ARTICLE IN PRESS

Trends in Food Science & Technology xxx (xxxx) xxx

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: www.elsevier.com/locate/tifs

Energy management for a net zero dairy supply chain under climate change

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ARTICLE INFO

Keywords:
Energy use
Dairy
Food supply chain
Climate change
Modelling
Net-zero
Sustainability

ABSTRACT

Background: The dairy industry requires substantial energy resources at all stages of production and supply to meet consumer needs in terms of quantity, quality and food safety. The expected future climate change effects will cause serious uncertainty to the dairy industry. Adapting to these upcoming conditions is a challenge and one that is compounded by the continuous increase in food demand, as a result of global population growth. Predictably, under current conditions, this situation might lead to a significant increase in the energy requirements of the dairy industry. Therefore, there is a clear need to mitigate energy use through enhanced energy conservation, waste reduction and waste management.

Scope and approach: This review paper presents and discusses alternative dairy operations and mitigation strategies that have the potential to lead the dairy industry towards net-zero carbon emissions. Further, the focus of this work turns to supply chain energy modelling (SCEM) as means to mitigate energy use, while relevant work in the literature is reviewed.

Key findings and conclusions: Supply chain energy models can provide a complete overview of the energy demand and the energy mix of a dairy supply chain. Additionally, they can highlight the most energy consuming processes and allow the evaluation of alternative energy-saving operations that can lead towards the net-zero carbon target. Overall, the development or use of computational tools for simulating the energy demand in the industry has strong potential for improving sustainability across the dairy supply chain.

1. Introduction

Our planet in 2021 is undergoing drastic changes that will continue over the next decades to affect the global food sector and its energy demand. Changes are incurred from the fast-growing world population, urbanization, and the ever-increasing effects of climate change. Energy consumption for food production and supply represents between 15 and 20% of the global total (Usubiaga-Liaño et al., 2020). Fig. 1 illustrates the annual per capita energy use for both food production and consumption across different regions around the world, indicating that North America and High-Income Asia-Pacific regions (APAC) consume significantly more energy in food systems than other parts of the world.

In 2019, the global energy use was estimated to be equal to 173,340 TWh, up 53% compared to 20 years ago and with a global energy mix comprised mostly of non-renewable resources, >80% of which are derived from fossil fuels (Ritchie, 2019). Although increasing energy resources are required to deliver against fast-rising demand, they are accompanied by significant environmental challenges which also need to be addressed. These include the global warming phenomenon, environmental degradation, pollution, loss of biodiversity and depletion of natural resources (Hussain et al., 2020). Not enough has been done to reduce energy consumption and the focus needs to be shifted to building a more energy-efficient food production and supply system. One of the factors bringing about change to our planet is the alarming rise in world population. An initial appraisal by the Food and Agricultural Organization of the United Nations (FAO) warns that a significant increase in food production will be required to cover demand, which in 2050 is expected to reach a growth of 70% versus the 2005 values (Alexandratos & Bruinsma, 2012). This expected rise in food demand predictably leads to a corresponding growth in energy demand in the food supply chain. Another critical future threat to the food industry is climate change, which is inevitably affecting the world's agricultural production and has serious repercussions for the food industry, including uncertainty for food quantity, quality, security and safety (Niles et al., 2018). Given the

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https://doi.org/10.1016/j.tifs.2022.01.015
Received 30 March 2021; Received in revised form 13 October 2021; Accepted 5 January 2022
Available online 14 January 2022

Please cite this article as: Maria Ioanna Malliaroudaki, *Trends in Food Science & Technology*, https://doi.org/10.1016/j.tifs.2022.01.015

climate change challenges that need to be addressed, precautionary practices may require additional energy supply to ensure delivery of food supply.

One key food sector that is highly vulnerable to the challenges of growing demand and climate change impact is the dairy industry (Feliciano et al., 2020). The impact of climate change on the dairy sector will be predominantly realised in three ways: First, although the global warming effects will not be adverse everywhere, a relevant increase of drought events is expected across the globe affecting the crop yield and as a result reducing availability of animal feed (Nardone et al., 2010). Secondly, rising temperatures can cause heat stress to cows, leading to decreased milk production and increased mortality risk (Schifano et al., 2012). Finally, food safety concerns escalate as a consequence of food-borne pathogens adapting to global warming, where heat resistance and their survival and/or reproduction rates may alter. In such scenarios, the current pasteurisation methods may no longer be effective and the implementation of stricter food safety measures would be inevitable e.g. more intense heat treatment and/or lower refrigeration temperatures (Feliciano et al., 2020; Miraglia et al., 2009). These challenges to the dairy industry are already in motion and need to be addressed throughout the dairy supply chain before their consequences become unmanageable and impact of safe and sufficient supply.

Although the dairy sector suffers the consequences of global warming, it is ironically concurrently responsible for the significant release of GHG (greenhouse gas) emissions, which contribute to the global warming phenomenon. As estimated in 2007, farm activities, product manufacturing, and logistics of the dairy sector accounted for 2.7% of the total anthropogenic GHG emissions (FAO, 2010). These are mainly derived from bovine enteric fermentation and extensive fossil fuel usage along the supply chain (Ladha-Sabur, Bakalis, Fryer, & Lopez-quiroga, 2019). Regrettably, the sector's emissions are rising at an alarming rate with the dairy sector's GHG emissions have increased by 18% between 2005 and 2015 levels (FAO & GDP, 2018).

Dairy products play a major role in human diets as they are an important source of protein and include essential minerals and vitamins such as calcium and Vitamin B (Caroli et al., 2011). In particular, the dietary energy intake of dairy products (between cheese, milk and butter) accounts for an estimated 14% of total consumption in developed countries and about 5% in developing countries (Gerosa & Skoet, 2012). In view of the fast-growing world population, the higher per capita income growth and "westernising" diet trends in the East, a significant rise in demand for dairy products sets the long-term sustainability of the sector into question (OECD-FAO, 2020; Pingali, 2007). In fact, an estimated rise of 1.0% per year is expected over the decade 2020–2030 for fresh dairy products (OECD-FAO, 2020). Although dairy products are important in diets, the energy use and GHG emissions associated with meat and dairy products production are much higher than those of plant-based food products (Green et al., 2018). Consumers, especially in the western world are growing increasingly concerned about environmental impact and animal welfare, with growing trends in adopting low-meat, vegetarian and vegan diets (Fehér et al., 2020; Hodson & Earle, 2018). Indeed, dietary GHG emissions of vegan diets are about half that of meat-eaters' diets (Scarborough et al., 2014). Thus, shifting eating habits towards plant-based diets could substantially contribute to environmental sustainability.

This paper explores the importance of reducing energy consumption in the dairy industry and recommends energy mitigation actions, in line with the "net-zero" carbon emissions target set by global organizations (IPCC, 2018; Bataille, 2020). First, the current patterns of energy use along the dairy supply chain will be presented, followed by proposed energy mitigation strategies and alternative technological dairy operations across the sector. Subsequently, the challenges emerging through the implementation of energy mitigation are ascertained. Finally, a discussion will follow on how supply chain energy modelling (SCEM) can play a catalytic role in addressing those challenges and contribute towards optimising the energy use along the supply chain.

2. Net zero carbon emission in the dairy industry

Global organizations and governments have set sustainability targets and relevant regulatory directives to address the climate change phenomenon and protect the environment (Gil et al., 2019). The United Nations has proposed 17 Sustainable Development Goals (SDGs) to be met by 2030 (Summit, 2019). For the food industry, these SDGs entail the improvement of natural resources management, the use of energy-efficient equipment, the production of valuable products from residues and waste and the limitation of waste and losses while supporting recycling at all supply chain stages (Kazancoglu et al., 2018; Summit, 2019). In addition, the Paris Agreement in 2015, established that all sectors will have to reach the net-zero carbon dioxide (CO_2) emissions target by 2050–2070 and drastically reduce non-CO_2 emissions that contribute to global warming such as methane (CH_4), to limit global warming well below 2 $^\circ C$ and towards 1.5 $^\circ C$ from the pre-industrial average temperature levels (IPCC, 2018; Bataille, 2020; Fuglestvedt et al., 2018).

"Net-zero carbon" or "carbon neutral" means that the anthropogenic carbon emissions that cross the boundaries of a system should be balanced by the anthropogenic carbon emissions removals through those boundaries (IPCC, 2018). Thus, for a whole sector such as the food industry, the net-zero carbon target indicates that all carbon emissions produced throughout the supply chain should be limited to a minimum by implementing efficient sustainability strategies and any remaining emissions should be balanced by carbon emission removal practices. For some sectors such as the dairy industry, the mitigation potential for

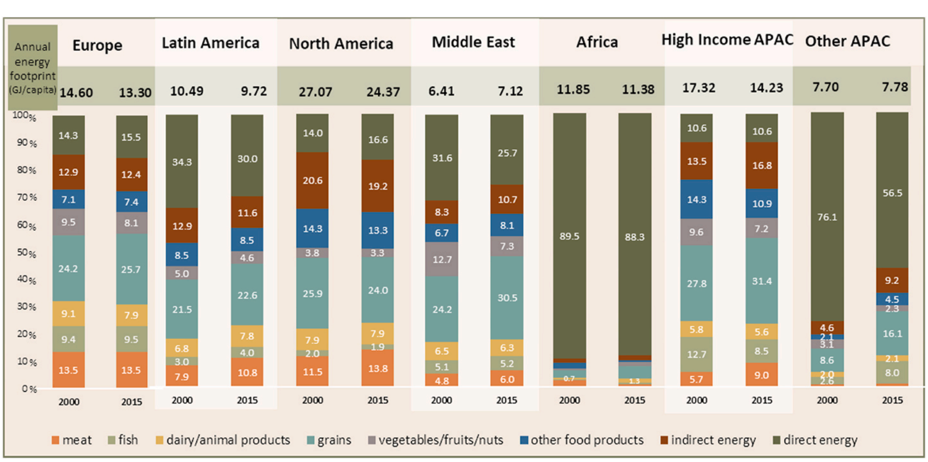

Fig. 1. Annual per capita energy use due to food consumption measured in GJ/capita in the year 2000 and 2015. The bar charts involve the share of energy use for the production and processing of different foods (meat, fish, dairy/animal products, grains, vegetables/fruits/nuts, other food products), the direct energy required for cooking and refrigeration and the indirect energy use which refers to the energy used in the production of the food-related energy products consumed within the household. "Grains" include grains and grain-based products such as bread and pasta as well as other products such as biscuits, pastries, and cakes. "Other food products" includes sugar products, beverages, oil seeds, and other vegetable fats which are all plant-based products. The data for this chart were obtained from the supporting information 1 of the study of Usubiaga-Liaño et al., 2020.

achieving the net-zero carbon target is limited under the current technology due to the inability to control the vast methane emissions caused by biological processes such as bovine enteric fermentation (FAO & GDP, 2018). Although the bovine-related emissions are the major challenge for the industry, the pursuit of bovine alternatives and synthetic milk production that can reduce the reliance on bovines for milk production and is compositionally equivalent (e.g. in terms of protein content) to dairy milk has yet to become a scalable realisation. Hence, such alternatives to bovine milk still require significant innovation to be viable at a commercial scale (Röös et al., 2017).

All party members of the Paris Agreement will inevitably have to set their own national governmental regulations to be legislated in order to enforce companies and stakeholders to become carbon neutral. Today, companies that choose to ignore the importance of net-zero carbon target or even delay any first steps in that direction risk having to implement legislative regulations under pressure, which may incur costly misjudgements and sub-optimum solutions (OECD, 2015). On the other hand, the industries and companies that acknowledge their social and environmental responsibility and start taking net-zero carbon actions from an early stage have the potential to significantly reduce the downside risks during adaptation (OECD, 2015). Amidst markets where there is a growing trend in favour of social environmental awareness, where products and manufacturers are preferred and awarded for their "green" strategies, companies with net-zero actions will gain social preference and recognition. Environmental sustainability will become the new norm of competency among the world company network.

Carbon neutrality may not always be achievable for each site owned by a company. The dairy industry is such a case and net-zero carbon target may only be achievable from a holistic perspective, within the framework of industrial symbiosis. Specifically, to achieve the net-zero carbon levels within the dairy supply chain, those supply chain actors who are net-negative, meaning that they release carbon emissions, can collaborate with other supply chain actors or industries out of the dairy sector which are or can become net-positive, meaning that their activities overall absorb carbon emissions, in order to achieve carbon neutrality altogether (Abreu & Camarinha-Matos, 2008). Creating a net-zero carbon dairy sector can provide significant benefits to both the environment and industry stakeholders (Abreu & Camarinha-Matos, 2008). From an air quality perspective, net-zero carbon can also contribute to a reduction in a particulate matter arising from fossil fuel combustion for energy generation, leading to considerable environmental and public health benefits (Wang et al., 2020). From the industrial perspective, energy mitigation strategies can make the sector energy-autonomous or semi-autonomous leading to fewer running expenses for energy use and fewer financial charges since the governmental tax incentives favour net-zero activities. Furthermore, the investment in activities such as the production of energy from waste or residues can generate an additional source of profit for the stakeholders. This review article presents the opportunities arising for the dairy sector to mitigate energy use, that can significantly contribute towards the net-zero carbon target.

3. Energy mapping for the dairy supply chain

The first step in the process of mitigating the energy use in the dairy supply chain is to assess the current energy use of every single component of the chain. This will clearly indicate the hotspots of energy use where mitigation actions will deliver the most value and savings. This section aims to offer an energy map of the dairy supply chain by providing estimates of the energy consumption at each supply chain stage obtained from the current literature. The dairy supply chain begins at the farm where raw milk is produced, and then is temporarily cold stored before being transported to the dairy plant for product manufacturing and packaging. The packaged products are then delivered via refrigerated trucks to the retail outlets via distribution centres. Finally, dairy products are bought by consumers for domestic use, which includes refrigeration and/or cooking. In this study, the dairy supply chain was divided into four major stages for convenient presentation of the energy patterns: the dairy farm, manufacturing, the cold-chain and consumption. Fig. 2 outlines the processes taking place in each of these four supply chain stages. After separately analysing the energy use in each dairy supply stage, a final overview of the carbon emissions derived from energy use along the entire dairy sector is provided.

This section aims to provide an energy map of the dairy supply chain by individually analysing each of the supply chain stages from the dairy farm, manufacturing, cold chain and consumption use. Developing an energy map of the dairy supply chain requires energy use quantification in suitable units of measurements, which enables the reader to develop a sense on how energy use is allocated along the dairy supply chain. Fig. 3 is an energy map illustration for the dairy supply chain providing energy data which can be used for broad estimation of the energy use of different dairy products along the dairy supply chain.

The majority of studies express energy consumption either in energy units or as carbon footprint per kg of product depending on their objective. The reason why energy use or carbon footprint is measured per unit of product is to allow the comparison of energy use between the supply chain stages. In studies that aim to measure the amount of electrical or thermal energy input, energy is usually expressed in MJ per kg of product. In studies that aim to assess the impact of energy use on global warming, they evaluate the carbon footprint of energy use, measured in kg of carbon dioxide equivalent (CO_2e) per kg of product (Flysjö et al., 2014). It is important to note that the carbon footprint in CO_2e of 1 MJ of energy use may vary significantly, depending on the fuel burned or the energy mix of electricity from the grid. The energy use of a process or product can be translated into the carbon footprint only if the energy mix and the emission factors of the fuels or energy resources consumed are known. Overall, the carbon footprint of energy use and the actual energy use express different values and should not be

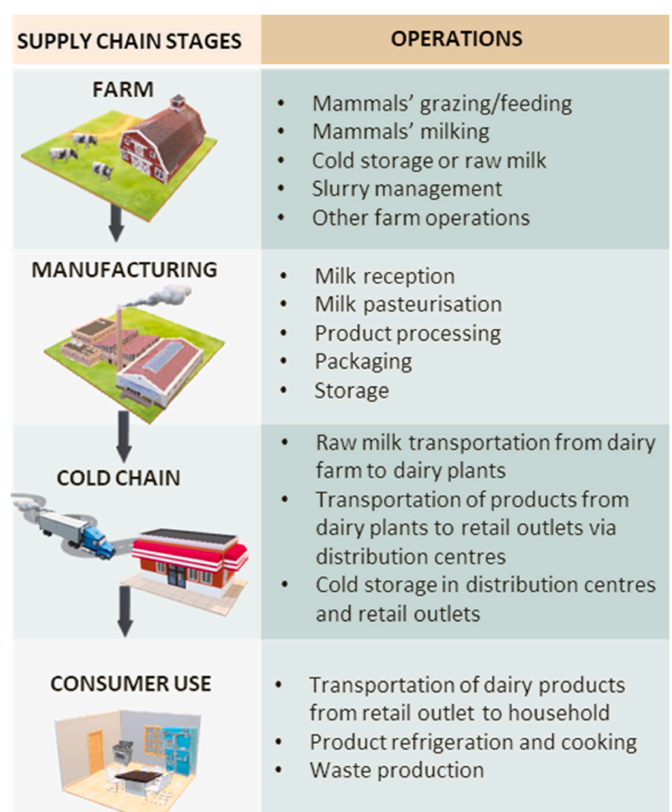

Fig. 2. Illustration of the four stages proposed for dividing the dairy supply chain including an outline of the processes taking place at each stage.

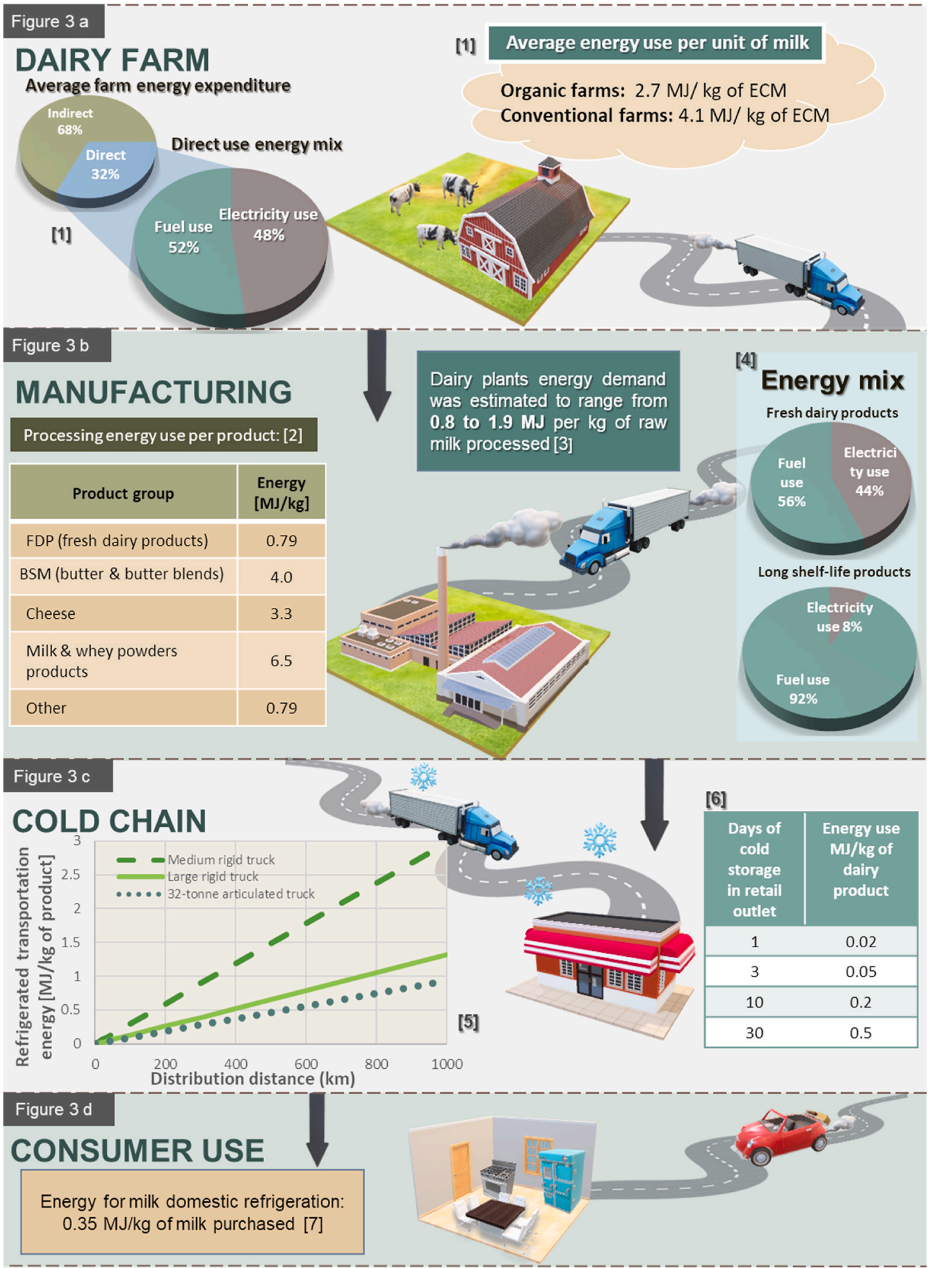

Fig. 3. Infographic providing information for the energy use in the dairy supply chain separated in 4 stages: the dairy farm (Fig. 3a), manufacturing (Fig. 3b), cold chain (Fig. 3c) and consumption use (Fig. 3d). The energy values provided in the tables and charts of Fig. 3 can be used for broad estimation of the energy use of different dairy products along the dairy supply chain. [GHG, greenhouse gas emissions]
[1] Information obtained from the study of (Shine et al., 2020). (Where, ECM stands for energy corrected milk (Bernard, 1997)).
[2] Data obtained from the study of (Flysjö et al., 2014) in Table 4, showing the energy use of different product categories manufacturing.
[3] Information obtained from (Xu et al., 2009).
[4] Adapted from data presenting the energy use in terms of fuel and electricity in kJ/kg of product for the manufacturing stage of different dairy products. The products were categorised into fresh and high process products and the average share of fuel and electricity was calculated for each category (Ladha-Sabur et al., 2019).
[5] Information adapted from the LCA study of (Thoma et al., 2013).
[6] Data obtained from the study of (Tassou et al., 2009) presenting the energy use per kg of product and km of transportation distance consumed by different type of refrigerating trucks (medium rigid, large rigid and 32-tonne articulated trucks).
[7] Data obtained from the study of (Burek & Nutter, 2020) in Fig. 15b.
[8] Information adapted from the LCA study of (Thoma et al., 2013).

compared with each other. The target of energy mitigation should aim for both an improvement in energy efficiency and thus reduction of the energy use and in carbon emissions reduction by utilising alternative fuels or electricity resources. In the following energy mapping process for each supply chain stage presented in **Sections 3.1 – 3.4** energy is quantified in MJ per unit of product, while **Section 3.6** presents carbon emissions data for the dairy supply chain.

3.1. Dairy farm energy mapping

Starting with the energy mapping of in the dairy farm, according to a recent review analysing of the energy consumption in dairy farms the total energy use was estimated to range from 2.7 MJ/kg of ECM in organic dairy farms to 4.1 MJ/kg of ECM in conventional ones (Shine et al., 2020). Here, ECM stands for energy corrected milk which standardises milk of any fat and protein content, to the caloric equivalent amount of milk of 3.5% fat and 3.2% protein content respectively (Bernard, 1997). The difference between conventional and organic farming energy use is attributed to the fact that conventional farming requires more indirect energy use for feed and fertiliser production compared to organic farming (Kumar & Chakabarti, 2019). In conventional farming, energy use for fertiliser and feed production is important although it is associated with indirect energy use. In fact, fertilisers and feed production are associated with 13% and 43% of the total energy consumption in conventional dairy farms. On the other hand, energy consumption for feed production in organic farming is related to direct energy use, due to the free-range grazing on-farm and is associated with 34% on average of total primary energy use, while the energy requirement for organic fertiliser production is negligible at <1% (Shine et al., 2020).

Across all studied dairy farms between conventional and organic, out of the total energy use of dairy farms, 32% on average is related to direct energy use from on-farm activities, while the remaining 68% is related to indirect energy use from out-of-farm activities such as feed and fertilisers production (Shine et al., 2020). Focusing on the direct usage, the energy mix is comprised of electricity and liquid fuels at a rate of 48%

and 52% respectively (Fig. 3a). Electricity is used in refrigeration for milk cooling, pumping for milk harvesting, water heating, water pumping, lighting, while the other main source of direct energy consumption are fuels such as diesel, kerosene, natural gas, liquefied petroleum gas (LPG), and lubricants which are used mainly for on-farm activities for water heating and powering mechanical machinery (Shine et al., 2020).

3.2. Manufacturing energy mapping

After the primary production of raw milk on the farm, the milk is transported to the dairy manufacturing plant where various processes occur to create the end-products. This includes the raw milk storage at the dairy plant reception, heat treatment, separation, bacterial fermentation, ripening, packaging and storage of the final product ready for distribution (Fig. 4). Dairy manufacturing requires substantial levels of energy due to the extensive heating and cooling processes taking place. The energy demand per kg of raw milk processed in dairy plants can exhibit variations ranging from 0.8 to 1.9 MJ, depending on the products and the scale of production (Xu et al., 2009). The processing plant also includes Clean-In-Place (CIP) processes to clean the inner surfaces of processing equipment and may also include a wastewater treatment process (or the used water is otherwise sent to a third-party wastewater treatment site).

Energy consumption mainly results from electricity and fuel use, with Fig. 3b presenting an overview of the energy use in dairy manufacturing. Processes such as refrigeration, packaging, homogenisation, standardisation, milk pumps and plant automation require electricity, whilst heat treatment processes require mainly steam that is produced from fossil fuel combustion (Tomasula et al., 2014). The table in Fig. 3b provides some estimates for the energy input for the production of dairy products from different categories, indicating that powder and butter products require the highest energy input (Flysjö et al., 2014). Ladha-Sabur et al. (2019) presented the manufacturing energy demand among different dairy products providing the share of electricity and fuel demand per product. Based on their data, it can be observed that fresh dairy products (cheese, fresh milk, butter, cream and ice cream) had a similar pattern in the energy mix, which was on average composed of 43.9% electricity and 56.1% fuel utility for the manufacturing stage. Whilst the long shelf-life products (casein and lactose, milk powder, whey powder, and concentrated milk) show similarities in the energy mix as well, which were on average 8.1% of electricity and 91.9% of fuel on average (Fig. 2b). This increased electricity ratio of the aforementioned fresh products is due to their extensive refrigeration needs, while the high fuel ratio in the aforementioned long shelf-life products is due to the multiple processes required for their production.

Finally, it is worth highlighting the significant energy demand of the CIP processes due to the high hygiene standards' requirements in the dairy industry. The CIP operations have been reported to utilise 9.5% of the energy needed for fluid milk production, 19% of cheese production and 26% of butter production (Ramirez et al., 2006). The high processing temperature of pasteurisation, burns milk onto the equipment's inner surfaces, requiring extended contact times with water and detergents at high temperatures to adequately clean. The reason why the energy needed for CIP is so high is the consequence of the high temperature of fluids required to clean fouled surfaces. For instance, the thermal energy requirement for the CIP process for a milk pasteuriser in an average-sized dairy was estimated to be 3.96 GJ/cleaning cycle (Eide et al., 2003).

3.3. Cold chain energy mapping

Upon leaving the manufacturing plant, the highly perishable nature of fresh dairy products requires controlled environmental conditions with an optimal storing and transportation temperature ranging from 0 to 2 °*C* (Mercier et al., 2017). This ensures food quality and safety between manufacture and consumer purchase. In the food industry, the cold-chain has a huge impact on the environment, accounting for approximately 1% of global CO_2 emission and the use of refrigeration worldwide is responsible for about 15% of the total electricity consumption (James & James, 2010). Fig. 3c provides information about the energy use in the dairy cold chain. According to a study that evaluated the energy consumption of diesel-fuelled refrigeration trucks, it was found that medium rigid trucks, large rigid trucks and 32-tonnes articulated trucks consumed on average 2.97 MJ, 1.31 MJ and 0.94 MJ per tonne of products transported and kilometre of distance respectively (Tassou et al., 2009). According to these estimates, the energy use per kg of product transported as a function of the distribution distance for these three types of trucks is presented in the graph of Fig. 3c. Fig. 3c also includes a further consideration of energy use specific to the varying duration of cold storage in retail outlets. The information for the energy usage for retail storage, was obtained from a study that has evaluated the fossil fuel usage and carbon footprint per day of cold storage for different categories of perishable food products (dairy products included) over a 30-day storage period (Burek & Nutter, 2020). For instance, for high-temperature short-time (HTST) pasteurised milk of an average 10-days shelf-life (Lorenzen et al., 2011), the energy use for cold storage in the retail outlet may be up to 0.2 MJ/kg of milk (Burek & Nutter, 2020).

3.4. Consumer energy use

In the consumption stage, energy utilisation is mainly required for transportation from the retail outlets to the households and refrigeration (Fig. 3d). The average electricity demand per kg of refrigerated milk is estimated to be 0.35 MJ/kg (Thoma et al., 2013). Regarding the travel distance for grocery shopping, the average route was estimated to be equal to 10.9 km per trip with 175 trips taking place annually per 3-person household in the US (Thoma et al., 2013). It is worth mentioning that unconsumed products wasted in the consumption stage cause indirect energy consumption, which is due to all the energy consumed

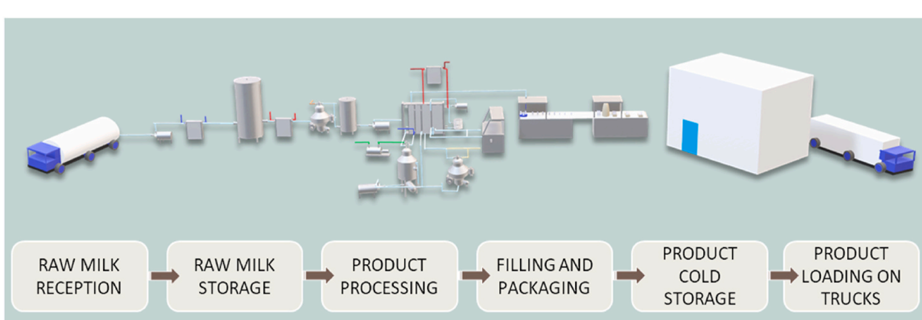

Fig. 4. Dairy manufacturing plant step-by-step operations for processing fresh dairy products spanning milk, cream, butter, cheese, and powdered products.

from product manufacture, transportation and refrigeration being effectively wasted. Every day 1.13 million tonnes of food products are wasted globally, corresponding to 178 g of food per capita per day (Chen et al., 2020). This total food waste comprises of 9% from dairy products on global average, while in high income nations this estimated rate is much higher, equal to 17% (Chen et al., 2020). Finally, it is important to emphasise that limited research exists on the energy consumption for dairy products at the consumer stages, and one may anticipate that this will vary significantly due to different global climates and consumer behaviours.

3.5. Waste in the dairy supply chain

Waste is an important component for understanding and offering opportunities to improve sustainability, with waste produced throughout all four stages of the dairy supply chain. Waste increases the energy use indirectly, due to the energy input required for the production of unused material and products, also being wasted. Dairy product loss accounts for approximately 20% of the total dairy products produced. The estimation of losses from dairy plant stage to consumption stage corresponds to 17–30% in the manufacturing stage, 9–12% at the transportation stage, 2–9% at the retail level, with the highest contribution in waste produced at the consumer level correspond to a share of 53–71% of total dairy products wasted (Bršćić, 2020).

3.6. Carbon emissions by the dairy sector

Most studies in the literature that present energy data focus either on a particular stage in the supply chain or are Life Cycle Assessment (LCA) studies. The LCA studies take energy use, bovine enteric fermentation emission and other emissions resources into consideration and estimate the carbon footprint (Guzmán-Luna et al., 2021). An LCA study evaluated all GHG emissions released from the farm, transportation, and manufacturing stages and identified a summative estimated carbon footprint for 1 kg of milk as 1 kg CO_2e, and 1 kg of yogurt as 1.75 kg CO_2e, which included the carbon footprint for packaging (Vergé et al., 2013). The same study clearly showed that when considering these three stages, it is the farm activities that contribute the most GHG emissions for these two dairy products (86.9% and 72.2% of total GHG emissions for milk and yogurt respectively). For the manufacturing stage, the contribution of different utilities between fossil fuels, electricity, waste/water, chemicals and refrigerants was also determined. This revealed that fossil fuels and electricity made the largest contribution to GHG emissions for the manufacturing stage. Specifically, fossil fuels and electricity were found to be responsible for 95% of milk's and 98.3% of yogurt's manufacturing GHG emissions This results in the contributions of water and wastewater, chemicals, and refrigerants to the product carbon footprint being comparatively small, corresponding to only 5% and 1.7% of milk and yogurt manufacturing respectively (Vergé et al., 2013).

The carbon footprint of dairy product manufacturing is attributed mainly to energy use and is product-dependent. For one study, where carbon footprint has been equated to the global warming potential (GWP), milk and cream was estimated to be 0.114 kg CO_2e per kg of product (Finnegan et al., 2017), which is a relatively low value due to the low energy-intensive processes of pasteurisation and separation. Comparatively, butter and cheese are more energy-demanding products since they require additional processes such as churning and ripening, with their carbon footprint estimated to be 0.415 and 0.464 kg CO_2e per kg of product respectively. Finally, powdered products, have the highest carbon footprint due to the need for evaporation and drying, which are highly energy demanding. Specifically, the carbon footprint was measured at 1.824 kg CO_2e per kg for milk powders and 2.474 kg CO_2e per kg of whey powder respectively (Finnegan et al., 2017).

According to a full LCA study for the milk supply chain from "farm to fork", to the total GHG emissions were estimated to be 2.05 kg CO_2e per kg of milk (Thoma et al., 2013). This study provided detailed numbers for the emissions per different GHG emissions source including fuels and electricity. For the needs of the present study, the focus was turned to the energy-derived emissions (fuel and electricity), which were processed to be effectively presented in Fig. 5. This figure presents the carbon footprint resulting from energy usage throughout the milk supply chain, including energy for feed production, activities on farm, product manufacturing and packaging, product distribution and storage in retail and consumption energy use. Of the total 2.05 kg CO_2e GHG emissions released from "farm-to-fork" per kg of milk, around 0.76 kg CO_2e result from energy usage, while the share of emissions per energy source is comprised of 51.4% of fuel and 48.6% of electricity (Thoma et al., 2013). From the carton of milk illustration in Fig. 5 that shows the emissions contribution in the four milk supply chain stages, it is clear that the cold chain stage has the highest GHG contribution of energy use. The table provided in Fig. 5 presents the fuel and electricity share expressed in CO_2e emissions per supply chain stage: farm, manufacturing, cold chain and consumption use. It can be concluded that the farm and the cold chain stage is responsible for substantially increasing the overall fuel use in the dairy chain. The emissions from the remaining supply chain stages are mainly derived from electricity usage, while manufacturing and consumption supply chain stages have the largest share of electricity-derived emissions.

4. Energy mitigation strategies for the dairy industry

The energy use in the dairy supply chain shows that each supply chain stage differs in terms of processes and equipment used, energy

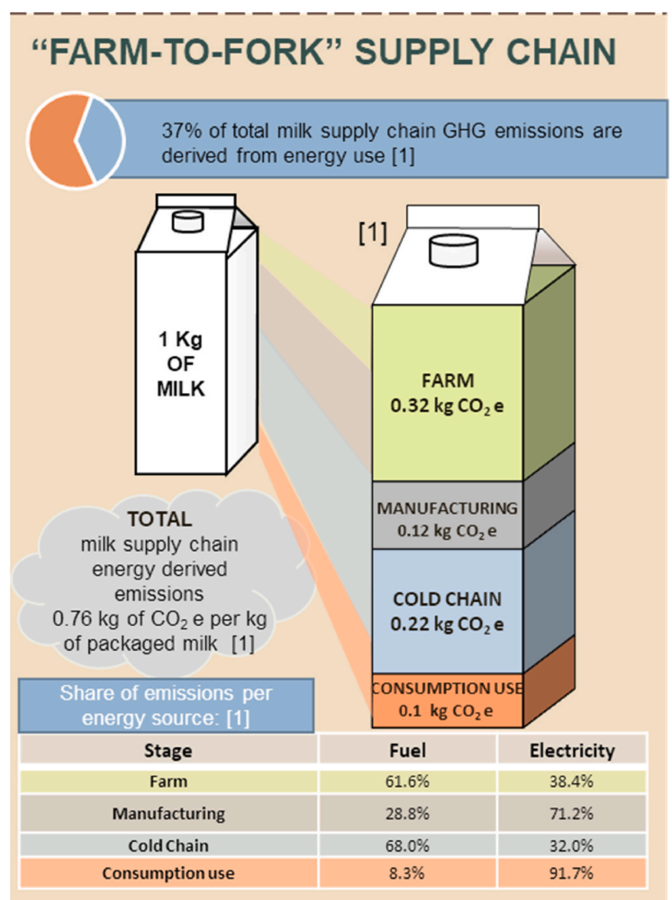

Fig. 5. Infographic providing information for the energy use throughout the "farm-to-fork" supply chain of drinking milk.
[1] Information adapted from the LCA study (Thoma et al., 2013).

mix, emission production and share in total chain energy utility. For this reason, the energy mitigation strategies for each stage have a different focus. Herein, are presented energy-efficient practices and several considerations for innovative technologies, which can address some of the energy consumption challenges within each stage of the supply chain. The environmental impact of food products can be reduced by adjusting farming, manufacturing, distribution and consumption patterns (Roy et al., 2009). According to LCA studies on dairy products, the most popular steps include reduction of fuel and electricity use within the dairy product life cycle, utilisation of energy-efficient process equipment, use of renewable energy resources, and the optimisation of logistics (Djekic et al., 2014; Üçtuğ, 2019). Mitigation practices should be prioritised according to the energy impact of an operation along the supply chain. The payback period should be considered and the benefits to the stakeholders and enterprises should be identified to enable effective adoption.

4.1. Mitigation strategy for the dairy farms

The ever-increasing installation of agricultural technology and automation allows for close monitoring of milk production and feeding processes. Moreover, animal tracking allows for the improvement of cattle, goat and sheep welfare which can lead to increased milk yield and early identification of diseases (Hansen et al., 2018). Automation in farms, also ensures improved hygiene which is an important parameter in dairy's supply chain food safety. Although those technologies are highly recommended, the installation of equipment with new technology automation may require additional energy input (Todde et al., 2017). Automation in farms should be coupled with mitigation practices that can reduce emissions and energy use in farms.

To mitigate the carbon emissions caused by energy use, the energy reduction practices for dairy farms can be categorised into carbon removal and emissions reduction practices. The former category is associated with on-farm energy production and land manage practices that enable soil carbon storage or sequestration (McEvoy, 2019), while the latter category, aims to improve the energy efficiency of the farm equipment.

In the former category of carbon removal practices, some of the most promising practices as indicated from the literature is biogas production from the digestion of dairy manure and other co-substrates from farm waste (Gebrezgabher et al., 2012). However, the capital costs for anaerobic digestion coupled with technical expertise for operation and maintenance would drive the case for offsite waste treatment and biogas production, and/or utilising small modular waste to biogas technologies on-site that are managed via cloud and digital technologies by an external waste management provider (Fisher et al., 2020). Moreover, electricity for farm use can also be produced from photovoltaic (PV) system installation or wind turbines on-site. PV systems and wind turbines can produce electricity with daylight and in the presence of wind respectively, but such electricity production may not be aligned with electricity demand due to load shifting which may be addressed with the installation of batteries to store the surplus energy. However, batteries may not always be necessary since warm water may act as energy reservoir for the needs of a farm's water heating (Breen et al., 2020). It is important to note, the electricity mix from the grid is completely exogenous to farms (Verge et al., 2013). Decisions on the national electricity mix are extremely complex, and way beyond the impact of the energy used by the whole dairy value chain (Aghajanzadeh & Therkelsen, 2019). Finally, the implementation of grassland practices is proposed in order to increase the carbon uptake by sequestering atmospheric carbon dioxide (FAO & GDP, 2018).

Regarding the latter category, of carbon emissions reduction practices related to energy use, the literature focuses on energy-conserving technologies to reduce on-farm energy consumption and carbon emissions. Several energy and cost conserving practices for dairy farms were recently reviewed and demonstrated promising energy savings potential. Some of the most common practices where technologies aim to reduce on-farm electricity consumption, including pre-cooling milk through a plate cooler, improving hot water tank insulation, and switching to energy-efficient lighting, etc. (Shine et al., 2020). In any emissions reduction practices the impact on water utility should be considered beforehand.

Finally, as regards the growth of the sector, increased organic farming is recommended since it is less energy consuming compared to conventional farming per kg of milk produced (Shine et al., 2020). It can be concluded that with proper mitigation actions, dairy farming can not only become net-zero but even net-positive, complementing other sectors such as the UK Water Industry operation of municipal wastewater treatment processes that have moved significantly from energy negative to even net-positive (Water UK, 2020).

4.2. Mitigation strategy for dairy manufacturing

Today, manufacturing companies are under pressure to improve sustainability throughout their systems (Fisher et al., 2021). Dairy plants appear in great variety both in terms of scale and products manufactured, and thus, net-zero mitigation actions may differ in each type and scale of dairy plant respectively. The manufacturing stage is highly energy-demanding due to numerous processes taking place many of which require high temperature, for processes such as pasteurisation, evaporation and drying. Dairy manufacturing plants can substantially reduce their carbon footprint by switching from conventional energy use to clean forms of energy. Fossil fuels should be replaced by biofuels while the electricity use is preferable to be derived from cleaner resources such as from wind, solar, hydroelectric, geothermal or nuclear energy (Rad & Lewis, 2014). On-site electricity production should be considered where local generation of electricity is feasible. Broader mitigation could be achieved more generally by a shift in the overall grid energy mix towards renewable sources alongside nuclear energy.

Some of the common practices followed by dairy manufacturers that can substantially reduce the energy use, is the installation of heating and cooling regenerators and energy-efficient equipment, the insulation of heating and cooling processing equipment, optimising combustion efficiencies in steam and hot water boilers and fixing steam leakages (Rad & Lewis, 2014). There is an increasing focus on emerging technologies to reduce energy use in dairy production (Martins et al., 2019). The non-conventional technologies to replace conventional heat treatment, such as pasteurisation, are categorised into thermal and non-thermal treatment processes. Microwave (MW) and radio frequency (RF) are two of the most promising non-conventional thermal treatment processing methods. Both MW and RF use electromagnetic energy to provide instantaneous volumetric heating, overcoming heat transfer limitations to achieve higher heating rates (Martins et al., 2019). Given that the capital cost of such technologies is significantly higher, the definition of the value proposition is key for successful application. The fact that MW and RF are promising technologies for improved product quality is also a common benefit, however as yet, very few bulk heating MW and RF applications have achieved commercial success (Kingman, 2018).

Non-thermal techniques proposed in the literature to replace heat treatment processes are ultrasound (US), high-pressure processing (HPP) and Pulsed Electric field (PEF). The efficiency of US in milk pasteurisation has been evaluated and shows promising results in terms of food safety and energy efficiency (Kotsanopoulos & Arvanitoyannis, 2015). HPP is increasingly used in the food industry for value-added products (Chawla et al., 2011), whilst non-thermal techniques provide the advantage of efficient preservation of milk nutrients using less energy consumption compared to conventional treatment (Martins et al., 2019). Again, the value proposition scenarios for non-thermal processes must be critically evaluated to corroborate such claims at industrially relevant scales.

Waste management plays an important role in energy savings and sustainability (Kazancoglu et al., 2018). Dairy manufacturing plants produce huge volumes of waste streams. Circular economy thinking, building on the waste hierarchy, provides opportunities to reduce dairy industry waste or valorise it through reusing, recycling and recovery operations (Fisher et al., 2021). Key waste streams in dairy manufacturing include whey, however avoidable wastes such as leaks, spillages, spoilage and equipment cleaning discharges are important to consider (Zero Waste Scotland, 2020). Cleaning-in-Place (CIP) technologies have a critical part to play in improving cleaning efficiency, reducing not only energy use but also overall water used and therefore waste generated. In fact, the installation of an energy-efficient CIP system can reduce cleaning cost by approximately 35% and cleaning energy use by 40% (Marriott et al., 2018).

For valorisation, biotechnological approaches have been shown to be applicable for the production of biopharmaceutical products, whey-derived food products and bioplastics (Ahmad et al., 2019). Moreover, there are opportunities for energy generation by producing biofuels from dairy plant waste. For example, dairy waste can be used as substrate for ethanol production using yeast, and high-strength effluent streams can be used for methane recovery via anaerobic digestion. Ethanol and methane can then be utilised by the manufacturing plant as a supplementary fuel supply (Ahmad et al., 2019; Rad & Lewis, 2014). In addition, electricity can also be produced from waste streams via bio-electrochemical processes by employing microbes as catalysts (Fisher et al., 2021).

4.3. Mitigation strategy for the cold chain

The cold chain requires significant changes to improve energy sustainability. The use of energy-efficient and carbon-free refrigeration technologies in all cold chain stages can boost the efficiency of the cold chain resulting in less CO_2e emissions (James & James, 2010). Cold chain logistics plays a crucial part in product's food safety in the supply chain and research focus is turned on new technologies such as the Internet of Things (IoT) for product monitoring (Shashi et al., 2018). Traceability in the cold chain brings multiple benefits to the cold chain's functionality while it can aid energy use reduction. The contribution of logistics in the energy utility of the dairy supply chain is important since dairy production is largely centralised, meaning that the transportation distances for distribution are significant (Ladha-Sabur et al., 2019). Thus, as the sector grows, a move to de-centralisation comprising shorter distribution routes could be considered. Minimizing the distance by optimising the distribution routes will reduce fuel consumption and refrigeration needs. One model proposed aims to optimise the energy demand of refrigerated distribution routes by minimizing transportation routes, whilst accounting for ambient temperature variations (Accorsi et al., 2017). More specifically, since high-ambient temperature requires increased energy for refrigeration, they suggested the consideration of the weather conditions during transportation, as well as traffic congestion during the day (Accorsi et al., 2017). Additionally, the energy efficiency of refrigerated trucks can also be improved, by re-designing the diesel-fuelled compressors and installing better insulation (Accorsi et al., 2017). Regarding the retail stage, products are recommended to be kept in fridges with enclosed doors, as they can offer better refrigeration and energy savings up to 68% when compared to current standards of open-door fridges (de Frias et al., 2020).

Consideration should be given in replacing fresh dairy products with their non-refrigerated processed dairy alternatives which will not spoil when stored at ambient temperature for up to 6–9 months (Guzmán--Luna et al., 2021). This will substantially decrease the energy load on the cold chain, however their processing is more intensive and thus more energy is required in manufacturing. These products may be more environmentally sustainable options, but this can only be proved through full LCA studies. For instance, UHT (Ultra High Temperature) pasteurised milk has been reported that it may have a lower energy consumption (Djekic et al., 2014) but also reported as having a higher energy consumption (Nicol, 2004) compared to regular pasteurised milk along their life-cycle. It is worth mentioning that UHT milk is more common in warmer climates, and this is because of the high energy cost associated with refrigeration (Mercier et al., 2017). This implies that with climate change and increased temperature, countries that currently prefer fresh dairy products may need to swich to long shelf-life products. However, the preference in dairy products is very dependent on consumer behaviours in a specific region and do not change immediately because a less energy intensive product alternative becomes available (Macdiarmid, Douglas, & Campbell, 2016).

4.4. Mitigation strategy for consumption use

To improve sustainability of the dairy supply chain, waste production and energy use at the domestic stage should be minimised. Both goals can be achieved by increasing public perception and their environmental awareness and adapting their consumption behaviour. Consumers should be encouraged to make use of low carbon footprint transportation, use energy-efficient appliances such as fridges in the household and minimise all types of consumer waste. Also, smart fridges are suggested which have recently been introduced to the market and are able to track the shelf-life of products preventing food wastage (Kumar & Chimmani, 2019). Moreover, to enhance sensitivity about a product's energy consumption, one effective approach is to place a fuel economy label on the products indicating the energy requirements of the product along the supply chain, in a familiar style to the consumers unit such as equivalent light-bulb minutes (Camilleri et al., 2019).

Overall, consumers, have a great impact on the energy demand of the food and dairy supply chain, though it can be considered more challenging to raise environmental awareness of consumers, compared to industrial stakeholders involved in the other stages of the chain who are conscious of their corporate images and government environmental incentives. Thus, positive changes in consumer behaviour could contribute significantly to the overall net-zero carbon target.

5. Challenges in the implementation of energy mitigation for the dairy industry

Moving towards net-zero carbon emissions in the dairy sector is a continuous process of reconstruction that is time-consuming. This is not only attributable to the actual time required for the mitigation practices to be applied but primarily because industry and society have to develop environmental awareness and place the environment at the top of their priorities. The dairy sector can substantially reduce their carbon emissions by proper resource management spanning energy to waste. However, due to the interconnectivity between the stages, this cannot be necessarily met on a stage-by-stage basis but rather from a holistic perspective. More specifically, some supply chain stages can become carbon net-positive, which means that their actions go beyond achieving net-zero carbon emissions. This can be achieved through appropriate energy management and by investing in bioenergy production (Gebrezgabher et al., 2012). This way, even if it is unrealistic to expect the carbon emissions of some stages to be reduced to zero there is the potential of the overall supply chain's carbon emissions to substantially decrease, and move towards net-zero carbon levels. Nevertheless, this is a multistep process that requires an in-depth analysis of the carbon emission performance of each step of the supply chain and evaluation of the contribution of each stage to the entire chain. The major challenge arising from meeting the net-zero carbon target under a holistic perspective is how all sectors can unite and work altogether within that scope.

Another emerging significant challenge for the dairy sector is climate change. Climate change will affect all supply chain stages, causing the whole sector to be at risk. At the farm stage, adverse climatic conditions might lead to lower crop-yield caused by reduced land productivity, while the increased ambient temperature and humidity levels may cause heat stress in cows. This could be addressed by developing new standards for the animal's living conditions and installing cooling systems (Harrison et al., 2017). At the manufacturing stage, the possible development of heat-resistant foodborne pathogens in raw milk arriving from farms, may need to be addressed by intensifying the standard heat treatments (Feliciano et al., 2020; van Asselt et al., 2017). However, under the existing processing technologies, more intensive heat treatment to address the arising food safety concerns would incur increased energy demand (Augustin et al., 2013). As regards the cold chain and consumption stage, food products may be required to be stored at lower refrigeration temperature than usual to prohibit the microbial growth to dangerous-for-consumption levels (James & James, 2010). This, in addition with the expected higher heat loads in the cold-chain systems due to increased ambient temperature will increase energy for product refrigeration. Fig. 6 illustrates the main climate change impacts per supply chain stage, and presents adaptation actions to address climate change impact, while outlining the main energy mitigation practices that can be put in place to address the expected growth in energy demand. The dairy sector not only has to adapt to climate change but also to respond to the expected increased global food demand arising from population growth. This will inevitably lead to a respective substantial increase of energy demand across the supply chain if energy mitigation practices are not applied throughout the entire sector.

6. The role of supply chain energy modelling towards net-zero carbon emissions

Today, environmental sustainability is a top priority in the agenda of every dairy company and should always be considered along with the social and economic impacts of dairy production. To simulate complex systems within the dairy supply chain and assist the decision-making process towards more sustainable decisions, computational models have significant role to play. A computational model, or model as it is referring to in the following section, is the representation of a systems through mathematical expressions, equations and algorithms (Calder et al., 2018).

Modelling plays a growing role in many industrial sectors allowing the assessment of parameters such as the cost, the process efficiency for individual unit operations (such as a processing device for dairy manufacturing) or systems (e.g. a wastewater treatment plant) (Fisher et al., 2021). A step further is the development of models which incorporate numerous or all components of a supply chain. Such models will allow the quantification and optimisation of parameters of interest (e.g. energy utilisation or carbon footprint) from a holistic viewpoint. Focusing on the improvement of energy management of the dairy supply chain, the supply chain energy models (SCEMs) are proposed as an efficient means to organise such broad systems and assess their energy use. A SCEM, is a synthesis of individual models that quantify the energy use for each operation in sequence taking place from farm-to-fork along a supply chain, to create a holistic energy model. The individual energy models should be combined in order to fulfil the mass balances along the chain, while accounting for product losses and waste. A SCEM will require quantitative and qualitative characteristics for each supply chain stage as inputs. For example, for the farm stage inputs may be the type of farming, and the number of cows. For the manufacturing stage, inputs may be the production scale and type of products produced. For the cold chain, the type of trucks and the transportation distance. Finally, for the retail outlet the temperature of refrigeration and the days of storage. The SCEMs can provide as output the supply chain energy use, the energy mix and the product embodied energy.

The development of SCEMs will be critical to achieve efficient energy management. Such models can be used for benchmarking the energy utility across the dairy sector allowing the identification of the most energy-demanding operations (Yakovleva et al., 2012). In this stage, experts and engineers could consider alternative energy-saving operations across the sector to address the identified hotspots. Moreover, the ability to acquire detailed data on energy use, will become extremely useful as inputs in LCA studies, due to the current lack or confidentiality of accurate data related to energy consumption (Rahimifard et al., 2010). The LCA studies will allow the estimation of the carbon footprint of the dairy supply chain and assess mitigation plans that can move the dairy sector towards net-zero carbon.

Supply chain energy models can prove to be beneficial in predicting possible collaborating actions between the actors of the supply chain within the context of industrial symbiosis (Kastner et al., 2015). For example, to achieve the net-zero carbon target through the entire supply chain, these models can be used to test the efficiency of collaborating actions by assessing which supply chain stages are net-negative and which are net-positive. In the future, the dairy industry will undergo radical changes due to the emerging global changes of climate change and population growth. For deciding whether an adjustment measure will be effective or not, SCEMs can be used to project this measure under future conditions and examine their stability at different timescales. Specifically, climate change effects can be simulated, by considering

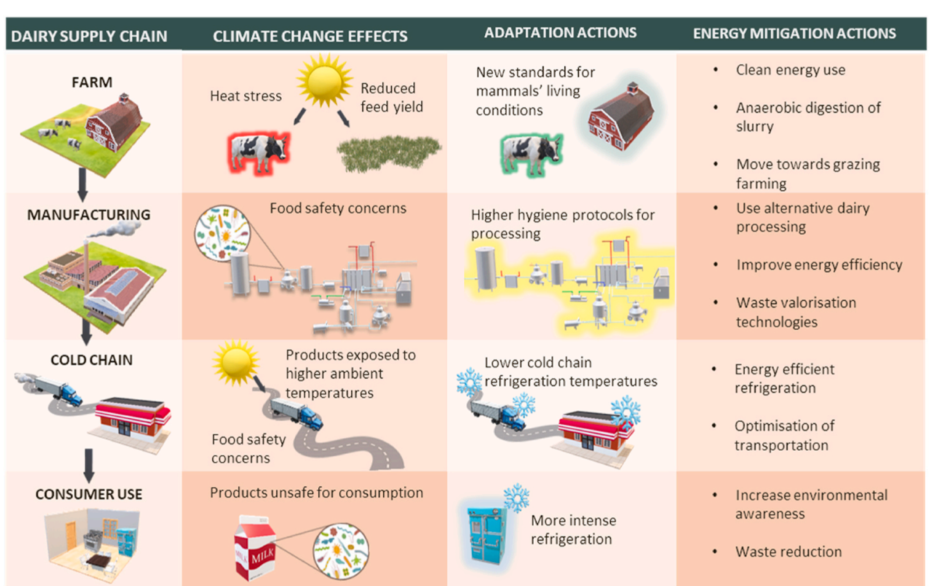

Fig. 6. Climate change impacts, climate change adaptation actions and energy mitigation practices for the dairy supply chain.

projected environmental conditions in different regions and times. For example, global warming will result in changes in average ambient temperatures, and thus simulations can be made to project the consequences on energy usage along the dairy supply chain using different ambient temperatures as model inputs.

An upcoming challenge for the dairy sector is that dairy production will have to grow to meet increased food demand, which is a consequence of population growth and increasing consumer desire. SCEMs can be used by dairy companies that aim to grow their production, in order to simulate future growth scenarios and decide which is the most energy-efficient plan to follow. For example, one growth plan for a company could be to build a network of small dairy production plants distributed across a geographical region, which will reduce transportation energy use and enhance the local development of the agricultural sector (Gimenez-Escalante & Rahimifard, 2018; Ladha-Sabur et al., 2019). In other cases, the best growth plan might be the expansion and technology up-grad of an existing dairy production plant. In this case, although the energy use for distribution will be demanding, the energy efficiency of the production plant will be improved since larger dairies tend to require less energy per unit of product (Xu et al., 2009). The SCEM's will indicate which growth plan will lead to an overall decrease in the energy consumption for the supply chain.

SCEMs can also prove to be extremely useful for unexpected situations, such as the Covid-19 pandemic which could be simulated to observe the stability and effectiveness of any possible measure and consider any immediate action (Rizou et al., 2020). Overall, SCEMs allows close monitoring of the entire supply chain and can provide useful information and many opportunities for optimisation in terms of sustainability of the supply chain. The development of tools available to all the supply chain members, can enhance the efficiency of common sustainability goals and help make decisions with greater certainty (Brandenburg et al., 2014).

6.1. Considerations for the development of SCEM

Any energy reduction actions to be adapted for a supply chain requires decision-making through well-established planning. A comprehensive understanding of complex systems such as the energy consumption in supply chains begins with a holistic quantification of the energy use and the interactions between the supply chain stages (Namany et al., 2019). Thus, for decision-making, trustworthy SCEMs should be developed.

Models for planning agricultural supply chains can be categorised as stochastic or deterministic, depending on whether uncertainty is considered or not respectively (Ahumada & Villalobos, 2009). Models are usually structured in a suitable way in order to be optimised. The most commonly used optimisation approaches for stochastic models are stochastic programming (SP), stochastic dynamic programming (SDP), simulation (SIM), risk programming (RP) while the most common deterministic approaches are linear programming (LP), dynamic programming (DP), mixed integer linear programming (MILP), and goal programming (GP) (Ahumada & Villalobos, 2009). These optimisation approaches differ on how the objective function depends on the decision variables. Mixed-integer linear programming has been observed as the most common modelling method for supply chain sustainability models (Nematollahi & Tajbakhsh, 2020). It is important to note that the supply chain network encompasses a huge variety of parameters and may present multiple risks. Supply chain models are mainly used to assist with strategic decisions that are usually long-term. Not incorporating this variability and risk in the models may lead to unsafe decisions (Baghalian et al., 2013). Thus, accounting for uncertainty in SCEM is highly recommended. Stochastic programming (SP) is the most commonly used optimisation approach for problems that incorporate strategic and operational randomness (Namany et al., 2019). SP considers the probability distribution of potential outcomes which allows the inclusion of the variability and risk of real-life problems and can create solutions that are robust to uncertainty (Ghadge et al., 2017).

Decision-making in a supply chain problem may depend on single or multiple objectives (or criteria), which is called single objective decision-making (SODM) and multi-objective decision-making (MODM) respectively (Allaoui et al., 2018). In SODM the objective is to minimise one important parameter of the problem, which in a SCEM will be the total energy use of a supply chain. SODM can also be used to achieve multiple objectives, by setting constrains to the optimisation problem. For example, for a SCEM this can be the minimisation of the energy use, with an upper limit of cost. Alternatively, when there is the need to optimise a supply chain from several different aspects, such as cost, time and energy, MODM is used. The aim of MODM being to provide the most efficient solution and ensure transparency in the decision-making process (Triantaphyllou, 2000).

In order to trust the solution of a SCEM and perform decision making with confidence, it is essential to test the results' sensitivity on highly uncertain parameters by undertaking sensitivity analysis (SA) (Baghalian et al., 2013; Yakovleva et al., 2012). Sensitivity analysis helps analyse the robustness of a model by investigating the influence of a model's input parameters on the model output variables of interest.

It is not always possible to use a SCEM to determine the optimal energy mitigation strategy since such models may have a complex structure that is not compatible with established optimisation approaches (e.g. LP, MILP etc.) to be able to generate a unique best case. In such cases, a scenario analysis approach can be used. Scenario analysis is the simulation and comparison of different realisations of the supply chain under different hypotheses. For example, several different future climate change scenarios for the dairy supply chain can be simulated and then compared in terms of their energy performance, their cost and other criteria. It is then upon the decision-makers to choose which of these scenarios is the most suitable to be implemented (GFS, 2021). Although scenario analysis can bring out the most sustainable decisions holistically, this does not mean that it will be the best and most profitable choice for each individual actor. When several actors of the supply chain have to make a common decision, game theory can aid the decision-making process and lead to a common solution that works equally for all the actors of the chain (Namany et al., 2019).

Importantly, SCEMs require system-relevant data that is available, and technological advances to be able to map the energy use along the chain. The rapid development of a new generation of information technology provides the ability to digitize and visualize data of food supply chains (Han et al., 2020). Specifically, cloud computing, blockchain, Industry 4.0 and the Internet of things (IoT) are technologies that have been increasingly adopted by some food supply chain actors especially in manufacturing, and they offer the ability to obtain and exchange data to improve efficiency on automation, product improvement and material management (Fisher et al., 2021). Such technologies can allow the analysis and visualisation of energy use and carbon emission into on-demand services and assist the decision-making process in supply chain monitoring (Fisher et al., 2018). For example, IoT allow the collection of multi-source data through sensing technology along the supply chain by using sensors that capture and transmit data through communication technologies (e.g. 5G or the internet). To capture the energy use along the supply chain such sensors could measure the electricity use of processing systems, the refrigerating temperature, the location of products along the chain and more. Such information can help the trackability of the products' embodied energy and carbon emissions along the supply chain. Specifically, through blockchain technology, each product's supply chain can be tracked and specific information on the energy use per product can be provided through energy labelling on the products. Also, through blockchain technology, the most energy-efficient supply chain sequence can be revealed and used as a prototype for future reconstruction of the supply chain.

Table 1 presents some valuable work undertaken in the field of SCEM and closely relevant areas that can be used as implemented examples of SCEM. For each study presented, the food product under analysis, the

Table 1
Application of supply chain models in individual and multiple supply chain stages for the dairy industry and related areas.

Title	Type of product	Model Inputs	Model Outputs	Supply chain stages included in model	Technical approach	Research focus and objective	Authors and year
Environmentally friendly management of dairy supply chain for designing a green products' portfolio	Dairy product: curd	Number of suppliers and markets, Distances, manufacturing volume, product quantities	Economic and environmental performances	Entire supply chain	Single criterion decision-making (SCDM)	Optimisation of profit and environmental impact for design of "green" products' portfolio of a supply chain for curd production	Kirilova and Vaklieva-Bancheva (2017)
Energy-neutral dairy chain in the Netherlands: An economic feasibility analysis	Biogas production	50% Manure 50% other (energy maize, grass silage and other co-substrates)	Green gas, Digestate investment costs	Dairy farm and manufacturing	Monte-Carlo Sensitivity analysis	A simulation model aiming to achieve energy-neutral chain from dairy farm to factory.	Gebrezgabher et al. (2012)
Environmental impact of future milk supply chains in Sweden: a scenario study	Dairy product: Milk	Material flow, Chemical composition, Physical properties Contamination by heavy metals	Net energy and environmental impacts	Entire supply chain	Life cycle assessment (LCA) Scenario analysis	Environmental impact analysis of future supply chains for dairy products, a scenario technique was chosen.	Sonesson and Berlin (2003)
Dairy waste-to-energy incentive policy design using Stackelberg-game-based modelling and optimisation	Dairy manure and waste	Farm's characteristics, weight of manure	minimizing total government intervention and minimizing its unit cost on generating a target amount of bioelectricity.	Dairy farm, biogas production plant	Game theory: Single-leader-multiple-follower Stackelberg game	Two conflicting objectives, minimizing total government intervention, and minimizing its unit cost on generating a target amount of bioelectricity.	Zhao and You (2019)
Selecting new product designs and processing technologies under uncertainty: Two-stage stochastic model and application to a food supply chain	Dairy product: Milk powder production technologies	Cost of raw material, transportation cost, demand, waste fraction, technologies used	Selection of new product designs and processing technologies in a supply chain context.	Manufacturing: Processing technologies' impact on the entire supply chain	Two-stage stochastic mixed integer linear programming (MILP) model	An assessment of new product technologies in a supply chain context Which may lead to extensive energy savings in production.	Stefansdottir and Grunow (2018)
An optimisation approach for managing fresh food quality throughout the supply chain	Fresh food	Transportation Distances, storage temperature, transportation time, Shelf life	Quality indicators, Transportation cost	Manufacturing and cold chain	Mixed-integer linear programming (MILP)	Modelling the production and distribution in a food supply chain using food quality as an indicator, which is strongly related to temperature control.	Rong et al. (2011)
A case analysis of a sustainable food supply chain distribution system—A multi-objective approach	Dairy product: milk	Characteristics of two processing plants with twenty-two drop off points	Carbon footprint measured in CO_2 emissions and costs	Cold chain: Distribution	Multi-objective decision-making (MODM) Multi-objective optimisation using Pareto fronts. A multi-attribute decision-making approach	Minimises CO_2 emissions from transportation and total costs in the distribution chain. Design of a capacitated distribution network.	Validi et al. (2014)
On the sustainable perishable food supply chain network design: A dairy products case to achieve sustainable development goals	Perishable products: milk products	Number of products shipped, type of product, distances of routes etc	Total supply chain's present value, Vehicles' fuel consumption, social influence.	Cold chain: Distribution	Multi-objective mixed integer programming (MOMIP) -Multi-objective decision-making (MODM) Optimisation using goal programming (GP) Uncertainty analysis	Optimisation the cost, the energy consumption, and the traffic congestion for multiple products with different properties, including perishability, weight, and price.	Jouzdani and Govindan (2020)
Chilled or frozen? Decision strategies for sustainable food supply chains	Perishable food products	Storage temperature and storage time	Optimal combination of energy use and quality degradation of food	Cold chain: Distribution and storage of frozen food	Multi-Objective Decision Making (MODM)	Cold chain optimisation by introducing energy as a key factor.	Zanoni and Zavanella (2012)

(continued on next page)

Table 1 (*continued*)

Title	Type of product	Model Inputs	Model Outputs	Supply chain stages included in model	Technical approach	Research focus and objective	Authors and year
A climate driven decision-support model for the distribution of perishable products	Perishable food products	Product's profile, Vehicles features, Network and Nodes, Packaging characteristic, Weather forecast or historical climate profiles	Optimal temperature at the warehouses, Optimal routes management, Energy-effective operations, Proper packaging solutions, Delivery scheduling according to the optimal weather conditions	Cold chain	Mixed-integer linear programming (MILP)	Modelling the refrigerated distribution of perishable products which incorporates climate considerations in the management of cold chain operations.	Accorsi et al. (2017)

inputs and outputs of the model, the supply chain stages modelled, the technical approach used and a short description of the research focus, and the main objective of the study are provided. The models are ordered starting from those accounting for the entire supply chain or multiple stages and then follow the supply chain sequence starting from farm, then manufacturing and then cold chain.

Most of the reviewed articles summarised in Table 1 focus on the dairy sector, while only a few present models in the general category of perishable food products (Accorsi et al., 2017; Rong et al., 2011; Zanoni & Zavanella, 2012). Several papers present models that deal with the entire supply chain (Kirilova & Vaklieva-Bancheva, 2017; Rong et al., 2011; Sonesson & Berlin, 2003) as they recognise the importance of optimising the variables of interest such as carbon footprint, sustainability, or energy use holistically, throughout the entire supply chain. In addition, in some papers the developed models aim to minimise the energy use, while some of them aim to optimise the cost as well use multi-objective methods (Accorsi et al., 2017; Jouzdani & Govindan, 2020; Zhao & You, 2019). Last but not least, some studies addressed sustainability (Kirilova & Vaklieva-Bancheva, 2017; Sonesson & Berlin, 2003; Validi et al., 2014) by optimising CO_2 emissions, while others aimed to optimise food quality (Rong et al., 2011). The most relevant study to the idea of net-zero carbon aimed to achieve an energy-neutral dairy supply chain developed a model which estimated the biogas from dairy farm manure required to create a self-sufficient dairy supply chain (Gebrezgabher et al., 2012). Also, they carried out a sensitivity analysis on their model to check for the robustness of their model in terms of cost and revenue. From Table 1 it can be seen that a range of different modelling methods have been used and within the area of SCEM in the food, and specifically dairy sector, no preferred modelling method has been identified by the research community.

Regarding the modelling methods applied in the reviewed models; 4 out of 10 studies followed a multi-objective decision making approach (Jouzdani & Govindan, 2020; Validi et al., 2014; Zanoni & Zavanella, 2012; Zhao & You, 2019) and 3 out of 10 studies have used mixed-integer linear programming (MILP) for optimisation (Accorsi et al., 2017; Rong et al., 2011; Stefansdottir & Grunow, 2018). Interestingly, a multi-objective problem where both expenditure and environmental impact needed to be optimised, was constructed as a single-objective optimisation problem by using cost as a common measure to rank both the expenditure and the environmental performance (Kirilova & Vaklieva-Bancheva, 2017). All in all, research is growing in the SCEM area with the majority of papers published within the last decade (2011–2021). The papers presented in Table 1 can inspire researchers to develop SCEMs, which can significantly contribute towards the net-zero carbon target.

7. Conclusion

All sectors around the globe will have to reach net-zero carbon emissions levels by 2050–2070 according to the Paris Agreement. Companies and stakeholders who adjust to the net-zero target sooner rather than later, can significantly reduce the downside risks during net-zero adaptation, while leading on environmental sustainability. With the dairy sector as a significant energy intensive food sector and alongside the requirements of environmental sustainability, reduction of energy use is essential. The "net-zero carbon" is the ultimate target, however it is extremely challenging for sectors such as the dairy industry, where zeroing the overall net carbon emissions is almost impossible to implement directly. This is because the current technology and practices is unable to tackle the huge source of emissions derived from bovine enteric fermentation. Although net-zero carbon is an important target, not all supply chain stages in the dairy sector can reach net-zero carbon levels. The dairy industry will more efficiently move towards net-zero carbon via collaborative actions between the four dairy supply chain stages (farm, manufacturing, cold chain and domestic use) within the context of industrial symbiosis.

To provide a holistic overview of the opportunities for moving towards net-zero carbon levels through energy mitigation, this paper firstly allocates the energy use along the entire dairy supply chain and subsequently presents energy mitigation actions. The increasingly alarming effects of climate change and global population growth will make the net-zero carbon challenge even more difficult since energy demand will increase even further. Nevertheless, mitigation actions without validation pose considerable uncertainty for the industry and the stakeholders/enterprises. In order to address those risks and make the reconstruction process more efficient, this paper proposes the development of supply chain energy models. Such models will be able to project the energy use across the dairy supply chain and indicate the most energy demanding operations, enabling the decision-makers to prioritise the energy conservation and net-zero mitigation actions. Furthermore, they can project future climate change scenarios of the food and dairy supply chain as well as the short- and long-term sustainability of the supply chain. Supply chain energy models will become essential to the industry since they will be able to indicate, with a great degree of certainty, which are the optimal decisions on a financial basis and with regards to environmental sustainability. Overall, the development of modelling tools able to simulate energy demand, assess energy reduction practices and project the future operating conditions under various climate change scenarios can substantially contribute to industrial and environmental sustainability and improvement of the dairy and any other food sectors.

Acknowledgments

This project is part of the PROTECT ITN (http://www.protect-itn.eu/) which is funded under the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 813329.

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