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Assessment of Energy Efficiency Measures in Food Cold Supply Chains: A Dairy Industry Case Study

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Abstract: The quality of human nutrition has acquired significant improvements thanks to the opportunity to store food in suitable temperature conditions. Refrigeration has allowed the slowing of chemical and biological degradation and hence the waste of foodstuff, but at the same time increases energy consumption. These effects impact the environment and the sustainability performance of the cold chain, and drive consumers' choices. The stakeholders of the chain are, therefore, constantly looking for improvement actions to reduce environmental impacts. This paper aims to provide a methodology for prioritizing and assessing the energy efficiency measures for cold chains in terms of quality losses and specific energy consumption, distinguishing between technological, maintenance, and managerial opportunities. This analysis is based on the cold supply chain tool, developed under the H2020 project ICCEE ("Improving Cold Chain Energy Efficiency") which focuses on a holistic approach, not looking only at the individual stages of the cold chain. Furthermore, an economic evaluation has been proposed considering cost savings and the investment needed.

Keywords: cold chains; refrigeration; energy efficiency; sustainability; food

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1. Introduction

Refrigeration has brought significant improvements to the quality of human nutrition, thanks to the possibility of storing perishable products in suitable temperature conditions. The lowering of the temperature of foodstuffs permits the slowdown of chemical and biological degradation and, consequently, lengthens the quality of products over time. While the cold chain has benefits in terms of product conservation, it is equally true that the energy consumption required to maintain low temperatures is high. Energy and resources consumption, as well as food waste, greenhouse gas emissions, and the lack of solid relationships between the players in the supply chain all have a significant impact on the sustainability of the supply chains, an increasingly important issue in consumers' choices. The stakeholders of the chain are, hence, constantly looking for improvement actions to reduce environmental impacts.

The food and beverage industry is the biggest consumer of energy and causes 67% of the greenhouse gas (GHG) emissions from the agri-food sector [1]. The main impacts derive from electricity consumption: worldwide, it is estimated that 17% of electricity is used for refrigeration and air conditioning [2]. The electricity is required for lighting, for the functioning of production plants, refrigeration, and as a driving force for machinery. Further required resources are thermal energy, necessary for the production process and for heating, and water which is mainly needed for cooling, cleaning, washing raw materials and products, producing steam, and as sanitary water. Then there is the environmental issue linked to the consumption of refrigerants and fuel (for transport) which are responsible for a high environmental impact. Transport is responsible for 23% of total CO_2 emissions and most of these are due to road transport (over 70% of transport emissions) (IEA). The refrigeration industry has negative effects on the environment: 20% of the impact on global warming is due to direct emissions resulting from leaks of fluorocarbons present in refrigerants (mainly HFCs), while the residual 80% is due to indirect emissions produced by fossil fuel power plants for electricity [3,4].

The impact of the cold chain on the environment depends also on the number and location of actors contributing to the production and distribution of the goods (i.e., short vs long-chain). Fresh product supply chains are almost always short, leading to the development of local economies, improving environmental performance and increasing transparency to the final consumers. Conversely, long supply chains exploit economies of scale, being generally more efficient, but at the same time face higher impacts on the environment, due to the longer storage and distribution time, which occur on a global scale. Another main issue in a food supply chain is waste: tons of edible food are wasted every year, about a third of global food production and four times the amount needed by 805 million undernourished people in the world. Achieving Zero Hunger by 2030 is the second SDG (Sustainable Development Goal) of the 2030 Agenda for sustainable development, which was approved by all the United Nations (UN) member states in 2015. The 2030 Agenda aims to develop an action plan for ending poverty in all its forms (i.e., for people and the planet). The 2030 Agenda is made up of 17 SDGs, further broken down into 169 targets, to be met by 2030. Each SDG impacts on the economy, the society, and the environment. For instance, considering the second SDG, hunger impacts the social dimension first, but the food wasted impacts also on the other two dimensions (i.e., economy and environment).

The food cold chain, to be defined as sustainable from an environmental, economic, and social point of view, must comply with some obligations, which face more than one SDG. In particular:

- Produce healthy and safe products in response to market demands (SDG 2, 3 and 12),
- Guaranteeing the possibility for all consumers to have accurate information on food products (SDG 2),
- Support the profitability of urban economies (SDG 11),
- Operate within the biological limits of natural resources (SDG 15),
- Achieve high standards of environmental performance by reducing energy consumption, minimizing resource inputs and, where possible, using renewable energy sources (SDG 7 and 13),
- Reduce food waste (SDG 12).

An improved global cold chain would allow a reduction of almost 50% of the CO_2 emissions and avoid also 55% of the food losses attributable to the current cold chain [5]. Energy efficiency represents a key resource for environmental, economic, and social development: in addition to emissions and cost savings, it is possible to obtain advantages such as greater competitiveness and quality, and additional revenues thanks to the increased awareness of the environmental issue by consumers. Therefore, energy efficiency is a strategic advantage for companies and represents one of the main drivers for achieving a corporate sustainability policy. However, many companies (especially small and medium-sized enterprises) are facing an implementation gap mainly due to a lack of capital, knowledge, and awareness in terms of obtainable benefits [6]. The collaboration among supply chain's actors represents an opportunity for overcoming these obstacles and for improving energy performance even for the weakest companies within the chain [7]. Collaboration on the physical, information, and financial flows adds value to each partner and to the whole chain, because risks can be shared, costs can be reduced, and lead times can be shortened. Furthermore, the holistic approach allows us to consider all the relevant costs and benefits introduced through the implementation of energy efficiency measures (EEMs), i.e., the initial cost and the energy savings are only one of the costs and benefits to be considered.

The aim of this paper is to provide an overview of the energy efficiency measures for cold chains, distinguishing between technological, maintenance, and managerial opportunities. Where available, the cost savings and the reduction of the environmental impact of the measures will be highlighted, also considering the presence of additional benefits not directly related to energy consumption. Subsequently, the dairy sector will be taken as a case study, since both raw material and finished product require refrigeration. Using the Cold Supply Chain (CSC) tool, developed under the H2020 project ICCEE ("Improving Cold Chain Energy Efficiency") [8], the beneficial impacts of some energy efficiency measures on the energy consumption of the supply chain will be assessed.

The paper first provides a brief overview on the energy efficiency measures relevant to the cold chain (Section 2). Section 3 defines the methodological approach used for the assessment of these measures. Then, Section 4 provides a case study based on the dairy industry. The paper concludes in Section 5 with a summary, main findings, and suggestions for future research.

2. Energy Efficiency Measures for Cold Chains

The two main targets for improving the sustainability of the cold chain are the reduction of primary energy used from fossil fuels (i.e., through the improvement of energy efficiency and the increase of renewables penetration), and the reduction of direct emissions of fluorocarbons into the atmosphere essentially due to refrigerant leaks. EEMs have excellent potential for introducing a wide range of sustainable benefits in addition to energy savings, namely, non-energy benefits (NEBs). The main ones include [9]: cost reduction and increased profitability; improved working environment; reduced vulnerability to fluctuations of the energy prices; increased sales; reduced spoilage; and enhanced public image. A survey conducted alongside the ICCEE project highlighted that increased productivity seems to play the most recognized role for driving energy efficiency decisions in food cold chains due to its direct economic relevance [10].

The EEMs in cold chains can belong to technical improvements of existing equipment, maintenance practices, or operations management (i.e., practices in the field of cold chain design and management such as temperature adjustment and control along the cold chain, joint deliveries, coordination of inventory, and transportation/delivery management) [11]. Technology solutions are usually more promising in term of energy savings (between 15% and 40% of energy consumption reduction) but at the same time more expensive; improvement in maintenance and operation practices occur at an almost negligible cost and allow significant savings (about 15%). The main measures can be grouped in accordance with the intervention area: i.e., auxiliary technologies, buildings, employee, energy generation and recovery, industrial symbiosis, maintenance, management, monitoring and control, refrigeration system, and transport.

In Table 1, the EEMs as best practices for cold chains are depicted and assessed in terms of energy savings and readiness level. The rating is estimated based on the information and data gathered from the ICCEE project for each specific best practice [12]. Furthermore, a synthetic KPI is proposed as the product of the parameters used for the technologies assessment. Many of the measures introduced appear to be promising; however, as can be observed form the Table, some of them are not yet mature and it is difficult to quantitatively determine the achievable improvement. It should be noted that emissions can be reduced also by using renewable energy sources, an aspect that today only affects 16% of the energy produced, even though they are not properly an EEM.

Table 1. Energy efficiency measures as best practices for cold chains. Notes: for energy saving and readiness level 1: low–3: high, for KPI 1: low potential–9: high potential.

Category	EEM	Energy Saving	Readiness Level	KPI
Auxiliary technology	LED lightening system	3	3	9
	Optimal sizing of the equipment (i.e., motor, pump, drive systems, steam generator)	2	1	2
	More efficient motors	1	3	3
	Use of natural light	1	2	2
	More efficient ventilation system	3	2	6
Building	Wall insulation	3	2	6
	Roof insulation and substitution of the windows	3	2	6
	Warehouse with separated compartments	3	1	3
Employee	Staff training (operators and drivers)	1	2	2
	Increased awareness, responsibility, and active engagement	1	2	2
Energy generation and recovery	Waste heat recovery	3	2	6
	Energy storage system (thermal and/or electrical)	3	2	6
Industrial symbiosis	By-product exchanges	3	1	3
	Sharing of infrastructure, utilities, or access to services (e.g., waste treatment)	2	1	2
	Cooperation on issues of common interest (e.g., sustainability planning)	2	1	2
Maintenance	Regular cleaning of condensers and evaporator coils	1	3	3
	Minimization of compressed air leakages	2	3	6
	Review and optimization of the cooling distribution system	3	2	6
Management	Energy audit	2	2	4
	Exploitation of energy benchmarks, and EnPIs	1	1	1
Monitoring and control	Real-time monitoring system	3	1	3
	Use of automatic control system	3	1	3
Refrigeration system	Usage of alternative refrigerant	3	2	6
	Free cooling	3	2	6
	Alternative refrigerant cycle (e.g., two stages)	3	2	6
Transport	Improved insulation through air barriers	2	3	6
	Optimized travel routes	2	2	4
	Portable refrigerated units	3	2	6
	Use of eutectic plates	2	3	6

3. Methodological Approach

The Cold Supply Chain (CSC) tool has been developed under the European H2020 project ICCEE and is used in this study for the assessment of the cold chain energy consumption and of the impact of the EEMs considered [12].

The purpose of this tool is to investigate the overall specific energy consumption (SEC), i.e., considering the SECs of the logistic activities (storage and transport) and the energy wasted due to the quality losses along the entire cold chain.

The tool considers the energy requirement in storage activities, the energy needs in transport activities and the time-temperature relationship effects on food quality and consequent energy consumption. The sample supply chain consists of seven stages from the raw material supplier to the final retailer (Figure 1). The supply chain under analysis may look different. In that case, it is possible to omit or aggregate input of some stages to match the actual chain.

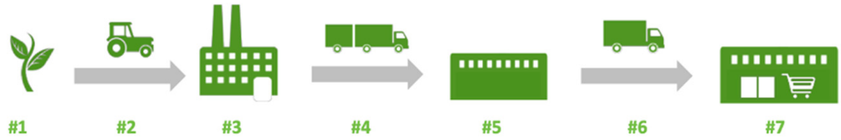

Figure 1. Sample supply chain. #1: raw material supplier, #2: single-drop transport from the supplier to the producer, #3: producer (with raw material and finished product warehouses), #4: single-drop transport from the producer to the distribution center, #5: distribution center, #6: multidrop transport from the distribution center to the retailer, #7: retailer (with a backroom warehouse and a display area).

The data required as input in the tool can be grouped into three categories: general information on the products and cold chain (i.e., type of products, final demand, space occupation of the products, and conversion factor from raw material to finished product), details on the storage activities (i.e., average internal and external temperatures, annual consumption of each energy carrier required for refrigeration, storage size, average warehouse utilization, average storage time, production rate), and details on the transportation activities (i.e., type of fuel, average distance covered in a trip, average travel time, distance traveled per unit of fuel, electrical power for auxiliary refrigeration equipment, payload, average amount of product transported, average internal and external temperature). These data should be gathered directly from the actors of the chain (for instance through energy audit or surveys) to obtain more accurate results. Missing data can then be estimated with the support of energy and operation experts or, eventually, taken from case studies in the literature. The output of the tool depicts the specific energy consumption by energy carrier, and the quality losses. The impact of the quality losses on the energy consumption is also evaluated, since the energy spent for goods that do not reach the requested quality is wasted. These results are reported for each link of the cold chain for the whole chain. This allows the identification of stages with the highest energy consumption and quality losses. Moreover, the average storage time is also reported for each link since this parameter is relevant for the determination of the quality degradation. This information can serve as a basis to support decision makers in the prioritization of the EEMs to reduce the overall energy consumption of the specific supply chain. Once the most promising measures are selected, a what-if analysis is performed to assess the impact of the EEMs on the overall SEC of the cold chain.

4. Results and Discussions

4.1. AS-IS Scenario

The case study proposed is based on a cold chain in the dairy industry. Specifically, a cheese requiring refrigeration in each step of the cold chain (e.g., spreadable cheese or grated cheese) has been selected as a finished product. Typically, these are regional supply chains. The raw material consists of fresh milk collected from the farms, which is shipped to an intermediary such as a milk supply center (i.e., raw material supplier), and then delivered to the dairies (i.e., producer). Raw milk is placed in a centrifuge to reach the required level of fat. In some types of cheese, a higher non-fat solids content is required, therefore the water present is removed. In addition, other products such as powdered milk or cream can be added. Once the desired consistency is reached, the milk is pasteurized and placed in a special cheese tank. Here, rennet and various enzymes are added, depending on the type of cheese desired and then the dough is cooked. After cooking, the curd is drained from the liquid whey. Finally, it is shipped to an intermediate distribution center and then to retail stores or supermarkets which face the consumers' demand.

Throughout the supply chain, there are critical factors that can affect the quality of the product supplied to the final consumer: milk and cheese transport and storage temperature, which must be kept within certain levels (i.e., milk should be stored at a maximum of 6 °C and transported at 12 °C, and cheese should be kept at ambient temperature if shaped while chilled if sliced or wedged), humidity levels, and regulations on product shipment. To slow down the degradation of the product, the milk in the considered cold chain is maintained at 2–3 °C, while cheese is kept at 5–6 °C. Furthermore, the following assumptions were made for the input data of the tool:

1. The considered cold chain is regional: in this way, the temperature of the external environment is kept constant and equal to 30 °C in each phase.
2. The production process requires different quantities of milk for every kg of cheese. For the specific case study, a value of 10 kg of milk to produce 1 kg of cheese has been considered.
3. The available data refers to the overall warehouse which stores different products (e.g., dairy products, fish, meat, fruit and vegetables, products intended for catering). Hence, the size of the warehouse and the energy consumption of the distribution center and the retailer were equally distributed to the products stored to obtain the percentage of electric energy necessary for the conservation of considered product (i.e., cheese).
4. The first transport (from the milk supplier to the cheese producer) does not use refrigerated vehicles, but instead uses tanks insulated with polyurethane foam able to keep the milk at the required temperature; the other two transports use vehicles of different sizes, both equipped with a refrigeration system. The transport from the manufacturer to the distribution center is a long-distance transportation, while the one from the distribution center to the retailer is a multidrop. Long distance transport is related to the use of refrigerated vehicles with transit times longer than one working day. Usually, the vehicle, in this case, is loaded with foodstuffs and directly delivered to a single customer point. Hence, less than two door openings are expected during the travel journey. On the contrary, in short distance multidrop refrigerated vans or small trucks, products are delivered to different points (e.g., different customers). Hence, these transports usually imply multiple door openings, short times for product temperature recovery, and generally shared cooling capacity between two or more compartments in a single vehicle (e.g., freezer and chiller compartments within the same truck).

The specific energy consumption (SEC) of each actor in the chain and that of the entire supply chain is obtained through the application of the ICCEE tool. The input data necessary for the evaluation of the SEC were directly gathered through interviews with European companies in the dairy industry and/or logistic companies. The energy consumption evaluated refers to the logistic activities carried out by the actors (storage and transport) and not to the production ones, since the latter are strictly dependent on the specific product considered and results are hardly generalizable. The results obtained for each logistic activity along the cold chain are shown in Figures 2–4.

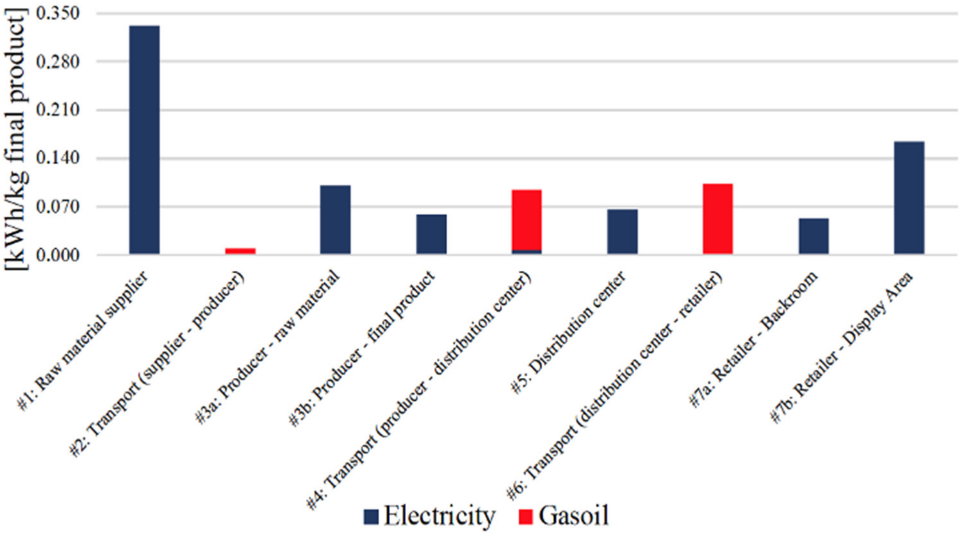

Figure 2. Specific energy consumption for each energy carrier and each actor of the cold chain.

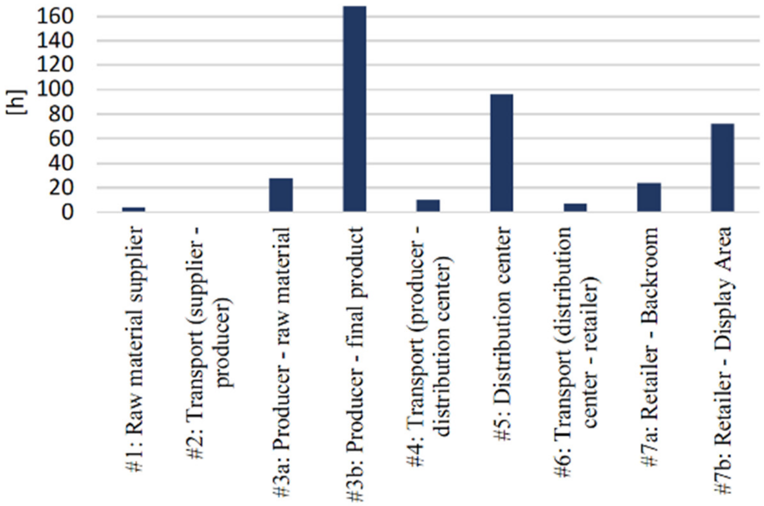

Figure 3. Storage time at each actor of the cold chain.

From the results, it can be observed that the higher SEC contribution is due to the milk supplier (#1). A good part of the overall consumption is also attributable to the refrigerated display area at the final sales point (#7b). However, the SEC obtained does not consider the effect of quality losses that occur along the supply chain. Losses affect consumption: in fact, for every unit of finished product lost, the amount of energy (and other resources) needed to produce it is wasted. Depending on the storage time (Figure 3) and the temperature set inside the warehouse, it is possible to obtain the trend of quality losses for each stage of the chain (Figure 4). By dividing the overall specific energy consumption previously obtained (0.984 kWh/kg of finished product) by the quality of the product supplied to the final consumer (64.78%), it is possible to obtain a value of the SEC which also considers the quality aspect (1.519 kWh/kg of finished product). The ratio therefore serves to divide the actual consumption of energy (and other resources) on the quantity effectively produced. It is obvious that the higher the quality of the finished product, the lower the supply chain consumption will be, and vice versa. The product supplied to the final consumer is a wedge of cheese, which, since the beginning of its production, has lost 35.22% of its quality.

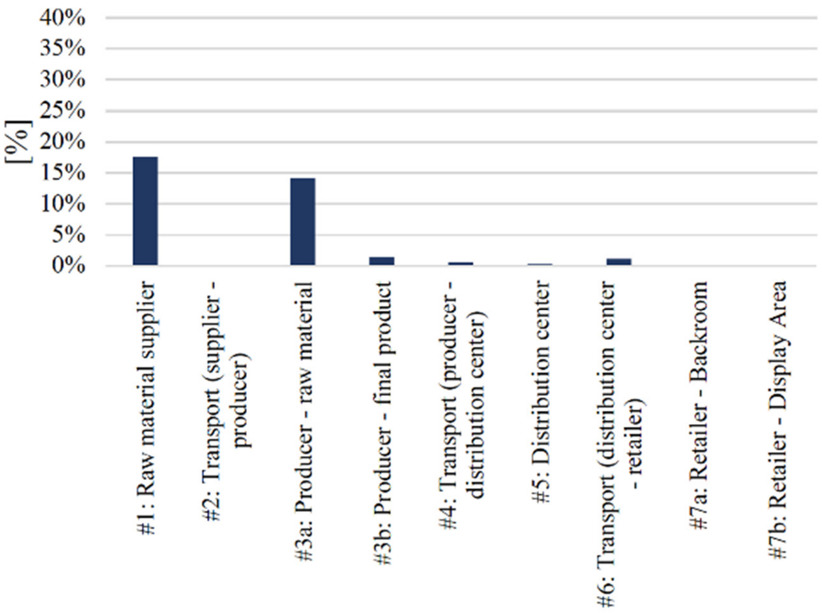

Figure 4. Quality losses at each actor of the cold chain.

Regarding activities' impact on the products' quality, it can also be stated that:

- The stages with the greatest quality losses are the storage at the milk supplier (#1) and at the producer (#3a). In fact, milk is a more easily perishable commodity than the seasoned cheese wedge (finished product).
- The higher share of quality losses of the finished product occurs at the producer (#3b) since the storage is higher than in other finished product warehouses.
- Considering quality losses, the SEC increases by about 50%. This is a non-negligible value, especially because in terms of energy efficiency it is important to avoid consuming energy for products that represent a waste and, as such, are not sold to the final consumer.
- Regarding transport, the greatest losses occur during multidrop transport, mainly due to the high number of vehicle door openings which introduce the highest temperature changes.

Table 2 shows for which warehouse the factors affecting the SEC (i.e., coefficient of utilization, quality losses, storage size, storage time, temperature set inside the warehouse) are relevant. The milk supplier's warehouse (#1) and the refrigerated display area at the final sales point (#7b), which are the ones with the highest SEC, are those that have a smaller storage size (i.e., less efficient activities) and, at the same time, a not particularly high coefficient of utilization of the warehouse. Part of the energy, therefore, is consumed to maintain the required temperature in the storage area, without fully utilizing the available space. Storage time and temperature impact on the SEC since they define the cooling requirements for the storing activities: i.e., the storage time impacts on the amount of equipment operating hours, while the temperature set inside the warehouse impacts on the cooling power.

Table 2. Factors affecting the specific energy consumption of the different warehouses.

Factor	#1	#3a	#3b	#5	#7a	#7b
Coefficient of utilization				x		x
Quality losses	x	x				
Storage size	x				x	x
Storage time			x	x		x
Temperature (inside the warehouse)	x	x	x	x	x	x

Table 3 shows that the SEC of the multidrop transport is the only one affected by the amount of door opening, in fact, in this route many retailers are reached. The fuel conversion factor and the fuel consumption (i.e., distance travelled per liter of fuel) are relevant for each transport. Specifically, all the vehicles considered are fueled through gas oil/diesel. Only the transport between the producer and the distribution center presents a higher energy consumption due to the presence of equipment that should be powered on with electrical power in addition to the fuel consumption. The travelling time requiring refrigeration is almost negligible in the first transport, due to the vehicle used for the transportation of milk (i.e., insulated tanks). Finally, the utilization of the vehicle is mainly an issue downstream in the cold chain (i.e., #6). Regarding transport activities, it can, thus, be observed that:

- The first transport, from the supplier to the producer (#2), is the one that has a lower SEC. This is because, on the one hand, it makes a relatively short journey; on the other, it uses insulated tanks and, therefore, does not require refrigeration.
- The second type of transport, from the producer to the distribution center (#4), should cover a greater distance, to which corresponds a higher fuel consumption. In addition, it has an SEC component related to the electrical power required by vapor compression refrigeration.
- The last transport, from the distribution center to the retailer (#6), covers minor distances, but it is the one with the greatest SEC: in fact, this value is affected by the vehicle door openings which, in the case of the multidrop transport, are greater and vary according to the points of sale visited. The hot air that enters the vehicle during the multiple unloading phases requires a higher energy contribution to bring the vehicle compartment back to the required temperature.

Table 3. Factors affecting the specific energy consumption of the different transport.

Factor	#2	#4	#6
Door opening			x
Fuel consumption	x	x	x
Fuel conversion factor	x	x	x
Refrigeration system		x	
Travelling time		x	x
Utilization of the vehicle			x

4.2. TO-BE Scenario

In this section, some energy efficiency measures will be applied to the reference case, to assess the impact that the latter have on the overall specific energy consumption. Specifically, the impact of the considered measures in terms of reduction of SEC has been applied to the actors that implement them. Then, the CSC tool allows us to define the impact on the overall chain.

The first analysis will concern transport: it will be observed the impact on the SEC resulting from the installation of air barriers in the single-drop transport from the producer to the distribution center, and from the adoption of portable refrigeration units (PRUs) in the multidrop transport from the distribution center to the retailer. No EEMs have been implemented on the transport activities between supplier and producer since, as can be observed from Figure 2, the contribution on the overall SEC is almost negligible.

In regards to the single-drop transport between the manufacturer and the distribution center, the use of air curtains positioned on the vehicle was opted for, with the aim of reducing electricity and fuel consumption at the same time, maintaining the internal temperature when the doors are opened. In fact, this measure is based on a high-speed jet of air that covers the entire opening, and creates an invisible air barrier on the passage to separate the external environment from the internal one. This system is mainly used in refrigerated vehicles, as opening the doors can cause hot air to enter the vehicle.

The use of portable refrigeration units is suitable when the distances traveled and the quantities transported are not particularly high, and leads to reduced economic and environmental impacts [11]. This way, the products can be kept at the desired temperature, avoiding extra refrigeration requirements and quality losses. Multidrop transport is usually not saturated, hence, the PRUs refrigerate only as much as needed without wasting additional energy. Furthermore, frequent door-opening does not influence the quality of the products since they are not exposed to the outside air, and do not undergo temperature changes. The portable units, in addition, can be stored at the point of sale, facilitating the operations required for the storage of goods in the warehouse. These measures also allow an increase of the quality of the final product by one percentage point, leading to a reduction of the overall SEC by 9.8% (6% for the use of PRUs and 3.8% for the installation of air barriers).

Then, technological measures applicable to cold warehouses can be assessed. The measures applied to transport will be maintained in later evaluations, as affecting different stages of the cold chain means they have no influence on the storage activities. The two categories of measures are in fact independent of each other. The EEMs are considered at each warehouse (except for wall insulation, which cannot be used in the display area) and are the following:

- Wall insulation. Thermal insulation of buildings allows the correct maintenance of the internal temperature of warehouses required by food products. Basically, this is the most efficient way to minimize heat transfer between two contiguous spaces. The materials most used today for wall cladding are multilayer panels, characterized by an internal insulating layer of polyurethane. The thickness and the composition of these panels, called sandwich panels, vary in relation to the insulation required to keep the products at the required temperature. The most important advantage obtained from the use of sandwich panels is the reduction of energy consumption required by the refrigeration systems. For the chain considered, it is possible to reach an additional reduction of the overall SEC of about 11.8% (with respect to the AS-IS scenario).
- LED lightning system. A traditional lighting system produces ultraviolet and infrared rays, which generate 80% heat and only for the remaining part lighting. The light is absorbed by the products and the internal structures of the warehouse and subsequently re-radiated in the form of additional heat. The heat produced becomes an additional load for the refrigeration system, which requires more energy for proper operation. Furthermore, the useful life of traditional systems in cold environments is significantly reduced, which means frequent replacement costs. By using an LED lighting system, it is possible to avoid this heat production, save energy (since they are more efficient) and face an extended lifetime even at low temperatures (50,000 h, compared to 1500 h of traditional systems). LEDs also contribute to the reduction of CO_2 emissions associated with electricity generation. LED systems are more expensive than other lighting systems, but the investment is offset by the considerable energy savings introduced. For the chain considered, it is possible to reach an additional reduction of the overall SEC of about 31.5% (with respect to the AS-IS scenario).
- Maintenance. Over time, the surfaces of coils become dirty as the air moving over the coils contains dust, dirt, pollen, moisture, and other contaminants. A buildup of

contaminants decreases the available surface area for heat transfer, reducing the efficiency of the heat transfer process, leading to excessive energy consumption and poor system performance. For this reason, it is important that air conditioning coils are regularly inspected and maintained to ensure they operate at optimum efficiency. With maintenance it is possible to incur energy consumption savings and economic savings. Furthermore, regular maintenance and cleaning allow greater durability of the lifespan of the system. Postponing maintenance and cleaning can have a detrimental impact on processing equipment and heating and cooling systems. When dirt and grime coat a chiller or air conditioner's coils, they can drastically increase the costs of running that system. Moreover, particular attention must be paid to check the distribution system of compressed air, from the compressor to end uses, avoiding leaks; even very small leaks can cause significant wastage of energy and consequently high costs. The regular verification of losses is an excellent strategy to minimize costs and save money, since predictive maintenance practices have an almost negligible cost with respect to technological measures. This measure can also improve the working environment by reducing the noise caused by inefficiencies such as the presence of holes. For the chain considered, it is possible to reach an additional reduction of the overall SEC of about 7.9% (with respect to the AS-IS scenario).

- Monitoring and control. Knowing the energy consumption related to the various activities becomes essential to understanding where to intervene for improving energy efficiency. Smart and real-time monitoring can provide analysis on future consumption, share information throughout an organization, and optimize resource consumption. It also allows maintenance of temperature in the desired range, limiting quality losses and temperature abuses. Moreover, if there are possible interruptions in the cold chain, prompt intervention can ensure the quality of the products. Remotely it is therefore possible to know the consumption of all the machinery used, both in the individual company and, in the most complex systems, the entire chain. For the chain considered, it is possible to reach an additional reduction of the overall SEC of about 3.9% (with respect to the AS-IS scenario).
- Waste heat recovery. Recovering heat from the refrigeration process can save energy and cut energy costs. Heat-recovery equipment can be fitted to existing plants or integrated in new plants. There are two types of heat recovery systems from refrigeration, depending on the installation and refrigerant used: high-grade heat recovery, where heat (between 60 and 90 °C) is recuperated in refrigeration systems from desuperheating the refrigerant between the compressor and the condenser, and low-grade heat recovery, where heat (between 20 and 40 °C) comes from the refrigerant being condensed. In the food industry, it is possible to recover heat from different sources: cooling systems and compressors, pasteurization, exhaust gases from burners, etc. Waste heat generated from the refrigeration unit can be used as a heat source (e.g., to preheat water to reduce the energy use of the boiler), and, at the same time, waste heat from other processes can be used for refrigeration, using absorption refrigeration. For the chain considered, it is possible to reach an additional reduction of the overall SEC of about 35.5% (with respect to the AS-IS scenario).
- Free cooling. Free cooling indicates the direct use of an external source, typically air, but also water, when its temperature (and humidity in case of direct external air use) allow its use directly (e.g., introduction of external air without any treatment) or indirectly (i.e., treating the air or exchanging heat with air or other heat carriers) with a lower energy consumption of the HVAC or cooling system. The most suitable environment for free cooling is a combination of a cold or mild climate zone and the need for cooling energy for most of the year. This encompasses many manufacturing industries, such as the food and beverage ones. Free cooling has the objective to reduce chiller energy consumptions: this can be done via a direct intake if there is external air, via a chiller with a built-in free cooling coil, or via a free cooler working in series with a chiller. The latter should usually be more efficient, due to the larger

surface area provided by the air cooler. A free cooling system, together with energy savings can offer different benefits, such as reduced water consumption, reduced operational costs, reduced carbon footprint, and reduced maintenance costs, due to the reduced number of operating hours of the compressor during the year. For the chain considered, it is possible to reach an additional reduction of the overall SEC of about 13.4% (with respect to the AS-IS scenario).

- Two-stage refrigeration system. Multistage systems have the purpose of solving issues in the classic vapor compression cycle (i.e., when the evaporator temperature becomes very low or when the condenser temperature becomes high). Apart from high temperature lift applications, multi-stage systems are also used in applications requiring refrigeration at different temperatures. A two-stage system is a refrigeration system working with two-stage compression and often also with a two-stage expansion. Flash gas is separated from liquid refrigerants in an intermediate receiver between the two expansion valves. The high-stage compressor will then remove the flash gas. The removal of the gas between the expansion stages reduces the quality of the refrigerant vapor that enters the evaporator. Each mass unit of refrigerant passing through the evaporator will then be able to absorb more heat, reducing the required refrigerant mass flow rate for a given cooling capacity. This in turn reduces the required low-stage compressor size. Because of the enhanced heat transfer coefficient in the evaporator, the heat transfer area needed is also reduced. The investment is, usually, lower than traditional systems, because smaller compressors and evaporators are required. For the chain considered, it is possible to reach an additional reduction of the overall SEC of about 55.2% (with respect to the AS-IS scenario).

Once the energy impact of the different investments is evaluated, it is interesting to also observe the savings introduced to evaluate feasibility and to provide a prioritization of them. These savings have been evaluated valorizing the annual savings in terms of energy consumption at the energy price (assumed as EUR 0.12/kWh), assuming that the EEMs are applied at each stage of the cold chain. Table 4 provides a first analysis of the economic performance of the EEMs, showing the annual savings introduced (i.e., the energy savings valorized at the energy price), the investment costs, the simple payback period, and the net present value (for 20 years at an interest rate of 4%). The information on the costs for the implementation of the EEMs has been obtained directly from suppliers of the measures.

Table 4. Economic analysis of the energy efficiency measures.

EEM	Annual Savings (€/year)	Costs (€)	PB	VAN (€)
Transport: use of PRU from DC to retailer	596	5000	8.4	3103
Transport: air barriers from producer to distribution center	611	12,000	19.6	−3700
Wall insulation	17,345	176,791	10.2	58,943
LED lightining system	46,255	370,489	8.0	258,136
Maintenance	11,563	60,000	5.2	97,156
Monitoring and control	5782	160,000	27.7	−81,422
Waste heat recovery	52,037	594,521	11.4	112,682
Free cooling	19,658	60,000	3.1	207,165
Two-stage refrigeration system	46,255	52,550	1.1	576,074
TOTAL	**200,105**	**1,491,351**		**1,228,137**

Investments have been prioritized for descending net present value, since this considers the time value of money, i.e., the discount rate. Figure 5 shows the cumulated savings (annual and total over 20 years) and investment costs associated with the prioritized EEMs. As can be observed from the figure, the cumulated savings generated during the lifetime (i.e., 20 years) are higher than the overall investment need. Hence, the defined prioritizations assure that the savings introduced with the implemented EEMs can be considered in the next energy efficiency budget and reinvested in view of the continuous improvement approach.

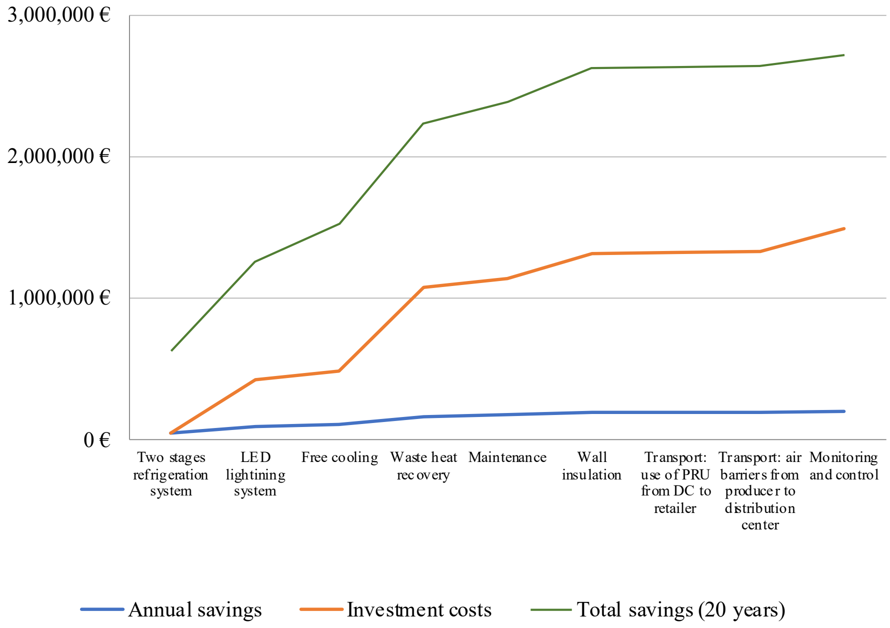

Figure 5. Economic impacts of the EEMs implementation in terms of cumulative annual and total savings over a period of 20 years, and investment costs.

5. Conclusions

The methodology proposed allow the assessment of quality losses and the specific energy consumption of the cold chain and of each stage, and the prioritizing of different energy efficiency measures to obtain a lower impact on sustainability performance. Specifically, the focus is on a cold chain in the dairy industry which produces a cheese requiring refrigeration in each step of the cold chain (e.g., spreadable cheese or grated cheese). The required data were directly gathered through interviews with European companies in the dairy industry and/or logistic companies. The results show that the highest SEC contribution is due to the milk supplier and the refrigerated display area at the final sales point. Depending on the storage time and the temperature set inside the warehouses, it is possible to obtain the trend of quality losses for each stage of the chain and to assess that the quality of the product supplied to the final consumer is lower than 70%. The stages with the greatest quality losses are the storage at the milk supplier and at the producer. In fact, milk is a more easily perishable commodity than the finished product. Considering quality losses, the SEC increases by about 50%. This is a non-negligible value, especially because, in terms of energy efficiency, it is important to avoid consuming energy for products that represent waste and, as such, are not sold to the final consumer. Regarding transport, the greatest losses occur during multidrop transport, mainly due to the high number of vehicle door openings which introduce the highest temperature changes. From the analysis of the initial scenario, some energy efficiency measures have been selected and applied to the reference case to assess the impact on the overall specific energy consumption (“TO-BE” Scenario). Once evaluated, the energy impact of the different investments and the costs savings introduced were evaluated to assess the feasibility of the intervention and to provide a prioritization based on economic point indicators (i.e., annual savings, investment costs, simple payback period, and the net present value). The proposed study is limited to the analysis of the trade-off between energy consumption and quality losses. Further extensions of this case study deal with the integration of different aspects of sustainability, i.e., environmental and social dimensions [13], for example through a multi-criteria analysis [14] or multiple benefits introduced with energy efficiency measures instead of only energy savings [10]. Including these aspects, additional measures may be of priority.

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Abbreviations

CSC	Cold Supply Chain
EEM	Energy efficiency measures
GHG	Greenhouse Gases
HFC	Hydrofluorocarbon
HVAC	Heating, ventilation and air conditioning
KPI	Key performance indicator
NEB	Non-energy benefit
SDG	Sustainable Development Goal
SEC	Specific energy consumption
UN	United Nations

References

1. European Commission—Joint Research Centre. *Energy Use in the EU Food Sector: State of Play and Opportunities for Improvement*; Publications Office: Luxembourg, 2015; ISBN 9789279482991.
2. Gwanpua, S.G.; Verboven, P.; Leducq, D.; Brown, T.; Verlinden, B.E.; Bekele, E.; Aregawi, W.; Evans, J.; Foster, A.; Duret, S.; et al. The FRISBEE tool, a software for optimising the trade-off between food quality, energy use, and global warming impact of cold chains. *J. Food Eng.* **2015**, *148*, 2–12. https://doi.org/10.1016/j.jfoodeng.2014.06.021.
3. Coulomb, D. Refrigeration and cold chain serving the global food industry and creating a better future: Two key IIR challenges for improved health and environment. *Trends Food Sci. Technol.* **2008**, *19*, 413–417. https://doi.org/10.1016/j.tifs.2008.03.006.
4. James, S.J.; James, C. The food cold-chain and climate change. *Food Res. Int.* **2010**, *43*, 1944–1956. https://doi.org/10.1016/j.foodres.2010.02.001.
5. International Institute of Refrigeration. The Carbon Footprint of the Cold Chain. 2021. Available online: https://iifiir.org/fr/fridoc/l-empreinte-carbone-de-la-chaine-du-froid-7-lt-sup-gt-e-lt-sup-gt-note-143457 (accessed on 11 August 2022).
6. Cagno, E.; Trianni, A. Evaluating the barriers to specific industrial energy efficiency measures: An exploratory study in small and medium-sized enterprises. *J. Clean. Prod.* **2014**, *82*, 70–83. https://doi.org/10.1016/j.jclepro.2014.06.057.
7. Marchi, B.; Zanoni, S. Supply chain management for improved energy efficiency: Review and opportunities. *Energies* **2017**, *10*, 1618. https://doi.org/10.3390/en10101618.
8. Zanoni, S.; Marchi, B.; Puente, F.; Neusel, L.; Hirzel, S.; Krause, H.; Saygin, D.; Oikonomou, V. Improving Cold Chain Energy Efficiency: EU H2020 project for facilitating energy efficiency improvements in SMEs of the food and beverage cold chains. *Refrig. Sci. Technol.* **2020**, 361–369. https://doi.org/10.18462/iir.iccc.2020.292878.
9. Zanoni, S.; Marchi, B. Environmental impacts of foods refrigeration. In *Environmental Impact of Agro-Food Industry and Food Consumption*; Academic Press: Cambridge, MA, USA, 2021; pp. 239–259, ISBN 9780128213636.
10. Neusel, L.; Hirzel, S.; Zanoni, S.; Marchi, B. Energy efficiency from farm to fork? On the relevance of non-energy benefits and behavioural aspects along the cold supply chain. *ECEEE Ind. Summer Study Proc.* **2020**, 101–110. Available online: https://www.eceee.org/library/conference_proceedings/eceee_Industrial_Summer_Study/2020/2-sustainable-production-towards-a-circular-economy/energy-efficiency-from-farm-to-fork-on-the-relevance-of-non-energy-benefits-and-behavioural-aspects-along-the-cold-supply-chain/2020/2-084-20_Neusel.pdf (accessed on 11 August 2022).

11. Marchi, B.; Zanoni, S.; Zavanella, L.E. Energy efficiency measures for refrigeration systems in the cold chain. *Proc. Summer Sch. Fr. Turco* **2019**, *1*, 222–228.
12. ICCEE. Deliverable 2.1—Main Report on Supply Chain Energy Impact Analysis and Best Practices. 2020. Available online: https://iccee.eu/wp-content/uploads/2020/07/D2.1-PU-UNIBS-Main-report-on-supply-chain-energy-impact-analysis-and-best-practices-1.pdf (accessed on 11 August 2022).
13. Diaz, F.; Vignati, J.A.; Marchi, B.; Paoli, R.; Zanoni, S.; Romagnoli, F. Effects of Energy Efficiency Measures in the Beef Cold Chain: A Life Cycle-based Study. *Environ. Clim. Technol.* **2021**, *25*, 343–355.
14. Marchi, B.; Zanoni, S.; Romagnoli, F.; Ferretti, I. Multi criteria decision analysis for improving cold chain sustainability. *Proc. Summer Sch. Fr. Turco* **2021**.