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Flexible Operation to Reduce Greenhouse Gas Emissions along the Cold Chain for Chilling, Storage, and Transportation—A Case Study for Dairy Products

Martin Stöckl [1,*], Johannes Idda [1,2], Volker Selleneit [1] and Uwe Holzhammer [1,3]

1 Institute of New Energy Systems, Technische Hochschule Ingolstadt, 85049 Ingolstadt, Germany; uwe.holzhammer@thi.de (U.H.)
2 Faculty of Electrical Engineering and Information Technology, Technische Hochschule Ingolstadt, 85049 Ingolstadt, Germany
3 Sustainability Research and Transfer Center Neuburg, Technische Hochschule Ingolstadt, 85049 Ingolstadt, Germany
* Correspondence: martin.stoeckl@thi.de

Abstract: The further expansion of renewable energies in Germany requires flexible consumers to balance fluctuations in electricity production from variable renewable energies. Cold storage warehouses, due to their inherent storage capacity and widespread use, are well-suited for integrating more renewable energies. The potential of cold storage warehouses is often viewed in isolation and not in conjunction with the cold chain's upstream and downstream processes. By adjusting the temperatures within the processes, the individual links in the cold chain can be made flexible. To assess the effects of flexibilization on emissions and electricity costs, thermodynamic models of the individual links in the cold chain and of a yogurt pallet are developed and linked together. Due to temperature fluctuations in the products resulting from the flexibilization, emission evaluations must be considered throughout the cold chain. Results of the simulation for the study period show that emissions reductions and electricity cost savings can be achieved in all three links when they are made flexible. However, the savings vary in magnitude. Only minor savings can be achieved in the cooling tunnel. The greatest potential for savings is in refrigerated transport, if deeper cooling occurs in the process before, i.e., in the cold storage warehouse.

Keywords: flexibility; flexible energy demand; system efficiency; cold storage warehouse; refrigerated transport; cold chain; variable renewable energies; industry; dairies

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Citation: Stöckl, M.; Idda, J.; Selleneit, V.; Holzhammer, U. Flexible Operation to Reduce Greenhouse Gas Emissions along the Cold Chain for Chilling, Storage, and Transportation—A Case Study for Dairy Products. *Sustainability* **2023**, *15*, 15555. https://doi.org/10.3390/su152115555

Academic Editors: Ron-Hendrik Hechelmann, Henning Meschede, Florian Schlosser and Alexander Schlüter

Received: 18 September 2023
Revised: 19 October 2023
Accepted: 31 October 2023
Published: 2 November 2023

1. Introduction

Germany's goal is to achieve greenhouse gas neutrality by 2045 [1]. To achieve this, one of Germany's objectives during the energy transition is to ensure that renewable energies (RE) account for at least 80% of gross electricity consumption by 2030 [2]. In 2022, the proportion was 46.2% [3]. Consequently, a significant increase in RE power plants is required. Since Germany has a limited number of controllable geothermal power plants and its hydropower potential is largely tapped, the expansion in RE capacity will predominantly come from wind and photovoltaic (PV) installations, replacing fossil fuel power plants. Both wind and PV power are categorized as variable renewable energies (VRE) since they are not directly controllable. The output from VRE fluctuates throughout the day and year. If not offset by energy storage systems, the gap between the minimum and maximum power provided by PV and wind will grow as more such plants are installed. This widening gap underscores the importance of flexibility in the energy system. The fundamental idea of flexibility is that during times of high production from VRE, additional flexible consumers are needed, e.g., by shifting loads from periods with a low proportion of RE generation. During times of low RE production, flexible power generators are required [4]. With a net electricity consumption share of 44% in 2021 [5], the industrial sector is particularly suited for flexibility measures. In Germany, 14% of the total electricity demand is attributed to the cooling sector [6]. Therefore, cooling supply systems in the industrial sector present a promising option as a flexible consumer with high scalability potential.

Brief literature review: There has been a fair amount of research on the topic of how to use cold storage warehouses for further integration of RE. From 2006 to 2008, the EU funded the research project "Night Wind" [7], which specifically aimed to store wind power in a cold storage facility for frozen goods in order to balance the mismatch between power demand and supply, thereby shaving the peak power consumption. Cold is inherently stored in the goods due to temperature fluctuations. Fikiin and Stankov [8] noted that the idea of integrating RE in large cold storage warehouses was still often neglected. Fikiin et al. [9] propose an approach to use a cryogenic energy storage for RE integration. To increase efficiency, they use the cold occurring during the process directly in the cold storage warehouse. Rosiek et al. [10] demonstrate that solar-assisted storage using phase change materials is suitable for integrating RE into industrial food chambers. With these, a load shift can be performed in the cooling system of the food chambers, providing flexibility for the grid. Repke et al. [11] use the products as inherent storage in a cold storage warehouse in their approach to electricity cost minimization. The air temperature in the cold storage facility is adjusted according to the forecast of the electricity exchange price. Only minor fluctuations in air temperature are allowed. The greatest savings are achieved when the temperature is adjusted to the upper permissible limit. However, the authors note that this can have an impact on the product. Svane et al. [12] also examine an approach using frozen meat as inherent storage in a cold storage warehouse. Here, the results also show that this approach can save electricity costs, and the savings increase when longer forecast periods are possible. The authors also emphasize that while operators of cold storage warehouse have aspirations to operate flexibly, they often lack the knowledge and data required. Khorsandnejad and Malzahn [13] demonstrate the flexibility of two different cold storage warehouses, one with inherent storage and the other with discrete storage, depending on the stored products and their tolerance to temperature fluctuations. The authors show that various objective functions are possible when making a cold storage warehouse flexible: minimization of electricity purchase costs, minimization of CO_2 emissions, maximization of the integration of RE into the grid, maximization of local PV integration, and peak shaving. While not investigating cold storage warehouses, but rather air-conditioned warehouses, Dadras Javan et al. [14] propose to use machine-learning-based predictions of the resulting energy consumption if a flexibility event (i.e., adjusting the set-points) occurs. The greater accuracy of energy consumption helps in participating in demand response programs. Recent meta-studies show that the majority (up to 90%) of cooling demand in Germany is met by electricity [15] and by a vapor-compression refrigeration system (VCRS) [16]. Another meta-study on different cooling applications also states that cold storage warehouses use VCRS [17]. VCRS is still the dominant technology for refrigeration supply systems.

Contribution and research questions: The aim of this paper is to further explore the flexibility of cold storage warehouses, especially when these cold storage warehouses are integrated along the cold chain and changes to individual links are considered holistically. This case study examines how the manufacturing industry can contribute to sustainability through improved integration of renewable energies and saving fossil fuels. This research shall address the following questions: "What is the CO_2 emission reduction potential of a cold chain for chilling, storing and transportation? What role does the temperature of the stored products at removal from the cold storage warehouse play in the emission reduction potential?" A description of the functions and the models of the individual links of the cold chain is presented in detail. Their potential for flexibilization is presented. For further investigation on the influence of the stored goods, a detailed model of yogurt pallets was developed. The various models are integrated into a simulation for comparison between reference values and the flexible operational mode. The results of flexibility in terms of changes in electricity costs and CO_2 emissions are presented both individually and for the cold chain over a selected period. It is shown that the CO_2 emissions reduction can be greater if transportation is included in the flexibilization. Results show that the products' temperature at removal from the cold storage warehouse is an important parameter, as it can influence whether more or less CO_2 emissions are required in the subsequent step.

Structure: The remainder of the paper is structured as follows: Section 2 describes the basics about the correlation between specific emissions and electricity exchange prices, the modelling of the cold chain, and its flexibilization. The cooling-related emissions of the individual links and of the two different variants of the cold chain are presented in Section 3. The impact of the simplifying assumptions is discussed in Section 4. A short conclusion and outlook are given in Section 5.

2. Materials and Methods

This case study uses the following steps to investigate the impact of flexibility on the cooling-related emissions of the cold chain:

1. Analysis of the specific CO_2 emissions from electricity from the public grid and the electricity exchange prices (see Section 2.1): Variations throughout the day are necessary for flexible concepts to be ecologically and economically feasible. Investigation of the correlation between CO_2 emissions and electricity exchange prices.
2. Distinguishing the different variants of the cold chain and defining the system boundaries of the case study (Section 2.2)
3. Creation of the thermodynamic models of the cold chain: pre-cooling in cooling tunnel (Section 2.3.1), cold storage warehouse (Section 2.3.3), refrigerated transport (Section 2.3.4), and products (Section 2.3.2): These models take into account the heat inputs and calculate the cooling demand. Based on the cooling demand and the energy sources used (i.e., electricity or fossil fuels), the cooling-related emissions can be calculated.
4. Setting up the simulation by transferring the models into Python 3 (see Section 2.4).
5. Flexibilization of the individual links of the cold chain by adjusting the temperature in the process parameters (see Section 2.5).
6. Comparison of cooling-related emissions between standard operational mode and flexible operational mode.

In the following, the basics about the grid emission factor (GEF), the modelling, and the flexibilization of the cold chain and its individual links are presented.

2.1. Correlation between Grid Emission Factor and Electricity Exchange Prices

Figure 1 shows the grid emission factor (left, blue line) and the electricity exchange prices (right, red line) from 1 October 2020 to 9 October 2020 in Germany.

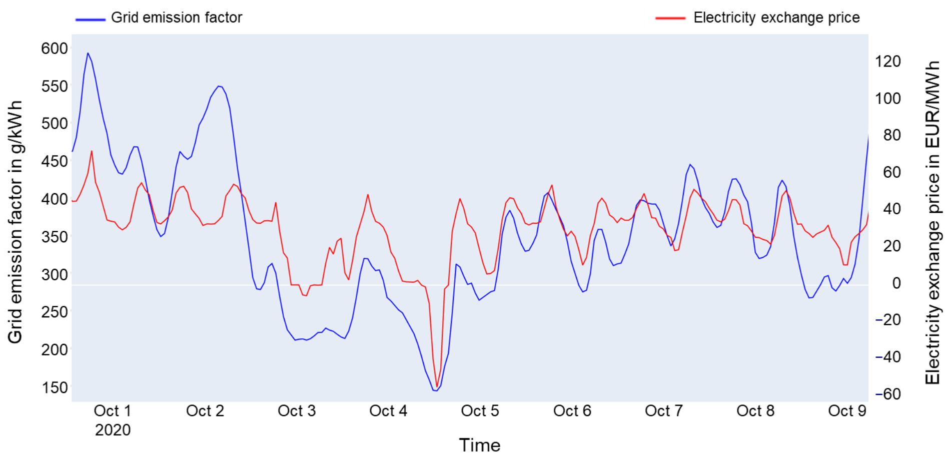

Figure 1. Grid emission factor and electricity exchange price for Germany, October 2020 [18].

The grid emission factor (GEF) is the amount of CO_2 emissions per kWh for consumption from the public grid. Different producers (energy carriers) cover the electricity demand: both conventional producers as well as RE. This leads to a fluctuating CO_2 emission factor (=GEF) for the power procurement from the public grid. Every hour, electricity generation is made up of different amounts of energy sources. Depending on this composition, the GEF for power procurement fluctuates over a specific period. The calculation of the GEF for a certain period is fundamentally based on Equation (1), i.e., on the weighted average emission factor based on production:

$$\mathrm{GEF} = \frac{\sum \text{Energy Carrier} \cdot \text{Emission Factor}}{\sum \text{Energy Carrier}} \tag{1}$$

Differences in the calculation of the GEF exist depending on how system boundaries (direct, indirect emissions, or the entire life-cycle; CO_2 or CO_2 equivalents) are defined and in the total energy amount (e.g., whether line losses, pumping work, etc., are excluded or not).

In Figure 1, it can be seen that both curves are dynamic, changing hourly and over the week. The fluctuating electricity exchange price, as evident from Figure 1, has significant relevance for economic incentives. During periods of low prices, consumers have the opportunity to increase their power consumption to benefit from more favorable conditions and reduce their consumption during periods of high prices. Conversely, high electricity prices offer generation plants the opportunity to achieve high economic returns by feeding into the public grid.

Analogous to the economic incentives from electricity exchange price fluctuations, consumers and producers can strategically exploit fluctuations in specific emissions (GEF). With a low GEF, consumers can increase their power consumption from the public grid, reducing it later when the GEF is higher. Energy supply is ensured overall but with fewer absolute emissions. On the other hand, when high specific emissions prevail, it offers generation plants with relatively lower emission values, such as gas-fired combined heat and power plants, the opportunity to feed into the grid. These plants can be preferred due to their comparatively lower emissions, to enhance the overall emission profile of the power grid. This emphasizes the relevance of flexible and adaptive strategies in energy management that take into account both economic and ecological factors. Fluctuating electricity exchange prices offer economic incentives, while fluctuating specific emissions from power procurement from the public grid offer an ecological incentive.

As seen in Figure 1, both curves, simplified, run "synchronously". This means that low electricity exchange prices often coincide with low specific emissions. Statistical analyses (e.g., Pearson correlation and Granger causality tests) show that there is a correlation between electricity exchange prices and specific emissions (GEF). Thus, optimization according to the electricity exchange prices, which are transparently available, sufficiently leads to the optimization of greenhouse gas emissions in power procurement and vice versa.

2.2. Different Variants of Cold Chains

In this case study, we investigate two different variants of a cold chain (part of the research project BlueMilk [grant number: 281A103616]).

Note: The temperatures presented indicate temperatures that were examined for the case study and will later serve for comparison with flexible operational modes. Temperatures can vary as long as they are within legal requirements. It also has to be noted that the term cooling refers to lowering the temperature of the dairy products to a temperature of about 4 °C. This is also often described by the term "chilling" ("Cooling of a substance without freezing it" [19]). The dairy product in consideration, i.e., yogurt, must not be frozen and there is no phase change.

- Variant 1: Cold chain consisting of "pre-cooling—cold storage warehouse—refrigerated transport".
- Variant 2: Cold chain consisting of "cold storage warehouse—refrigerated transport".

In variant 1 of the cold chain, dairy products to be cooled (e.g., yogurt; in contrast, mozzarella, for example, does not have to be cooled) are cooled in a cooling tunnel before the dairy products are stored in the cold storage warehouse. In the cooling tunnel, the yogurt is cooled down from about 25 °C to about 5 °C. The yogurt is then stored in the cold storage warehouse. In the cold storage warehouse, the temperature of the dairy products is maintained at a temperature of 5 °C. The loading space temperature of the truck is 2 °C to 4 °C [20], so further cooling takes place during transport in the truck. The cold chain of variant 1 is shown schematically in Figure 2.

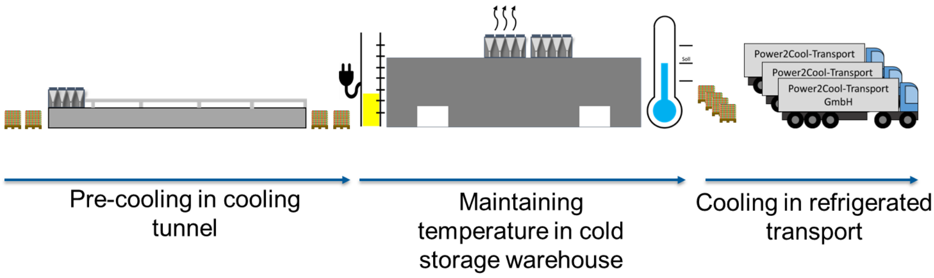

Figure 2. Schematic representation of the cold chain variant 1.

In variant 2 of the cold chain, dairy products to be cooled are stored in the cold storage warehouse without pre-cooling. The dairy products are cooled in the cold storage warehouse. After an appropriate cooling period, the dairy products are transported by truck in the same way as in variant 1. The cold chain of variant 2 is shown in Figure 3.

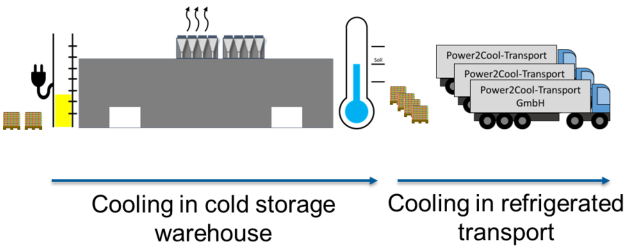

Figure 3. Schematic representation of the cold chain variant 2.

2.3. Functional Description of the Individual Links of the Cold Chain

The three links in the cold chain are described in more detail below: cooling tunnel, cold storage warehouse and refrigerated transport.

2.3.1. Pre-Cooling in Cooling Tunnel

The cooling in the cooling tunnel is referred to as pre-cooling. The pre-cooling is an active cooling of dairy products after production and before storage in the cold storage warehouse. Cooling occurs due to convection. The air in the cooling tunnel is blown through the pallets with the dairy products (thus between the individual cups of the pallet). The air entry temperature (AET) in the cooling tunnel is 4 °C. The retention time of the dairy products depends on the heat to be dissipated (temperature at the beginning, mass of the dairy products). The retention time is approximately 60 min to 120 min. In the case of yogurt, the pallet has a temperature of 5 °C after pre-cooling (and thus before storage in the cold storage warehouse).

The cooling of the products is based on the assumptions of a thin-walled vessel. Therefore, the cooling of a yogurt cup is calculated as follows [21]:

$$\vartheta_{\mathrm{YC}} = \vartheta_{\mathrm{AET}} + (\vartheta_{\mathrm{YC,start}} - \vartheta_{\mathrm{AET}}) \cdot \exp\left(\frac{k_{\mathrm{YC}} \cdot A_{\mathrm{YC}} \cdot t}{m_{\mathrm{YC}} \cdot c_{p,\mathrm{YC}}}\right) \tag{2}$$

In the modeling, it is assumed that each yogurt cup is cooled with the air entry temperature. Heating of the air within the pallet is not taken into account (which would mean that not every yogurt cup is cooled with air at the temperature of ϑ_{AET}). The cooling curve of a yogurt cup is representative of the cooling of all yogurt cups and the entire pallet (pallet of yogurt cups). The cooling curve is shown in Figure 4. Due to the constant speed of pallets in the cooling tunnel, the time axis is representative of the position in the cooling tunnel.

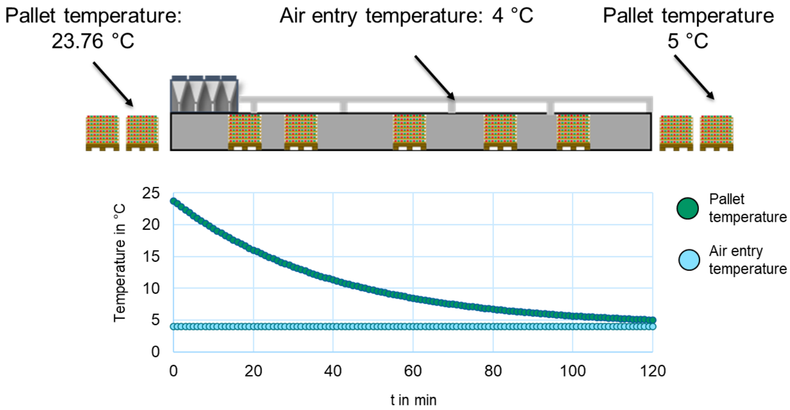

Figure 4. Pallet temperature over time/length of the cooling tunnel.

The temperature of the pallets after pre-cooling is assumed to be constant at 5 °C. Since specific heat transfer capacity, mass and cooling duration are known, the temperature before pre-cooling can be calculated and is 23.76 °C. In the simulation, the time-dependent temperature of a yogurt cup is calculated for each pallet located in the cooling tunnel every minute. From the difference between the new and old temperature, the amount of heat to be dissipated during this time can be calculated:

$$Q_{\text{YC}} = (\vartheta_{\text{YC}}(t_n) - \vartheta_{\text{YC}}(t_{n-1})) \cdot m_{\text{YC}} \cdot c_{p,\text{YC}} \tag{3}$$

The amount of cooling capacity for cooling the yogurt cups for each time step is calculated from the heat quantity per pallet and all pallets located in the cooling tunnel:

$$\dot{Q}_{\text{CT,yogurt}} = \frac{\sum\sum Q_{\text{YC}} \cdot n}{\Delta t} \tag{4}$$

The transmission losses of the cooling tunnel are calculated as follows:

$$\dot{Q}_{\text{CT,trans}} = k_{\text{CT}} \cdot A_{\text{CT}} \cdot (\vartheta_{\text{hall}} - \vartheta_{\text{AET}}) \tag{5}$$

The heat input from the fans ($\dot{Q}_{\text{CT,fans}}$ in Equation (6)), corresponds to the electrical reference power of all fans from the cooling tunnels. The total cooling capacity required by the cooling system to cool the air to the air entry temperature results from the portion used for cooling dairy products, the transmission losses to the environment, and the heat input from the fans:

$$P_{\text{CT}} = -(\dot{Q}_{\text{CT,yogurt}} + \dot{Q}_{\text{CT,trans}} + \dot{Q}_{\text{CT,fans}}) \tag{6}$$

The storage times in the cold storage warehouse are known. To create a time series, the duration of the cooling tunnel is subtracted from the storage time. This is used as the starting time for cooling in the cooling tunnel.

The electrical power consumption is calculated from:

$$P_{\text{CT,el}} = \frac{-P_{\text{CT}}}{EER_{\text{CT}}} \tag{7}$$

Cooling-related CO_2 emissions for the cooling tunnel are calculated from the time series of Equation (7) and the GEF time series.

2.3.2. Yogurt Pallet Model

The stored dairy products play a central role in the consideration of the cold storage warehouse. The approach used in this research for flexibility is based on the use of inherent storage, i.e., no dedicated cold storage. In the cold storage warehouse, the dairy products are the inherent cold storage, as the storage capacity of dairy products is greater than that of the air. However, acting as a storage capacity must not impair the quality of the dairy products. Therefore, it is necessary to know the temperature of the dairy products. Likewise, determining the temperature for calculating the heat flow between the air and the pallet is essential to determine the cold energy stored and released. Regarding the temperatures of a pallet, the core temperature, i.e., the temperature of the yogurt cups in the middle of the pallet, plays an important role. The core temperature is particularly crucial when the cold storage warehouse is designed with variant 2 (see Section 2.2), as it must be ensured that even the yogurt in the middle has been cooled to the appropriate temperature. To calculate the temperatures and heat flows of each pallet in the cold storage, a model for a pallet was developed. The model is based on the assumption that a pallet, consisting of filled yogurt cups in packaging cartons, represents a solid body, as the air between the yogurt cups is considered to be standing and not flowing. The thermal conductivity is adjusted to take it into consideration that the solid body is somewhat a "mixture" of yogurt and air. The following model is used to represent yogurt as dairy products. For simplification, no other dairy products are considered.

The heat conduction in solids can be described by the following differential Equation [21]:

$$\frac{\partial \vartheta}{\partial t} = a \cdot \Delta \vartheta \tag{8}$$

The second-order differential equation can be solved numerically using a "Forward in Time, Centered in Space" approach. Convection occurs on the side surfaces, which represents a Cauchy boundary condition [22].

Figure 5 shows the temperature distribution of a yogurt pallet with a starting temperature of 8 °C at a specific time during cooling with an ambient air temperature of 4 °C. It can be seen that the cooling in the core takes longer than the cooling on the side surfaces.

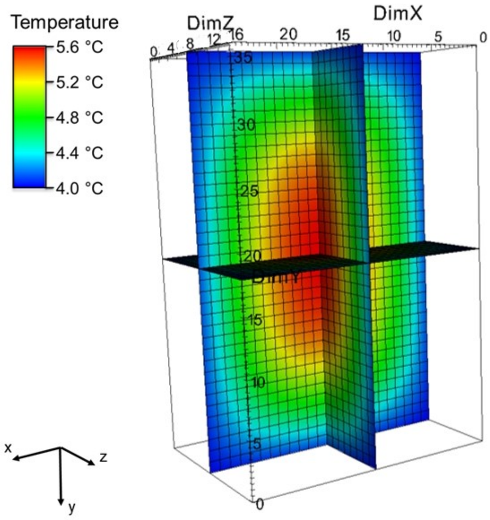

Figure 5. Representation of the temperature distribution within the pallet during cooling with an air temperature of 4 °C.

The heat exchange between one side of a pallet and the air is calculated by:

$$\dot{Q}_{\text{pallet,side}} = \alpha_{\text{CSW,inside}} \cdot A_{\text{pallet,side}} \cdot (\vartheta_{\text{pallet,side}} - \vartheta_{\text{CSW,air}}) \tag{9}$$

The sum per pallet is calculated from sum of the heat flows per side:

$$\dot{Q}_{\text{pallet}} = \sum \dot{Q}_{\text{pallet,side}} \quad (10)$$

The total heat flow of the products is calculated from the heat flow of all pallets in the cold storage warehouse:

$$\dot{Q}_{\text{CSW,product}} = \sum \dot{Q}_{\text{pallet}} \quad (11)$$

2.3.3. Cold Storage Warehouse

The cold storage warehouse is used, depending on the variant 1 or 2, for maintaining temperature or for cooling dairy products. The refrigerating plant of the cold storage warehouse serves to compensate for heat inputs and to maintain the air temperature at a nominal temperature. The following heat flows are taken into account:

- Transmission
- Solar radiation
- Door opening losses
- Heat inputs from electrically operated devices (conveyor technology, fans, etc.)
- Heat exchange with the steel construction in the cold storage warehouse
- Dairy products

Heat transmission is calculated separately for each wall since ϑ_W can vary for each adjacent room. A wall of the cold storage warehouse can either be an outer wall or a wall of another building. Temperatures of other buildings/rooms are considered to be constant:

$$\dot{Q}_{\text{CSW,trans,W}} = k_{\text{W}} \cdot A_{\text{W}} \cdot (\vartheta_{\text{W}} - \vartheta_{\text{CSW,air}}) \quad (12)$$

The total transmission heat flow is calculated from the sum of the partial heat flows:

$$\dot{Q}_{\text{CSW,trans}} = \sum \dot{Q}_{\text{CSW,trans,W}} \quad (13)$$

The solar heat input on the roof surfaces of the cold storage warehouse is taken into account using the following equation [23]:

$$\dot{Q}_{\text{CSW,solar}} = k_{\text{CSW,roof}} \cdot A_{\text{CSW,roof}} \cdot \frac{a_{\text{CSW,roof,outside}} \cdot I}{\alpha_{\text{CSW,outside}}} \quad (14)$$

The electrical power consumption within the cold storage warehouse is considered as a heat input since, for example, the kinetic energy of the storage technology or the kinetic energy of the air due to fans is converted into heat. The electrical power consumption is known from measurements:

$$\dot{Q}_{\text{CSW,el}} = P_{\text{el}} \quad (15)$$

Any mass in the cold storage warehouse reacts to temperature changes and will thereby absorb or release heat. In addition to the dairy products, steel is also considered:

$$\dot{Q}_{\text{CSW,steel}} = \alpha_{\text{CSW,inside}} \cdot A_{\text{steel}} \cdot (\vartheta_{\text{steel}} - \vartheta_{\text{CSW,air}}) \quad (16)$$

The total heat flow for changing the air temperature is calculated from the sum of the mentioned heat flows, including the heat flow of the products (i.e., dairy products; the calculation of the heat flow of the products is addressed in Section 2.3.2), and door opening losses based on the extended Formula by Tamm ($\dot{Q}_{\text{CSW,door}}$), and the cooling capacity of the refrigeration plant of the cold storage warehouse (P_{VCRS} will have values < 0):

$$\begin{aligned}\dot{Q}_{\text{CSW,air}} = {} & \dot{Q}_{\text{CSW,trans}} + \dot{Q}_{\text{CSW,solar}} + \dot{Q}_{\text{CSW,door}} \\ & + \dot{Q}_{\text{CSW,el}} + \dot{Q}_{\text{CSW,steel}} + \dot{Q}_{\text{CSW,products}} + P_{\text{VCRS}}\end{aligned} \quad (17)$$

From the heat flow, the amount of heat can be calculated:

$$Q_{\mathrm{CSW,air}} = \dot{Q}_{\mathrm{CSW,air}} \cdot \Delta t \tag{18}$$

From the amount of heat $Q_{\mathrm{CSW,air}}$, the temperature change of the air in the cold storage warehouse can be calculated:

$$\Delta\vartheta_{\mathrm{CSW,air}} = \frac{Q_{\mathrm{CSW,air}}}{\rho_{\mathrm{air}} \cdot V_{\mathrm{air}} \cdot c_{p,\mathrm{air}}} \tag{19}$$

Cooling-related CO_2 emissions for the cold storage warehouse are calculated from the electrical power consumption of the refrigerating plant (similar to Equation (7)) and the GEF time series.

2.3.4. Refrigerated Transport

In refrigerated transport (by truck), long-distance travel is examined without loading and unloading phases. The infiltration load, i.e., heat input due to air entry because of open doors, is not taken into account.

In the model for refrigerated transport, the following heat flows/heat quantities are considered (see also Figure 6):

- Transmission (1 in Figure 6)
- Solar radiation (2)
- Product (3)
- Pre-cooling of insulation (4)

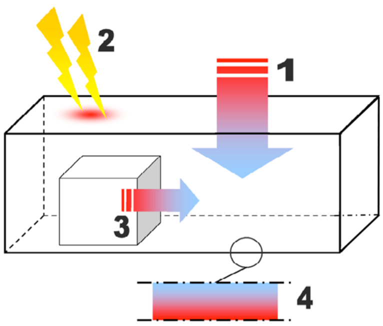

Figure 6. Heat flows considered in the refrigerated truck transport model ([24] with own adjustments).

The cooling unit inside the loading space will compensate for the heat flows and will keep the temperature at the loading space temperature (temperature of the air inside the loading space; set temperature of the cooling unit).

Heat transmission between the ambient air and the truck loading space is calculated as follows:

$$\dot{Q}_{\mathrm{truck,trans}} = k_{\mathrm{truck}} \cdot A_{\mathrm{truck}} \cdot (\vartheta_{\mathrm{ambient}} - \vartheta_{\mathrm{truck,air}}) \tag{20}$$

Solar heat input on the surfaces of the truck loading space is taken into account using the following equation:

$$\dot{Q}_{\mathrm{truck,solar}} = k_{\mathrm{truck}} \cdot (A_{\mathrm{truck,side}} + A_{\mathrm{truck,roof}}) \cdot \frac{a_{\mathrm{truck,outside}} \cdot I}{\alpha_{\mathrm{truck,outside}}} \tag{21}$$

The heat exchange between the air in the truck and the product is calculated using predetermined time series (similar to Equations (9)–(11)). These are calculated per pallet for various scenarios (truck loading space temperature and product temperature). This output can be scaled with the number of pallets in a truck:

$$\dot{Q}_{\mathrm{truck,product}} = n_{\mathrm{pallets}} \cdot \dot{Q}_{\mathrm{truck,scenario}} \tag{22}$$

The pre-cooling of the insulation describes the necessary amount of energy to bring the insulation from a starting temperature to the nominal truck loading space temperature $\vartheta_{\text{truck,target}}$ (if the starting temperature is above the nominal truck loading space temperature, otherwise it is ignored). Similarly, the air in the truck is cooled. The starting temperature is set to the outside temperature one hour before the start of the trip. Values of $Q_{\text{truck,ins}}$ are only considered, if they are >0:

$$Q_{\text{truck,ins}} = (m_{\text{ins}} \cdot c_{p,\text{ins}} + \rho_{\text{air}} \cdot V_{\text{truck}} \cdot c_{p,\text{air}}) \cdot (\vartheta_{\text{start}} - \vartheta_{\text{truck,target}}) \tag{23}$$

The total cold that the cooling unit in the truck needs to provide is calculated from the heat quantities during transit and the pre-cooling of the insulation:

$$Q_{\text{truck,cooling}} = Q_{\text{truck,ins}} + \sum \left(\dot{Q}_{\text{truck,trans}} + \dot{Q}_{\text{truck,solar}} + \dot{Q}_{\text{truck,product}} \right) \cdot \Delta t \tag{24}$$

From the total energy, the required amount of diesel can be calculated based on the efficiency of the cooling unit and the energy content of diesel:

$$V_{\text{diesel}} = \frac{Q_{\text{truck,cooling}}}{\eta_{\text{truck,cooling}} \cdot H_i} \tag{25}$$

From the required amount of diesel, the cooling-related CO_2 emissions for the refrigerated transport are calculated.

2.4. Simulation

The described models are implemented in the programming language Python 3, along with packages such as NumPy, Numba, and pandas. The three links of the cold chain (described in Sections 2.3.1, 2.3.3 and 2.3.4) are calculated individually. The links are interconnected through the exchange of data (e.g., a varying storage temperature of the products due to flexibilization is exchanged via a time series in files).

The simulations are based on the models being solved for a specific time step, meaning heat flows and new temperatures are calculated. Above all, the temperatures are used as starting values for the next time step to solve the models in this time step. Typically, the time step size is 1 min. Larger time steps can make the simulations unstable, as temperatures and heat flows may oscillate. Smaller time step sizes result in longer computation times. The conducted simulations are ex-post analyses, meaning the simulations are carried out retrospectively, when all data (power exchange price time series, storage operations, power consumption, etc.) are already known. The aim is to examine which changes arise compared to references when the operation mode of the respective link in the cold chain is adjusted. This investigates the potential of flexibilization. No forecasts are made, since no schedule for the refrigerating plant is intended to be created for real-time operation. The simulation of the cold storage warehouse is usually carried out over one month. As there are only time series about storage and retrieval available, and not an occupancy of the cold storage, a kind of lead time in the simulation must be used to "fill" the initially empty cold storage warehouse through the storage and retrieval operations. The average storage time is about six days. A lead time of seven days was chosen. This is calculated in addition to the desired month, meaning that a simulation lasts one month and one week.

2.5. Flexibilization of the Cold Chain

The following describes the flexibilization of the individual links in the cold chain.

2.5.1. Pre-Cooling in Cooling Tunnel

Flexibilization of the cooling tunnel takes place by varying the air entry temperature (AET) in the cooling tunnel. The air entry temperature is adapted to the GEF. The air entry temperature is increased to reduce the cooling capacity in the cooling tunnel and thus reduce the electrical power consumption. Similarly, the air entry temperature is reduced to increase the cooling capacity in the cooling tunnel and increase the electrical power consumption.

An overview of the cooling tunnel flexibilizations in this study are described in Table 1 and shown in Figure 7.

Table 1. Listing of the different flexibilizations of the cooling tunnel.

Label	High GEF	Low GEF	Impact
Flex X-Y	increase AET	decrese AET	mean AET remains
Flex X-4	AET remains at 4 °C	decrese AET	mean AET decreases
Flex 4-Y	increase AET	AET remains at 4 °C	mean AET increases

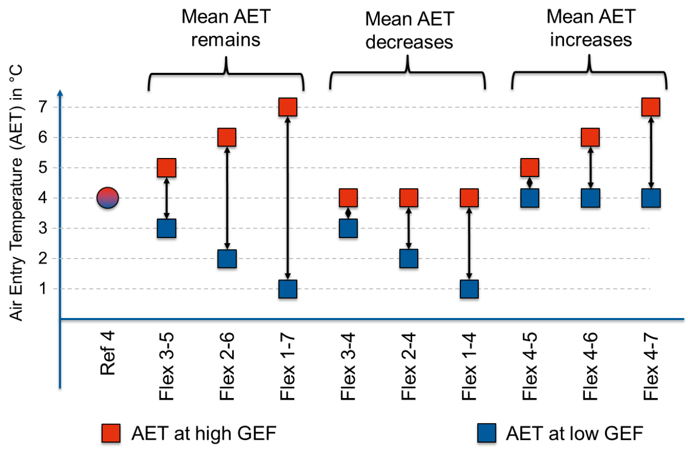

Figure 7. Air entry temperatures at high and low specific emissions for different flexibilizations.

The classification of hours into high GEF and low GEF is done daily using the median of the GEF (this is known because this study uses ex-post analyses, see Section 2.4). Due to the use of the median (instead of mean), 12 h per day are classified as high GEF and 12 h as low GEF. Pallets that pass through the cooling tunnel exclusively during a high or low emission phase have a temperature that is approximately 1 K higher than the air entry temperature (see Table 2 for exact temperatures). Pallets that pass through "both phases" have a temperature in between.

Table 2. Temperature of the pallet after the cooling tunnel for certain air entry temperatures.

Air Entry Temperature	Product Temperature after Cooling Tunnel
1 °C	2.15 °C
2 °C	3.10 °C
3 °C	4.05 °C
4 °C	5.00 °C
5 °C	5.95 °C
6 °C	6.90 °C
7 °C	7.85 °C

The flexibilization of the cooling tunnel results in the storage temperature of pallets into the cold storage warehouse (i.e., the temperature of the pallets after the cooling tunnel) not being constant.

2.5.2. Cold Storage Warehouse

The flexibilization of the cold storage warehouse is shown in Figure 8.

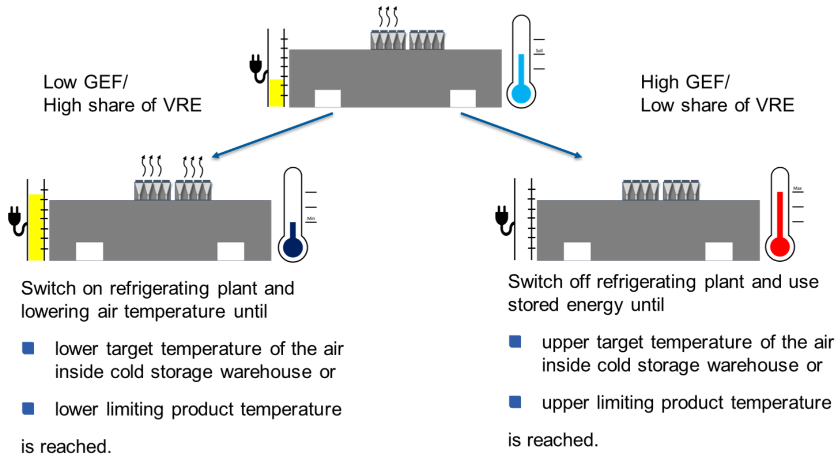

Figure 8. Flexibilization of the cold storage warehouse.

The reference case (top-center in Figure 8) represents the standard operational mode of a cold storage warehouse. The refrigerating plant balances the heat inputs as described in Section 2.3.3 and maintains the air temperature at a certain nominal temperature, e.g., 5 °C. In the case of flexibilization with inherent storage, the air temperature is changed. In this study, the air temperature was adjusted to the GEF. In the flexibilization applied in this study, two different temperatures are important. One is the air temperature in the cold storage warehouse and the other is the temperature of the dairy products.

Dairy products in the cold storage warehouse must be exposed to a temperature difference to create a storage capability, since the products can store only sensible heat and not latent heat (due to quality assurance, it is not possible to use latent heat since it prohibited to freeze the dairy products under consideration):

$$Q_{\text{storage}} = m \cdot c_p \cdot \Delta\vartheta \tag{26}$$

The maximum temperature difference from Equation (26) is given by the limiting product temperatures (LPT). If GEF is low (i.e., high share of VRE in the public power supply system), the refrigerating plant of the cold storage warehouse is switched on and/or the cooling capacity is increased by lowering the air temperature in the cold storage warehouse. The air temperature is lowered until the lower target temperature of the air (TTA) in the cold storage warehouse or the lower limiting product temperature is reached. When the GEF is high (i.e., low VRE share), the refrigerating plant is turned off and the cold stored in the dairy products is utilized. The refrigerating plant remains off until the upper target temperature of the air in the cold storage warehouse is reached or until the upper limiting product temperature is reached. Figure 9 shows the GEF, GEF median, and the refrigerating plant timetable for a week in May 2021.

Table 3 shows an overview of the different operational modes depending on the air and product temperature.

Figure 10 compares the two temperatures. The variation in air temperature in the cold storage warehouse can be larger than the variation in product temperature. The lower limit of the air temperature, for example, can also be below the permissible lower limiting product temperature. The lower air temperature does not necessarily have to be reached in the product. However, a higher difference between air temperature and the pallet causes faster cooling because the heat flow between air and the pallet is greater (see also Equation (9)).

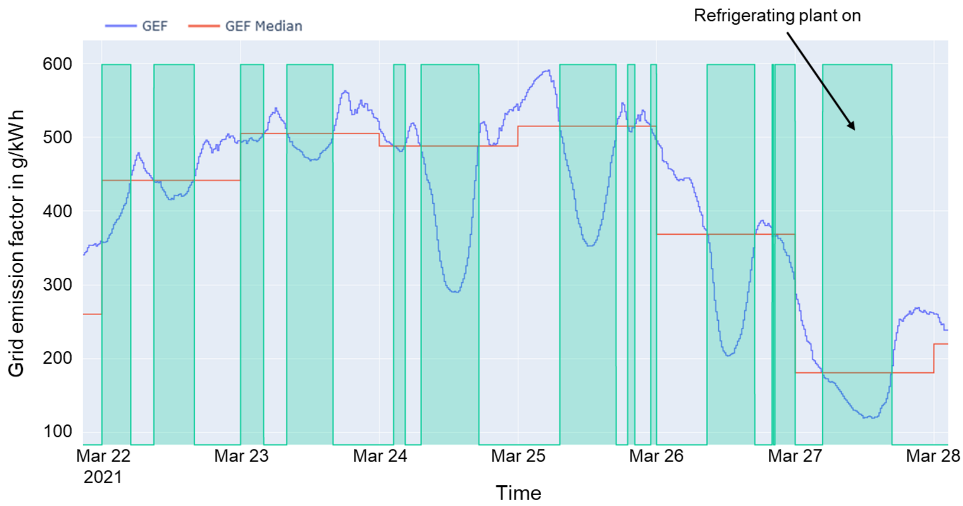

Figure 9. GEF and refrigerating plant timetable.

Table 3. Listing of operational modes of the flexibilization of the cold storage warehouse.

GEF	Limiting Product Temperature	Air Temperature	Action
low	within limit	within limit	cooling; decrease air temperature
low	within limit	lower target temperature of air reached	cooling; keep lower target temperature of air
low	below lower limit	independent of air temperature	prevent further cooling of the products; set target temperature of air to 4 °C
high	within limit	within limit	refrigerating plant switched off
high	within limit	upper target temperature of air reached	cooling; keep upper target temperature of air
high	above upper limit	independent of air temperature	prevent further heating of the products; set target temperature of air to 5 °C

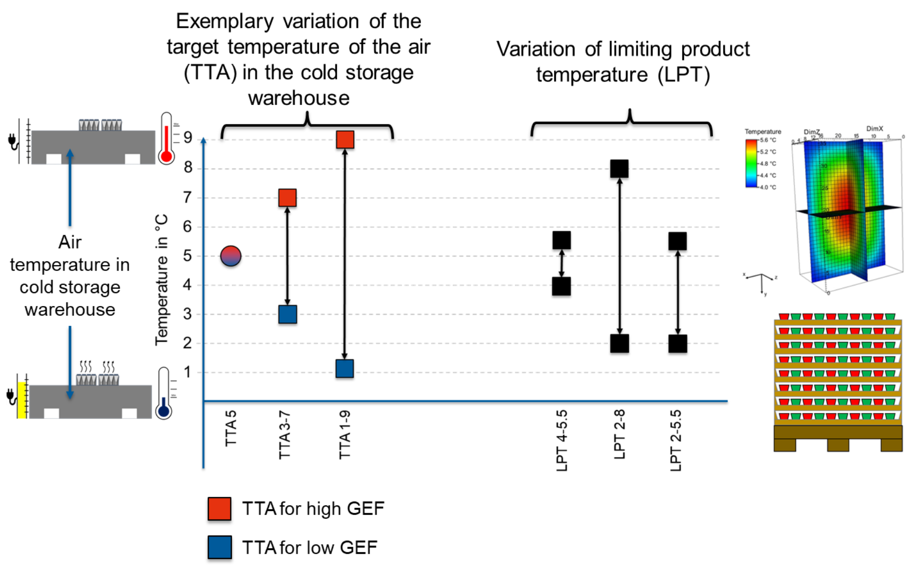

Figure 10. Comparison of the variation in target temperature of the air in the cold storage warehouse and the variation in limiting product temperature.

The following limits were investigated for the limiting product temperatures:

- LPT 4-5.5: Only small variations, based on the usual operation of a cold storage warehouse at 5 °C,
- LPT 2-8: Utilization of broader limits, but still within food regulations [25] and
- LPT 2-5.5: Upper limit is close to the usual operational mode at 5 °C, lower limit allows significantly further cooling. Products can thus become colder than usual, but they do not become significantly warmer.

2.5.3. Refrigerated Transport

The flexibilization of the refrigerated transport consists of adjusting the temperature of the refrigerated loading space (internal truck temperature). The final temperature of the dairy products at delivery to the customer (e.g., supermarket) is influenced by:

- Start temperature of the products at trip,
- loading space temperature,
- duration of trip and,
- weather.

If trip duration and start time are the same (so the weather influence is constant), the start temperature and loading space temperature can be matched to achieve the same final temperature at delivery.

Figure 11 shows the temperatures necessary for comparing the different scenarios. Table 4 states three combinations of pallet temperature at the start of delivery ($\vartheta_{\text{prod,start}}$, equivalent to the temperature on removal from the cold storage warehouse) and the temperature inside the truck ($\vartheta_{\text{truck,air}}$). In Scenario 1 in Table 4, the pallets have a temperature of 5 °C at the start. The truck has a loading space temperature of 4 °C. After a ten-hour trip in May with weather conditions of the test reference year [26] for the location of the dairy, the pallets have an average temperature of 4.7 °C at the destination ($\vartheta_{\text{prod,dest}}$). The temperature of 4.7 °C can also be achieved with a pallet temperature of 4.25 °C at the start of the delivery at a loading space temperature of 5.5 °C. In this case, the pallets heat up to an average temperature of 4.7 °C, with the products warming up by 0.45 K compared with the start of delivery. In the reference case above, the products are actively cooled down by 0.3 K by the truck. If the pallet temperature is lowered further (Scenario 3 from Table 4), the loading space temperature can be increased even further.

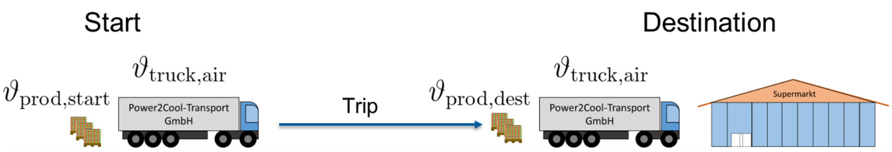

Figure 11. Overview of temperatures for comparing different trip scenarios.

Table 4. Three different combinations of pallet temperature at retrieval and truck-loading space temperature to achieve the same pallet temperature at the end of delivery.

	$\vartheta_{\text{prod,start}}$	$\vartheta_{\text{truck,air}}$	$\vartheta_{\text{prod,dest}}$
Scenario 1	5.00 °C	5.0 °C	4.7 °C
Scenario 2	4.25 °C	5.5 °C	4.7 °C
Scenario 3	3.75 °C	6.5 °C	4.7 °C

3. Results

In the following section, simplifications, results for the individual, and results for the cold chain are presented.

3.1. Simplifying Assumptions

The simulations, and therefore, results are based on several simplifying assumptions:

- One month: Due to the large amount of data (measurement data, production data, etc.) and the numerous options for flexibility, only one month will be studied in this level of detail for the cold chain.
- Test reference year: For the calculation of heat inputs in the model for refrigerated transport, data sets from a test reference year [26] have been used.
- Average pallet temperature: Due to the flexibility in the cold storage warehouse, the temperatures at removal are not constant. To keep the computational time low, the average temperature at removal for a whole month is used instead of specific daily temperatures for refrigerated transport.
- Trip length: It is assumed that the same 10-h trips are made daily in refrigerated transport.
- No infiltration loads: Infiltration loads in refrigerated transport are not taken into account (see also Section 2.3.4).
- Standard operational mode: In this study, for the "standard operational mode", the temperatures for the cold storage warehouse and the loading space temperature in refrigerated transport are set at 5 °C and 3 °C, respectively.
- Electricity costs: When calculating the cooling-related electricity costs for the cold storage warehouse, it is assumed that the cold storage warehouse operates directly on the electricity exchange.

3.2. Results for Flexibilization of Individual Links in the Cold Chain

In the following section, the results of the flexibilization of individual links in the cold chain are presented. The results of the cold storage warehouse are divided into variant 1 and variant 2 (see also Section 2.2).

3.2.1. Pre-Cooling in Cooling Tunnel

Flexibilization of the cooling tunnel is achieved by varying the air entry temperature. This varies the electrical power consumption (see Section 2.3.1). Figure 12 shows the relative CO_2 emission change compared to the reference in %. The reference denotes the standard operational mode where the air entry temperature in the cooling tunnel is at 4 °C regardless of the GEF. The figure shows that for the month shown (May 2021), CO_2 emissions from electricity purchase decrease when the air entry temperature is varied while the average air entry temperature remains the same. The savings (negative change) are greater, the greater the variation in the air entry temperature is. However, the savings are in the low range of up to 1% for the time period studied.

If the average air entry temperature decreases, i.e., the cooling capacity increases on average, higher CO_2 emissions occur compared to the reference. The lower the average air entry temperature, the higher the CO_2 emissions. This results in additional consumption of up to approximately 5%.

When the average air inlet temperature rises, resulting in a decrease in cooling capacity, CO_2 emission savings of up to six percent occur.

Figure 13 shows the changes in electricity consumption for the variation in air entry temperatures. For the case "mean AET remains constant", up to three percent more electricity is required, but at the same time, CO_2 emissions are saved. This demonstrates that the timing of electricity consumption from the public grid has an impact on emissions. For "mean AET decreases", the percentage increase in electricity consumption is greater than the percentage increase in emissions. For the last case studied, "mean AET increases", the emissions savings are greater than those resulting from lower electricity consumption alone. This shows that additional consumption of electricity can be compensated to some extent by appropriate timing of electricity purchases.

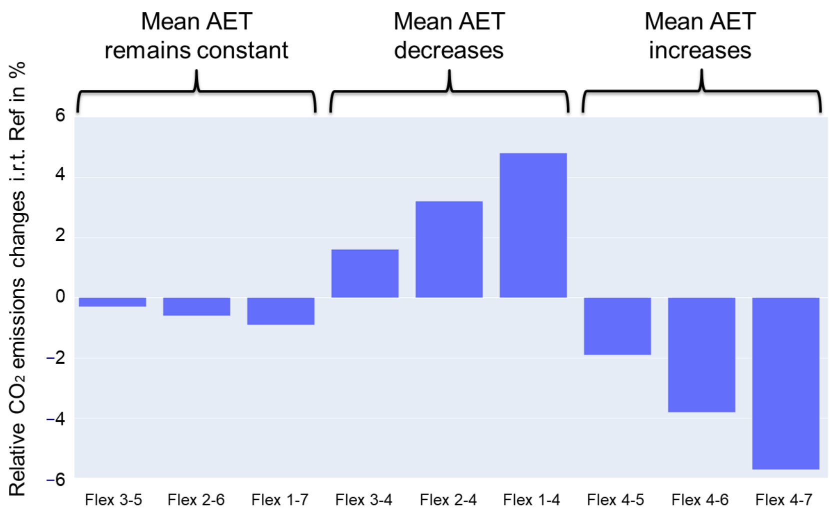

Figure 12. Relative change in CO_2 emissions compared to Ref in % for the month of May 2021.

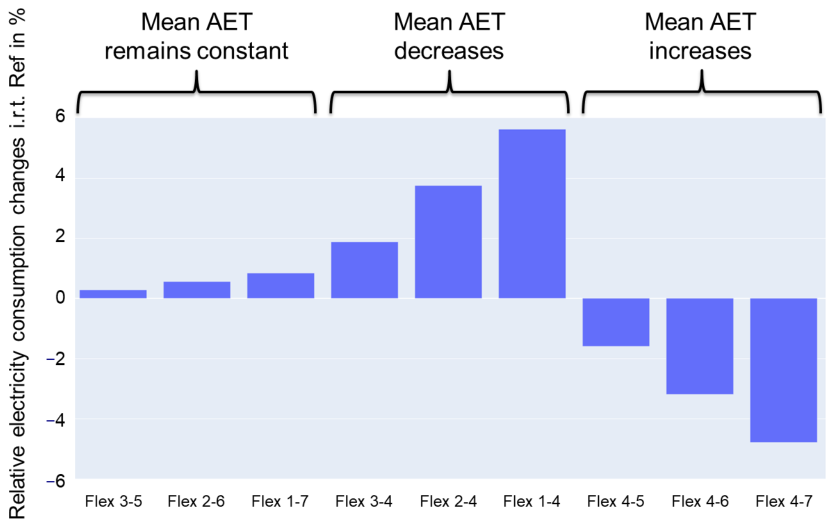

Figure 13. Relative change in electricity consumption compared to Ref in % for the month of May 2021.

3.2.2. Cold Storage Warehouse for Maintaining Temperature

In the following, the results for the flexibilization of the cold storage warehouse for maintaining temperature (variant 1, see Section 2.2) are described. As described in Section 2.5.2, cold storage warehouse flexibilization consists of the target temperatures of the air and the limiting product temperatures. For the flexible operational mode, the lower target temperature of the air is set to 0 °C and the upper target temperature of the air is set to 10 °C. On average, this results in a target temperature of 5 °C, which corresponds to the target temperature of the air for the standard operational mode. The limiting product temperatures are varied as described in Section 2.5.2. The flexible operational mode is compared to two different standard operational modes (TTA 5 with a nominal temperature of 5 °C, and TTA 4 with a nominal temperature of 4 °C).

Figure 14 shows the results of flexibilization of the cold storage warehouse for maintaining temperature for the month of May in 2021. The TTA 5 scenario describes the standard operational mode with a constant target temperature of the air of 5 °C and represents the reference value. This is compared with the other scenarios. The mean product temperature at removal from storage, the changes in CO_2 emissions and the changes in electricity costs are compared. The mean product temperature at removal represents the average temperature of the retrieved pallets over the month weighted by the number of pallets. The mean product temperature at removal is not constant due to flexibilization. The mean product temperature at removal is a crucial parameter, because on the one hand it is an indicator of how much cooling capacity is consumed in the cold storage warehouse, and on the other hand the mean product temperature at removal has a decisive impact on the further energy consumption in the subsequent steps. CO_2 emissions and electricity costs both refer to the electrical energy demand for the compressors of the refrigerating plant. CO_2 emissions are determined via the GEF. Electricity costs refer to German day-ahead electricity exchange prices [27]. Figure 14 shows that the three flexibilities—LPT 4-5.5, LPT 2-8, and LPT 2-5.5—achieve savings in both CO_2 emissions and electricity costs while lowering average temperatures. Savings are the largest for the widest range of limiting product temperatures (LPT 2-8). Emission savings for LPT 2-5.5 are lower than for LPT 4-5.5, but lower monthly average temperatures are achieved for LPT 2-5.5.

Figure 14. Results for flexibilization of cold storage warehouse to maintain temperature for May 2021.

3.2.3. Cold Storage Warehouse for Cooling

In the following, results for flexibilization of the cold storage warehouse for cooling (variant 2, see Section 2.2) are presented.

In this investigation, both the limiting product temperatures as well as the target temperatures of the air are varied. The cold storage warehouse is used for cooling and not only to maintain temperature. Depending on the production, new pallets are always stored with a temperature of approx. 20 °C at the beginning. Due to this, and the fact that in most cases, there are always pallets with a temperature above the upper limiting product temperature (as presented in Section 2.5.2), only the lower limiting product temperature (i.e., 2 °C for LPT 2-5.5) and the lower target temperature of the air (i.e., 3 °C for TTA 3-7) are decisive. Similarly, it only makes sense to select a lower target temperature of the air that is below the lower limiting product temperature. Otherwise, the limiting product temperature cannot be reached because the temperature of the product cannot be below the air temperature. A total of six variants of flexibilization are investigated.

Figure 15 shows the results of flexibilization of the cold storage warehouse for cooling for May 2022. Shown are the average temperature at removal from storage (left axis), the changes in CO_2 emissions (right axis) and the changes in electricity costs (right axis).

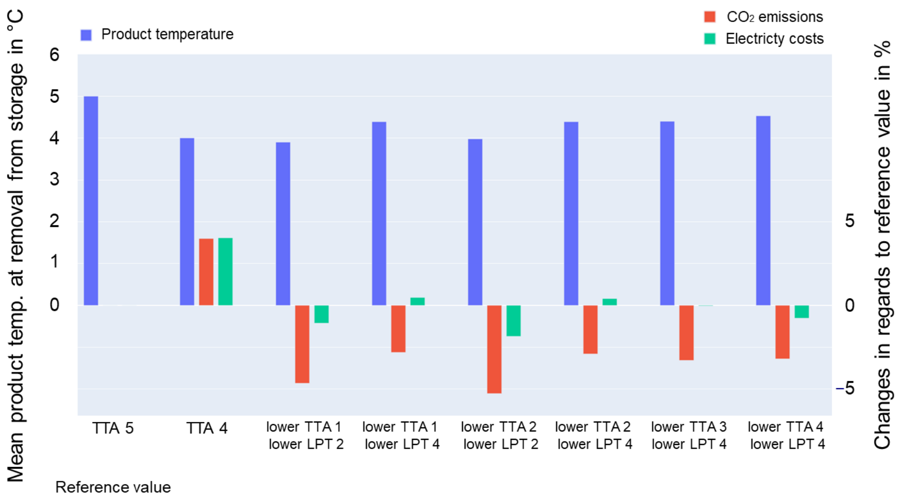

Figure 15. Results for flexibilization of cold storage warehouse for cooling for May 2021.

The constant target temperature of the air with a nominal temperature of 5 °C represents the reference value. In all the flexibilizations shown, the average temperature at removal from storage is lower than the temperature at removal for the standard operational mode. In all cases, CO_2 emission savings (negative changes) are achieved. The savings are greater for lower limiting product temperatures for the same lower target temperature of the air. Lower target temperatures of the air for equal lower limiting products temperatures have lower emission savings.

Electricity cost savings are less than the CO_2 emission savings, in some cases there are low additional costs for the purchase of electricity.

3.2.4. Refrigerated Transport

For refrigerated transport, diesel-related emissions and costs are relevant. In both cases, only the cooling-related emissions and costs are considered and not those for the trip itself and the energy share for overcoming the driving resistances.

Figure 16 shows the relative changes in CO_2 emissions compared to the reference value in % for the month of May from the test reference year [26] for the location of the dairy of this case study. The values refer to the monthly consumption for daily ten-hour trips of a full truck load. Each trip start at 07:00. The weather influences are thus identical for all scenarios considered. The loading space temperature is adjusted to the average product temperature (prod. temp) so that the average temperature at the end of delivery is 4 °C in all scenarios.

The results show that the higher the loading space temperature, the less CO_2 is emitted, as the truck needs to provide less cooling capacity. For the considered case (month of May, travel time, duration), emissions can be reduced by over 90%. It is also evident that the curve has an inflection point between a product temperature of 3.5 °C and 3.75 °C or a loading space temperature of 5 °C. To the left of this inflection point (as product temperature continues to decrease or loading space temperature rises), further cooling of the products results in smaller additional emission savings than to the right of the inflection point (where the slope of the curve is less steep). The reason is that at high loading space temperatures, very little cooling capacity needs to be provided by the truck. Emissions are primarily generated for the pre-cooling of the insulation.

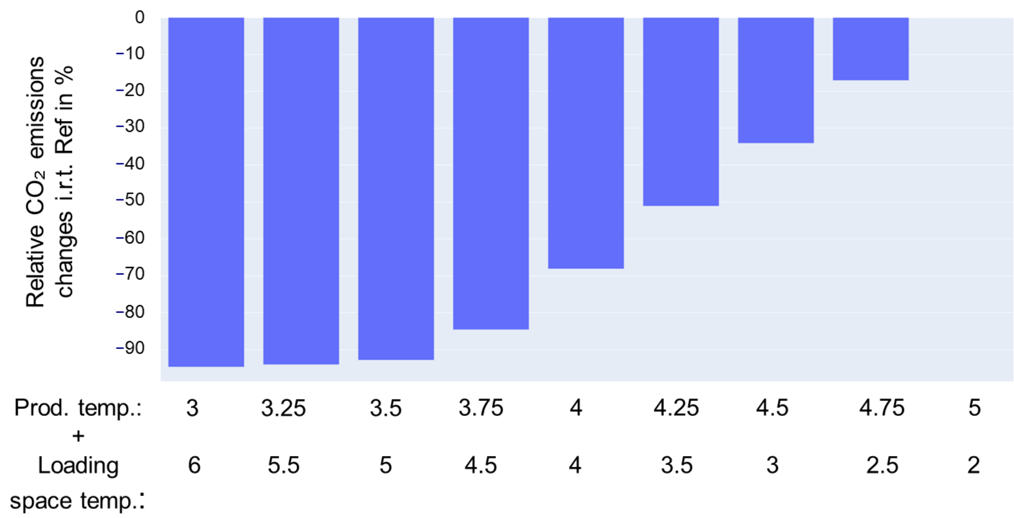

Figure 16. Relative changes in CO_2 emissions compared to the reference in % for the test data set in May.

The results for diesel savings and/or cost savings appear identical to the emission savings, as there is a constant conversion factor between these values.

It must be noted that the loading space temperature may be out of the regulations. The goal of this study is to show via simulations how much CO_2 emissions can be saved if more cooling takes place in the cold storage warehouse and the loading space temperature is adjusted accordingly. The cold chain is always intact, but with different temperatures. If emissions can be saved, then there must be additional studies to determine whether temperature fluctuations affect the quality of the products.

3.3. Results for Flexibilization of the Cold Chain

In Sections 3.2.1–3.2.4, the effects of flexibilization on the individual links of the cold chain were presented. However, the individual links of the chain have an impact on the subsequent links, especially if less cooling is applied in one step, i.e., the product temperature at the beginning of the subsequent step is higher. Therefore, the results (e.g., CO_2 emissions) are considered as a whole in the following. Theoretically, there are a large number of possible total flexibilizations if all single flexibilization are combined. However, certain combinations can be ruled out in advance. For example, it does not make sense if the product exit temperature from the cooling tunnel is around 3 °C to 8 °C, but the LPT in the cold storage warehouse is around 4 °C to 5.5 °C. Almost every pallet stored in the cold storage warehouse would thus be outside the LPT, depriving the cold storage warehouse of its flexibility as it would have no degrees of freedom. These combinations, which do not make sense, are eliminated before calculating the results.

3.3.1. Cold Chain for Maintaining Temperature in Cold Storage Warehouse

The following examines the cold chain with pre-cooling and a cold storage warehouse for temperature maintenance.

Figure 17 displays the relative change in the cooling-related emissions for the cold chain with an end temperature of 4.3 °C upon unloading for the study period of May 2021, based on the average temperature at removal from the cold storage warehouse. Since the results of the cooling-related emissions from refrigerated transport are only available in 0.25 °C increments, the unloading temperatures after the cold storage warehouse are rounded to the values shown in the figure. The shape of the depicted values (e.g., circle) represents the operating mode of the cold storage warehouse. The color indicates the operating mode of the cooling tunnel. From Figure 17, it can be inferred that reducing the average temperature at removal from the cold storage warehouse leads to a decrease in CO_2 emissions up to a certain temperature. There is an inflection point in the curve between 3.75 °C and 3.75 °C. To the right of this point, a temperature decrease leads to a reduction in CO_2 emissions. To the left, further cooling results in a slight increase in CO_2 emissions. This point is similar to the inflection point in Figure 16. For the illustrated month and the displayed trip in the refrigerated transport, a further decrease in product temperatures yields only very minor CO_2 reductions since there is a minimal cooling need. A further decrease in product temperature causes more CO_2 emissions in the preceding links than the reductions achieved in the refrigerated transport.

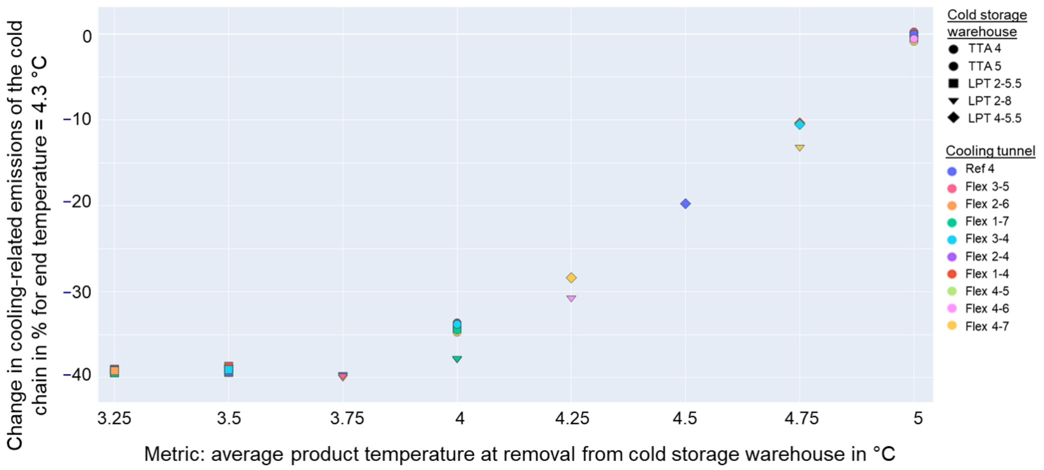

Figure 17. Results of the relative change in cooling-related emissions of the cold chain in % for an end temperature upon delivery of 4.3 °C for the study period of May 2021.

Figure 18 contrasts the emissions from each segment of the cold chain for a standard operating mode and a potential flexible operational mode for the study period of May 2021. Only cooling-related emissions are presented. The standard operational mode consists of a cooling tunnel with an air entry temperature of 4 °C, a constant temperature of 5 °C in the cold storage warehouse, and a loading space temperature of 3 °C in the refrigerated transport. During this period, for the standard operational mode (top of Figure 18), 42.8% of the emissions are due to pre-cooling, 16.3% to the cold storage warehouse, and 41.0% to refrigerated transport.

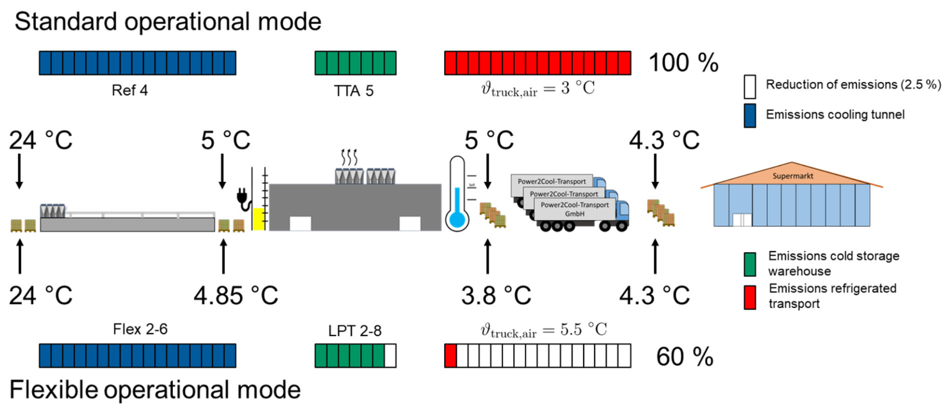

Figure 18. Comparison of the distribution of emissions among the individual links of the cold chain with pre-cooling for standard operational mode and a potential flexible operational mode for the study period of May 2021.

The term "standard operational mode" refers to the fact that in this mode there is no flexibilization. It does not mean that necessarily all cold chains use these temperatures. If temperatures are within the regulations, the temperatures may vary.

The distribution of the emissions on the links depends heavily on the assumed journeys and the loading space temperature of the refrigerated transport. At the bottom of Figure 18, a flexible operational mode is shown with Flex 2-6 for the cooling tunnel, LPT 2-8 for the cold storage warehouse, and a loading space temperature of 5.5 °C. Here, 42.5% is attributed to pre-cooling, 14.4% to the cold storage warehouse, and 3.2% to the refrigerated transport. The savings for the cooling tunnel are very minimal both individually and throughout the cold chain. For the cold storage warehouse, an emission reduction of 12% individually for LPT 2-8 (see Figure 14) leads to a 1.9% emission reduction in the cold chain. The largest emission reduction is achieved in refrigerated transport. Here, emissions can be reduced from 60% of the total in the cold chain to 3%.

Figure 19 shows the relative change in cooling-related costs for the cold chain during the investigation period. The cooling-related costs comprise electricity expenses for pre-cooling and the cold storage warehouse and the diesel proportion for cooling of the refrigerated transport. Electricity costs are based on the electricity market price as well as grid fees and levies [28]. Diesel costs are net prices for 2021 [29]. The curve progression is similar to the relative changes in emissions shown in Figure 17.

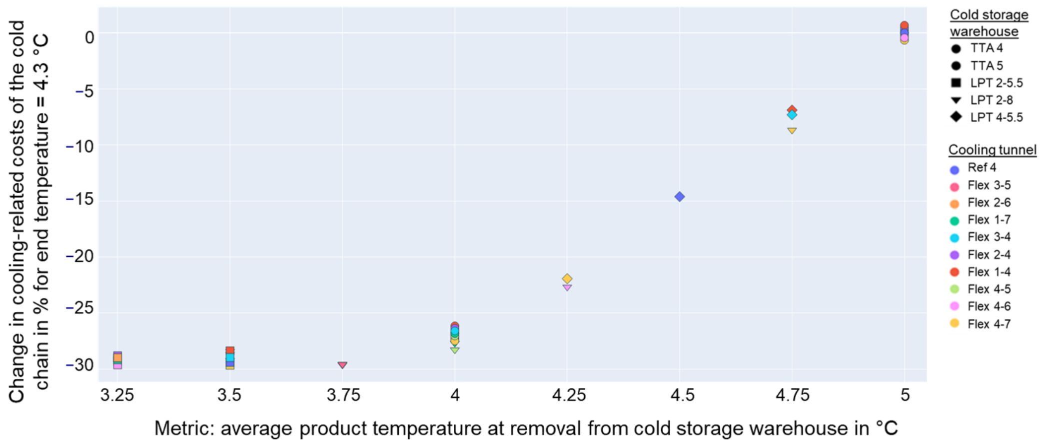

Figure 19. Results of the relative change in cooling-related costs of the cold chain in % for an end temperature upon delivery of 4.3 °C for the study period of May 2021.

3.3.2. Cold Chain for Cooling in Cold Storage Warehouse

Figure 20 compares the emissions of the individual links of the cold chain without pre-cooling for standard operational mode and a potential flexible operational mode for the study period of May 2022. The emissions related to cooling are presented. The standard operational mode involves a constant temperature of 5 °C in the cold storage warehouse and a loading space temperature of 3 °C. During this period, for the standard operational mode (at the top of Figure 20), 57.5% of the emissions are attributed to the cold storage warehouse, and 42.5% to the refrigerated transport. The distribution depends on the actual or assumed delivery trips and the loading space temperature of the refrigerated transport.

The flexible operational mode consists of a TTA 1-9 and LPT 2-5.5 in the cold storage warehouse, as well as a loading space temperature of 5 °C. The flexible operational mode accounts for 58% of the emissions compared to the standard operational mode. Of these 58%, 55 percentage points are attributed to the cold storage warehouse. The remaining 3% are caused by refrigerated transport. Just as in Section 3.3.1, the majority of emission savings are attributed to the refrigerated transport.

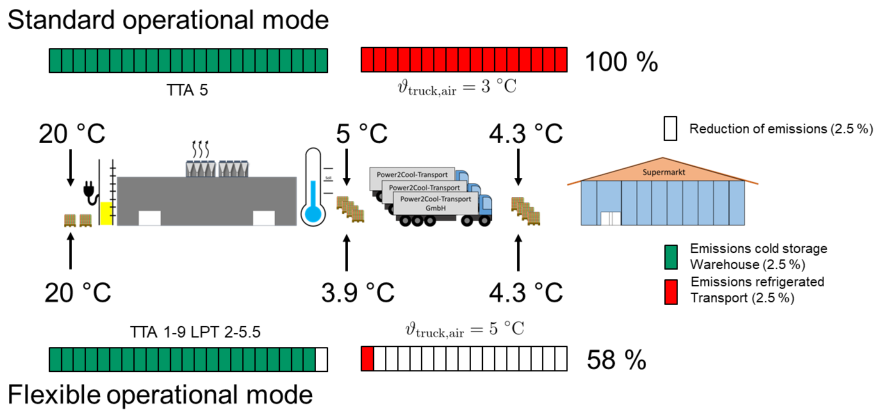

Figure 20. Comparison of the distribution of emissions among the individual links of the cooling chain without pre-cooling for standard operation and a possible flexibility for the study period of May 2022.

4. Discussion

This section discusses the outcome of the simplifying assumptions on the results. Terms written in bold refer to the same terms from Section 3.1.

- One month: Calculating one whole year will be crucial since the course of the GEF and the level of specific emissions depend on the seasons. Additionally, heat inputs vary significantly throughout the year. Effects like higher specific emissions in winter coupled with a lower cooling requirement have not yet been examined.
- Test reference year: Data from the test reference year might differ from the actual weather data on-site, even though this influence is limited by using monthly values for refrigerated transport.
- Average pallet temperature: The savings in refrigerated transport plotted over the product temperature (see Figure 16) are not constant; the slope changes. Thus, effects resulting from averaging "warmer" and "cooler" pallets in refrigerated transport may not cancel each other out.
- Trip length: The assumption of daily 10-h trips is a high estimation. With shorter trips, fewer cooling-related emissions are caused in refrigerated transport. The allocations shown in Figures 18 and 20 will change. However, flexibility might result in even less cooling being required by the truck's cooling unit, as the temperature in the product is sufficient to compensate for the heat input (which is less likely for long trips).
- No infiltration loads: Infiltration loads change little or not at all by adjusting the loading space temperature, but the total emissions and the proportional share due to flexibility would change.
- Standard operational mode: As a result, the amount of emissions for the refrigerated transport is high. Emissions (and therefore the amount of saved emissions and the distribution of the emissions among the individual links) would be different if the nominal temperature of the cold storage warehouse were 4 °C.
- Electricity costs: The financial benefits may decrease or vanish due to other stakeholders being involved in the flexible electricity purchase at the electricity exchange. Furthermore, grid fees might change due to flexibility, affecting the total electricity costs [30].
- It is important to emphasize that the results strongly depend on local conditions, such as plant technology and trips made. Therefore, the identified potentials must be carefully examined on a case-by-case basis.
- The goal of this study was to examine the effects of flexibility on emissions and electricity costs. Temperatures of dairy products are within regulations, but appropriate studies have to be undertaken to evaluate whether the quality is affected or not. If flexibilization of one or more links in the cold chain affects quality, then there cannot be flexibilization since the high quality of the products needs to be maintained.

5. Conclusions

In Section 1, the following research questions were stated: 'What is the CO_2 emission reduction potential of a cold chain for chilling, storing and transportation? What role does the temperature of the stored products at removal from the cold storage warehouse play in the emission reduction potential?' The results of this study show that the CO_2 emission reduction potential is much greater if the flexibilization of the cold storage warehouse is not viewed in isolation but as a part along the cold chain of chilling, storing, and transportation. In Sections 3.2.2 and 3.2.3, it is shown that the cooling-related emissions can be reduced by 40 % compared to the standard operational mode. The reason for this answers the second research question: A key finding of this study is that in the case of the cold chain, the transfer parameter between the links, i.e., the temperature of the products, is of great importance. If the cooling capacity decreases in one link, meaning the temperature of the products rises, emissions might be reduced in this link. However, the subsequent process step will need to provide more cooling, potentially leading to increased emissions. By reducing the temperature at removal from the cold storage warehouse due to more cooling, the cooling demand in the refrigerated transportation decreases. However, it has to be mentioned that the average temperature of removal from storage could be reduced in the cold storage warehouse and the amount of emissions could also be reduced due to the flexibilization. Emission savings should be considered across the cold chain. The results show that the flexibilization of the cold chain presents another approach for the industry to contribute to sustainability.

Outlook: Sector coupling (coupling electricity with other sectors, e.g., transport and heating) is one of the approaches to ensure the success of the energy transition [31]. In 2019, already 91 % of cooling demand in Germany was powered by electricity [32]. The emissions required for cooling provision in cooling tunnels and/or cold storage warehouses are continuously decreasing with the expansion of renewable energies, but there is also potential to reduce the electricity demand of VCRS [33]. However, flexibility will also be needed in the future to respond to the fluctuating energy supply from renewable energies [34]. Cold storage warehouses, with their inherent storage capacity, will continue to play an important role in providing flexibility. A large part of the emission reductions from the conducted analysis comes from saving diesel in refrigerated transport, as cooling with electricity is much more efficient than with diesel. Truck transport will also be part of sector coupling, development moving towards battery-electric vehicles and fuel cell electric vehicles [35]. Therefore, future truck transport will require electricity either directly or indirectly. Until the transformation of electricity generation to exclusively renewable energies is achieved, these technologies, due to different efficiencies, will also have a variable CO_2 footprint that depends on the time of charging/conversion. Flexibility strategies of the cold chain must be re-examined to include the variable CO_2 demand for the various links in the cold chain.

Author Contributions: Conceptualization, M.S., V.S. and U.H.; methodology, M.S., J.I. and V.S.; software, M.S. and J.I.; validation, M.S. and J.I.; formal analysis, M.S. and J.I.; investigation, M.S. and J.I.; data curation, M.S.; writing—original draft preparation, M.S.; writing—review and editing, M.S. and J.I.; visualization, M.S.; supervision, U.H.; project administration, U.H.; funding acquisition, U.H. All authors have read and agreed to the published version of the manuscript.

Funding: The project ["BlueMilk", grant number: 281A103616] was supported by funds of the Federal Ministry of Food and Agriculture (BMEL) based on a decision of the Parliament of the Federal Republic of Germany via the Federal Office for Agriculture and Food (BLE) under the innovation support programme. We acknowledge support by the Open Access Publication Fund of Technische Hochschule Ingolstadt.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data related to the cooling tunnel and cold storage warehouses (load profiles, production data, building plans, ...) are unavailable due to privacy restrictions. Other data (e.g., electricity market data) are referenced in the text.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Nomenclature

The following abbreviations and symbols are used in this manuscript:

Abbreviations	
AET	air entry temperature
CSW	cold storage warehouse
CT	cooling tunnel
GEF	grid emission factor
LPT	limiting product temperature
PV	photovoltaic
RE	renewable energies
TTA	target temperature of the air
VCRS	vapor-compression refrigeration system
VRE	variable renewable energies
YC	yogurt cup
Latin symbols	
$A_{\mathrm{CSW,roof}}$	Area of the cold storage warehouse roof in $\mathrm{m^2}$
A_{CT}	Area of the cooling tunnel surface in $\mathrm{m^2}$
$A_{\mathrm{pallet,side}}$	Area of the surface for a specific pallet side in $\mathrm{m^2}$
A_{steel}	Area of the steel surface inside the cold storage warehouse in $\mathrm{m^2}$
A_{truck}	Area of the truck loading space surface in $\mathrm{m^2}$
$A_{\mathrm{truck,roof}}$	Area of the roof of the truck's loading space in $\mathrm{m^2}$
$A_{\mathrm{truck,side}}$	Area of the side surface of the truck's loading space in $\mathrm{m^2}$
A_{W}	Area of wall W of the cold storage warehouse in $\mathrm{m^2}$
A_{YC}	Area of the yogurt cup surface in $\mathrm{m^2}$
a	Thermal diffusivity of the yogurt pallet model in $\mathrm{m^2\,s^{-1}}$
$a_{\mathrm{CSW,roof,outside}}$	Absorption coefficient of the cold storage warehouse's roof exterior
$a_{\mathrm{truck,outside}}$	Absorption coefficient for the truck's exterior
c_p	Specific heat capacity in $\mathrm{J\,kg^{-1}\,K^{-1}}$
$c_{p,\mathrm{air}}$	Specific heat capacity of air in $\mathrm{J\,kg^{-1}\,K^{-1}}$
$c_{p,\mathrm{ins}}$	Specific heat capacity of insulation in $\mathrm{J\,kg^{-1}\,K^{-1}}$
$c_{p,\mathrm{YC}}$	Specific heat capacity of a yogurt cup in $\mathrm{J\,kg^{-1}\,K^{-1}}$
EER_{CT}	Energy efficiency ratio of the refrigerating plant of the cooling tunnel
H_i	Heating value in $\mathrm{J\,m^{-3}}$
I	Solar radiation in $\mathrm{W\,m^{-2}}$
$k_{\mathrm{CSW,roof}}$	Thermal transmittance of the cold storage warehouse roof in $\mathrm{W\,m^{-2}\,K^{-1}}$
k_{CT}	Thermal transmittance of the cooling tunnel in $\mathrm{W\,m^{-2}\,K^{-1}}$
k_{truck}	Thermal transmittance of the truck's loading space in $\mathrm{W\,m^{-2}\,K}$
k_{W}	Thermal transmittance of wall W in the cold storage warehouse in $\mathrm{W\,m^{-2}\,K^{-1}}$
k_{YC}	Thermal transmittance of a yogurt cup in $\mathrm{W\,m^{-2}\,K}$
m_{ins}	Mass of insulation in kg
m_{YC}	Mass of a yogurt cup in kg
n	Number of yogurt cups per pallet
n_{pallets}	Number of pallets in truck's loading space
P_{CT}	Cooling capacity of the cooling tunnel in W
$P_{\mathrm{CT,el}}$	Electrical power consumption of the refrigerating plant of the cooling tunnel in W
P_{el}	Electrical consumption in W
P_{VCRS}	Cooling capacity of the cold storage warehouse in W
$Q_{\mathrm{CSW,air}}$	Heat change of the air in J
$Q_{\mathrm{truck,cooling}}$	Energy required for cooling during refrigerated transport in J
$Q_{\mathrm{truck,ins}}$	Energy required for pre-cooling the truck's loading space in J

Q_{YC}	Heat from a yogurt cup to be dissipated in J
$\dot{Q}_{\mathrm{CSW,air}}$	Heat flow in the cold storage warehouse air in W
$\dot{Q}_{\mathrm{CSW,door}}$	Heat flow due to door openings in the cold storage warehouse in W
$\dot{Q}_{\mathrm{CSW,el}}$	Heat flow input due to electricity in the cold storage warehouse in W
$\dot{Q}_{\mathrm{CSW,product}}$	Total heat flow of all pallets inside the cold storage warehouse in W
$\dot{Q}_{\mathrm{CSW,products}}$	Heat flow between air and products inside the cold storage warehouse in W
$\dot{Q}_{\mathrm{CSW,solar}}$	Solar heat input on the cold storage warehouse roof in W
$\dot{Q}_{\mathrm{CSW,steel}}$	Heat exchange between the steel and air inside the cold storage warehouse in W
$\dot{Q}_{\mathrm{CSW,trans}}$	Total heat transmission through the cold storage warehouse in W
$\dot{Q}_{\mathrm{CSW,trans,W}}$	Heat transmission through wall W of the cold storage warehouse in W
$\dot{Q}_{\mathrm{CT,fans}}$	Heat input from the cooling tunnel fans in W
$\dot{Q}_{\mathrm{CT,trans}}$	Heat transmission through the cooling tunnel in W
$\dot{Q}_{\mathrm{CT,yogurt}}$	Cooling capacity required for cooling yogurt inside the cooling tunnel in W
$\dot{Q}_{\mathrm{pallet}}$	Total heat flow of a pallet in W
$\dot{Q}_{\mathrm{pallet,side}}$	Heat flow on a specific side of a pallet in W
$\dot{Q}_{\mathrm{truck,product}}$	Total heat flow of all products inside the truck's loading space in W
$\dot{Q}_{\mathrm{truck,scenario}}$	Heat flow from a pallet under a specific scenario in W
$\dot{Q}_{\mathrm{truck,solar}}$	Solar heat input on the truck's loading space in W
$\dot{Q}_{\mathrm{truck,trans}}$	Heat transmission through the truck's loading space in W
t	Cooling duration in s
Δt	Time difference between time steps in s
V_{air}	Volume of air in m^3
V_{diesel}	Volume of diesel in m^3
V_{truck}	Volume of the truck's loading space in m^3
Greek symbols	
$\alpha_{\mathrm{CSW,inside}}$	Heat transfer coefficient inside the cold storage warehouse in $\mathrm{W\,m^{-2}\,K^{-1}}$
$\alpha_{\mathrm{CSW,roof,outside}}$	Heat transfer coefficient on the outside of the cold storage warehouse roof in $\mathrm{W\,m^{-2}\,K^{-1}}$
$\alpha_{\mathrm{truck,outside}}$	Heat transfer coefficient on the outside of the truck in $\mathrm{W\,m^{-2}\,K^{-1}}$
$\eta_{\mathrm{truck,cooling}}$	Efficiency of the truck's cooling unit
ϑ	Temperature in the yogurt pallet model at a specific location and time in °C
$\frac{\partial \vartheta}{\partial t}$	Partial derivative of temperature with respect to time t
ϑ_{AET}	Air entry temperature in the cooling tunnel in °C
$\vartheta_{\mathrm{ambient}}$	Ambient temperature outside the truck's loading space in °C
$\vartheta_{\mathrm{CSW,air}}$	Temperature of air inside the cold storage warehouse in °C
$\Delta\vartheta_{\mathrm{CSW,air}}$	Temperature change of the air inside the cold storage warehouse in K
$\vartheta_{\mathrm{hall}}$	Temperature inside the production hall in °C
$\vartheta_{\mathrm{pallet,side}}$	Temperature of a pallet us specific side at the surface in °C
$\vartheta_{\mathrm{prod,dest}}$	Product temperature at start of delivery in °C
$\vartheta_{\mathrm{prod,start}}$	Product temperature at destination of delivery in °C
$\vartheta_{\mathrm{start}}$	Temperature of the truck before pre-cooling in °C
$\vartheta_{\mathrm{steel}}$	Temperature of steel inside the cold storage warehouse in °C
$\vartheta_{\mathrm{truck,air}}$	Temperature inside the truck's loading space in °C
$\vartheta_{\mathrm{truck,target}}$	Target temperature for pre-cooling in °C
ϑ_{W}	Temperature of the room adjacent to wall W of the cold storage warehouse in °C
$\vartheta_{\mathrm{YC,start}}$	Starting temperature of a yogurt cup in °C
ϑ_{YC}	Temperature of a yogurt cup at time t in °C
$\vartheta_{\mathrm{YC}}(t_n)$	Temperature of a yogurt cup at time t_n in °C
$\vartheta_{\mathrm{YC}}(t_{n-1})$	Temperature of a yogurt cup at time t_{n-1} in °C
ρ_{air}	Density of air in $\mathrm{kg\,m^{-3}}$
Operators	
Δ	Laplace operator

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