Energy efficiency measures for refrigeration systems in the cold chain

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Abstract: The refrigeration industry plays a major role in the global economy and has significant contributions in the energy and environmental domains which stakeholders need to better take into account. In particular, the electricity consumption for refrigeration and air conditioning increased over the last few years, reaching about 17% of the electricity worldwide used, and it is expected to further grow. In cold chains, an accurate refrigeration is required to ensure an optimal preservation of perishable goods and, in the food sector, it can be responsible for up to 85% of the total energy consumption, depending on the specific foodstuff considered. Refrigeration has relevant adverse effects on the environment. It is responsible of direct emissions due to leakage of fluorocarbons, and indirect emissions produced by fossil fuel power plants. Energy efficiency improvements of refrigeration systems represent a noteworthy solution for reducing the environmental impacts and can be obtained by investing in new and more efficient technologies, or by implementing simple and less expensive maintenance and operational practices. In addition to energy savings, and the consequent reduction of energy costs and greenhouse gas emissions, these measures have the potential to introduce multiple benefits, such as reduced operation and maintenance costs, and improved reliability and productivity. This work aims to investigate possible eco-efficient solutions related to the refrigeration systems and to briefly evaluate the related barriers and benefits. In particular, the study will be based on a holistic perspective on the life cycle of the perishable products which considers the whole cold chains including transport and storage activities.

Keywords: Eco-efficiency; cold chain; refrigeration; energy efficiency; life cycle.

1. Introduction

In recent years, the refrigeration industry is playing a major role in the global economy. Almost 12 million people are worldwide employed in this sector, and the employment rate is expected to further grow, faster than the average of all occupations (International Institute of Refrigeration, 2015). However, cold chains, which are based on refrigerated technologies, have significant global warming impacts due to the high energy consumption and to the refrigerants leakage into the atmosphere (Gwanpua *et al.*, 2015). The electricity consumption for refrigeration and air conditioning increased over the last few years in both developed and developing countries, reaching about 17% of the electricity worldwide used, even though the energy efficiency of refrigerated equipment is constantly progressing. Furthermore, this share is expected to grow in the coming years because of an increasing demand of goods requiring refrigeration and of higher requirements imposed by quality, hygiene and safety standards. For instance, a 60% increase of food demand is expected by 2050 (EU Food & Drink Industry, 2018). At the same time, the recent climate change increases the likelihood of more extreme temperatures and unpredictable weather events, which affects the production process of perishable products and requires for more refrigeration. Refrigeration technologies have been recently considered as a mean for capturing CO_2 from power stations and industrial plants, and they can enable the liquefaction of CO_2 for the underground storage. Moreover, new technologies are more and more environmental-friendly and are, generally, powered by renewable energy sources. However, refrigeration presents also several adverse environmental effects which should be addressed. 20% of its global-warming impact is due to direct emissions form the leakage of fluorocarbons (i.e., CFCs, HCFCs and HFCs). While, the remaining 80% comes from indirect emissions produced by fossil fuel power plants for the electricity generation required to power the systems (Coulomb, 2008; James and James, 2010). Indeed, nowadays, 84% of heating and cooling is still generated from fossil fuels, while only 16% comes from renewable energy. In the industrial sector, refrigeration is crucial especially for perishable products, e.g. in the food production, since it ensures the optimal preservation and provides consumers with safe and wholesome products. In particular, the primary focus is on cold chain of chilled and frozen food products since their main shelf-life is highly affected by the temperature at which they are preserved. Furthermore, logistics and warehousing activities of these goods are the activities that mostly consume energy and impact on the environment, since a continuous and ubiquitous refrigeration is necessary throughout the chain, from production to consumers. For instance, around 45% of the overall electricity consumed in supermarkets is used by refrigeration systems for chilled and frozen food storage in display cabinets and cold rooms (Energy Star, 2008). This share can grow up to 85% of energy consumption depending on the industrial sector considered (Table 1). Since refrigeration systems are highly energy-intensive, electricity costs account for a relevant share of the running costs of these businesses.

Table 1: Share of the electricity used for refrigeration in the food and beverage sector (Sustainability Victoria, 2008)

Industrial Sector	Electricity share for refrigeration (%)
Liquid milk processing	25%
Breweries	35%
Confectionery	40%
Chilled ready meals	50%
Frozen food	60%
Cold storage	85%

In order to fulfil the EU's climate and energy goals, the heating and cooling sector must sharply reduce its energy consumption and cut the dependence on fossil fuels. The refrigeration stakeholders are hence implementing actions to fight global warming focusing on two main objectives: i.e., (i) the reduction of direct emissions of fluorocarbons in the atmosphere through better containment of refrigerants, refrigerant-charge reduction, development of alternative refrigerants with negligible or no climate impact, design of alternative technologies to the traditional vapour-compression system, and training and certification of technicians, and (ii) the improvement of the energy efficiency of refrigeration systems in order to reduce their primary energy use. In light of this, Energy Efficiency Measures (EEMs) have a great potential for introducing noteworthy economic, environmental, and social benefits. In addition to energy savings, which represent their main purpose, other multiple sustainable benefits can be achieved, namely non-energy benefits (NEBs), such as reduced resource consumption and lower greenhouse gas (GHG) emissions (IEA, 2014). These EEMs range from the investment in new and more performant technologies, to the implementation of simpler and less expensive maintenance and operational practices for the refrigeration system and the overall production process. A holistic viewpoint of the cold chain over the life cycle of the products can generate a positive pressure on sustainability by spreading costs and risks across supply chain actors, by decreasing the issues due to conflicting priorities of financial targets, and by enabling the overcoming of the main barrier against the implementation of EEMs (Marchi and Zanoni, 2017). Furthermore, it allows to identify additional opportunities which can be hidden in a single company perspective. To the best knowledge of the authors, currently there are no studies in literature investigating EEMs focused on refrigeration systems and cold chains. Aim of the present work is, thus, to provide a summary of the most relevant energy efficient practices for this specific context. The remainder of the paper is organized as follows. Section 2 presents the standards for the measure and evaluation of the energy efficiency of refrigeration equipment and systems. In Section 3, the energy savings opportunities in the cold chain are identified and investigated. Section 4 provides a case study focused on the energy efficiency improvement of refrigerated transportation activities obtainable with refrigerated portable units. Finally, Section 5 summarizes the main findings of this work.

2. Measures of energy efficiency for refrigeration equipment and systems

Traditionally, the energy efficiency of cooling equipment is measured through the Energy Efficiency Ratio (EER), which is defined by the ratio of the output cooling energy (BTU) to the input electrical energy (W h) at a given operating point. EER is generally calculated using a temperature of 95 °F outside and of 80 °F inside (actually return air) with 50% relative humidity. From the EER, it is possible to obtain the coefficient of performance (COP), as defined in Eq. (1), which is a unit-less measure commonly used in thermodynamics.

$$EER = 3.41214 \times COP \tag{1}$$

where 3.41214 represents the conversion factor from BTU/h to Watts. However, refrigeration systems are usually used at their rated power, i.e. in a full load condition, for only a limited period of time in a year. In order to have a better estimation of the actual efficiency, a number of seasonal efficiency indexes have been introduced taking into account the partial load conditions, since they are much more representative parameters for the evaluation of the unit energy consumption per year. Among these indexes, the most known and used in Europe is the Seasonal Energy Efficiency Ratio (SEER). The SEER is a representative measurement of how the system behaves over a season where the outdoor temperature varies and is obtained as the weighed mean of efficiency ratios realized by the refrigeration equipment at various load nominal steps (e.g., 25%, 50%, 75% and 100%).

3. Energy savings opportunities in refrigeration systems and cold chains

Cold chains are responsible for the preservation and transportation of perishable goods (e.g., chilled and frozen foods, and pharmaceutical products), which need to be kept in a refrigerated state along the supply chain to slow deterioration and to deliver safe and high-quality products to consumers. These products, generally, have a shorter shelf life and higher sensitivity to the surrounding environment (i.e., temperature, humidity, and light intensity). Hence, they must be distributed within a specified time and require special equipment and facilities (e.g., refrigeration and dehumidification systems) throughout the entire cold chain, from sale, storage and distribution, in order to maintain the prescribed environmental conditions (Laguerre, Hoang and Gennes, 2013). The cold chain can last for short periods, as few hours, or for several months or even years (e.g., frozen food products) depending on the specific product and the target market (Gogou *et al.*, 2015). In order to properly manage these peculiar supply chains, the concept of cold chain management (CCM) was introduced which is defined as the process of planning, implementing, and controlling the efficient and effective flow and storage of perishable goods, and related services and information from one or more points of origin to production, distribution and consumption (Bogataj, Bogataj and Vodopivec, 2005). The cold chain management focuses also on the management of the energy consumptions due to the huge refrigeration requirements. The implementation of EEMs allows to reduce the considerable energy consumptions related to the refrigeration systems, and the waste of products which entails the loss of the energy consumed for processing and storing the goods, the production of methane and other GHGs during degradation, and the societal impact of wasting resources (Gwanpua *et al.*, 2015). These measures introduce also additional multiple benefits: e.g., reduced operation and maintenance costs, increased profitability, reduced vulnerability to energy price fluctuations, improved system reliability, improved safety, increased productivity, better matching of refrigeration load and equipment capacity, reduced resource consumption and GHG emissions, and enhanced public image (Sustainability Victoria, 2008; IEA, 2014). Industrial EEMs can be summarized into the following three categories (Thiede, Posselt and Herrmann, 2013): measures concerning the design and control of machines as well as process parameters; actions concerning the production planning and control, aiming at improving energy and resource efficiency ranging from the avoidance of consumption peaks to the optimal usage of equipment; and measures related to the technical building services, which are responsible for an efficient supply of the required form of energy and resources ensuring optimal operation and environment conditions. Technical improvements of refrigeration systems components can achieve a potential reduction of the energy consumption between 15% and 40%, while improvements in maintenance and operating practices in the facilities can often provide a reduction of about 15%, or even more, with less expensive efforts. The following subsections are focused on the different types of EEMs: i.e., technology solutions, maintenance practices, and operation and energy management in the cold chain.

3.1 Technology solutions

The performance of refrigeration systems is related to the design of the same (e.g., technologies, refrigerant choice, system design and selection), and greatly affects the CO_2 emissions (Söğüt, 2015). There is a wide range of possible design modifications for reducing the refrigeration power, which can be grouped into changes in the structure and in the refrigerant composition, alternative refrigeration technologies and applications, and adjustments of the operating conditions. The type of refrigerant can affect the efficiency of a system by up to 10%. At present, the HFC R404A and R507A are still the mostly utilized refrigerants, as substitutes of the ozone-depleting HCFC R22 and R502, even though they still present low energy performance and high global warming potential (GWP). However, the European F-gas regulation No 517/2014 of the European Parliament imposed the phasing out of high GWP refrigerants in order to reduce GHG direct emissions. Currently, "natural" refrigerants (e.g., ammonia) are the most promising alternatives since they are environmentally friendly refrigerants with a GWP equal to zero (Cardoso *et al.*, 2017). Energy consumptions can also be reduced by upgrading heating and cooling equipment to the latest, most efficient technologies. In accordance with the technology, refrigerating systems can be categorized into (US DOE, 2014): mechanical refrigerating systems (e.g., vapour-compression systems), thermal refrigerating systems (e.g., absorption system, adsorption and thermochemical system), solid-state refrigeration systems (e.g., magnetocaloric and thermoelectric), and electro-mechanical refrigeration system (e.g., thermoacoustic and thermoelastic). Vapour-compression systems are by far the most widely used, due to their flexibility: i.e., the refrigeration load may be switched on/off, and the capacity modulated through the installation of an inverter to set the required temperature. However, this flexibility comes at a cost in terms of performance, since the refrigeration system are optimized for operating at full load while, actually, they operate over a wide range of loads. There are new promising refrigeration systems and applications based on non-vapour-compression technologies that will play important roles in ensuring a sustainable development, such as absorption and adsorption cooling systems, solar refrigeration, desiccant technologies, and trigeneration. The rated efficiency of these technologies is lower with respect to the mechanical ones. However, they can exploit the heat dissipated by the components to power on the system through heat recovery. For instance, (Zhao *et al.*, 2016) presented a NH_3 heat pump for heat recovering from low temperature refrigeration system. Another way to improve energy efficiency consists in providing better information to users and monitoring the energy loads with intelligent devices and sensors. The devices based on the Big Data and Blockchain concepts, connected through the Internet of Things (IoT) technologies, allow to implement real-time monitoring systems which, integrated to the logistic system, enable the centralization, traceability and accessibility to all the relevant information for each stakeholder and the record of large amounts of data (Tsang *et al.*, 2017). Automated products tracing in the supply chain is possible, for example, with radio frequency identification (RFID) technology and wireless sensor networks. To gather information from RFID tags, a reader connected to the Internet is necessary. IoT technologies can bridge the communication gap between the objects and users, supporting the decision making process, and make possible to address environmental concerns by reducing the consumption of energy and other resources (Shih and Wang, 2016). Energy efficiency and Renewable Energy Sources (RESs), such as photovoltaic power generation, are strictly connected, since the distributed generation based on renewables technologies can reach higher energy performance, for instance, by lowering the high losses that characterise the distribution grid. Furthermore, the integration of RES can provide cost-efficient means for reducing electricity requirements from the grid especially for refrigerated supply chains (Fikiin *et al.*, 2017; Meneghetti, Dal Magro and Simeoni, 2018). In addition, through the installation of electrical and thermal Energy Storage System (ESS), it is also possible to increase the hosting capacity of renewables since they allow to overcome or, at least mitigate, the main drawbacks of RES caused by their intermittency and uncertainty. The main applications of ESSs (i.e., load shifting and peak shaving) allow to shift refrigeration loads from peak to low consumption periods, increasing the self-consumption share and, consequently, reducing the environmental impacts and economic costs due to the lower purchase of energy generated from fossil fuels (Marchi et al., 2016). However, the benefits introduced and the return of the investment are strictly dependent on the electricity tariff (Marchi et al., 2017). Despite the growing maturity and availability, the improved reliability, and the more cost-competitiveness, the diffusion of these new technologies has still to overcome the resistance of several barriers to become fully spread solutions, such as the lack of knowledge and awareness and other social, organizational or political factors (May *et al.*, 2018).

3.2 Maintenance practices

A refrigeration system frequently runs inefficiently since the actual system requirements differ from the nominal design conditions. The actual condition of the refrigeration equipment has also a substantial effect on the energy consumption (Knowles and Baglee, 2012). There are several challenges to improve system efficiency through the training of maintenance operators for energy efficiency and simple maintenance practices, such as reviewing the insulation and the coolant distribution system (e.g., check if the pump system flexibility responds to variable refrigeration loads and if the insulation is in good order), optimising the maintenance activities, repairing doors seals and curtains, ensuring that doors can be closed, and cleaning the condensers (Sustainability Victoria, 2008). In particular, uninsulated or poorly insulated coolant pipes can absorb heat from their surroundings affecting the performance of the refrigeration system. In fact, the system heat gain increases the temperature of the evaporator and, consequently, the energy consumption in the compressor. Insulation should also be regularly inspected for moisture ingress, as this can form ice on the pipework, further damaging any insulation. Then, evaporator coils should be regularly cleaned since the build-up of dirt and ice on evaporator coils slows down the rate of heat transfer and causes an increase in the energy consumption for keeping the same temperature. Furthermore, refrigerant leakages, which mainly occurs for pipe or joint failure and leaking seal/gland/core in the compressor pack and the high pressure liquid line, increase the operational costs (e.g., refrigerant refilling), the electricity consumption and the CO_2 emissions, highly reducing the system efficiency and impacting on the climate change (Francis *et al.*, 2017). Hence, the improvement of design, installation and maintenance of pipework and valves, the replacement of worn seals and gaskets on refrigerator and freezer doors, the installation of automatic door closers and/or strip curtains to walk-in doors, and the use of night covers on both vertical and horizontal display cabinet are solutions that potentially can improve the insulation of the distribution system. To avoid efficiency issues, procedures for monitoring and testing the performance of the overall system, as well as of the system components, should be regularly implemented (Knowles and Baglee, 2012). These maintenance practices should be routinely done, as they can allow to identify problems in an early stage which avoids larger energy consumptions. In addition, installing gauges and switches on filters and valves allow to monitor and control the operations and to alert workers when system pressure drops, or other malfunctions occur.

3.3 Operation and energy management in cold chains

Cold chains are usually characterized by severe operating conditions. Perishable goods are usually affected by a significant variability in several parameters, among which the temperature represents the most relevant factor. A failure to keep perishable items in a suitable environment or to ensure on-time delivery to customers leads to a waste of resources. In particular, in food supply chains, the temperature has a substantial impact on the risk of spoilage, on the shelf life of the products, and ultimately even on the quality of the product (Laguerre, Hoang and Gennes, 2013). This variability affects different stages of the production process, from the raw material to the consumers, as well as different storage locations within a shipment or in the display cabinets of the retailers. For instance, Raab et al., (2008) showed temperature differences of approximately 10 °C at different places in the truck. Hence, it is necessary to continuously monitor and control the process parameters in order to keep the appropriate environment along the cold chain, since random measurements (e.g., at incoming inspections) do not reveal the temperature history of the product. The CCM deals with the optimisation of logistics, supporting the decision-making process and increasing the information exchange among the different actors. CCM takes into account both the inter- and intra-organizational complexity of the process. Moving the focus from one company to the entire chain, it includes aspects of interdependencies between organizations (e.g., producers, suppliers, customers, transport companies, warehouse and retailers) which are based on horizontal as well as vertical collaborations and coordination. This holistic approach that considers the life cycle of the goods, with real-time information, can prevent waste, improve the economic performance and reduce the environmental impact. Hence, a significant challenge for an efficient cold chain deals with the different requirements of perishable products in terms of optimal temperature ranges in order to maximize their shelf-life and commercial potential by ensuring, at the same time, safety along the supply chain (Mercier *et al.*, 2017). Moreover, often different types of perishable products are shipped in the same refrigerated vehicle and, consequently, the inside temperature has to be a compromise between different requirements (Bijwaard, Havinga and Kleiboer, 2011). The efficiency of the cold chain is often less than ideal, as temperature abuses and fluctuations above or below the optimal product-specific temperature range occur frequently and are the main reasons for product returns and financial losses. This situation significantly increases resources waste, and, at the same time, it results in an increase in the energy used by the refrigeration systems. The quality of the perishable products tackles a trade-off with energy consumptions: the higher the refrigeration, the higher the quality preservation, but the higher the energy consumption with a consequent increase in costs and GHGs emissions. In particular, temperature abuses are notably in storage (such as display cabinets), transport activities and domestic refrigeration (Laguerre *et al.*, 2014; Ndraha *et al.*, 2018). A high rate of temperature abuse occurrence indicates that the operators of the cold chain have a limited knowledge of temperature control. In order to better manage the energy consumption, firstly, it should be assessed the cooling load and requirements throughout the chain. Making a comprehensive list of products and cooling processes, and their specific cooling requirements, helps to understand what the theoretical refrigeration load should be. In this way, it is possible to plan an optimized energy balance for the refrigeration systems. Then, the real time monitoring and control of the most relevant parameters affecting the quality of the perishable goods along the cold chain (e.g., temperature, pressure, and humidity), as well as the implementation of energy management systems, represent a key role in improving of the overall efficiency. The implementation of an effective management systems based on real-time measurement requires a holistic approach in which the actions of each stakeholder in response to a parameter deviation are coordinated to create a responsive and flexible chain. The major challenges of these management systems stem for the presence of various stakeholders. In particular, these interorganizational challenges deal with the share of cost and benefits among the stakeholders, and the creation of harmonized and synchronized information-sharing channels throughout the cold chain. However, the heterogeneity in the supply chain, that significantly affects the shelf-life of the products, makes the implementation of inventory management systems based on time-temperature measurement much more complex. Another lever for the energy efficiency improvement deals with the study of the optimal inventory policy and replenishment quantity by taking into account the energy performance, the process and product quality of the whole supply chain (Marchi *et al.*, 2019; Marchi, Zanoni and Jaber, 2019). In particular, (Zanoni and Zavanella, 2012) proposed a model aiming at studying the optimal replenishment quantities along the cold chain, considering the energy effort in the production process, and along the distribution channel for the preservation of the food quality at the required temperature. Furthermore, the supply chain perspective allows to increase the implementation rate of EEMs (Marchi et al., 2018a) and to enable the potential of integrated waste heat recovery (Marchi et al., 2018b).

4. Case study: energy efficient transportation and storage with portable refrigerated units

Today globalisation results in long distances travelled and duration of land transportation. Moreover, transport refrigeration systems operate in a harsh environment and undergo a wide range of cooling demand and constraints. While, inside the refrigerated vehicle, there are substantial temperature differences caused by the air distribution. Hence, in cold chains, keeping the temperature of perishable goods in the desired range during the transportation activities is critical. There are many factors affecting the performance and design of the transportation unit, such as extreme exterior weather conditions, desired interior conditions, insulation properties, infiltration of air and moisture, trade-offs between construction and operating costs and physical deterioration from shocks and vibrations. Furthermore, there are some logistic activities that lead to air infiltration with remarkable increase of the cooling demand and, consequently, of the energy usage, which may also affect the product temperature and quality: e.g., frequent temporary opening of the vehicle doors for the delivery of the products, temporary interruptions of the refrigeration function due to engine power off, loading and unloading of the products (Carullo *et al.*, 2009). For instance, a food product can be subject to about 50 door-openings during a multi-drop delivery (James, James and Evans, 2006). While, ground operations for loading and unloading products frequently report increases in temperature due to the length of time that pallets are kept at inappropriate ambient temperatures waiting for material handling activities. As a result, these systems have lower COP than the stationary systems. In addition, the increasing quantity of transported goods and of home deliveries, and the higher quality expectations of customers, bring to an increased use of refrigeration in order to reach lower temperatures, which result in tremendous amount of energy consumption (Tassou, De-Lille and Ge, 2009). As a consequence, the stakeholders' awareness on these significant environmental impacts put an increasing demand for the definition of new solutions for more sustainable refrigerated transport activities. Recently, a portable refrigerated unit (PRU) has been proposed as a new solution for overcoming, or at least mitigating, the previously defined issues (Ferretti, Mazzoldi and Zanoni, 2018). The PRU is an active transportable insulated and refrigerated unit designed and produced by the company Euroengel Srl. These units can be powered through: (i) a direct connection to the 12V or 24V batteries of the vehicle, (ii) an integrated AC/DC power supply for connection on AC mains, and (iii) a battery pack installed to the unit for a cooling autonomy of about 36 hours. This solution is widely accepted by logistic operators since it introduces several advantages (Ferretti, Mazzoldi and Zanoni, 2018). For instance, PRU units allow to deliver perishable products to destinations not supported by a refrigerated hub, with faster transit and lower costs, in full respect of products' quality and cold chain international regulations. Their employment gives also the opportunity to logistic companies to enter the “refrigerated” market or to improve their fleet, in terms of performance and value, without expensive and irreversible investments for purchasing specialized refrigerated fleets and warehouses.

For the case study we consider a multi-drop delivery route which covers a distance of 500 km in about 10 h. The freight service provider faces a demand of 5,000 kg/year and uses a van with an inside volume of 8 m^3, which can transport 2 PRUs or 3 traditional stock keeping units (SKUs) per trip. The purchasing costs of the van is not differential, the traditional refrigeration system is of 7000 $, while each PRU costs 2500 $. The model for the evaluation of CO_2 emissions and costs, and the additional data required are provided in (Ferretti, Mazzoldi and Zanoni, 2018). In

Figure **1**, the overall CO_2 released in the two scenarios are compared. Specifically, three components are evaluated:

i.e., the emissions due to (i) the electricity generated from vehicle engine, necessary for refrigeration system (traditional solutions) or for PRU and ventilation system (PRU solution), (ii) the refrigerant consumption, and (iii) the fuel consumption for motive function of the vehicle. The use of PRUs instead of the traditional solution leads to lower environmental impact. Specifically, thanks to the lower weight, higher insulation, lower power consumption of the PRUs and lower refrigerant leakage, this solution allows to lower the emissions and the energy utilisation linked to the transport of small loads of perishable goods. Even though the lower capacity increases the number of trips required to satisfy the demand and the consequent emissions related to the fuel consumption.

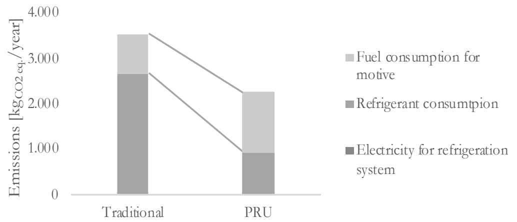

Figure 1. CO_2 emissions for the two transportation modes

The operation costs are obtained by evaluating the following costs components: i.e., fuel consumption cost for the refrigeration system (and ventilation system in the PRU scenario), fuel consumption cost for motive purpose, refrigerant consumption cost. As can be seen in

Figure 2, the PRUs leads to higher annual costs due to the higher number of trips needed to satisfy the yearly demand. However, if we consider a lifetime of 10 years (with a discount rate of 4%) with both purchasing and operation costs, it results that the PRU scenario represents the best solution (Figure 3).

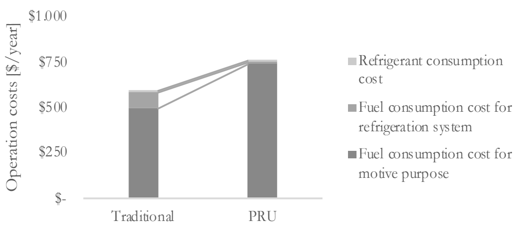

Figure 2. Operation costs for the two transportation modes

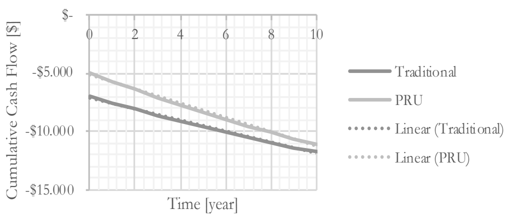

Figure 3. Economic performance of the two transportation modes over a lifetime of 10 years

5. Conclusions and future research

Cold chains are responsible for the preservation and transportation of perishable goods, which need to be kept in a refrigerated state along the supply chain to slow deterioration and to deliver safe and high-quality products to consumers. Refrigeration systems are highly energy consuming and have significant environmental impacts. To reduce these huge impacts, several energy efficiency measures can be implemented, which at the same time can introduce other multiple benefits. Previous studies observed that technological improvements can achieve a potential reduction of the energy consumption between 15% and 40%, while improvements in maintenance and operating practices can provide a reduction of 15%, or even more, with less expensive efforts. The aim of the present work was to investigate the eco-efficient solutions related to refrigeration systems and to briefly examine their related barriers and benefits. This analysis was based on a holistic perspective which considers the cold chain as a whole. Furthermore, a specific case study concerning the use of portable refrigerated units in order to increase the energy efficiency of transportation and storage activities has been introduced. Specifically, this solution was compared with a traditional refrigerated vehicle, in terms of costs and environmental impacts. The analyses can be further improved by considering the quality degradation of goods caused by the frequent temperature variations due the numerous doors opening, and the degradation of the refrigeration equipment.

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