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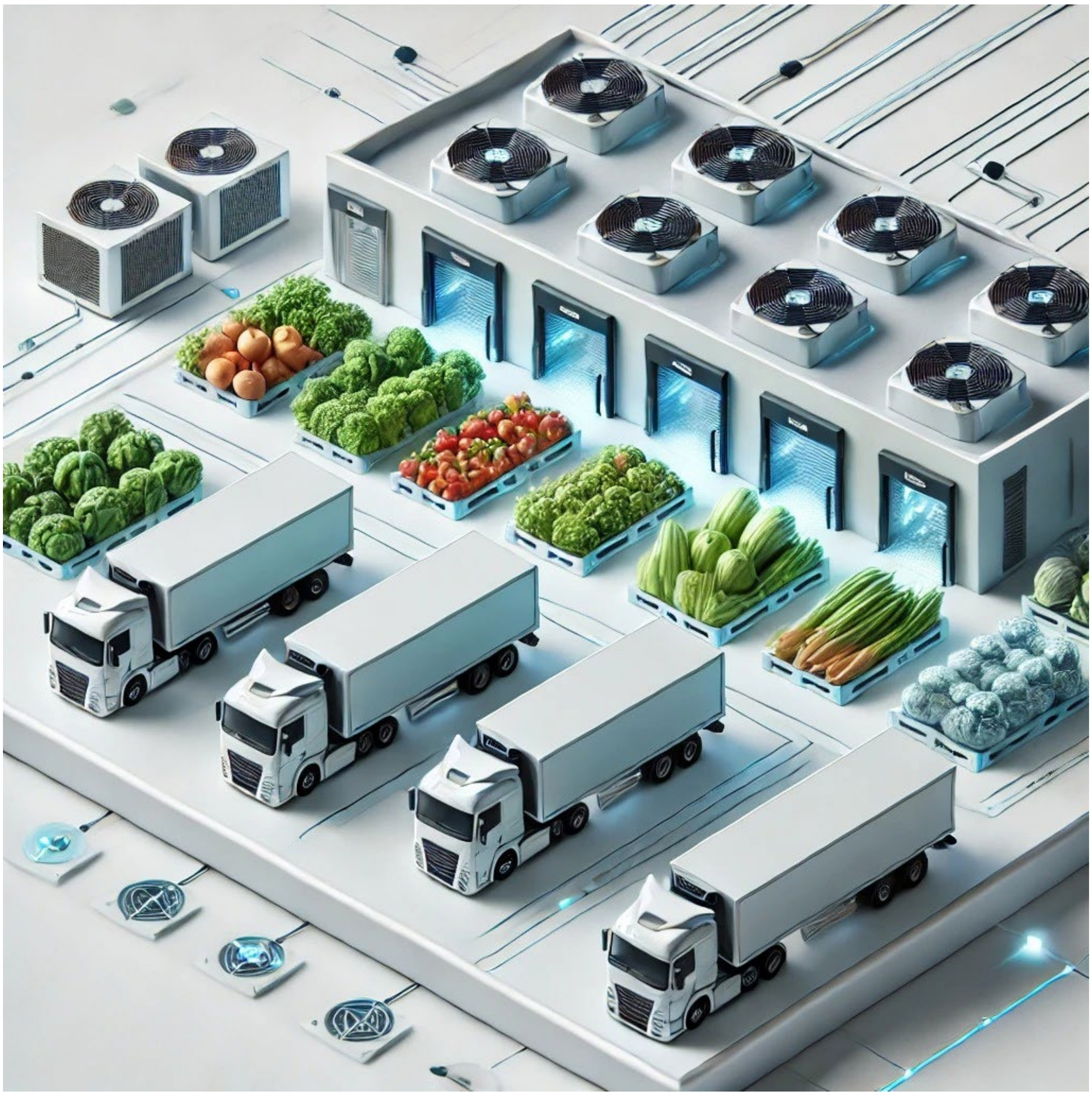
Frigero

Towards energy autonomous temperature-controlled supply chains



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Summary

In temperature-controlled supply chains (TCSC), perishable goods are processed and handled near or below the freezing mark. This involves the use of refrigerated production lines, warehouses, transhipment, infrastructure, and trucks that consume large quantities of energy for refrigeration. Currently, 60% of the food consumed globally requires refrigeration at some stage in the supply chain (SC). TCSC emissions already account for an important proportion of total developed country emissions, between 2% and 4%. This figure will increase as living standards improve in developing countries. However, the environmental impacts of TCSC and their mitigation have not been sufficiently studied. This research project addresses this gap by focusing on the environmental and economic optimisation of temperature-controlled food supply chains in the Swiss context. Two TCSCs of project partners from the fruit and vegetable industry and the dairy industry served as the unit of analysis for this research project.

An initial supply chain survey revealed that the structure and design of the use cases of the TCSCs analysed in this research project differ significantly from a fully vertically integrated supply chain, i.e. with own fleet and main value-added activities in logistics in the fruit and vegetable supply chain, to a more fragmented SC, i.e. with outsourced logistics activities and main value-added activities in production in the dairy supply chain. Consequently, 68% of the hotspots of GHG emissions in the fruit and vegetable industry are due to transport, with a further 25% attributable to transport refrigeration. In the dairy industry supply chain, 77% of emissions are caused by production.

Subsequently, expert interviews were conducted to identify GHG emission mitigation measures for TCSCs, which were then complemented with a literature review. It was identified that both, intra- and inter-organisational measures, are essential for the cost-effective reduction of greenhouse gas emissions. In particular, three applications within TCSCs offer the potential for mutual benefit through inter- and intra-organisational cooperation. The first such application is the recovery of waste heat from refrigeration machines, which can be efficiently reused from neighbouring industries or district heating networks. The second area of focus is the role of warehouses as a switchable load for peak shaving, particularly considering the increasing integration of intermittent renewable energy supplies. A third potential area for collaboration is the promotion of photovoltaic (PV) adoption at the sites of upstream suppliers through the establishment of purchasing agreements.

The analysis of the interrelationships and the interdependencies of the prior established GHG reduction measures using Decision-Making Trial and Evaluation Laboratory (DEMATEL) technique revealed the following. According to the prominence value (R+C), “optimisation of the refrigeration machine” is the most important factor for reducing GHG emissions in temperature-controlled SCs, followed by “demand-oriented and dynamic cooling load adjustment”. These two factors are highly interdependent. At the same time, they are strongly influenced by other factors. Managing their influencing factors is key, including the use of warehouses for peak load reduction to integrate renewable, intermittent energy sources into the electricity mix. At the same time, employee training and technical measures should be taken to reduce heat infiltration through door openings, which would also allow more efficient use of the refrigeration machine. In addition, retrofitting the building envelope would also contribute to more efficient operation of the refrigeration machine by reducing heat transmission losses.

These measures were then translated into marginal abatement cost curves (MACC) to quantify their environmental and economic performance. The MACCs were applied to the use cases, which allowed ranking and prioritisation. The MACC has demonstrated that most measures for warehousing and production can be implemented cost-effectively. In contrast, alternative refrigeration and drive technology for transport always require investments without any return over the lifespan. The ranking of the measures across the various scenarios analysed revealed that, in addition to the cost-effective measures, the following should be prioritised for the Fruit and Vegetable SC: 1) phase change material (PCM) based transport refrigeration, and 2) battery electric vehicles (BEVs) and 3) photovoltaic (PV) systems over the car park. In the case of the dairy SC, the ranking suggested the following three measures as priorities: 1) optimisation of the milk run for transport, 2) installation of a frequency converter in the heat exchange retrofit in production, and 3) renewable energy purchasing agreements with suppliers for cold warehousing and production. In the fruit and vegetable SC, 8% to 28% GHG emission reductions can be achieved cost-effectively. In addition, 41% to 46% of emissions can be reduced at an annual cost of CHF 2.19 to 5.52 million. In the dairy SC, the full potential of the practices can be implemented cost-effectively, with GHG emission reductions of 15% to 19%.

The pilot tests were implemented in the dairy processing company. Following the analysis of the results of the preceding work packages and technical discussions with process engineers of the project partner, an initial estimation of the efficiency and cost-saving potential was made. Based on these findings, the project partner has decided to implement a high-temperature heat pump (HTHP) for the cheese vat and an optimisation of the existing thermo swing in 2025. It is projected that the former will result in energy savings of 76% and cost savings of 51% compared to the current situation, while the latter will result in energy savings of 80% and cost savings of 54% compared to the current situation.

A supply chain simulation model was constructed using the Python programming language. In designing the user interface (UI), Nielsen's heuristics were employed to prioritise simplicity and ease of use. The software was subsequently compiled into a standalone executable application, compatible with both Windows and macOS operating systems. The simulation model generates an interactive dashboard that presents comprehensive cost and emission data for key supply chain activities, including refrigerated transportation, production, and warehousing. Furthermore, the application incorporates dynamic benchmarking capabilities. The interactive charts on the dashboard facilitate the adjustment of input parameters thereby enabling companies to simulate a range of scenarios.

Résumé

Dans les chaînes d'approvisionnement à température contrôlée, les denrées périssables sont traitées et manipulées à proximité ou en dessous du point de congélation. Cela implique l'utilisation de lignes de production réfrigérées, d'entrepôts, de transbordement, d'infrastructures et de camions qui consomment de grandes quantités d'énergie pour la réfrigération. Actuellement, 60 % des aliments consommés dans le monde nécessitent une réfrigération à un stade ou à un autre de la chaîne d'approvisionnement. Les émissions de CTCS représentent déjà une part importante des émissions totales des pays développés, entre 2 et 4 %. Ce chiffre augmentera à mesure que le niveau de vie s'améliorera dans les pays en développement. Cependant, les impacts environnementaux des CTPC et leur atténuation n'ont pas été suffisamment étudiés. Ce projet de recherche comble cette lacune en se concentrant sur l'optimisation environnementale et économique des chaînes d'approvisionnement alimentaire à température contrôlée dans le contexte suisse. Deux chaînes d'approvisionnement à température contrôlée de partenaires du projet issus de l'industrie des fruits et légumes et de l'industrie laitière ont servi d'unité d'analyse pour ce projet de recherche.

Une première étude de la chaîne d'approvisionnement a révélé que la structure et la conception des cas d'utilisation des CSCT analysés dans ce projet de recherche diffèrent considérablement d'une chaîne d'approvisionnement entièrement intégrée verticalement, c'est-à-dire avec une flotte propre et les principales activités à valeur ajoutée dans la logistique dans la chaîne d'approvisionnement des fruits et légumes, à une chaîne d'approvisionnement plus fragmentée, c'est-à-dire avec des activités logistiques externalisées et les principales activités à valeur ajoutée dans la production dans la chaîne d'approvisionnement des produits laitiers. En conséquence, les points chauds des émissions de GES dans l'industrie des fruits et légumes sont le transport (68 %) et la réfrigération du transport (25 %), et dans l'industrie laitière, la production (77 % des émissions totales de la chaîne d'approvisionnement).
Ensuite, des entretiens avec des experts ont été menés afin d'identifier les mesures d'atténuation des émissions de GES pour les CTCS, qui ont ensuite été complétées par une analyse documentaire. Il est apparu que les mesures intra- et inter-organisationnelles sont essentielles pour une réduction rentable des émissions de gaz à effet de serre. En particulier, trois applications au sein des CTPC offrent la possibilité d'un bénéfice mutuel par le biais d'une coopération inter- et intra-organisationnelle. La première application est la récupération de la chaleur perdue des machines frigorifiques, qui peut être efficacement réutilisée par les industries voisines ou les réseaux de chauffage urbain. Le deuxième

domaine d'intérêt est le rôle des entrepôts en tant que charge commutable pour l'écrêtement des pointes, en particulier si l'on tient compte de l'intégration croissante des sources d'énergie renouvelables intermittentes. Un troisième domaine potentiel de collaboration est la promotion de l'adoption de l'énergie photovoltaïque (PV) sur les sites des fournisseurs en amont par l'établissement d'accords d'achat.

L'analyse des relations et des interdépendances des mesures de réduction des émissions de gaz à effet de serre préalablement établies à l'aide de la technique DEMATEL (Decision-Making Trial and Evaluation Laboratory) a révélé ce qui suit. Selon la valeur d'importance (R+C), « l'optimisation de la machine frigorifique » est le facteur le plus important pour réduire les émissions de GES dans les CS à température contrôlée, suivi par « l'ajustement dynamique de la charge frigorifique en fonction de la demande ». Ces deux facteurs sont fortement interdépendants. En même temps, ils sont fortement influencés par d'autres facteurs. La gestion de ces facteurs est essentielle, y compris l'utilisation des entrepôts pour réduire les pics de charge afin d'intégrer les sources d'énergie renouvelables et intermittentes dans le mix électrique. Parallèlement, la formation des employés et des mesures techniques devraient être prises pour réduire les infiltrations de chaleur par les ouvertures des portes, ce qui permettrait également une utilisation plus efficace de la machine frigorifique. En outre, la modernisation de l'enveloppe du bâtiment contribuerait également à un fonctionnement plus efficace de la machine frigorifique en réduisant les pertes de transmission de chaleur.

Ces mesures ont ensuite été traduites en courbes de coûts marginaux de réduction (MACC) afin de quantifier leurs performances environnementales et économiques. Les MACC ont été appliquées aux cas d'utilisation, ce qui a permis de les classer et de les hiérarchiser. Les MACC ont démontré que la majorité des mesures relatives à l'entreposage et à la production peuvent être mises en œuvre de manière rentable. En revanche, les technologies alternatives de réfrigération et d'entraînement pour le transport nécessitent toujours un investissement sans retour sur la durée de vie. Le classement des mesures dans les différents scénarios analysés a révélé que, outre les mesures rentables, les mesures suivantes devraient être considérées comme prioritaires pour le secteur des fruits et légumes : 1) réfrigération des transports à base de matériaux à changement de phase (MCP), 2) véhicules électriques à batterie (BEV) et 3) systèmes photovoltaïques (PV) sur le parking. Dans le cas de la SC laitière, le classement a suggéré les trois mesures suivantes comme priorités : 1) l'optimisation du transport du lait, 2) l'installation d'un convertisseur de fréquence dans l'échangeur de chaleur en production, et 3) des accords d'achat d'énergie renouvelable avec les fournisseurs pour les entrepôts frigorifiques et la production. Dans le secteur des fruits et légumes, il est possible de réduire les émissions de GES de 8 à 28 % de manière rentable. De plus, 41 à 46 % des émissions supplementaires peuvent être réduites pour un coût annuel de 2,19 à 5,52 millions de francs suisses. Dans le secteur des produits laitiers, il est possible de mettre en œuvre tout le potentiel des pratiques de manière rentable, avec des réductions d'émissions de GES de 15 à 19 %.

Les essais pilotes ont été mis en œuvre dans l'entreprise de transformation des produits laitiers. Suite à l'analyse des résultats des lots de travaux précédents et aux discussions techniques avec les ingénieurs des procédés du partenaire du projet, une première estimation de l'efficacité et du potentiel de réduction des coûts a été réalisée. Sur la base de ces résultats, le partenaire du projet a décidé de mettre en place une pompe à chaleur haute température (HTHP) pour la cuve à fromage et d'optimiser le thermo swing existant en 2025. La première devrait permettre de réaliser des économies d'énergie de 76 % et des économies de coûts de 51 % par rapport à la situation actuelle, tandis que la seconde devrait permettre de réaliser des économies d'énergie de 80 % et des économies de coûts de 54 % par rapport à la situation actuelle.

Un modèle de simulation de la chaîne d'approvisionnement a été construit à l'aide du langage de programmation Python. Lors de la conception de l'interface utilisateur, l'heuristique de Nielsen a été utilisée pour donner la priorité à la simplicité et à la facilité d'utilisation. Le logiciel a ensuite été compilé en une application exécutable autonome, compatible avec les systèmes d'exploitation Windows et macOS. Le modèle de simulation génère un tableau de bord interactif qui présente des données complètes sur les coûts et les émissions pour les principales activités de la chaîne d'approvisionnement, notamment le transport réfrigéré, la production et l'entreposage. En outre, l'application intègre des capacités d'analyse comparative dynamique. Les graphiques interactifs du tableau de bord facilitent l'ajustement des paramètres d'entrée, permettant ainsi aux entreprises de simuler une série de scénarios.

Main findings («Take-Home Messages»)

- Taking a holistic approach to understanding all stages of the temperature-controlled supply chain and its structure is key to pinpointing effective levers for reducing GHG emissions.
- In the field of transport refrigeration, alternatives that emit fewer GHG emissions than traditional vapour compression refrigeration units, but these are rarely used due to the reliance on large refrigeration system providers. Therefore, sharing knowledge of successful implementation examples is crucial for spreading alternative technologies.
- In refrigerated warehousing, there is currently untapped potential for improvement through the optimisation of existing refrigeration systems. This can be achieved by implementing flexible cooling load adjustment and waste heat recovery.

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BEV	Battery Electric Vehicles
CNG	Compressed Natural Gas
COP	Coefficient of performance
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DSS	Decision support system
FCEV	Fuel Cell Electric Vehicles
GHG	Greenhouse gas
HP	Heat pump
HTHP	High-temperature heat pumps
HVO	Hydrotreated Vegetable
LCO2	Liquid carbon dioxide
LN2	Liquid nitrogen
LNG	Liquefied Natural Gas
MACC	Marginal Abatement Cost Curve
NPV	Net Present Value
PCM	Phase Change Material
PV	Photovoltaic
SC	Supply chain
SFOE	Swiss Federal Office of Energy
TCSC	Temperature-controlled supply chain
UI	User-interface
UX	User experience
VCR	Vapor compression refrigeration
WP	Work package

1 Introduction

1.1 Context and motivation

Climate change has already shown widespread impacts on human and natural systems. Limiting global warming to well below 2°C therefore requires a drastic reduction in global greenhouse gas (GHG) emissions by 2050 with subsequent negative emissions (Karlsson et al., 2020). The agri-food sector alone accounts for 25-30% of total global GHG emissions of which 18% can be attributed to supply chain operations such as packaging, transport and food processing as can be seen in Figure 1 (Piester et al., 2020).

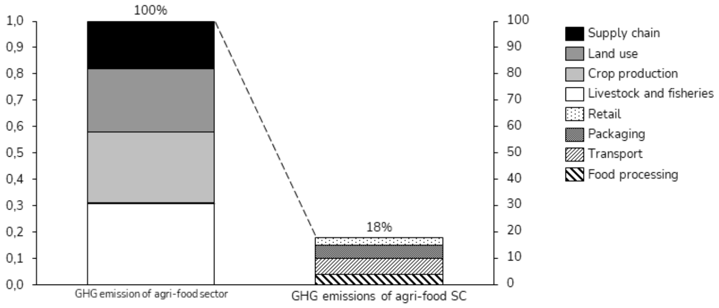

Figure 1: Global GHG emissions in the agri-food sector

The handling of perishable food within agri-food supply chains is of critical importance for ensuring the provision of diversified, safe, and high-quality food with sufficient nutrients, while simultaneously minimising food losses (Ravishankar et al., 2020; Trotter et al., 2023). However, this necessitates temperature-control at all stages of the supply chain (SC), where perishable goods are processed and handled near or below the freezing mark. This involves the use of refrigerated production lines, warehouses, transhipment infrastructure, and trucks that consume significant quantities of energy for refrigeration (Saif & Elhedhli, 2016).

Currently 60% of the food consumed worldwide requires refrigeration at least at one point in the supply chain. Emissions from temperature-controlled food chains are already significant in developed countries, accounting for 2-4% of total GHG emissions (Ravishankar et al., 2020).

With improved living standards in developing countries, the demand for temperature-controlled products (e.g. food/pharmaceutical products) will further increase, leading to a further increase in energy consumption and associated CO_2 emissions (Trotter et al., 2023).

Although temperature-controlled supply chains (TCSC) were acknowledged in the 2022 IPCC AR6 WGIII report as an important lever for climate change mitigation, the environmental impacts of TCSCs and their mitigation measures have not yet been extensively studied in the literature (Jouzdani & Govindan, 2021; Trotter et al., 2023). Existing attempts to increase the efficiency of TCSC focus on isolated solutions such as specific technologies or a single link in the SC. Only few studies address this issue comprehensively at a system level for the entire SC (Han et al., 2021; Malliaroudaki et al., 2022; Trotter et al., 2023). Emission reductions cannot always be achieved for each stage of SC by itself, but from a holistic perspective, where SC actors with a large mitigation potential cooperate with other SC actors whose activities require large amounts of energy and thus release GHG emissions. The optimal management of TCSCs should therefore ensure that the sum of total SC activities minimises GHG emissions (Malliaroudaki et al., 2022).

1.2 Project objectives

To close the existing gap, this study analysis measures to improve environmental performance along the entire temperature-controlled food SC that serves as a basis for a SC decision-making simulation tool. This tool provides a catalogue of GHG emission reduction measures through energy efficiency and technology change and energy generation at all stages of the TCSC and thus refrigerated transport, warehousing and production. Therefore, the main research question is:

“How can the combination of GHG emission reduction measures in refrigerated production, transport, and warehousing be analysed and optimised to achieve low carbon temperature-controlled supply chains?”

To answer this, the following sub-questions need to be answered:

- In which areas of the temperature-controlled supply chain are hotspots for realising energy efficiency potentials?
- What energy efficiency optimisation measures can be implemented and what effect do they have on environmental and economic sustainability?
- How can these individual measures and their effects on GHG emissions be quantified and translated into a holistic model?
- How can the overall supply chain, based on a simulation, be analysed to derive the most beneficial solution in terms of energy efficiency?
- How can trade-offs between different energy efficiency dimensions in the temperature-controlled supply chain be evaluated in terms of ecological and economical values?

The scope of this research project includes all supply chain activities from the farm or factory gate of the raw materials (e.g. in this case the dairy or vegetable and fruit farmer) to the final distribution point before consumption. Production is treated as a black box, so only heat and electricity consumption is accounted for. In terms of emissions, this can be translated into Scope 1 and 2 emissions as well as certain items of Scope 3 emissions of the Greenhouse Gas Protocol (Greenhouse Gas Protocol, 2004). These items include upstream purchased goods and services and transport and distribution as well as downstream transport and distribution.

2 Approach, method, results, and discussion

2.1 Work package 1: As-is product journey

2.1.1.Objectives

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<tr><td>Title:</td><td colspan="10">As-is product journey</td></tr>
<tr><td rowspan="2">Involved partners</td><td>ZHAW-INE</td><td>ZHAW-IFM</td><td>SUPSI</td><td>RALOG</td><td>SVTL</td><td>Clemap</td><td>Carbon Care</td><td>Aryzta</td><td>Züger</td><td>STISA</td></tr>
<tr><td colspan="3">Work package leader</td><td colspan="4">Work package involvement high</td><td colspan="3">Work package involvement low</td></tr>
<tr><td colspan="11"></td></tr>
<tr><td>Goal</td><td colspan="10">1. Mapping of the material flows from raw material collection to last distribution point before the customer of the temperature-controlled supply chains of the two involved partners Schwab and Züger, and their involved suppliers and customers for a selected product portfolio as unit of analysis
2. Collection of already implemented energy efficiency measures of the three case companies and their involved suppliers and customers</td></tr>
<tr><td>Tasks</td><td colspan="8">▪ Mapping of the material flow of the temperature-controlled supply chains of the two cases using company documentations and conducting interviews at the case companies and their involved suppliers and customers
▪ Getting an overview of already implemented energy efficiency measures in production, warehousing, cooling, transport and infrastructure of the case companies and their suppliers and customers, and, if possible, quantify the effects on energy savings, through company documentation and interviews</td><td colspan="2">ZHAW-INE
ZHAW-INE</td></tr>
<tr><td>Results</td><td colspan="10">D1.1 Process maps of as-is material flows for products of analysis
D1.2 Overview of energy efficiency activities at case companies</td></tr>
<tr><td colspan="11"></td></tr>
<tr><td>Diversity</td><td colspan="5">☑ Young scientists/PhD involved</td><td colspan="5">☑ Women involved*</td></tr>
</table>

2.1.2.Methods

The method employed in this work package (WP) is a case study approach, which was conducted in the fruit and vegetable industry at Schwab Guillod AG and in the dairy industry at Züger Frischkäse AG in Switzerland, combined with supply chain mapping. By using supply chain mapping, a network perspective was adopted to identify the nodes (who are participants in the supply chain) and the links (how the participants in the supply chain are connected) of the supply chain (MacCarthy et al., 2022). The interviews conducted and the site visits during the case studies helped to gain an in-depth understanding of:

- the supply chain structure (including tier 1)
- the activities, processes and temperatures involved at each stage of the supply chain

2.1.3.Results

The products traded within Schwab Guillod AG can be divided into four categories: (1) standard products from Swiss farmers or from abroad, (2) convenience products (3) original products and (4) storage products.

(1) Standard products, such as lettuce, are stored at 3°C for a short time after delivery and receipt of goods, and usually undergo a low level of processing for preparation, such as washing, removal of leaves and stems, etc. They are then packaged and temporarily stored at 7°C before being picked at 15°C and distributed at 5°C. (2) Convenience products such as potato salad are further processed into dishes, i.e. either standard products or stored products are used. The vegetables or fruits are washed, cut, centrifuged/dried, packed, and temporarily stored in the production before the products are picked and distributed. In contrast, (3) original products such as bananas are not processed at all. They are already delivered in their original packaging and are only stored, picked and distributed. (4) Storage products such as potatoes or carrots are delivered unwashed and undergo a washing and sorting process before long-term storage.

The distribution channels include, on the one hand, with 30% of sales, wholesale markets for restaurants, hotels, system catering, retail trade, and commerce. On the other hand, 50% of sales are delivered to branches of a Swiss retail chain. The remaining 20% are delivered very heterogeneously to supermarkets and trade. Deliveries are made in a star pattern with their own fleet of 18t- 20t diesel trucks based on a fixed tour planning.
The entire supply chain is illustrated in Figure 2.

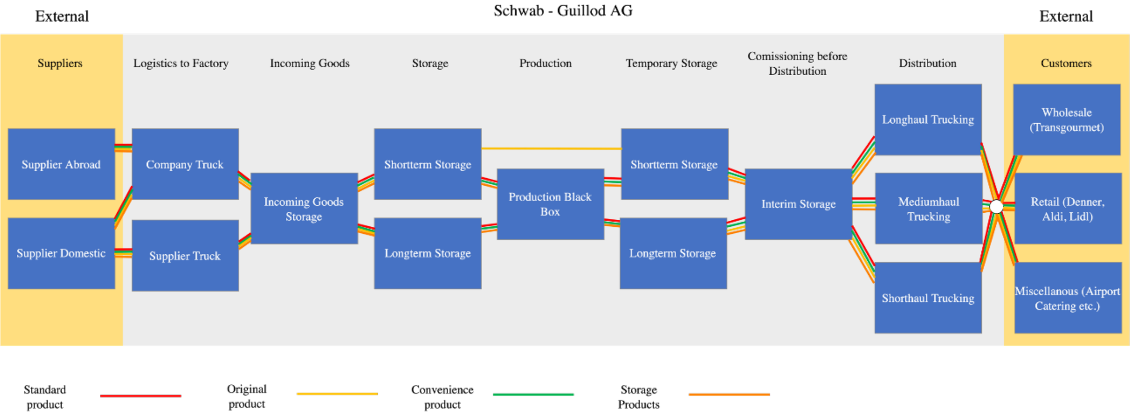


Figure 2: Supply chain map of the analysed company in the vegetable and fruit industry

The products analysed within Züger Frischkäse AG encompass (1) mozzarella fresh and frozen, (2) pizza mozzarella fresh and frozen, (3) butter fresh and frozen as well as (4) cottage cheese. This product portfolio accounts for 78% of the produced products.
The supply chain (Figure 3) starts with the milk supply, 80 % of which comes from the company's own farmers and is collected by an in-house transport fleet. Only 20 % of the milk is delivered by a dairy trader, which is contracted out to a third logistics provider. Auxiliary materials and additives such as rennet come from France, herbs and spices mainly from Switzerland. Packaging materials such as PE films come from Germany. These products are mostly delivered by lorry with a freight forwarder contracted by the trader. Citric acid can only be purchased in China and is shipped.
In Züger's production facility, the milk is stored at 4-8 °C, and the auxiliary substances and additives are stored either in a cold store or unrefrigerated. Then the milk undergoes very intensive processing, being thermised and pasteurised at 75°C. The milk is then cooled down again and then sent to the dairy for further processing. It is then cooled again and reheated at 35°C for cheese production. Within production, measures are already being implemented to recover waste heat with an efficiency of 92%.
Depending on the final product, it is stored either cooled (4°C) or frozen (-20°C). After picking and outbound, the products are distributed to the Swiss market (50%), which consists of retailers, wholesalers for the catering and food industry, and exported (50%). Distribution is sub-contracted to a third-party logistics service provider.
In addition to the main product streams, there is also a waste product stream of whey. This is a sidestream of the cheese production. This waste product is put to secondary use and sold either to the milk powder industry or to pig farms.

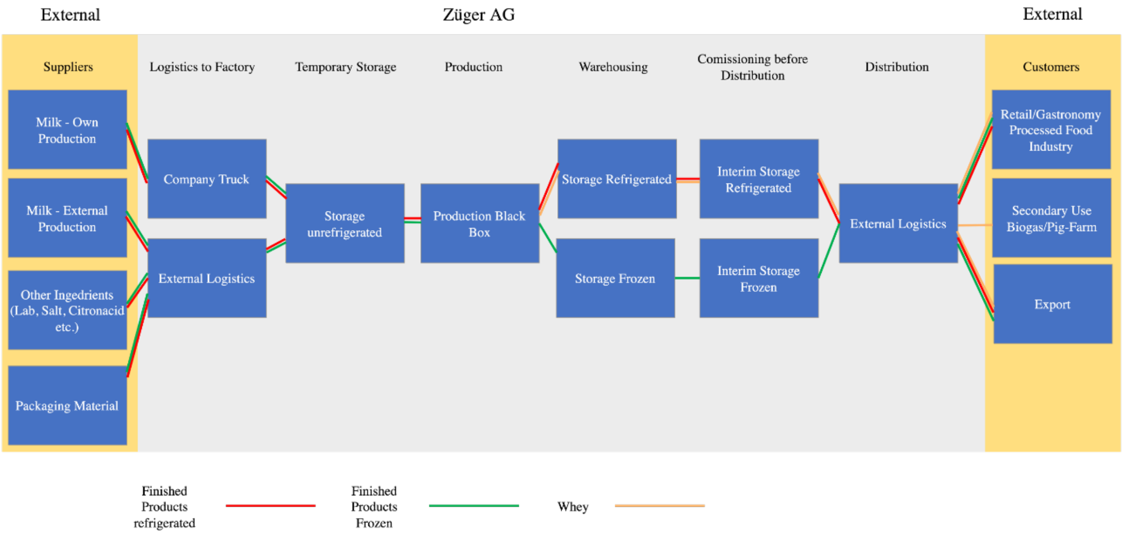


Figure 3: Supply chain map of the analysed company in the dairy industry

2.1.4. Discussion

Overall WP1 provided detailed and valuable insights into the structure and design of the supply chains of the two companies studied. With regard to the structure of the supply chains, the two companies differ, with Schwab Guillod AG being fully vertically integrated, i.e. having its own vehicle fleet. In the case of Züger Frischkäse AG, on the other hand, the supply chain is not vertically integrated, as it outsources its logistics activities for the distribution of finished products to third-party logistics service providers. This is mainly due to the different focus on value-added activities. Schwab Guillod, for example, generates value by trading a diversified range of vegetables and fruits, buying them from farmers and distributing them to wholesalers and retailers. Its advantage is its local and global network of fruit and vegetable producers and its reliable and flexible (seasonal) supply to its customers. The strength of Züger Frischkäse AG, on the other hand, lies in the processing and refinement of milk as a raw material into end products such as fresh cheese. These different configurations of the supply chain place different demands on optimisation measures and must be considered in the further course of the project.

2.2 Work package 2: Energy consumption heat map

2.2.1. Objectives

Work package	WP2			Start month		4	End month			9
Title:	Energy consumption heat map									
Involved partners	ZHAW-INE	ZHAW-IFM	SUPSI	RALOG	SVTL	Clemap	Carbon Care	Aryzta	Züger	STISA
	Work package leader			Work package involvement high			Work package involvement low			
Goal	1. Collected data of energy consumption data in production, warehousing, cooling, and transport for the three case companies and their involved suppliers and customers 2. Identification of energy consumption hotspots in all three temperature-controlled supply chains 3. Conduction of life cycle assessment for the as-is product journey of all three cases									
Tasks	▪ Collecting energy consumption data for product of analysis in production, warehousing, cooling, transport and infrastructure through company documentation and interviews									ZHAW-INE, ZHAW-IFM, SUPSI
	▪ Analysing energy consumption data to identify energy consumption hotspots									ZHAW-INE, ZHAW-IFM, SUPSI
	▪ Conduct life cycle assessment to calculate the GHG emissions of the three supply chains of analysis									ZHAW-INE SUPSI
Results	D2.1-2.4 Collected energy consumption in production, warehousing, cooling, and transport D2.5 Identified energy consumption hotspots D2.6 LCA for as-is product journey of the three case examples									
Diversity	☑ Young scientists/PhD involved				☑ Women involved*					

2.2.2. Methods

A questionnaire was sent out to the two companies under investigation to collect primary data on the energy consumption from the initial product (i.e., farmer's site) to the last distribution point before transfer to the consumer (i.e. warehouse of a wholesaler for commercial customers such as restaurants, caterings etc.; store for private consumers). However, production was treated as a black box where energy in- and outputs are analysed. The specific energy use in production, e.g. ventilation, compressed air, heating, etc., was not recorded. In a first step the overall annual supply chain energy use was conducted. In a second step specific energy consumption data for different product groups were collected. Thereby the annual amount of product category produced (kg) and weight per pallet was conducted. To obtain the SC GHG emissions, the energy consumption was multiplied with the respective life cycle emission factors for diesel and the Swiss electricity mix (Krebs & Frischknecht, 2021; Rai & Tassou, 2017).

2.2.3. Results

The following (Table 1) annual energy consumption data and associated GHG emissions per SC stage were collected.

Table 1: Overview of the energy use and GHG emissions per stage of the SCs under investigation, i.e., the dairy, and fruit and vegetable case studies. Reference year is 2022.

	Energy use **dairy** SC [MWh/year]	Energy use **fruits and vegetable** SC [MWh/year]	GHG emissions **dairy** SC [t CO_2-eq/year]	GHG emissions **fruits and vegetable** SC [t CO_2-eq/year]
Incoming goods (inbound)	50	83	6	11
Refrigerated production	24 000	1 724	4 864	221
Refrigerated warehousing	3 300	3'615	422	463
Commissioning (outbound)	200	139	26	18
Transport	2 952	21 484	861	6 023
Transport refrigeration	466	8 074	126	2 174
Total	**30 968**	**35 119**	**6 304**	**8 910**

The energy and GHG emission hotspots in the vegetable and fruit SC can be found in transport (84-92%) which is mainly attributed to the distribution of the final product to the customer. Within transport a quarter of the energy use and GHG emissions can be attributed to refrigeration. The analysis further shows that cold warehousing is the second biggest contributor with 10% of the SC energy use and 5% of the SC GHG emissions.

A different picture emerges for the dairy SC, whereby production is the process with the highest impact with shares of 77 % for the energy use as well as for the GHG emissions. This is mainly due to heat-intensive production. Transport, mainly the milkrun, and refrigerated warehousing are other important contributors to the SC energy use with shares of 12% and 11% respectively and to the SC GHG emissions with shares of 16% for refrigerated transport and 7% for refrigerated warehousing. A detailed analysis per product category can be found in interim report for WP1 and 2.

2.2.4. Discussion

The quantitative analysis of the energy hotspots has shown where the relevant levers are within the SCs. In the vegetable and fruit SC the main levers lie in the use of alternative drive and refrigeration technologies in order to decarbonise transport as route optimisation tools are already widely applied. The main lever in the dairy SC lies in the expansion of renewable energy generation to decarbonise the energy-intensive production processes as waste heat recovery within the production is already exploited.

2.3 Work package 3: Energy efficiency increase potential

2.3.1. Objectives

<table>
<tr><td>Work package</td><td colspan="4">WP3</td><td colspan="3">Start month 10</td><td colspan="3">End month 18</td></tr>
<tr><td>Title:</td><td colspan="10">Energy efficiency increase potential</td></tr>
<tr><td rowspan="2">Involved partners</td><td>ZHAW-INE</td><td>ZHAW-IFM</td><td>SUPSI</td><td>RALOG</td><td>SVTL</td><td>Clemap</td><td>Carbon Care</td><td>Aryzta</td><td>Züger</td><td>STISA</td></tr>
<tr><td colspan="3">Work package leader</td><td colspan="4">Work package involvement high</td><td colspan="3">Work package involvement low</td></tr>
<tr><td colspan="11"></td></tr>
<tr><td>Goal</td><td colspan="10">1. Identification of possibility to increase energy efficiency through energy efficiency, energy recuperation, and energy production in production, warehousing, cooling, transport, and infrastructure
2. Conduction a life cycle assessment for GHG emission effects of energy efficiency, energy recuperation, and energy production possibilities</td></tr>
<tr><td rowspan="2">Tasks</td><td colspan="9">▪ Desk research to develop an overview of energy efficiency, energy recuperation, and energy production possibilities, including technologies and process change/ reorganisation measures</td><td>ZHAW-INE
ZHAW-IFM
SUPSI</td></tr>
<tr><td colspan="9">▪ Conduct life cycle assessment to calculate the GHG emissions of the energy efficiency possibilities</td><td>ZHAW-INE
SUPSI</td></tr>
<tr><td>Results</td><td colspan="10">D3.1-3.4 Overview of energy efficiency possibilities
D3.5 LCA for energy efficiency possibilities</td></tr>
<tr><td colspan="11"></td></tr>
<tr><td>Diversity</td><td colspan="5">☑ Young scientists/PhD involved</td><td colspan="5">☑ Women involved*</td></tr>
</table>

2.3.2. Methods

To perform a technology assessment, a mix of qualitative and quantitative research was used. A qualitative research approach was used to identify SC GHG mitigation measures (energy saving through efficiency and recovery measures and energy generation measures) by means of semi-structured interviews with experts and key stakeholders, and secondary research (i.e., literature research, internet search).

Experts from the field of (a) refrigerated transport such as logistics service providers, refrigeration technology providers, and associations, and from the field of (b) refrigerated warehousing such as cold warehouse operators, warehouse planners, refrigeration technology providers, and from (c) refrigerated production from research were chosen as interview partners. All interviewees were from the management level to guarantee good insights into the variety of different questions. A total of 29 interviews were conducted from December 2022 to March 2023 in the form of face-to-face interviews, online interviews via MS Teams, and telephone interviews. Two researchers from the field of sustainable supply chain management attended all interviews to gain as much objectivity as possible in result interpretation. The duration of each interview was between 30 and 45 minutes. The interviews were recorded and subsequently transcribed. All data were anonymised to ensure the confidentiality of the interviewees and the researched companies.

Qualitative content analysis was used to evaluate the interview material (Mayring, 2014). The analytical categories were derived inductively from the interview data in an iterative process. The material was coded using MAXQDA software, which facilitated the qualitative data analysis. During coding, the analytical framework was inductively refined by adding categories. A summary table was created in MAXQDA with the results of the coding. The findings from the interviews were then enriched and completed with secondary research.

2.3.3. Results

The main improvement potential according to the experts is seen in adopting new drive technologies for the lorries. According to the interviewees from the logistics sector, diesel trucks with an internal combustion engine remain the most used drive technology. At the same time, the interviewees are aware of the current challenges regarding climate change and are increasingly testing alternative drive technologies. However, according to the interviewees, no single alternative drive technology has yet emerged in the heavy goods transport sector that will be widely adopted. Rather different technologies are being tested and, depending on the purpose of the vehicle, a technology may be selected. The main alternatives to diesel lorries in transport mentioned in the interviews and encountered in the literature are Battery Electric Vehicles (BEV), Fuel Cell Electric Vehicles (FCEV), Bio-Diesel and Hydrotreated Vegetable Oil (HVO), E-fuels, Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), and Bio-LNG as well as rail freight.

In refrigerated transport, the focus of decarbonisation lies in the selection of refrigeration systems, according to the interviewees. In contrast, the insulation of the cooling chamber on trucks is less relevant in Switzerland, as it is already state-of-the-art. The vapor compression refrigeration (VCR) systems are the most widely used refrigeration technology today, with a market share of about 80% (Maiorino et al., 2021). This can be confirmed by the insights gained from the interviews, and according to the interviewees, VCR will continue to be the most important cooling technology on vehicles in the future. Regarding the optimisation potential of VCR systems, the interviewees observe a growing trend toward battery-powered VCRs. Here, the cooling unit is powered by an electric motor, which is supplied with energy via a battery on the truck or trailer. The battery can also be charged via axle generators or photovoltaic (PV) panels on the roof of the refrigerated body (Maiorino et al., 2021; Rai & Tassou, 2017). Alternative transport cooling technologie encountered in the interviews include latent heat storage through Phase Change Material (PCM), cryogenic systems with liquid nitrogen (LN_2) or liquid carbon dioxide (LCO_2) and sorption systems.

According to the interviewees, the most commonly used cooling technology for refrigerated warehousing and production at present is ammonia-based refrigeration for large buildings with high cooling demand, and CO2-based refrigeration for small to medium-sized buildings. Technological practices to improve the environmental performance of refrigerated warehousing and production mentioned in the interviews include optimisation of refrigeration machines (installing frequency converters on pumps and fans, pre-cooling of the refrigerant), demand-oriented cooling, waste heat recovery for own use, heating networks or for neighbouring industries, highly efficient air curtains and improved insulation. In production efficiency gains can be realised by optimising ventilation and hot water boilers and by installing frequency converters for pump systems. Regarding renewable energy generation on the building infrastructure of warehousing and production, the interviewees agreed that the potential of PV systems on the roofs, facades, and parking spaces is not yet fully exploited.

A detailed list of measures identified can be found in Appendix 1.

2.3.4. Discussion

Putting the interview results into a SC configuration and coordination perspective, the following can be summarised. While the potential for route optimisation is already being exploited, according to all interviewees, through the use of dedicated software and ensuring that only full truck loads are undertaken, we identified further potential for improvement in the milk run in the dairy SC. Employee training as a SC coordination practice was mentioned by two of the interviewees to reduce unnecessary energy losses, for example through air exchange due to long opening times of doors. Furthermore, various forms of industrial symbiosis were found as important practices to reduce GHG emissions in TCSCs, which require both SC configuration and coordination. The following forms of industrial symbiosis are possible according to the expert interviews: a) PV power purchases from suppliers. Thereby the supplier, who usually only supplies raw materials, can expand its business model, and also provide renewable electricity, b) sell waste heat from refrigeration machines to other companies within an industrial park that perform heat-intensive processes and avoiding distribution losses, c) peak-shaving by acting as a switchable electrical load with the refrigerated warehouse to compensate for the oversupply of nearby PV plants during the day and relieve the power grid in the evening. This requires the coordination of all actors involved (provider of energy, energy consumer and authorities as mediators) as well as configuration decisions regarding the strategic placement of facilities. It should be noted that these industrial symbiosis opportunities alone will not be sufficient to meet the companies' entire power or heat demand.

2.4 Work package 4: Simulation model

2.4.1. Objectives

Work package	WP4			Start month	17		End month	22		
Title:	Simulation model									
Involved partners	ZHAW-INE	ZHAW-IFM	SUPSI	RALOG	SVTL	Clemap	Carbon Care	Aryzta	Züger	STISA
	Work package leader			Work package involvement high			Work package involvement low			
Goal	1. Identified positive and negative correlations between different energy efficiency measures and the between energy efficiency measures and existing processes 2. Calculated active and passive sums of correlation dimensions to derive those energy efficiency measures which have the highest positive effect on energy efficiency increase and having transparency on direct and indirect negative influences when implementing an energy efficiency measure									
Tasks	▪ Developing an impact matrix for each supply chain case for the energy efficiency measures in each case supply chain through workshops with case company representatives and their suppliers and customers									ZHAW-INE
	▪ Analyse the correlations of the dimension in the impact matrix through mathematical models									ZHAW-INE
	▪ Calculate active and passive sums of dimensions in the impact matrix through mathematical models									ZHAW-INE
	▪ Develop the simulation model based on the results of the correlation matrix									ZHAW-INE
Results	D4.1	Developed impact matrix								
	D4.2	Developed correlation matrix								
	D4.3	Calculated correlations								
	D4.4	Developed simulation model								
Diversity	☑ Young scientists/PhD involved					☑ Women involved*				

2.4.2. Methods

In this WP, a fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) approach was applied to evaluate the interdependence and interrelationships of measures identified in WP3 as shown in Table 2.

Table 2: Analysed factors for the reduction of GHG emissions of temperature-controlled SC

Code	Factor
F1	employee training
F2	alternative transport refrigeration
F3	alternative drive technology
F4	efficient and dynamic route planning
F5	minimisation of heat infiltration
F6	expansion of PV systems
F7	demand-orientated and dynamic cooling load adjustment
F8	waste heat recovery
F9	optimisation of ventilation control
F10	retrofitting frequency inverters
F11	cold warehouses for peak load reduction
F12	optimisation of the refrigeration machine
F13	control of the hot water boiler
F14	alternative energy sources for steam generation
F15	retrofitting the cold warehouse building envelope
F16	high temperature heat pumps
F17	biogas plant for the utilisation of waste products (whey etc.)

The DEMATEL technique has been used to analyse the causal relationships and strength of influence between the measures to reduce GHG emissions. The Fuzzy DEMATEL technique is a structural modelling approach to analyse relationships and interdependences among constituents of a system by dividing these constituents in cause-and-effect groups. Additionally, the technique supports in identifying the critical factors of complex systems using a causal diagram (Thakkar, 2021) and quantifies the strength of the relationships and interdependencies among the factors analysed in comparison to other Multi-Criteria Decision Analysis methods (Saroha et al., 2022). In this research, fuzzy set theory has also been embedded in DEMATEL to overcome the vagueness and uncertainty of experts' decision-making (Saroha et al., 2022). A detailed overvirew over the steps conducted for the fuzzy-DEMATEL can be found in Appendix 2.

2.4.3.Results

Improving the GHG emission footprint of temperature-controlled supply chains while remaining competitive is a complex decision problem where several factors are interrelated and influence each other. Thus, improving only one factor or stage in the supply chain does not necessarily mean that the SC as a whole will improve due to the dependence of factors on each other (Feng & Ma, 2020). Therefore, DEMATEL method was used to identify the dependence relationship of the GHG emission reduction measures and to identify critical reduction measures for the SC as a whole.

In Table 3 an overview over the the results can be found. The (R + C) vector named "Prominence" stands for the degree of central role that the factor plays in the system and is measured by the strength of influences that are given and received of the factor. Alike, the vector ($R{-}C$) called "Relation" shows the net effect that the factor contributes to the system. Thus, if R–C > 0 it indicates a given factor is a causal factor and it has the potential to influence other factors. On the other hand, if R–C < 0, then the factor belongs to the effect group and such factors are influenced by other factors. This analysis can be found in Table 7.

Table 3: Influence degree (R), affected degree (C), relation degree (R-C), prominence degree (R+C) and ranks

Code	Factor	R	C	R-C	Cause/effect group	R+C	Rank
F1	employee training	4.792	4.221	0.571	Cause	9.013	4
F2	alternative transport refrigeration	3.282	3.419	-0.137	Effect	6.701	10
F3	alternative drive technology	4.119	3.925	0.194	Cause	8.044	7
F4	efficient and dynamic route planning	3.332	3.231	0.100	Cause	6.563	11
F5	minimisation of heat infiltration	4.639	4.759	-0.120	Effect	9.398	3
F6	expansion of PV systems	3.334	3.108	0.226	Cause	6.442	12
F7	demand-orientated and dynamic cooling load adjustment	4.415	5.619	-1.204	Effect	10.034	2
F8	waste heat recovery	4.181	4.626	-0.445	Effect	8.807	5
F9	optimisation of ventilation control	3.684	3.850	-0.166	Effect	7.534	9
F10	retrofitting frequency inverters	3.160	2.469	0.691	Cause	5.629	16
F11	cold warehouses for peak load reduction	4.469	4.265	0.204	Cause	8.734	6
F12	optimisation of the refrigeration machine	4.806	5.293	-0.487	Effect	10.098	1
F13	control of the hot water boiler	2.655	3.189	-0.534	Effect	5.845	14
F14	alternative energy sources for steam generation	2.541	3.246	-0.706	Effect	5.787	15
F15	retrofitting the cold warehouse building envelope	4.244	3.511	0.733	Cause	7.755	8
F16	high temperature heat pumps	2.999	2.869	0.131	Cause	5.868	13
F17	biogas plant for the utilisation of waste products (whey etc.)	2.753	1.805	0.948	Cause	4.557	17

Based on the values of (R+C), the factors could be prioritised as shown in Table 7. According to this ranking, optimisation of the refrigeration machine (F12) is the most important measure to reduce GHG emissions in temperature-controlled SCs. Demand-orientated and dynamic cooling load adjustment (F7) is the second important measure. The third important measure is the minimisation of heat infiltration (F5). Other important factors for the reduction of GHG emissions in temperature-controlled SC are employee training (F1) followed by waste heat recovery (F8) and cold warehouses for peak load reduction (F11).

In Figure 4 the influential relation map is provided. It shows the prominence and relation dataset, which provides valuable insights for decision making. In addition, the influential relation map is divided into four quadrants I-IV by calculating the mean of R+C..

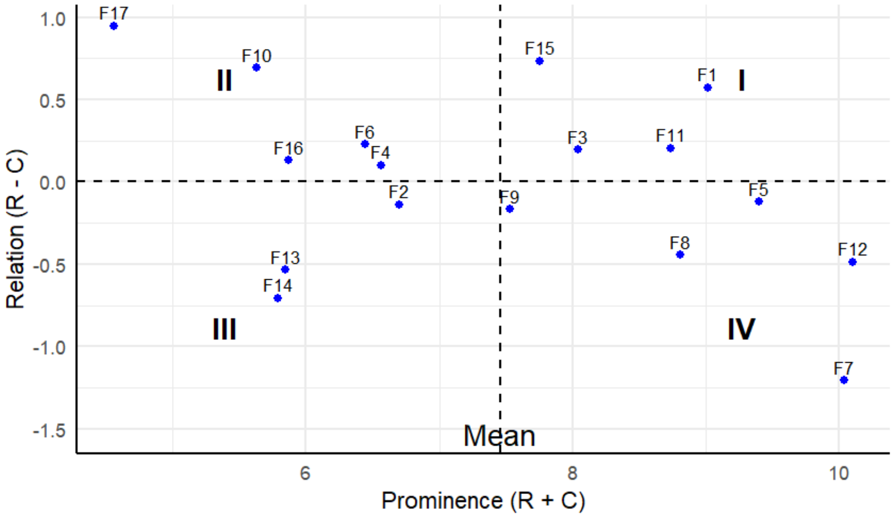


Figure 4: Influential relationship map

Quadrant I (High Prominence, Positive Relation): Factors in quadrant I are the core factors. These are the measures that are highly important for the SC and have a high influencing degree over other factors such as employee training F1, alternative drive technology F3, cold warehouses for peak load reduction F11, retrofitting the cold warehouse building envelope F15.

Quadrant II (Low Prominence, Positive Relation): Factors in quadrant II are the driving factors because they are less important to the system but have a high influencing power over other factors. The following measures belong to this group: Efficient and dynamic route planning F4, expansion of PV systems F6, retrofitting frequency inverters F10, high-temperature heat pumps F16, biogas plant for the utilisation of waste products (whey etc.) F17.

Quadrant III (Low Prominence, Negative Relation): Factors in quadrant III have low importance and are mainly influenced by others and are considered autonomous and independent to the SC. These are mainly alternative transport refrigeration F2, control of the hot water boiler F13, alternative energy sources for steam generation F14.

Quadrant IV (High Prominence, Negative Relation): Factors in quadrant IV are central to the temperature-controlled SC, but they are more influenced by other factors than they influence others and must therefore be seen as one measure in a complex and interdependent system. Investment in these measures can only be effective if their drivers are also considered... This involves minimisation of heat infiltration F5, demand-orientated and dynamic cooling load adjustment F7, waste heat recovery F8, optimisation of ventilation control F9, optimisation of the refrigeration machine F12.

Whereas the top-ranked factors (based on prominence in Table 7) should be prioritised for decision making in general, the factors in quadrant I (employee training, alternative drive technology, cold warehouses for peak load reduction, retrofitting the cold warehouse building envelope) should be prioritised for interventions and the factors in quadrant IV (minimisation of heat infiltration, demand-orientated and dynamic cooling load adjustment, waste heat recovery, optimisation of ventilation control, optimisation of the refrigeration machine) require strategies to mitigate their dependence on other factors.

2.4.4.Discussion

According to the key influencing factors for the mitigation of GHG emissions of temperature-controlled SCs captured under the mean + 2 and standard deviation threshold (0.378), we can draw a relationship path diagram as shown in Figure 5 between these key factors using Table 3.

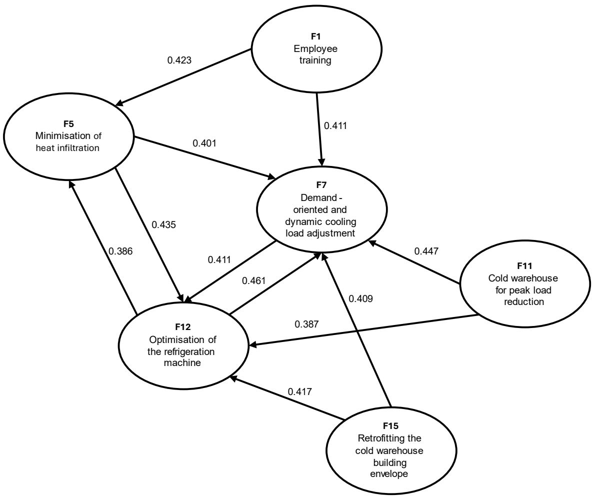


Figure 5: Relationship paths between key influencing factors

Figure 5 summarises the key findings. From the figure it can be deduced that F7 “Demand-oriented and dynamic cooling load adjustment” and F12 “Optimisation of the refrigeration machine” are the most central enablers to minimise GHG emissions in temperature-controlled SCs. These two factors are themselves highly interrelated due to their very strong interdependencies. At the same time, they are strongly influenced by other factors. F11 “Cold warehouse for peak load reduction”, F1 “Employee training”, F15 “Retrofitting the cold warehouse building envelope” and F5 “Minimising heat infiltration” have the highest influence on F7 “Demand-oriented dynamic cooling load adjustment”. F12 “Optimisation of the refrigeration machine” in turn is strongly influenced by F15 “Retrofitting the cold warehouse building envelope”, F5 “Minimisation of heat infiltration” and F11 “Cold warehouse for peak load reduction”. It becomes clear that F12 “Optimisation of the refrigeration machine” and F5 “Minimisation of heat infiltration” are also highly interrelated.

In terms of the implications of the findings for managers of temperature-controlled SCs, the clear priority should be to have specialists optimising the layout of the refrigeration machine. This involves upgrading the machine to allow dynamic load adjustment rather than an inert base load. This would also enable the use of warehouses for peak load reduction to integrate renewable, intermittent energy sources into the electricity mix. At the same time, employees should be trained and technical measures taken to reduce heat infiltration through door openings. This would also allow more efficient use of the refrigeration machine. In addition, retrofitting the building envelope would also contribute to a more efficient operation of the refrigeration machine by reducing heat transmission losses.

Work package 5: Modelling of energy autonomy

2.4.5.Objectives

Work package	WP5	Start month 19	End month 27
Title:	Modelling of energy autonomy		
Involved partners	Work package leader: ZHAW-INE Work package involvement high: SUPSI, Clemap Work package involvement low: ZHAW-IFM, RALOG, Aryzta, Züger, STISA SVTL, Carbon Care		
Goal	1. Developed scenarios for the three supply chain cases to increase energy efficiency through energy efficiency, recuperation, and production in production, warehousing, cooling, transport, and infrastructure 2. Derived measures to increase energy efficiency in the three case supply chains		
Tasks	▪ Development of scenarios through scenario technique, including interviews and workshops with the three case supply chains individually	ZHAW-INE SUPSI ZHAW-IFM	
	▪ Derivation of measures for energy efficiency increase in the three case supply chains	ZHAW-INE SUPSI ZHAW-IFM	
Results	D5.1 Developed scenarios of each of the three case supply chains D5.2 Derived energy efficiency measures for the three case supply chains		
Diversity	☑ Young scientists/PhD involved	☑ Women involved*	

2.4.6.Methods

A Marginal Abatement Cost Curve (MACC) was used as a tool to quantify and prioritise the measures identified in the interviews in chapter 2.3 (see Appendix 1). A MACC ranks mitigation measures according to their total cost per unit of CO_2-eq, and thus according to the options that offer jointly the greatest financial return and reduction in GHG emissions (Duffy et al., 2021; Huang et al., 2022). In this way, MACCs provide decision-makers with an evidence base for setting targets and making decisions regarding mitigation options (Duffy et al., 2021). A list of potential GHG emission abatement measures was established based on the expert interviews and complementary secondary research. The standard equation (Eq. 1) provided by Huang et al. (2022) was used to calculate the marginal abatement cost an ESC practice.

$$Marginal\ Abatement\ Cost = \frac{(I * CRF + O\&M - B)}{\Delta C} \quad (1)$$

Where,

I: Initial investment
CRF: Capital recovery factor
O&M: Annual operating and maintenance cost
B: Annual benefit gained by implementing an abatement practice
ΔC: Annual GHG emissions savings with respect to the baseline

The CRF is determined by using equation 2.

$$CRF = \frac{(1+r)^L * r}{(1+r)^L - 1} \quad (2)$$

Where,

r: Discount rate set to 4% (Swiss inflation rate of 2.8% in 2022, plus interests[1])
L: Lifetime of abatement practices

Active wall cooling system for enhanced integration of solar PV in warehouse cooling

A further study was conducted to examine strategies for reducing grid dependency through a better exploitation of renewable energy sources in warehouse buildings by combining active wall cooling with conventional cooling systems. Warehouses and their respective cooling chambers typically feature highly insulated envelopes with U-values below 0.1 W/m²K and typically have no windows in storage zones, leaving minimal potential for efficiency gains through envelope upgrades. Conversely, the integration of renewable energy sources for cooling operation is not yet well exploited, leaving some untapped potential. Consequently, this research proposes and evaluates an active wall cooling system combined with cooling management control strategies to better align the energy demand for cooling with the availability of renewable energy sources, namely solar radiation.

The active wall cooling system acts as a thermal energy storage and operates similarly to radiant floor cooling systems but is integrated directly into warehouse walls. Pipes embedded within the walls circulate a water-glycol mixture, enabling efficient heat exchange with the thermal mass of the walls. By utilizing the thermal mass of the walls, this system shifts peak cooling loads to better align with available solar energy, thereby decreasing the building's grid dependence and lowering CO_2 emissions.

The results obtained from these analyses can be used to predict the CO_2 reduction potential for user-input warehouse parameters through interpolation. Figure 6 presents the study's conceptual framework.

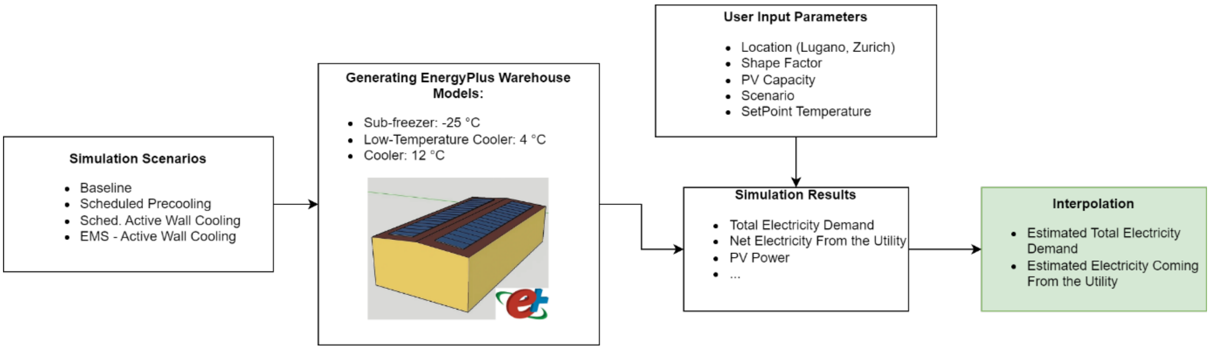


Figure 6: Framework for examining emission reduction potential of active wall cooling in refrigerated warehouses

Four distinct simulation scenarios were developed and analyzed using the EnergyPlus simulation software:

- Baseline Scenario: No active wall cooling system is implemented, serving as a reference (current status) for evaluating other scenarios.
- Scheduled Precooling Scenario: Conventional convective cooling systems precool the warehouse air to 4°C below the setpoint temperature on a fixed daily schedule (11:00–14:00) to reduce peak cooling loads.
- Scheduled Active Wall Cooling Scenario: The active wall cooling system cools down the walls to 4°C below the setpoint temperature, operating on the same fixed schedule (11:00–14:00).
- EMS-Based Active Wall Cooling Scenario: An Energy Management System (EMS) activates the active wall cooling system only when on-site photovoltaic (PV) generation exceeds the warehouse’s power demand, cooling down the walls to 4°C below the setpoint temperature.

To comprehensively assess the impact of renewable energy integration on warehouse’s grid dependence, multiple photovoltaic (PV) system capacities were evaluated. Three distinct PV installation levels 75%, 100%, and 125% of each warehouse's peak electrical load (determined from baseline simulations), were simulated for all scenarios. This tiered approach serves two key purposes: (1) it enables interpolation of results for intermediate PV coverage percentages, and (2) it facilitates a robust analysis of the interaction between active cooling strategies and renewable generation. Particular emphasis was placed on quantifying the additional benefits achieved through energy management system (EMS) optimization.

Warehouse buildings were modeled in EnergyPlus, incorporating three distinct setpoint temperatures representing typical warehouse refrigeration requirements:

- Sub-Freezer: maintained at −25 °C,
- Low-Temperature Cooler: maintained at 4 °C,
- Cooler: maintained at 12 °C.

Key performance metrics obtained from simulations included:

- Total Electricity Demand
- Electricity coming from the Utility / PV

After running scenario simulations based on various parameters, including setpoint temperature, PV capacity, inclusion of wall cooling, and management strategies such as EMS, scheduled precooling, or baseline control, a total of 216 combinations were generated. This comprehensive set of simulation results serves as a database that enables interpolation for any warehouse a user wishes to analyze or improve, allowing them to estimate the potential impact of each applied measure.

User-defined parameters to interpolate:

- Location: Defines the climate conditions (e.g., Lugano or Zurich).
- Set Point Temperature: -25°C, 4°C, 12°C.
- Shape Factor: A geometric parameter that influences the cooling chamber’s envelope performance (surface area of the building divided by its volume).
- PV Capacity: The capacity of the photovoltaic system integrated into the warehouse, defined based on the pre-calculated peak electricity demand.
- Scenario: Selected from the previously defined simulation scenarios.

2.4.7.Results

The following Tables 4 and 5 provide an overview of the identified quantifiable and non-quantifiable options for reducing GHG emissions and the associated GHG savings potential and costs in the two TCSCs analysed.

Table 4: MAC calculations for the GHG emission mitigation measures of the vegetable and fruit SC

	Emissions abated [t CO2 eq.]	MAC [CHF/t CO2 eq.]	Lifetime [years]
Biodiesel <40t	5539	2365	8
HVO <40t	8068	1461	8
E-diesel <40t	5522	6645	8
LNG <40t	0	0	8
Bio-LNG <40t0F[1]	6021 - 7242	2329 - 2447	8
FCEV <40t	5625	1629	8
BEV <40t	8415	491	8
Transport 40t			
Biodiesel 40t	16197	1967	8
HVO 40t	23449	1189	8
E-diesel 40t	18291	4689.90	8
LNG 40t	0	0	8
Bio-LNG 40t1F[2]	20765 - 22459	1253 - 1870	8
FCEV 40t	16612	1478	8
BEV 40t	23372	626	8
Rail freight 40t	1943	205276	10
Transport refrigeration <40t			
VCR battery <40t	1659	1039	8
VCR battery and axle generator <40t	2021	668	8
VCR battery and PV <40t	2599	259	8
PCM <40t	3050	39	8
Cryogenic LNO2 <40t	0	0	8
Cryogenic LCO2 <40t	0	0	8
Sorption <40t	311	6745	8
Transport refrigeration 40t			
VCR battery 40t	6163	1027	8
VCR battery and axle generator 40t	7506	640	8
VCR battery and PV 40t	9654	237	8
PCM 40t	11394	20	8
Cryogenic LNO2 40t	0	0	8
Cryogenic LCO2 40t	0	0	8
Sorption 40t	577	13835	8
Refrigerated warehousing and production			
Optimization refrigeration machine	643	-861	15
Waste heat recovery refrigeration machine	386	-896	15
Demand oriented cooling (adjustment by 2 degrees)	231	-1129	15
Higly efficient air curtains	976	-740	10
Building retrofit through floor and wall insulation	1029	-368	15
Frequency converter	11	1100	15
Hot water boiler control	3	-806	15
Steam generation	14	843	25
Ventilation control optimization	7	-904	5
Employee training			
PV roof +25%	546	-907	30
PV facade	0	0.00	25
PV parking	3510	605	30
PV purchasing agreement	2429	-1565	30
High-temperature heat pump (HTHP)	0	0	25
Peak Shaving			
Biogas	0	0	25

Table 5: MAC calculations for the GHG emission mitigation measures of the dairy SC

	Emissions abated [t CO2 eq.]	**MAC [CHF/t CO2 eq.]**	**Lifetime [years]**
Transport <40t			
Biodiesel <40t	152	2892	8
HVO <40t	221	1822	8
E-diesel <40t	151	7174	8
LNG <40t	0	0	8
Bio-LNG <40t2F[3]	165 - 198	2944 - 2980	8
FCEV <40t	154	2100	8
BEV <40t	230	980	8
Transport 40t			
Biodiesel 40t	2997	1999	8
HVO 40t	4339	1211	8
E-diesel 40t	3385	4718	8
LNG 40t	0	0	8
Bio-LNG 40t3F[4]	3843 - 4156	1292 -1902	8
FCEV 40t	3074	1771	8
BEV 40t	4325	1735	8
Rail freight 40t	405	301368	10
Rout optimisation milkrun	648	-582336	4
Transport refrigeration <40t			
VCR battery <40t	16	2848	8
VCR battery and axle generator <40t	20	4630	8
VCR battery and PV <40t	26	3339	8
PCM <40t	30	1843	8
Cryogenic LNO2 <40t	0	0	8
Cryogenic LCO2 <40t	0	0	8
Sorption <40t	3	33329	8
Transport refrigeration 40t			
VCR battery 40t	436	1101	8
VCR battery and axle generator 40t	531	789	8
VCR battery and PV 40t	683	353	8
PCM 40t	807	89	8
Cryogenic LNO2 40t	0	0	8
Cryogenic LCO2 40t	0	0	8
Sorption 40t	41	15884	8
Optimization refrigeration machine	587	-831	15
Waste heat recovery refrigeration machine	352	-855	15
Demand-oriented cooling (adjustment by 2 degrees)	211	-1125	15
Highly efficient air curtains	891	-740	10
Building retrofit through floor and wall insulation	939	-107	15
WRG for whey cooling	363	-259	15
Replace compact fluorescent lamp with LED lights	19	-481	15
Retrofit frequency converter in heat exchange	27	-561	15
Retrofit frequency converter in heat exchange	1727	-547	10
Employee training			
PV roof +25%	219	-333	30
PV facade	33	2225	30
PV purchasing agreement	4486	-223	30
Peak shaving			

[1,2,3,4] Indication in a range, as these are findings from the literature and results from the Hello LBG project.

Active wall cooling system for enhanced integration of solar PV in warehouse cooling

The results of the simulation regarding active wall cooling in refrigerated warehouses clearly demonstrate its potential, especially when integrated with energy management strategies, in reducing grid electricity demand and enhancing renewable energy utilisation in warehouse buildings. A total of 216 simulations were performed across various combinations of warehouse setpoint temperatures, photovoltaic (PV) system capacities, and control strategies.

Overall, both Scheduled Active Wall Cooling and EMS-Based Active Wall Cooling scenarios showed significant reductions in grid electricity demand compared to the Baseline scenario. In contrast, the Scheduled Precooling strategy had a limited effect due to the absence of thermal mass from stored goods, as the simulations assumed empty warehouses to isolate the thermal mass effects of the walls. Key findings include:

- Scheduled Active Wall Cooling led to moderate load shifting and a reduction in grid electricity consumption, particularly in the 12 °C and 4 °C setpoint cases.
- EMS-Based Active Wall Cooling provided the highest overall benefits by dynamically operating in sync with on-site PV generation. This strategy maximised renewable energy usage and minimised grid dependency across all tested scenarios.
- The Baseline Scenario, which did not use any active wall cooling, served as a reference point for quantifying improvements.

Figures 7, 8, and 9 illustrate representative cases for the three warehouse temperature settings 12 °C (cooler), 4 °C (low-temperature cooler), and −25 °C (sub-freezer) under the following common conditions:

- Total Volume: 4000 m³
- Shape Factor: 0.4
- Warehouse Status: Empty (no internal loads from goods)
- PV Capacity: 100% of peak load from baseline scenario

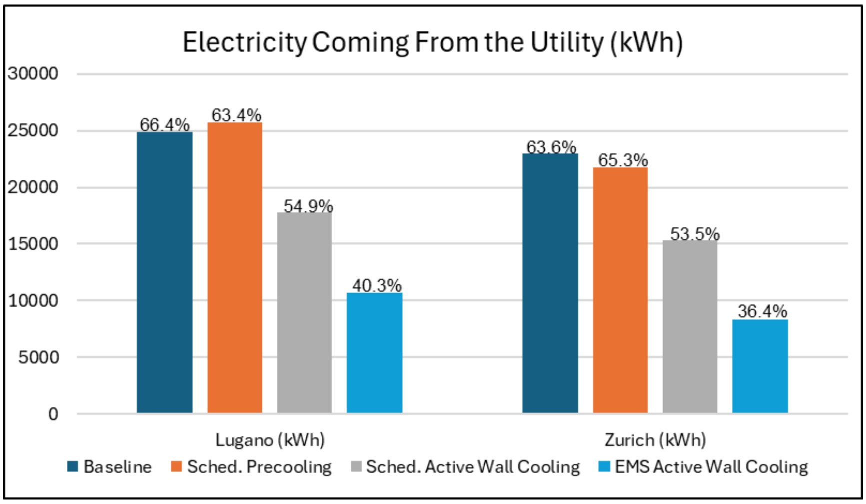


Figure 7: Comparison of Cooling Strategies at 4 °C Setpoint with 100% Peak Load PV Capacity (Empty Warehouse, Volume: 4000 m³, Shape Factor 0.4)

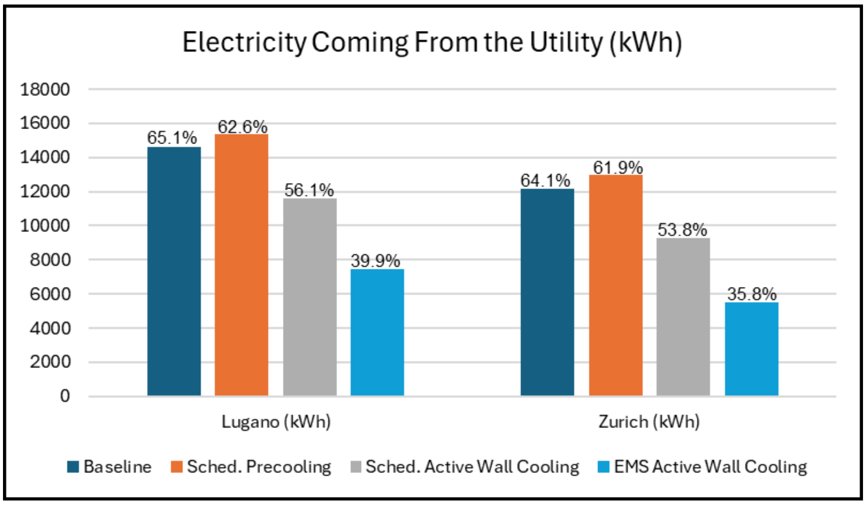


Figure 8: Comparison of Cooling Strategies at 12 °C Setpoint with 100% Peak Load PV Capacity (Empty Warehouse, Volume: 4000 m³, Shape Factor 0.4)

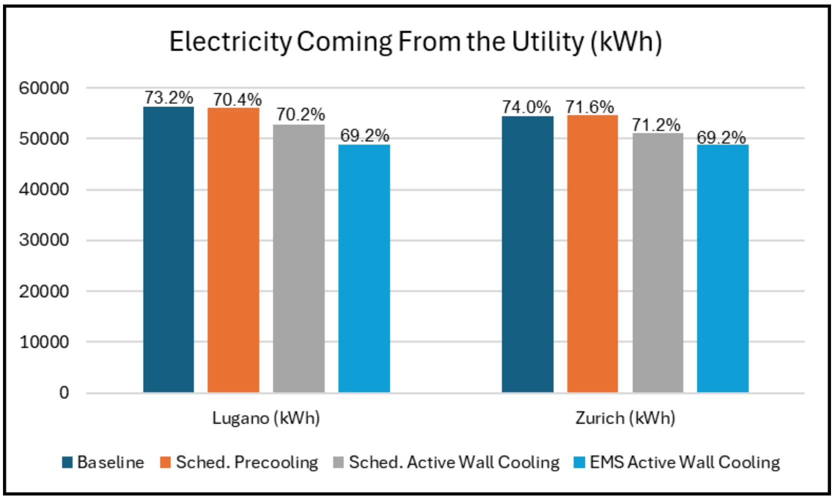


Figure 9: Comparison of Cooling Strategies at −25 °C Setpoint with 100% Peak Load PV Capacity (Empty Warehouse, Volume: 4000 m³, Shape Factor 0.4)

These charts show how different cooling strategies affect energy use. EMS-based wall cooling performs best at moderate temperatures, such as 12 °C and 4 °C, reducing electricity consumption from the utility by approximately 36%. However, the proposed measures are less effective at −25 °C, where the system struggles to meet the increased cooling demand, and the utility electricity share is reduced, from 74% in the baseline case to approximately 69% with EMS active cooling walls.

This dataset forms the foundation of an interpolation-based tool, allowing users to input their specific warehouse characteristics and obtain estimated energy and grid dependence reduction from implementing the proposed measures. The tool provides a flexible and robust way to support decision-making for warehouse energy retrofits or new designs, especially in facilities considering on-site renewable energy integration.

2.4.8. Discussion

The results are presented in the following two MACC curves (Figure 6 and Figure 7), which illustrate the scenario in which transport and transport refrigeration are depicted as a fleet mix with equal shares. The MACC can be interpreted as follows: the y-axis represents the costs per measure. If these costs are negative, this indicates that these measures can be implemented cost-effectively with a net gain over the entire lifetime. The x-axis represents the potential for saving greenhouse gas emissions. The greater the width of the rectangle, the higher the reduction potential. The analysis of WP3 for both TCSCs has demonstrated that the majority of measures for warehousing and production can be implemented cost-neutrally or even with a profit, as these are predominantly energy-saving measures. With regard to transport refrigeration, cooling based on phase change materials (PCM) is preferable for both weight classes ≤40 t and 40 t from both an economic and GHG emissions perspective. In transport, it is recommended that battery-powered electric vehicles (BEV) for ≤40 tonnes and BEV or vehicles powered by hydrogenated vegetable oil (HVO) for 40 t transport should be prioritised.
The results specific to each SC show that in the vegetable and fruit SC, in addition to cost-efficient measures, priority should be given to 1) PCM-based transport refrigeration, 2) BEVs and 3) PVs above the car park. The total potential for greenhouse gas emissions abatement in the vegetable and fruit SC is estimated to be between 55% and 70% of total SC emissions, with the exact figure depending on the vehicle fleet mix. It is estimated that 24% of these SC emissions could be reduced cost-effectively.

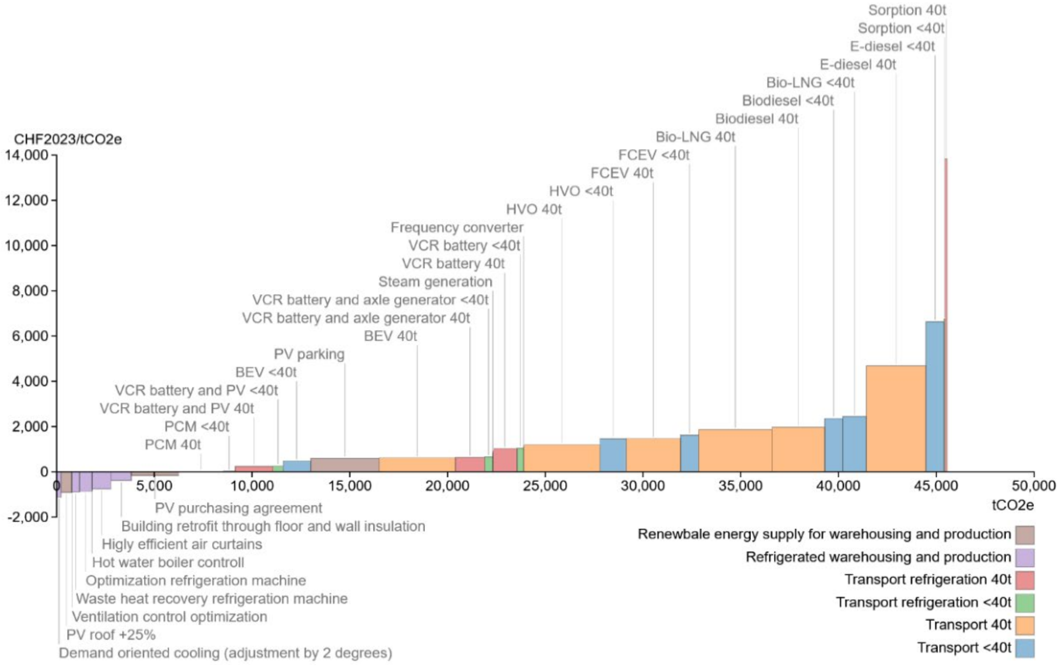


Figure 10: MACC of the vegetable and fruit SC

In the dairy SC, in addition to cost-effective measures, priority should be given to three key areas: 1) route optimisation of the milk run; 2) retrofitting frequency converters in the heat exchanger; and 3) the supply of renewable energy through purchasing agreements with suppliers. In the dairy SC, the maximum GHG reduction potential is 21% of the SC emissions, all of which can be implemented cost-effectively.

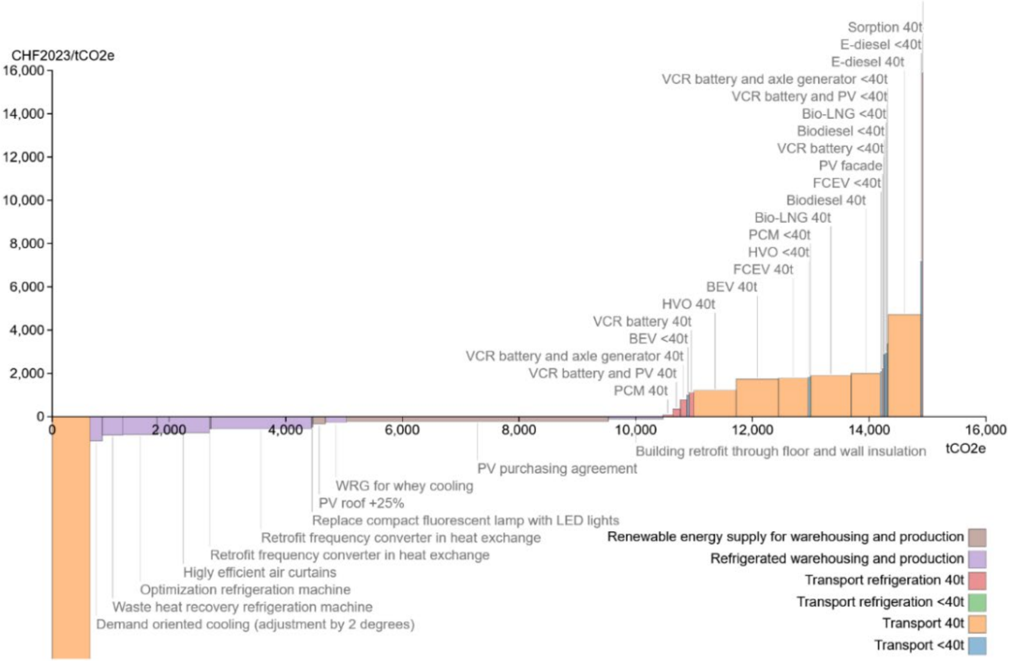


Figure 11: MACC of the dairy SC

2.5 Work package 6: Pilot tests

2.5.1.Objectives

Work package	WP6	Start month 22	End month 36
Title:	Pilot tests		
Involved partners	ZHAW-INE ZHAW-IFM SUPSI RALOG SVTL Clemap Carbon Care Aryzta Züger STISA		
	Work package leader	Work package involvement high	Work package involvement low
Goal	1. Implemented measures to increase energy efficiency in all case supply chains 2. Measured energy consumption after implementation 3. Analysed energy efficiency increases in all three case supply chains 4. Conducted life cycle assessment for pilot tests		
Tasks	▪ Accompany case companies in implementing energy efficiency increase measures ▪ Install sensors to analyse energy consumption ▪ Analyse data from sensors to derive energy efficiency effects through pilot tests with data analysis techniques ▪ Conduct life cycle assessment to quantify pilot test impacts GHG emission	ZHAW-INE ZHAW-IFM SUPSI ZHAW-INE ZHAW-INE ZHAW-INE SUPSI	
Results	D6.1 Implemented energy efficiency measures for tests D6.2 Measured energy consumption D6.3 Analysed energy efficiency increase D6.4 LCA for pilot tests		
Diversity	☑ Young scientists/PhD involved	☑ Women involved*	

The aim of implementing energy efficiency measures in WP6 was both to implement these measures and to record the savings actually achieved. However, as only one practice partner, Züger Frischkäse AG, was ultimately prepared to implement measures in its business, the selection of measures that could be implemented was limited. This is particularly true for this company, as it has already implemented many efficiency measures and is therefore well advanced. The proposed measures require considerable investment and/or infrastructural adjustments, which delays their introduction. Detailed proposals were therefore drawn up and presented to the practice partner with the aim of implementing them after budget approval in 2025.

2.5.2.Methods

The practice partners were contacted for the implementation of the energy efficiency measures; Züger Frischkäse AG showed interest in the implementation. After analysing the data from WPs 1-3, specific proposals were drawn up for Züger Frischkäse AG and categorised by type (transport, production, and building envelope). At a meeting with employees of Züger Frischkäse AG, the proposals were discussed together and their feasibility checked. Two specific energy efficiency measures were finally defined, both of which are based on the use of electrical energy in heat pumps instead of fossil fuels for heat generation.

The following steps were carried out to determine suitable energy efficiency measures for the practice partner:

- Data analysis from WPs 1-3: A detailed evaluation of the data for the areas of transport, production, and building envelope was carried out. On this basis, specific energy-saving measures were developed for the respective categories.
- Technical discussions with process engineers from Züger Frischkäse AG: In order to validate and expand the proposed measures, an exchange took place with the process engineers of the milk processor Züger Frischkäse AG and an expert from the EnAW. Supplementary data and

reports were used to define two specific efficiency measures in the production process together with the project partner.

- Calculation of efficiency and costs based on empirical values and technical literature: The expected efficiency gains and costs were calculated for each measure in order to create a sound basis for decision-making.

2.5.3.Results

Measure 1: Cheese vat
The practice partner uses a total of three cheese vats, each with a volume of 18 cubic metres. The milk in these tanks is currently heated by double outer shell from 32°C to 65°C within 1.5 hours using a jacket of hot water. The hot water (up to 90°C using fossil fuels) is injected at the top and runs downwards in this shell, with a total amount of 70m3 in the circuit (Figure 8 and 9).

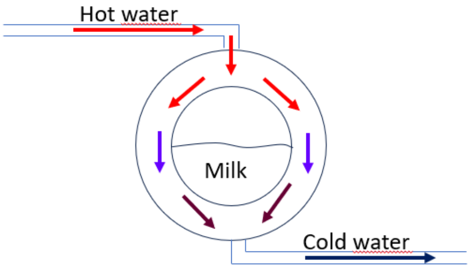


Figure 12: Principle of heating the milk in the cheese vat

Figure 13: Cheese vat

In future, this process step is to be replaced by modern high-temperature heat pumps (HTHP). The recooler on the roof, whose source temperature is 20-30°C, is to serve as the heat source. This requires a temperature range of 60-70°C. The required heat output is 780 kW, which, with a process duration of 1.5 hours, results in a total requirement of 1170 kWh of process heat. An HTHP from Engie, type HHR 720, was selected, which achieves a heat pump coefficient of performance (COP) of 4.2 at a temperature range of 20°C to 80°C. The thermal power requirement is around 650 kW, which the HTHP covers with its maximum output of 720 kW. With a COP of 4.2, the energy savings achieved by using this heat pump amount to around 735 MWh per year. By switching from gas to high-efficiency heat pump technology, energy costs can be reduced by around CHF 28,400 per year and greenhouse gas emissions can be reduced by around 165 tonnes of CO_2 per year. A detailed overview over the calculation can be found in Table 1, Appendix 3.

Measure 2: Thermo-swing

Measure 2 aims to optimise an already installed heat exchanger, which has a capacity of 210 m³ and is divided into three temperature layers: the top layer is at 40-45°C, the middle layer is at 35°C and the bottom layer has a temperature of 14°C. The top layer, which is required for the coagulator, is currently heated with an average of 1000 kWh per day using fossil fuels in order to maintain the target temperature. At the same time, the bottom layer is too warm and has to be actively cooled. With measure 2, the water from the bottom layer is cooled via a heat pump (HP) in order to heat the top layer to the required target temperature of 42-45°C. To increase redundancy and flexibility, a total output of 20 kW is aimed for, for which two heat pumps with an output of 10 kW each are planned. The efficiency of the heat pump (COP) was estimated at around 4.5, but could, according to experts, increase to around 7-8 by additionally utilising the waste heat for cooling.

This measure can save around 260 MWh per year by dispensing with fossil-fuelled heating and using heat pumps. In addition, further savings are achieved through the reduced cooling capacity, although these are heavily dependent on the chiller used and are therefore not yet included in this calculation. Switching from gas to electrical energy with the estimated COP brings savings of around CHF 10,000 and a reduction in greenhouse gas emissions of around 59 tonnes of CO_2 per year (see Table 2, Appendix 3).

2.5.4. Discussion

The previous packages of measures contained a large number of potential solutions. However, the reduction to just one industrial partner willing to implement possible measures narrowed down the selection considerably. The partner had already implemented numerous efficiency improvement measures after exchange with energy counsltants and experts. In addition, customised solutions are often required in the area of milk processing due to specific requirements and different volume flows. Measures in the area of transport and logistics were also excluded, as transport services are procured externally. Further adjustments to existing buildings are hardly feasible at present, as a new building is under construction and therefore considerable resources are already tied up. The measures presented here could ultimately only be developed through intensive consultation with the industrial partner's process engineers and additional discussions with a technical expert from the EnAW consultancy firm.

The calculations for both proposed measures show that the use of heat pumps could enable high energy savings and an overall CO_2 reduction of over 200 tonnes per year by replacing fossil-based heat. However, implementation involves budgeting, purchasing, mechanical and electrical work. According to the contact persons, the thermo-swing measure could be realised in 2025 and the cheese vat measure in 2026, depending on the actual implementation costs, which can only be quantified more precisely once offers have been obtained. These uncertainties, particularly regarding costs, have so far led to less concrete results. This is a fundamental problem with measures of this kind, as each production plant requires individual, customised solutions, which on the one hand makes cost estimation more difficult and on the other hand increases costs due to the lack of standard solutions.

2.6 Work package 7: Generalisation of simulation model

2.6.1.Objectives

Work package	WP7	Start month 34	End month 42
Title:	Generalisation of simulation model		
Involved partners	ZHAW-INE ZHAW-IFM SUPSI RALOG SVTL Clemap Carbon Care Aryzta Züger STISA	Work package leader Work package involvement high Work package involvement low	
Goal	1. Generalisation of simulation model 2. Translation of simulation model into customer friendly software solution		
Tasks	▪ Validation of simulation model through cross case comparison and panel discussions with case companies ▪ If necessary, adaptation of simulation model ▪ Generalise simulation model through cross case analysis ▪ Transfer simulation model into software for user friendliness	ZHAW-INE ZHAW-IFM SUPSI ZHAW-INE ZHAW-INE SUPSI	
Results	D7.1 Validated and adapted simulation model D7.2 Generalised simulation model D7.3 Developed simulation software		
Diversity	☑ Young scientists/PhD involved	☑ Women involved*	

The aim of the simulation model is to enable Swiss companies in the food production industry to make informed decisions to follow the path towards net zero for their TCSC. It calculates the costs and emissions of key supply chain activities like transportation, production, and warehousing. This enables companies to make informed decisions that promote energy efficiency and sustainability. The developed application incorporates sophisticated computational logic, the results of which are presented through an intuitive user interface (UI). It enables users to input supply chain-specific data, such as transportation distances and warehouse energy consumption. The outcomes are dynamically visualized, providing clear insights into potential energy savings and alternative strategies through real-time benchmarking. This benchmarking functionality establishes the application as a decision support system (DSS) for companies engaged in TCSC, empowering them to make informed decisions regarding current operations and future investments.

2.6.2.Methods

The simulation model was developed using the Python programming language. Python was selected due to its flexibility and the availability of a wide range of open-source libraries tailored to data handling and UI-related tasks. In particular, the *pandas* library was employed for efficient data manipulation and analysis, while the entire UI was developed using the *nicegui* framework, which enabled the creation of a responsive yet aesthetic front end with minimal overhead.

Python's extensive ecosystem of libraries facilitated the accurate modelling of costs and emissions across various supply chain activities, including transportation, production, and warehousing. Its modular architecture also allowed for the seamless integration of user inputs and real-time output visualisation, forming the foundation for an intuitive, interactive experience.

The software was later compiled into a stand-alone executable application for both Windows and macOS platforms. This ensures ease of distribution and local execution without the need for additional installations or dependencies. To support development, version control was managed using the Git system, while GitHub served as both the collaborative development platform and a secure digital repository for code distribution and backup throughout the project lifecycle.

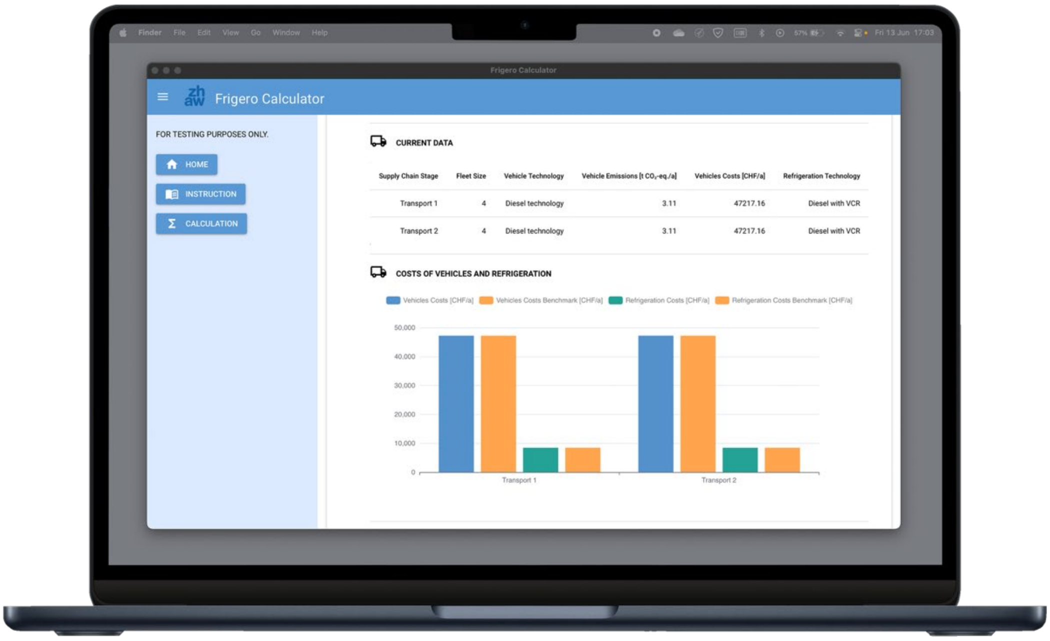
During the development phase, Microsoft Excel was employed to store and manage the initial datasets. Excel's versatility enabled easy manipulation of supply chain data, such as transportation mileage and warehouse energy consumption, which was then fed into the simulation model for testing and validation purposes. User interface design adhered to Nielsen’s usability heuristics, emphasizing simplicity, clarity, and minimal cognitive load.

2.6.3.Results

The primary output of the simulation model is an interactive dashboard designed to present comprehensive cost and emission data for key supply chain activities. As seen in Figure 10, the dashboard displays the calculated results in two formats: tables and charts, allowing users to analyse the energy efficiency and sustainability of their supply chain. The information covers transportation, production, and warehousing costs, and emissions, giving companies a complete overview of their supply chain's energy consumption.

Additionally, the application features dynamic benchmarking capabilities. The interactive charts on the dashboard enable users to adjust input parameters. These adjustments allow companies to simulate different scenarios and immediately view the impact on costs and emissions. This dynamic benchmarking feature provides decision-makers with a clearer understanding of how various operational changes can lead to potential energy savings and sustainability improvements. For example, users can compare their current operations to alternative energy sources or alternative drive technologies, instantly visualising how these adjustments would affect overall energy consumption and emissions. The combination of visual clarity and dynamic inputs enables companies to identify areas where energy autonomy can be improved.

Particular attention was given to user experience (UX) during development. The design of the user interface was guided by established usability principles, including Nielsen’s heuristics, with a focus on simplicity, clarity, and intuitive navigation. The use of clean visual structures, responsive elements, and clear data presentation contributed to a streamlined interaction process, aiming to ensure that users can effectively engage with the tool with minimal training or prior technical knowledge.



CURRENT DATA

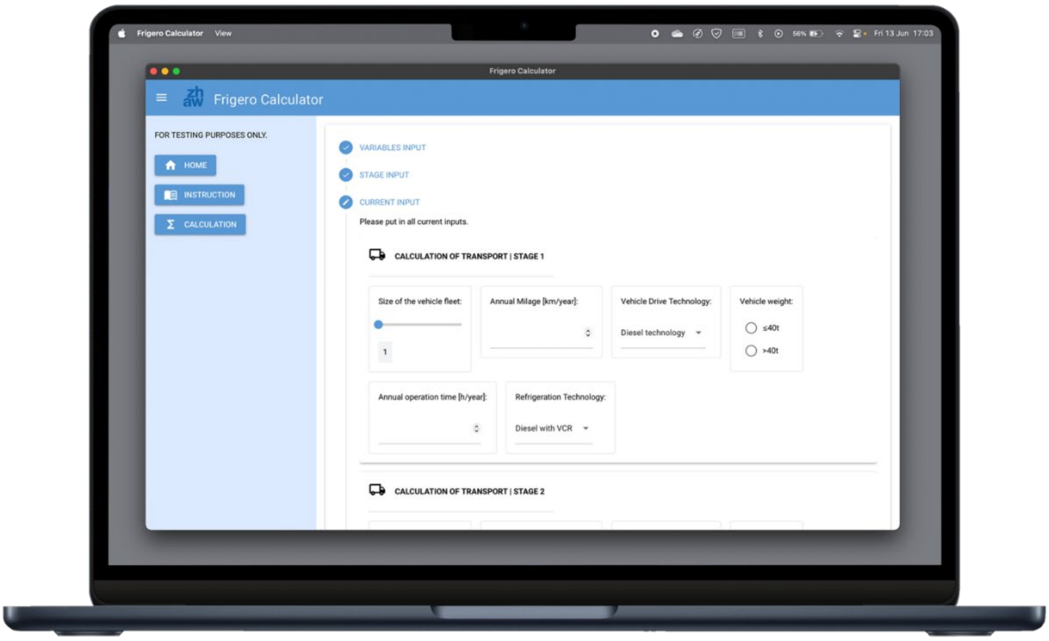
Supply Chain Stage	Fleet Size	Vehicle Technology	Vehicle Emissions [t CO_2-eq./a]	Vehicles Costs [CHF/a]	Refrigeration Technology
Transport 1	4	Diesel technology	3.11	47217.16	Diesel with VCR
Transport 2	4	Diesel technology	3.11	47217.16	Diesel with VCR

COSTS OF VEHICLES AND REFRIGERATION

Figure 14: Graphic output of the simulation model

2.6.4.Discussion

The simulation tool developed in this project provides a solid foundation for companies in the food production industry to make informed decisions toward achieving a TCSC striving towards net zero. It enables the calculation and visualisation of costs and emissions related to key supply chain activities, such as transportation, production, and warehousing. The tool features a user-friendly interface that allows businesses to input their specific data, as displayed in Figure 11, and explore the impact of various operational changes. This dynamic approach helps companies understand the potential energy savings and improvements in sustainability by comparing their current operations with alternative scenarios.



Please put in all current inputs.

Size of the vehicle fleet: 1

Annual Milage [km/year]:

Vehicle Drive Technology: Diesel technology

Vehicle weight: ○ ≤40t ○ >40t

Annual operation time [h/year]:

Refrigeration Technology: Diesel with VCR

Figure 15: Input stage of the simulation model

The tool's main strengths lie in its user-friendliness, speed, and versatility. The interface is designed to be intuitive, minimising the learning curve for users while providing fast results that can be dynamically adjusted based on different input parameters. This allows companies to quickly assess the energy and cost implications of various decisions, promoting better energy management within their supply chains.

However, the accuracy of the tool's calculations is somewhat limited due to the balance between simplicity and precision. To keep the tool accessible and easy to use, some complexity had to be sacrificed, which may impact the accuracy of the results in highly detailed or complex supply chain scenarios. Despite this limitation, the tool offers valuable insights and serves as a practical resource for companies aiming to improve their energy efficiency and work toward energy autonomy in their operations.

3 Conclusions and outlook

3.1 Conclusion

The Frigero project has taken a holistic approach to understanding the environmental impacts associated with temperature-controlled perishable food products from a supply chain perspective. Rather than focusing on isolated solutions at one stage of the supply chain, the project seeks to optimise environmental impacts across multiple stages of temperature-controlled supply chains. This overarching perspective has proven effective in identifying and targeting GHG mitigation opportunities at the most influential points with the greatest lever within the chain.

The impact of these leverage points depends on several key factors, including the degree of vertical integration in the supply chain. This refers to the extent to which activities are outsourced to other partners versus managed internally by the focal company. In addition, the focal company's value-added focus - whether primarily manufacturing or logistics - influences which activities dominate in terms of GHG emissions. Other important factors are the degree of control the focal company exerts over each stage of the supply chain and the partner structures within the supply chain. The project has shown that together, these elements determine both the feasibility and strategic placement of GHG reduction measures throughout the supply chain.

From a technological perspective, we have found that temperature-controlled food supply chains present significant potential for cost-effective GHG emission reduction, particularly through collaborative efforts among supply chain partners. Key areas of collaboration include:

- **Partnerships between warehouse operator and neighbouring industries (Industrial symbiosis)**: Utilising waste heat from large refrigerated warehouse facilities for other neighbouring industrial applications.
- **Partnerships between warehouse operator and municipality**: Utilising waste heat from large refrigerated warehouse facilities for for feeding into an anergy network.
- **Partnerships between warehouse operator and local electricity provider:** Partnering with electricty providers to use refrigerated warehouses switchable load for surplus electricity supply during peak production of intermittent renewable energy sources.
- **Partnerships between food processing company and upstream suppliers:** Working with upstream suppliers (e.g., farmers) to collect biogenic waste for biogas production or to provide rooftop space for photovoltaic (PV) systems through power purchasing agreements.

In the context of refrigeration technology for buildings, advancements focus primarily on transitioning to natural refrigerants, such as CO_2 and ammonia, rather than entirely new technological innovations. Optimisation in refrigeration machine design and dynamic cooling load adjustments to the actual demand have also shown potential for efficiency gains.

In the area of transport refrigeration, advancements are also occurring gradually. The shift away from fossil-fuel-based diesel vapor compression refrigeration (VCR) systems toward alternative technologies is progressing incrementally. Major transport refrigeration providers are primarily focusing on electrification, with opportunities to integrate axle generators or PV systems on cooling chambers for additional GHG emission savings. One notable niche innovation, already adopted by a logistics company interviewed, involves latent heat storage using phase change material (PCM) based cooling, which has shown reduced life cycle costs and emissions compared to the VCR systems. However, despite its benefits, this solution has yet to achieve widespread implementation across the industry.

Although innovation within the temperature-controlled sector tends to be incremental, this project has successfully demonstrated a wide range of GHG reduction measures across each stage of the supply chain. This comprehensive overview provides supply chain managers and decision-makers with valuable insights into various options, including niche solutions, enabling them to make informed choices for GHG emission reductions and cost savings. Rather than focusing solely on individual stages, this approach helps to identify the optimal solution for the entire temperature-controlled supply chain (TCSC). This is further supported by a simulation tool with a user-friendly and intuitive interface, making it easy to use.

When looking at ways to scale up and disseminate the findings of this research project to the entire food processing sector, it is recommended that an understanding of the prevalent supply chain structures in the sector is first created in order to determine where the leverage points are. Key approaches for supply chains involving value-adding activities in temperature-controlled production should ensure that waste heat is recovered and used within the facilities themselves, or provided to district heating networks or neighbouring buildings. Another aspect that can be transferred across the entire sector is that large amounts of energy are usually required if the main value-adding activities lie in production. This means that, in addition to generating their own renewable energy (e.g. via photovoltaic installations), decarbonisation can only be achieved by purchasing green energy.

In supply chains where the main value-adding activities lie in logistics, decarbonising temperature-controlled transport activities can be achieved in two ways: either by electrifying the drive technology, including integrated refrigeration machines, or by decoupling the drive technology from the refrigeration system in the vehicle. This allows for greater flexibility in using niche cooling solutions, such as phase change material (PCM)-based cooling.

3.2 Outlook

This research project has highlighted the critical role of understanding supply chain power dynamics and partner structures before implementing GHG abatement solutions. These factors significantly influence which measures can be applied at specific stages in the supply chain and how sucessfully they are implemented. Building on these findings, the Institute for Sustainable Energy (INE) will continue research on supply chain power and partner structures to explore their impact on the successful adoption of sustainability measures across various industries.

Additionally, we aim to further develop the simulation tool and enhance the backend database. There remains a knowledge gap in emissions and cost data for specific transport modes, such as temperature-controlled and chemical transport etc. Expanding the database will provide more accurate insights into logistics chains, supporting industry stakeholders in making well-informed, sustainable decisions.

4 National and international cooperation

4.1 Current cooperations

Utrecht University, Copernicus Institute of Sustainable Development

- Prof. Dr. Ernst Worrell
- Dr. ir. Wina Crijns-Graus

Cranfield School of Management, Logistics, Procurement and Supply Chain Management

- Prof. Dr. Michael Bourlakis

Texas Christian University, Neeley School of Business, Center for Supply Chain Innovation

- Prof. Dr. Morgan Swink

5 Publications and other communications

5.1 Articles

Viola Rühlin, Maike Scherrer, Wina Crijns-Graus, Ernst Worrell (2025). Marginal abatement cost curves for cold food supply chains–A hybrid adoption of the practice-based and supply-chain practice view. *Journal of Cleaner Production*, *518*, 145902.

Viola Rühlin, Maike Scherrer (2024). *Identifying configuration dimensions for temperature-controlled supply chains under the contingencies of climate change*. [Paper] In EurOMA (Ed.), 31th Euroma Conference. Barcelona, Spain. European Operations Management Association.

Viola Rühlin, Maike Scherrer (2023). *Distribution of power as moderator between supply chain integration and environmental performance*. [Paper] 10th International EurOMA Sustainable Operations and Supply Chains Forum, Hamburg, Germany, 20-23 March 2023.

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