temperature inside the insulated box and electrical power consumption are compared throughout the whole duration of the test, together with the overall value of the electrical energy consumption.

6.3 Results

Experimental test of baseline solution

As a first step, the baseline system based on a cooling unit employing the synthetic refrigerant R452A and on the use of eutectic plates as TES, which represents the solution currently employed in the market and which is meant to be replaced by the solution developed in this demonstrator, has been experimentally tested to assess its performance under nominal operating conditions.

The evolution of the ambient temperature (T_{amb}), of the air temperature inside the insulated box (T_i) and of the refrigerant evaporation temperature (T_{ev}) over the 36 hours of the experimental test is presented in Figure 11. The test highlighted that the energy stored in the eutectic plates during the 24-hours pulldown is sufficient to guarantee a 12-hours autonomy below the internal air temperature setpoint of -20°C with fixed external temperature conditions. The total energy consumption over the 24-hours pulldown was equal to 16.7 kWh_{el}.

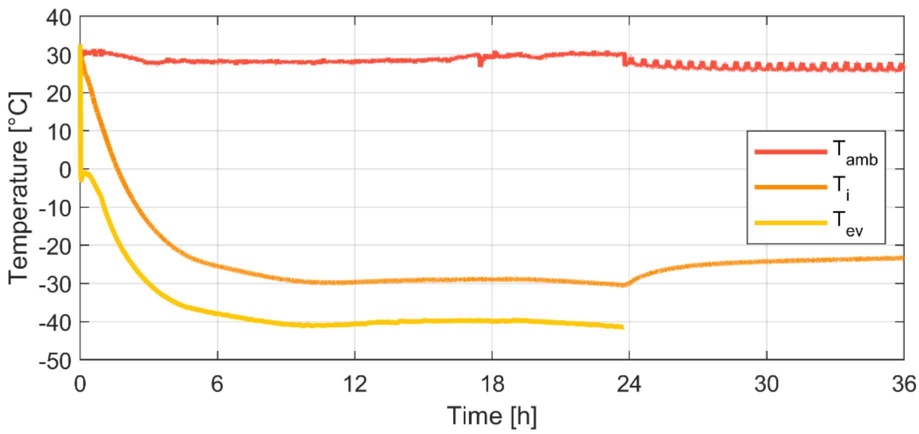


Figure 11. Experimental test on baseline R452A system with eutectic plates: ambient temperature, air temperature inside the insulated box, evaporation temperature of the refrigerant.

The same experiment was then conducted employing the same baseline cooling unit with R452A but with eutectic tubes as TES in place of eutectic plates. Results are presented in Figure 12. In this case, due to the reduced capacity of TES, an almost 8 hours autonomy below the internal air temperature setpoint of -20 °C was achieved. Moreover, the reduced heat exchange area compared to the eutectic plates case determined the slight differences in internal air temperature and evaporation temperature which can be observed by comparing Fig. 10 and Fig. 11. The total energy consumption over the 24-hours pulldown was equal to 14.3 kWh_{el}.

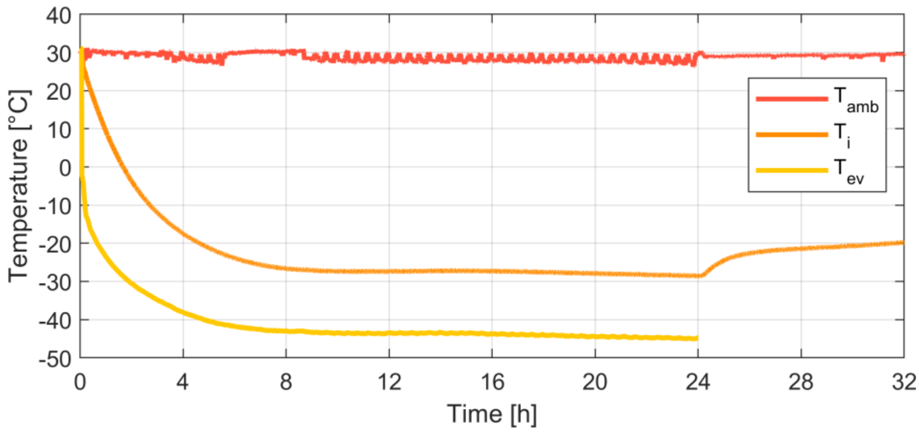


Figure 12. Experimental test on baseline R452A system with eutectic tubes: ambient temperature, air temperature inside the insulated box, evaporation temperature of the refrigerant.

Numerical evaluation of natural refrigerant cooling unit

The numerical models of the baseline systems were validated against the experimental data presented above by comparing the simulated and measured air temperature inside the insulated box and the electrical power consumption over the whole test duration. The numerical results highlighted an error on the total energy consumption between the model and the experiments equal to -1.2% in case of the system with eutectic plates and to +0.8% in case of the system with eutectic tubes.

The validated numerical approach was then used to simulate the performance of the propane cooling unit in the same operating conditions in which the baseline system with eutectic tubes was experimentally tested.

The R290 system presents a better performance compared to the baseline R452A system along the pulldown: the cooling energy provided by the R290 cooling unit in the 24 hours is slightly higher (+4.6%) than the one provided by the R452A unit and, at the same time, a significant decrease of the compressor power input (-7.1%) is assessed for the R290 unit. As a result, the overall pulldown COP, defined as the ratio between the total cooling energy provided by the unit and the total electrical energy consumption of the unit during the 24-hours pulldown, is equal to 0.63 for the R452A baseline system and to 0.71 (+12.6%) for the R290 system. The comparison between the R290 system and the baseline R452A system is presented in Figure 13 in terms of power consumption and COP over the 24-hours pulldown.

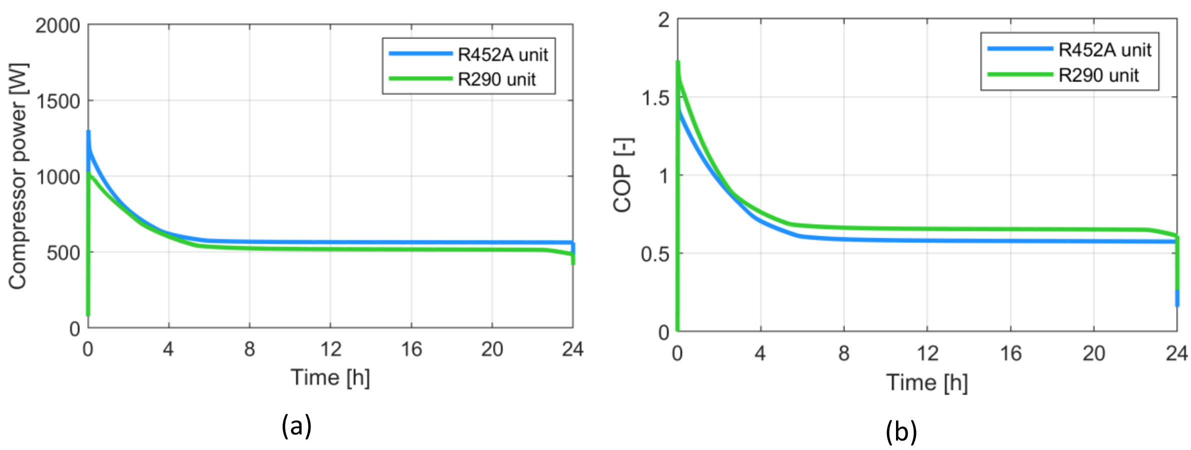


Figure 13. Comparison between baseline R452A system (with eutectic tubes) and novel R290 system: a) compressor power consumption; b) COP.

In addition to the energy saving during operation, the use of the natural refrigerant R290 also allows to reduce the direct emissions related to possible refrigerant leakages to negligible values, thus reducing the overall carbon footprint of this kind of systems over their entire life cycle. Furthermore, numerical simulations suggest that the refrigeration unit can operate with a quantity of propane lower than 150 g, limiting the need for risk assessment or specific precautionary measures related to the flammability of the refrigerant.

Notably, the reduction in the overall carbon footprint of the proposed solution compared to the baseline system is mainly attributed to the elimination of direct emissions linked to synthetic refrigerant leakage (calculated as 15% of the total charge, corresponding to 0.38 kg of R452A, per year), which represent approximately 50-70% of the total carbon emissions of the baseline system, depending on climatic zone. In fact, the baseline system was already powered by grid electricity; therefore, the emission reduction due to primary energy consumption is only affected by the variation of the unit efficiency, since baseline and new systems share the same primary energy source.

Experimental assessment of natural refrigerant cooling unit

The R290 system has been manufactured, installed in the laboratories of the industrial partner and experimentally tested following the same methodology described for the R452A system. The same insulated box and eutectic tubes are maintained from the R452A system, while the refrigeration unit has been updated from the baseline R452A to the propane one, shown in Figure 14.

Figure 14. R290 cooling unit installed in the lab.

The experimental results are presented in Figure 15. The R290 compressor selected for the novel cooling unit is characterized by a larger size and capacity compared to the R452A compressor employed in the test presented in Figure 12. This leads to an increase of the overall pulldown energy consumption (25.5 kWh_{el}), but at the same time to an increase of the total cooling energy provided to the eutectic tubes. In fact, it can be observed comparing Figure 12 and Figure 15 that the internal air inside the insulated box is significantly colder with the novel R290 unit compared to the baseline R452A one. Moreover, it is also highlighted that the period of time in which the internal air temperature is kept below the threshold of -20°C after the unit is turned off increases substantially with the R290 unit, confirming a higher amount of cooling energy stored in the eutectic tubes.

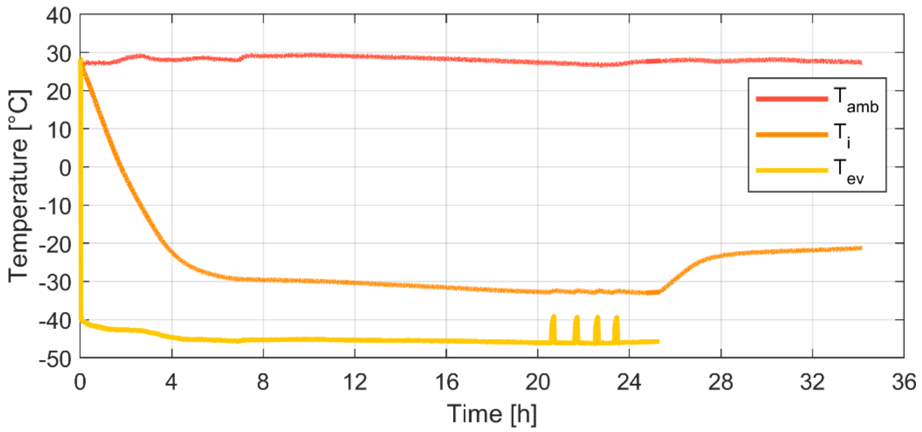


Figure 15. Experimental test on novel R290 system with eutectic tubes: ambient temperature, air temperature inside the insulated box, evaporation temperature of the refrigerant.

Therefore, to compare the baseline R452A system and the novel R290 system, an autonomy-specific energy consumption of the cooling units per hour of autonomy below the threshold temperature is calculated.

The R452A unit presents an energy consumption of 14.3 kWh_{el}, with an autonomy below -20°C after the end of the pulldown of 7.5 h, leading to an autonomy-specific energy consumption of 1.91 kWh_{el} h^{-1}. Conversely, in the R290 test the air temperature is expected to reach -20°C 14.5h after the end of pulldown (Figure 16). The energy consumption during the pulldown is equal to 25.5 kWh_{el}, leading to an autonomy-specific energy consumption of 1.76 kWh_{el} h^{-1}., with a reduction compared to the baseline R452A unit equal to -7.9%.

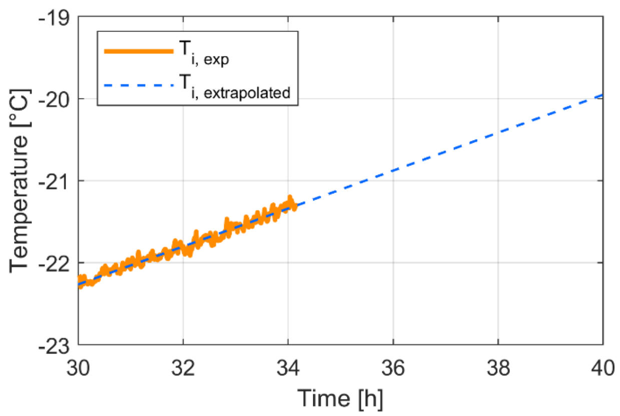


Figure 16. Time autonomy with internal air temperature below -20°C, extrapolated based on experimental R290 test measurements.

Publications

The following publications provide more in-depth information to the system, the experimental tests and the numerical analysis:

- Fabris, F., Minetto, S., Marinetti, S., Rossetti, A. (2024). Numerical characterization of a propane-CO2 refrigeration system developed for TES last-mile delivery. 8th IIR International Conference on Sustainability and the Cold Chain, June 9-11 2024, Tokyo, Japan. https://doi.org/10.5281/zenodo.13985656

- Fabris, F., Shah, W., Marinetti, S., Minetto, S., Rossetti, A. (2025). A novel propane-CO2 refrigeration system for mobile insulated boxes in last mile delivery. International Journal of Refrigeration. *(UNDER REVIEW).*
- Fabris, F., Minetto, S., Marinetti, S., Rossetti, A. (2024). Numerical evaluation of a propane cooling unit for transportable insulated boxes equipped with eutectic tube TES. 1st IIR International Conference on Refrigeration Adapting to Rising Temperatures, August 10-13 2025, Manchester, UK. *(ACCEPTED FOR ORAL PRESENTATION).*

6.4 Impacts

The demonstrator focused on developing a compact, efficient and sustainable solution to improve the cold chain resilience and to allow environmentally friendly last-mile delivery of frozen products in urban areas, by employing thermal energy storage and a natural refrigerant-based cooling unit.

The presented solution allows to completely avoid the use of fossil fuels. The TES also allows temperature-controlled transportation in non-specialized vehicles. In case electric vehicles are employed for transportation, this solution does not impact on the vehicle driving autonomy, thanks to the TES passive refrigeration effect during transport. Local emissions and noise during deliveries are also avoided, making this a suitable solution for last-mile deliveries in Zero Emission Zones (ZEZ).

The employment of the natural refrigerant (propane) cooling unit leads to the double advantage of increasing the overall system efficiency during operation by reducing the primary energy consumption and reducing to negligible values the direct emissions due to refrigerant leakages by replacing the currently used synthetic refrigerant R452A.

A quantitative assessment of the primary energy saving and of the emissions reduction derived by the implementation of the solution developed in Demo 8 in various European climatic conditions is reported in Section 7.

6.5 Business potential

The market of light commercial vehicles, especially in highly populated urban areas, often characterized by the presence of Zero-Emission Zones in which pollutant and noise emissions are strictly limited, is rapidly moving towards hybrid/electric power. Moreover, flexibility and resilience in logistics management are a crucial goal for the stakeholders, as the optimization and reduction of delivery routes, the maximization of the vehicle's driving autonomy and the possibility of simultaneous transport of different types of products might result in significant environmental and economic advantages.

The system developed in this demonstrator provides a solution that can allow simultaneous transport of refrigerated and non-refrigerated products in a standard truck, as the insulated box equipped with TES can occupy only part of the total transport capacity of the vehicle, thus providing significant flexibility to logistic companies in their fleet management. Moreover, the passive refrigeration provided by the eutectic solution, frozen by means of grid electricity when the vehicle is parked in the depot before deliveries, can help increasing electric vehicles driving autonomy, as the refrigerated box does not require any power draw during missions.

Logistics and delivery companies aiming to reduce their overall carbon footprint and to comply with Zero-Emission Zones restrictions in city centres might be the primary customers for this solution, followed by retailers focused on sustainable supply chains or fleet managers seeking to increase the efficiency of electric vehicles. On a rural and agricultural context, this kind of units might also be employed by farmer cooperatives to avoid high-quality agricultural products loss and waste.

GENERAL CONCLUSIONS

7 GENERAL KPIS/IMPACT

The application of natural fluids to transport refrigeration unit has been demonstrated in two different applications.

Primary energy savings

The use of properly designed thermodynamic cycle and components can guarantee an increase in performance compared to baseline synthetic units. This results in a saving of energy used by the unit that in case of the DEMO 7 varies from 12% to 13% depending on the reference climatic conditions while DEMO 8 energy savings are 9%, as presented in detail in Figure 17.

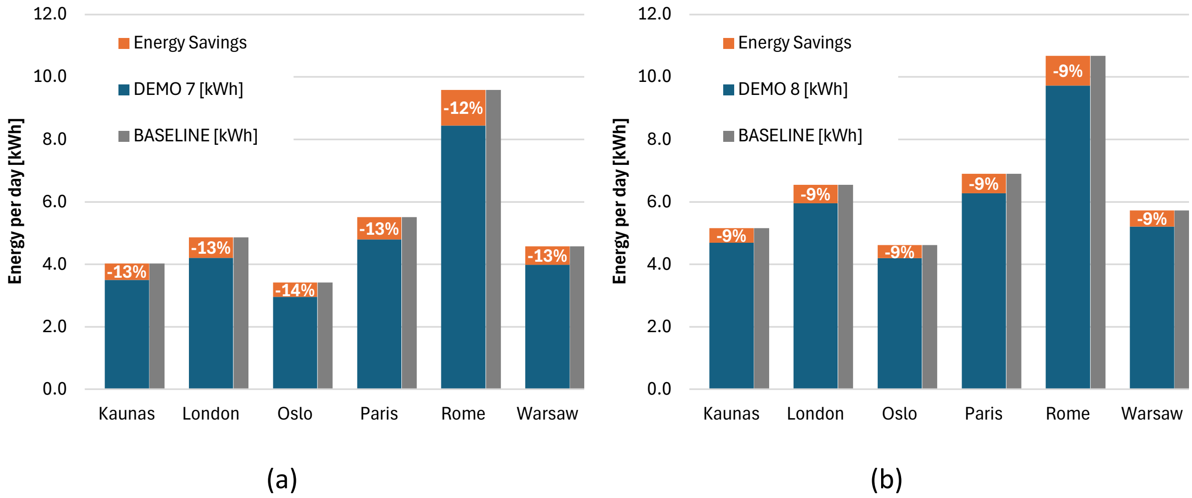


Figure 17. Average yearly energy consumption (for a daily mission) in different European cities: a) DEMO 7; b) DEMO 8.

Emissions

Figure 18 presents the emissions savings (yearly average for a daily mission) obtained by the two demonstrators. The impact of refrigerant leakage is an important share of the transport refrigeration unit footprint. The use of natural refrigerant can reduce this source of GHG to a negligible amount. The saving associated to this change amounts to 22% to 44% of the total operational emissions for DEMO 7 and 46% to 67% for DEMO8.

Electrification of the cooling unit play an important role in DEMO 7, as it allows to reduce the GHG operational emissions by 31% to 44%. This contribution is not present in DEMO 8 as the baseline, in this case, is already powered by grid electricity.

The relative impact of energy saving in terms of GHG appears here to be reduced, as it is normalized over the whole unit operational carbon footprint (energy related emissions + direct leakages emissions).

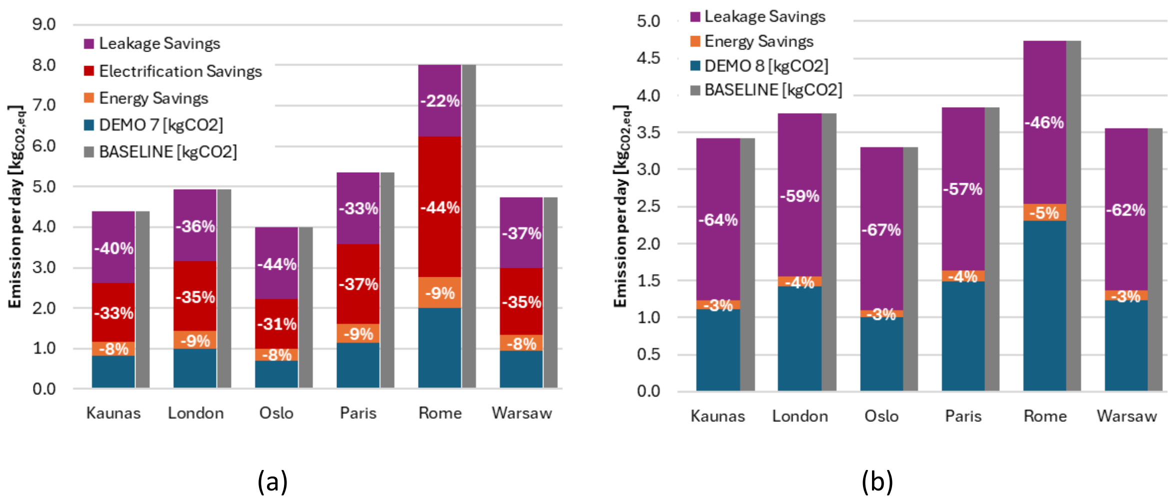


Figure 18. Average yearly GHG emissions (for a daily mission) in different European cities: a) DEMO 7; b) DEMO 8.

Air quality in city centre and densely populated areas

Both demonstrators succeed in the objective of improving the localized air quality and in urban areas as both demonstrators are characterized by zero local emissions. In DEMO 7, the refrigeration unit is driven by electricity, avoiding the emissions related to combustion engine. DEMO 8, thanks to the use of thermal energy storage do not require any energy input during transport, leading not only to zero local emissions, but also to a noiseless operation.

Renewables

Furthermore, DEMO 7 demonstrates the application of solar panel to light refrigerated commercial vehicles as a practical way to reduce the power drawn by the unit from the electrical vehicle, preserving thus the vehicle driving autonomy.

Conclusions

In conclusion, the demonstrator activities proved that technological solutions to realize efficient and sustainable transport refrigeration systems for short-range delivery can be developed and realized in today's market, as they are characterized by a high technological readiness level.

8 DISSEMINATION AND COMMUNICATION

Several dissemination and communication activities were realized, covering a wide range of audience, ranging from scientific and academic audience through international congresses, to stakeholders and important actors in the industry and in the market through sector fairs and seminars, to the general public through open seminars, researchers' nights and events hold in city centres. A list of the events in which the transport demonstrators were presented is reported here:

- 15th IIR-Gustav Lorentzen conference on Natural Refrigerants, 13-15/06/2022, Trondheim, Norway.
- 10th IIR Conference on Ammonia and CO_2 Refrigeration Technologies, 27-29/04/2023, Ohrid, North Macedonia.
- 26th International Congress of Refrigeration, 21-25/08/2023, Paris, France.
- "How to improve the sustainability of the cold chain?", ENOUGH webinar, online, 07/12/2023.

- 8th IIR International Conference on Sustainability and the Cold Chain, 09-11/06/2024, Tokyo, Japan.
- 16th IIR-Gustav Lorentzen conference on Natural Refrigerants, 11-14/08/2024, College Park, Maryland, USA.
- Nanoinnovation 2024, “Hybrid energy storage for mobility” (joint with ENEA & EERA Joint Programme Energy Storage), 09-13/09/2024, Rome, Italy.
- Industry Workshop “ENOUGH industry workshop: demonstrating solutions for minimizing emissions from food supply chains”, 19/09/2024, Leuven, Belgium.
- European Researchers’ Night, “Science 4 All – Energia Termica e decarbonizzazione”, 29/09/2024, Padova, Italy.
- Arneg World Refrigeration Workshops 2024, 11/10/2024, Campo San Martino, Italy.
- Thermal Energy Storage Workshop 2024, 05-06/11/2024, Trondheim, Norway.
- “The Latest Technologies in Refrigeration, Air Conditioning and Heat Pumps”, Centro Studi Galileo, 12-13/06/2025, Milano, Italy.
- 1st IIR International Conference on Refrigeration Adapting to Rising Temperatures, 10-13/08/2025, Manchester, UK.

9 GENERAL FUTURE OUTLOOK

In the latest years, the refrigerated transport sector has been experiencing a significantly slower and less developed ecological transition compared to other refrigeration sectors, such as commercial refrigeration or industrial applications, due to the combination of a high quantity of old equipment being still in use, more permissive refrigerant phase-down timelines and a limited market size compared to the above-mentioned sectors, leading to refrigeration equipment manufacturers to develop less components specifically dedicated to this kind of application. Therefore, the vast majority of transport refrigeration units are still based on fossil fuel power (either from the vehicle main engine or from a dedicated engine) and on synthetic refrigerants.

To help the development towards carbon neutrality in the refrigerated transport sector within the next 15 years, the solutions proposed and tested in the transport demonstrators show that electricity-based and environmentally friendly units can be already developed and can lead to energetic, economic and environmental savings compared to traditional systems. It is hoped that the proposed solutions can convince stakeholders, components manufacturers and final users on the feasibility of this ecological transition.

Significant effort must be put to communicate that energetic advantages and long-term sustainability can be achieved with this transition, and to overcome the scepticism and resistance of the stakeholders, who initially might be not willing to part from cheap, well-known and widespread synthetic refrigerant-based equipment, and be not familiar with the use and peculiarities of natural working fluids, requiring proper knowledge from the unit designers and adequate training for the maintenance operators.

The proposed solutions mainly address light commercial vehicles and short-range deliveries in urban contexts. However, based on the project results other solutions could be developed in the upcoming years for different applications, such as medium/heavy commercial vehicles and semi-trailers, or multi-temperature vehicles.

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