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DECARBONISATION OPTIONS FOR THE DUTCH DAIRY PROCESSING INDUSTRY

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MIDDEN

Manufacturing Industry Decarbonisation Data Exchange Network

Decarbonisation options for the Dutch dairy processing industry
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MIDDEN project coordination and responsibility

The MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network) was initiated and is also coordinated and funded by PBL and TNO. The project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. Correspondence regarding the project may be addressed to:
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The companies mentioned did not review this report. PBL and TNO are responsible for the content. The decarbonisation options and parameters are explicitly not verified by the companies.

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FINDINGS

Summary

This report describes the situation of dairy processing in the Netherlands as of 2020, and looks into the possibilities for decarbonisation of this sector, based on publicly available literature. The goal is a general view on the present production processes that are used in the sector, and decarbonisation options coupled to these processes.

In the Netherlands, there are 53 dairy processing facilities, which are supplied with around 14 billion kilograms of milk annually. 43 of them, including all EU-ETS registered facilities, participate in the MJA3 covenant of the dairy sector. They consumed about 21 PJ of energy in 2018 (RVO, 2019), and used 7.7 PJ electricity and 12.1 PJ natural gas (Doornewaard, Hoogeveen, Jager, Reijs, & Beldman, 2019, pp. 210, 211). Of these 43 facilities, 11 are, largely because of their size, registered under the EU ETS, being FrieslandCampina (7 locations), Promelca Dairy Foods (Gorinchem), DOC Kaas (Hoogeveen), Royal A-ware / Fonterra (Heerenveen), and Danone Nutricia (Cuijk). The total greenhouse gas emissions of the diary processing sector are approximately 1.1 Mt CO_2-eq, of which the aforementioned EU ETS facilities are responsible for 0.47 Mt.

These facilities produce a wide variety of products, among which are cheese, butter, condensed milks, milk powders, whey powders and lactose. For many of these products large amounts of water have to be removed from the feedstock, which requires large amounts of heat. This heat is typically supplied through the combustion of natural gas, either in gas boilers or combined heat and power (CHP) plants. Some facilities use biogas instead of natural gas. Since the production processes do not emit CO_2, all registered emissions can be attributed to natural gas combustion.

Options for decarbonisation exist in the form of changing the heat supply from natural gas boilers to boilers using biogas, hydrogen or electricity. Geothermal energy can also be used as a carbon-neutral heat source. Because of the large amounts of waste heat available in dairy processing facilities, heat pumps can be used to use all waste stream efficiently.

Other options relate to the energy-efficiency of the facilities and include using zeolite in a closed-loop spray drying process, pre-concentrating of the feedstock through the use of membranes, and the application of energy-efficient mechanical vapour recompression during evaporation.

FULL RESULTS

Introduction

This report describes the current situation for production of dairy products in the Netherlands and the options and preconditions for its decarbonisation. The study is part of the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network). The MIDDEN project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. The MIDDEN project will update and elaborate further on options in the future. MIDDEN encompasses reports and data from all large industry sectors with Dutch production locations in the EU ETS. In this way a complete picture of the industry is formed, as well as a complete picture and potential size of the decarbonisation options. MIDDEN can also contribute to synergy potential across the different industry sectors or location.

Aim of this report is mapping the different types of processes and the potential and relevance of specific decarbonisation options. The processes at the companies were not individually investigated, but default processes were chosen based on the best available information, looking to the processes from feedstock (milk/whey) to end product. Therefore, the specific and current situations may deviate from the general numbers in this report due to diversity in processes, products and use (e.g. semi-finished vs final product). Also, different companies may be in different phases of the renewal cycles or turnaround periods. This report does not aim at comparing the companies and does not provide decarbonisation advice or an assessment concerning individual companies or the sector. Furthermore, the report focuses on the technical processes and decarbonisation options and does not focus on specific business cases including subsidy schemes etc.

Scope

The global mapping of the sector is based on the production locations that are part of the EU ETS and the registration at the Dutch Emissions Authority NEa. Decarbonisation is equally important for the other dairy production locations that are not part of the scope of this report. The Dutch dairy production locations in the EU ETS (and thus in the scope of this report) include[1]:

- DOC Kaas BV, location Zuivelpark; Hoogeveen, Drenthe
- FrieslandCampina Bedum; Bedum, Groningen
- FrieslandCampina Beilen; Beilen, Drenthe
- FrieslandCampina DMV location Veghel; Veghel, Noord-Brabant
- FrieslandCampina Domo location Borculo; Borculo, Gelderland
- FrieslandCampina Leeuwarden; Leeuwarden, Friesland
- FrieslandCampina Lochem; Lochem, Gelderland
- FrieslandCampina Workum; Workum, Friesland
- A-ware and Fonterra; Heerenveen, Friesland
- Promelca Dairy Foods (Vreugdenhil); Gorinchem, Zuid-Holland.

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[1] Since 2018 Danone Nutricia Early Life Nutrition in Cuijk is also part of the register at NEa. Its emissions have been small with respect to the listed locations. The location is discussed shortly in Section 1 but not taken into account in the remainder of the report.

Production processes include:

- Standardisation
- Heat treatments
- Evaporation
- Spray drying (with fluid-bed drying)
- Membrane processes.

Products include:

- Milk powders
- Whey powders
- Cheese
- Butter
- (Sweetened) condensed milk.

The main options for decarbonisation are:

- The use of zeolite for spray-drying
- Innovative use of membrane processes
- Application of mechanical vapour recompression
- Electric and biogas boilers
- Heat pumps
- Geothermal energy
- Water reuse.

A number of these options have already been addressed or considered by the companies, which are all participants in the MJA3 covenant for energy efficiency improvement (RVO, 2019).

Reading guide

Section 1 introduces the Dutch dairy processing industry. Section 2 describes the current situation for production processes for dairy products, and Section 3 describes the relevant products of these processes, while options for decarbonisation are systematically quantified and evaluated in Section 4. The feasibility of and requirements for those decarbonisation options are discussed in Section 5.

1 Dairy processing in the Netherlands

Contributing to around 7% of the trade balance of the Netherlands, the dairy processing industry is one of the main industries in the country (ZuivelNL, 2020). Yearly, an amount of around 14 billion kilograms of milk is processed and turned into consumer's milk, butter, cheese, milk and whey powders and other products (CBS, 2020). The Dutch dairy chain consists of 16,250 companies providing milk, keeping 1.6 million heads of cattle, delivering milk to 53 milk processing factories, employing 49,000 people and creating products with a value of EUR 12.5 billion in 2017, of which EUR 7.6 billion by the milk processing industry (ZuivelNL, 2020). Of the products, 35% remains in the Dutch market, while 45% is exported to the European Union and 20% to other countries. The Netherlands also imports dairy products with a total value of EUR 3.8 billion, mostly from Germany and Belgium (ZuivelNL, 2019a). A part of the quantities above includes transit products.

The dairy sector emitted about 22 million tonnes (Mt) of CO_2-equivalents in 2018, taking into account the entire production chain. Of this amount, over 93% stem from processing at the dairy farm (the majority of emissions coming from enteric fermentation in the form of methane, ~13.3 Mt) and production of the required feed (in the form of CO_2 and nitrous oxide, ~7.4) (Doornewaard, Reijs, Beldman, Jager, & Hoogeveen, 2018; Doornewaard, Hoogeveen, Jager, Reijs, & Beldman, 2019). In total, an amount of 1.48 kg CO_2-eq is emitted per kg of Dutch milk delivered to the factory (Dolfing, 2017).

Only a small fraction (~1.1 Mt) of the emissions of the dairy sector occurs at the dairy processing locations. Processing of the different dairy products is included in these numbers, but not transport. The scope of the industry is defined by SBI ('Standaard BedrijfsIndeling') class 105: manufacturing of dairy products.

The largest dairy processing company in the Netherlands is FrieslandCampina, which processed around 11.8 billion kilograms of milk in 2018. The company is the 6th largest dairy processing company in the world, generating a turnover of EUR 11.55 billion in 2018 (FrieslandCampina, 2019a). Other large companies in the Dutch dairy sector are Royal A-aware (turnover of EUR 1.3 billion in 2017), Vreugdenhil (EUR 730 million in 2018) and DOC Kaas (EUR 276 million in 2018) (DOC Kaas, 2019a; Royal A-ware, 2018; Vreugdenhil Dairy Foods, 2019a). An overview of the Dutch dairy companies registered under the ETS is given in Table 1 below, with their registered CO_2 emissions in 2018. The locations of the production facilities are mapped in Figure 1.

Based on public sources and the analysis of the processes, we have estimated the production volumes of the different locations. An overview of this can be found in Appendix A, together with estimates of the number of employees.

Table 1 Overview of ETS registered dairy product producers in the Netherlands, including the absolute CO_2 emissions in 2018 as registered with the NEa, with the thermal capacities of heat supply at different processing locations

Producer/ETS registration	Direct CO_2 emissions in 2018 registered at NEa (tonne)[2]	Fuel input (PJ)[3]	Type of heat supply	Heat capacity [MW_{th}]
Danone Nutricia Early Life Nutrition Cuijk	1,329	0.02	Natural gas boilers and heaters	40[4]
DOC Kaas BV, location Zuivelpark	45,488	0.80	CHP	
Friesland Campina Bedum	37,136	0.66	Natural gas boiler	
Friesland Campina Beilen	52,554	0.93	Natural gas boiler	65[5]
Friesland Campina DMV B.V., location Veghel	103,830	1.80	Natural gas boiler	
Friesland Campina Domo location Borculo	41,845	0.89 natural gas, 0.09 biofuel[6]	Mixed fuels boiler (biofuels, natural gas)	130[5]
Friesland Campina Leeuwarden	57,779	1.00	CHP	95[5]
Friesland Campina Lochem	34,746	0.61	Natural gas boiler	
Friesland Campina Workum	24,919	0.44	Natural gas boiler	
Cheese- and wheypowder factory A-ware and Fonterra H.	19,597	0.35	Natural gas boiler	
Promelca Dairy Foods	50,002	0.88	Natural gas boiler	

In Table 1, the calculated natural gas use is shown, as well as the heat capacities of the heat-generating installations of the various processing facilities. The natural gas use is based on the CO_2 emissions of that facility in 2018, assuming these arise from combustion of natural gas. The heat capacities are based on data available on large combustion plants (with a size of over 50 MW_{th}) or local permit information. The total fuel use of these installations amounts to about 8.5 PJ in 2018.

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[2] Dutch Emissions Authority, 2019.

[3] Unless otherwise mentioned, calculated based on emission data from 2018 from NEa, assuming natural gas use and an emission factor of 56.6 kg CO_2/GJ natural gas used.

[4] Based on local permit information (Provincie Noord-Brabant, 2019); two 15.8 MW_{th} steam boilers and two heaters of 5.6 and 3.1 MW_{th}.

[5] Taken from data on LCP (EEA, 2019). For FrieslandCampina Leeuwarden there are two entries (for different combustion plants), the higher value was used.

[6] Taken from LCP (EEA, 2019). Most recent data used, for 2017. Natural gas use is calculated based on the emissions reported by the NEa for 2017. The used biomass consists of pyrolysis oil and biogas. In 2019, 35% of the natural gas demand was replaced by pyrolysis oil and biogas (FrieslandCampina, 2019f).

Figure 1 Locations of the EU ETS registered production facilities of the Dutch dairy producers. FC means FrieslandCampina.

Development over time of the CO_2 emissions in the Dutch dairy processing industry is depicted in Figure 2. The emissions have continuously decreased since 2016, which is almost entirely attributed to reduced emissions at FrieslandCampina, which showed a simultaneous increase in production (see Figure 3).

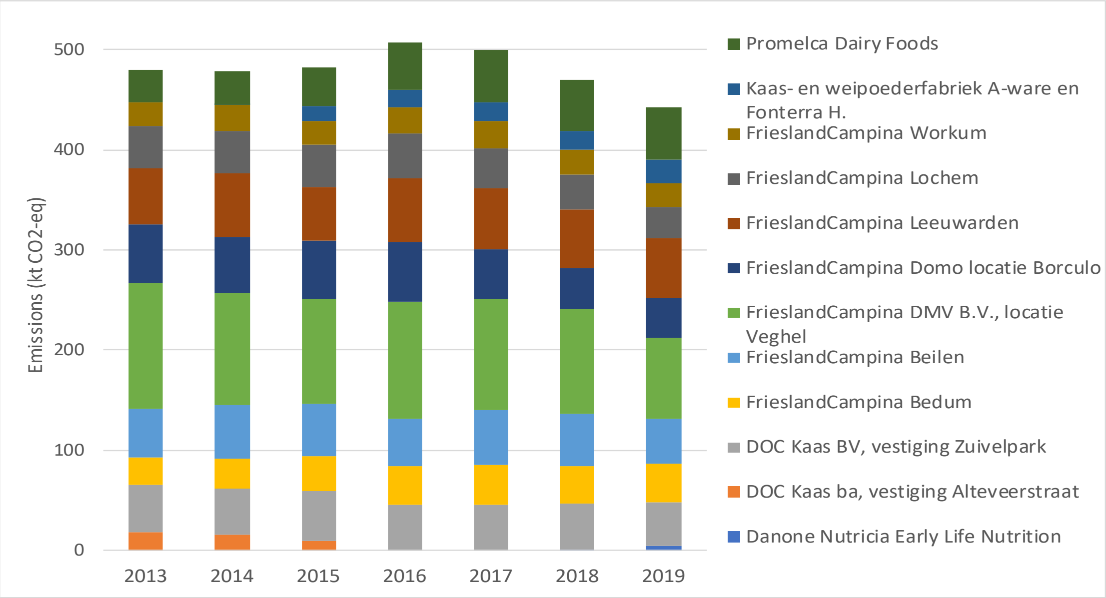

Figure 2 Development of emissions in dairy processing sector per production location (Dutch emissions authority, 2020)

1.1 FrieslandCampina

FrieslandCampina was created through the merger of two Dutch dairy companies, Friesland Foods and Campina, in 2008. However, the company can trace back its roots to 1871, when nine dairy farmers took over a Dutch cheese factory, to secure the sale of their milk before it spoiled (FrieslandCampina, 2019c). Nowadays, FrieslandCampina is still a cooperation, owned by dairy farmers. FrieslandCampina has branch offices in 34 countries, of which 49 are in the Netherlands, and employs 23,769 people globally (FrieslandCampina, 2019d; FrieslandCampina, 2019a). Of these locations, only seven are registered under the European ETS scheme, the largest of which is located in Veghel, where production started in 1926. All of these production locations produce, among others, dried dairy products. For the production of these types of products, large amounts of water have to be removed from the milk or whey input (see Section 2 for a more detailed explanation), which is an energy intensive process. Because of this, these locations have relatively high CO_2 emissions and therefore they are registered under the ETS. Together, the seven ETS registered locations have a processing capacity of around 8.2 billion kilograms (see Appendix A) of milk yearly, which amounts to around 58% of the total Dutch milk supply in 2018.

The total milk supply and turnover of FrieslandCampina, the emissions from the ETS registered locations and a breakdown of the total turnover of FrieslandCampina in 2015 (EUR 11.265 billion[7]) per geographical area are shown in Figure 3 below.

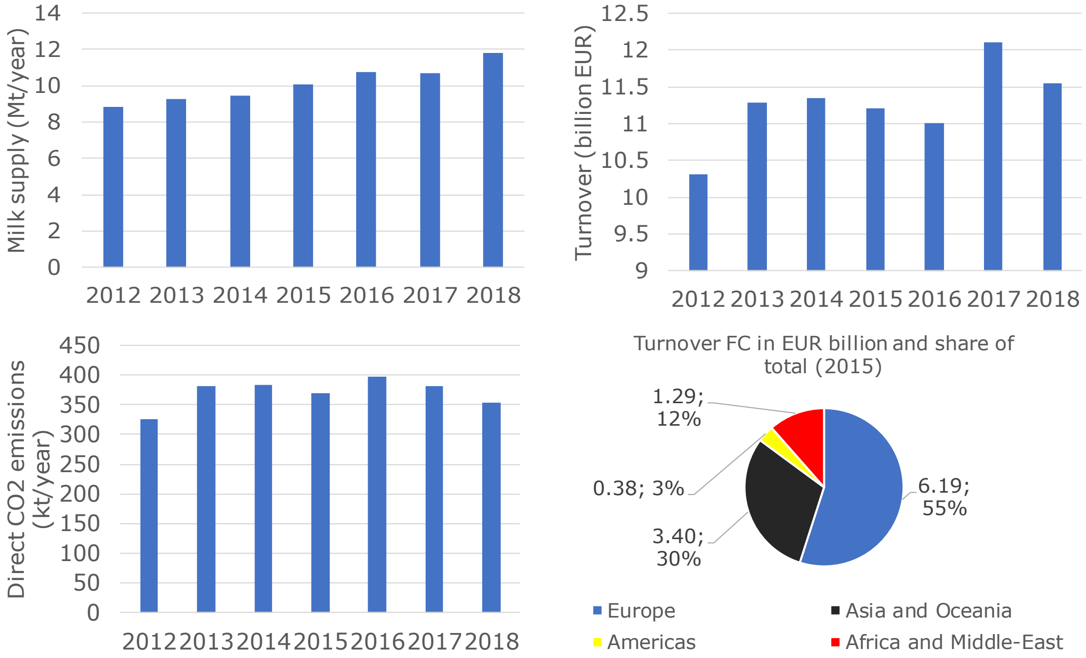

Figure 3 Milk supply (top-left), turnover (top-right), direct CO_2 emissions of ETS registered locations (bottom-left) and breakdown of total revenue per geographical location in 2015 (bottom-right, showing turnover in billion EUR and share of the total) of FrieslandCampina (Dutch Emissions Authority, 2014; Dutch Emissions Authority, 2019; FrieslandCampina, 2016; FrieslandCampina, 2017a; FrieslandCampina, 2018; FrieslandCampina, 2019a)

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[7] This number is inconsistently reported in documents by FrieslandCampina. The number for the turnover (top-right) in 2015 used in Figure 2 (EUR 11.21 billion) is taken from FrieslandCampina (2017)

From this figure, it can be determined that, in the time period shown, FrieslandCampina had its highest turnover per amount of milk in 2013 (EUR 1218 per ton of milk supplied) and its lowest in 2018 (EUR 979 per ton of milk supplied). Also, the direct CO_2 emissions per unit turnover or unit milk supply have been the lowest in 2018 for the whole time period, with 30.5 g CO_2/EUR and 29.9 g CO_2/kg milk supplied respectively.

FrieslandCampina aims to reduce its emissions in 2020 to the level of 2010. In 2010 the company emitted 12,307 kton of CO_2-equivalents across its entire production chain (including emissions from the dairy farms). In 2018, this amount was 12,462 kton, meaning that the company has to reduce its emissions with 155 kton CO_2-equivalents (1.24%) in 2019 and 2020 to reach this target (FrieslandCampina, 2019a).

1.2 Royal A-ware & Fonterra

A-ware Food Group, a Dutch cheese manufacturing and processing company, was created in 2010 through the merger of Anker Cheese and Bouter Cheese. These separate companies were founded in 1890 and 1963 respectively, and were originally focused on the sale and storage of cheese (Royal A-ware, 2019a). Nowadays, the activities of the company have expanded to include the production of cheese and other dairy products, giving the company access to the entire supply chain from milk to consumer (Royal A-ware, 2019b). This was achieved through the construction of a new cheese factory in Heerenveen in 2013.

The factory originally had a production capacity of 60-80 ktons of cheese per year, but this was expanded in 2015 to 100 ktons (Royal A-ware, 2012; Boerderij, 2015). The new factory was realised in cooperation with Fonterra, from New Zealand, one of the largest dairy processing companies in the world. Fonterra receives the whey, that is produced during the cheese-making process, from Royal A-ware, and processes lactose and whey protein powder from it in a neighbouring facility.

In 2018, A-ware started with the construction of a new factory in Heerenveen, where mozzarella will be produced. The company will do this for FrieslandCampina, which will take care of the milk supply. The new factory was scheduled to be opened at the end of 2019. Fonterra will buy the excess produced cream and whey to turn it into other products (Royal A-ware, 2019c).

1.3 Promelca/Vreugdenhil Dairy Foods

Promelca Dairy Foods is a subsidiary of Vreugdenhil Dairy Foods, a Dutch dairy company that was founded in 1954. Since then, Vreugdenhil has opened production locations in Voorthuizen (1964), Barneveld (1991), Scharsterbrug (2002) and Gorinchem (2005) (Vreugdenhil Dairy Foods, 2019c). The company specialises in the production of different types of milk powders, such as full cream milk powder and fat filled milk powder, a powder in which milk fat has been replaced by 100% sustainable palm oil. The company processed 1.3 billion kilograms of milk in 2018, from which it produced around 160-170 ktons of milk powders[8] (Vreugdenhil Dairy Foods, 2019d).

Specifically for the production location in Gorinchem, production of milk powder started with the take-over of a factory from Nestlé. The name chosen for the production company here

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[8] Vreugdenhil states that 8 litres of milk are needed for 1 kilogram of whole milk powder (Vreugdenhil Dairy Foods, 2019d)

was Promelca Dairy Foods. Production was then expanded in 2016 with the completion of a new factory next to the old one. The production location then has a total capacity of 120 kt powder (Gemeente Gorinchem, 2013). Vreugdenhil exports its products to 130 countries, with 75% of its products leaving Europe (Vreugdenhil Dairy Foods, 2019d). Because of its favourable location at the Merwede river, almost all transport of products from the factory in Gorinchem happens over water, with 95% of the containers leaving the factory by water in 2014 (Vreugdenhil Dairy Foods, 2015).

1.4 DOC Kaas B.V.

The start of DOC (Drents-Overijsselse Coöperatie) Kaas B.V. can be traced back to the foundation of the cooperative Stoomzuivelfabriek in 1895. In 1962 the cooperation DOC was founded, when the Stoomzuivelfabriek joined with other cooperations. First DOC produced mostly butter and condensed milk. Then, in 2003, a cheese factory was taken into use, at the Zuivelpark in Hoogeveen. DOC Kaas reached its final form after merging with German dairy company DMK Group in 2016, becoming its subsidiary. At the same time the cooperation DOC Kaas B.A. became part owner of DMK Group (DOC Kaas, 2019c).

In 2018 DOC Kaas processed 796 million kilograms of milk from its own dairy farmers, 4.3% less than in 2017 (832 million kilograms) (DOC Kaas, 2019a).
At its location at the Zuivelpark, DOC Kaas produces around 90 ktons of cheese yearly, with an additional 30 ktons being produced at their other location in Hoogeveen, at the Alteveerstraat (DOC Kaas, 2016). The whey that is produced at the Zuivelpark is processed by a joint venture between DOC Kaas and Volac International, called DVNutrition, which is also located at the Zuivelpark, preventing the need for long-distance transport. At the Zuivelpark, electricity and heat are provided by a Combined-Heat-and-Power (CHP) plant, which uses natural gas as fuel and has a total efficiency (energy content of heat and electricity output divided by the energy content of the gas input) of around 90%. DOC Kaas also produces its own process water, which it obtains by leading the moisture that is evaporated from the processed whey through reverse osmosis membranes. By doing this, the company saves around 800 million litres of water yearly at the Zuivelpark (DOC Kaas, 2019d; SenterNovem, 2006).

1.5 Danone Nutricia Early Life Nutrition

Danone is a French-based food company that took over the Dutch food company Nutricia in 2007 (Nutricia, 2020). The company manufactures early life nutrition products, in particular infant milk powder, in Haps, gemeente Cuijk, Noord-Brabant. A new factory was opened in 2019, which is able to produce milk powder for 3.5 million babies per day (Omroep Brabant, 2019). The annual production is aimed to be 60 kt milk powder, which will be extended to 102 kt of milk powder (Provincie Noord-Brabant, 2015). No realised production numbers are known yet.

The energy consumption of the company is mainly due to the drying of the milk to obtain milk powder. The company utilises two steam boilers with a capacity of 15.8 MW_{th} each and two drying tower heaters of 5.6 and 3.1 MW_{th}, respectively (Provincie Noord-Brabant, 2019).

2 Dairy production processes

The Dutch dairy industry produces a wide range of products, all with different production processes and techniques. In this section the processes for the main products of the production locations under the ETS will be discussed. The processes are described in generic terms, since no information relating to the variety of processes at the specific production locations was available. Therefore, the actual processes at the production locations may be different, both in terms of the process steps itself and in terms of the exact numbers. Also, differences may exist because companies are in different phases of renewal cycles or turnaround periods.

A detailed study of the location-specific processes was beyond the scope of this report and its aims. As a best estimate, a summary of the mass and energy in- and outputs is given in Table 2 below. The values shown for the heat and electricity in- and outputs correspond to the values shown in Figure 4, Figure 6 and Figure 7. The calculations on which these numbers are based can be found in Appendix B.

Table 2 Energy (final energy) and mass in- and outputs for various dairy products. These numbers refer to default processes; the actual numbers at the production locations discussed in this report may be (significantly) different, depending on the specific type and use of product

Product	Heat input (GJ/t product)	Electricity input (GJ/t product)	Milk/whey input (t/t product)	Other input (input/t product)	Output by-product (t/t product)
Cheese[9]	2.4	0.93	Milk: 9.36	Water: 1.27 t Salt: 0.05 t Rennet: 2809 ml Lactic acid bacteria: 65.5 kg	Cream: 0.27 Whey: 9.36
Butter	1.6	0.71	Milk: 17.9		Skimmed milk: 15.9 Buttermilk: 1.01
Milk powder[10]	7.4	0.95	Milk: 7.46		Cream: 0.22 Moisture: 6.24
Milk protein powder[11]	7.7	1.7	Milk: 22.5		Cream: 0.66 Milk permeate: 17.0 Moisture: 3.77
Condensed milk	0.79	0.27	Milk: 2.00		Cream: 0.06 Moisture: 0.94

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[9] Gouda assumed.
[10] Whole milk powder assumed.
[11] Protein content of 80% of total dry matter assumed.

Product	Heat input (GJ/t product)	Electricity input (GJ/t product)	Milk/whey input (t/t product)	Other input (input/t product)	Output by-product (t/t product)
Sweetened condensed milk	0.74	0.27	Milk: 2.23	Sugar: 0.44 t Lactose crystals: 0.005 t	Cream: 0.06 Moisture: 1.61
Whey powder[12]	7.6	1.1	Whey: 15.4		Cheese fines and whey cream: 0.46 Moisture: 13.9
Whey protein powder[13]	11.2	2.95	Whey: 62.6		Cheese fines and whey cream: 1.88 Whey permeate: 50.4 Moisture: 9.32
Lactose[14]	5.0	1.0	Whey permeate: 17.0		Whey concentrate: 0.58 Moisture: 15.4

In Table 3 the energy inputs as determined in this report (the base values from Figure 4, Figure 6 and Figure 7) are compared against values found in literature. There is a significant discrepancy between some of the inputs. A number of possible reasons can be given for this. First, it is important to note that the values found in literature correspond to technologies typical for the late 1990s, and therefore efficiency developments will have taken place in the meantime. Furthermore, the energy requirements for the shown products depend strongly on the exact type of technology use. For instance, the energy requirements for evaporation can be either more than twice as high or twice as low as the value used in this report. To show the impact of this choice, a range in the energy consumption of evaporated products is shown in Table 3, using a value between 77 kJ per kg water evaporated (for MVR (TetraPak, 2019a)) and 0.5 MJ per kg water evaporated (for three stage TVR (European Commission, 2018a)). For cheese and butter, the impact of a deviation of 5 percentage points in the amount of heat regenerated from in- or outflowing flows is shown. Finally, there is a large heterogeneity in the products that fall under one product-category as those shown in Table 3, and all specific products will have their own specific energy consumptions. For instance, the energy consumption for lactose found in literature also includes another product group, namely caseins, which can have a significantly different energy consumption than lactose.

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[12] Demineralised whey powder assumed.
[13] Protein content of 35% of total dry matter assumed.
[14] Lactose produced from whey permeate assumed.

Table 3 Comparison of determined energy input for different dairy products with values found in literature. The range in energy input indicates the sensitivity of the inputs to regenerative heating (for cheese and butter) or the evaporation energy (for milk powder, condensed milk, whey powder and lactose). The variation is only in heat; electricity is the same as in Table 2

Product	Energy input determined in this report (GJ/t product)	Energy input from literature (GJ/t product)[15]
Cheese	2.9 – 3.7	4.3
Butter	1.6 – 2.9	2.2
Milk powder	7.4 – 10.0	11.1
Condensed milk	0.9 – 1.4	2.5
Whey powder	8.0 – 9.9	8.2
Lactose	2.9 – 11.4	5.6

2.1 General

2.1.1 General processes

In general, when milk is received by the processing plant, it first undergoes thermisation. This entails heating the milk to around 65°C for 15 seconds, thereby preventing the growth of bacteria that can cause a deterioration of the milk's quality (Tetra Pak, 1995). Afterwards, the milk undergoes standardisation. During this process the milk is subjected to centrifugation to separate the fat content from the skimmed milk. Afterwards, the two are mixed back together in the desired ratio. Doing this ensures the composition of the used milk is correct for the subsequent steps (Brush, 2012).

Often milk is homogenised before further treatment, except milk destined for cheese production. During homogenisation, the fat globules in the milk are reduced in size (to a mean diameter of 1 to 2 μm) (European Commission, 2018a). The reduction in size is achieved by forcing the milk through small holes, across which a large pressure gradient is created. This process inhibits the separation of the water- and fat-soluble components of the milk (Brush, 2012).

Afterwards, the milk generally receives some form of heat treatment, depending on the product being made. This is done to increase the shelf-life and decrease the amount of harmful microorganisms. Typically milk is pasteurised, which entails heating it to 72 °C and subsequently keeping it at that temperature for 15 seconds. The heat for pasteurisation can be supplied by hot water at a temperature slightly above 72°C, or low-pressure steam (Tetra Pak, 1995). Another option is to sterilise the milk, which is achieved by heating it to a minimum of 135 °C and keeping it for 1 second. Sterilisation yields milk with a longer shelf-life, but this type of milk is generally not used to make other dairy products (European Commission, 2018a). The energy-requirements for heat treatment are reduced by using the cold inflowing milk to cool down the hot outflowing milk, and vice versa. This process, called 'regenerative heating', can reduce the energy needed for pasteurisation by 95% (Tetra Pak, 1995).

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[15] Ramírez, Patel, & Blok (2006).

2.1.2 Cleaning-in-place (CIP)

During operation a residue will form on the used equipment, which will inhibit proper further functioning and might cause contamination of the products. Typically this occurs by deposition of material on a mono-molecular layer which forms quickly during processing. A distinction between two types of deposition can be made. One forms at temperatures above 100°C (called milkstone or scale), while the other forms at lower temperatures.

To remove the deposits, and to clean the equipment for subsequent processing, sanitation is needed. This generally takes the form of Cleaning-In-Place (CIP). This entails cleaning of the equipment without disassembling or moving it. Equipment with a small internal volume (like heat exchangers) can be cleaned by operating them normally, using a cleaning liquid instead of product feed. Larger pieces of equipment require spraying of cleaners (Walstra, Wouters, & Geurts, 2006). CIP generally takes place at 65–75°C, which means it requires a significant amount of energy, around 10–26% of the total energy requirements (Ramírez, Patel, & Blok, 2006).

2.1.3 Wastewater treatment

The dairy industry produces a large volume of waste water, of around 0.2–10 litres of effluents per litre of milk processed (Vourch, Balannec, Chaufer, & Dorange, 2008). This amount mostly comes from CIP-operations, which require large volumes of water to operate, thereby generating 50–95% of the total waste water volume (Daufin, et al., 2001). Apart from the chemicals used for CIP, dairy wastewater has relatively high Chemical- and Biochemical Oxygen Demand (COD and BOD), which indicate the amount of oxygen needed to break down the effluents present in the wastewater, meaning it is a measure of the impact a waste-source will have on its receiving environment (Kothari, Kumar, Pathak, & Tyag, 2017). The wastewater can be treated at an offsite sewage treatment plant or an onsite wastewater treatment plant. If treatment occurs onsite, it happens either aerobically or anaerobically. During aerobic treatment, microorganisms break down the organic matter present in the waste stream, turning it into carbon dioxide and water. Anaerobic treatment happens similarly, but in an oxygen-free environment, in which the organic material is converted into methane and carbon dioxide (Britz, Van Schalkwyk, & Hung, 2004).

2.2 Cheese

Like the wide variety of products made from dairy, there is a large number of different cheeses that can be made, all with slightly differing production methods. However, a general production process can be described, which is shown in Figure 4 below.

The milk is first standardised to achieve the desired fat content for the cheese being made. To change the solids non-fat content (SNF), ingredients such as cream or milk powder can be added. For Gouda cheese (one of the major types of cheese produced in the Netherlands), the fat content of the milk has to be around 26% to achieve the final desired cheese fat content of between 48 and 52% on a dry basis (Bijloo, 2015; FAO, 1988).

After pasteurisation, certain microorganisms will still be present in the milk. These organisms could disrupt the cheese-making process, and therefore need to be sterilised, generally before pasteurisation occurs. This is done in one of two ways: bactofugation or microfiltration. During bactofugation, special centrifuges are used to separate the bacteria strains from the milk. The bacteria-containing concentrate can then be sterilised (at 130 °C for a few seconds) and mixed back in with the milk, which can then be pasteurised. Microfiltration makes use of membranes with pores of 0.8 to 1.4 micrometre and an applied pressure of less than 1 bar. These membranes can filter bacteria from skimmed milk. Skimmed milk and cream are separated during standardisation and the skimmed milk undergoes microfiltration, after which the bacteria concentrate is sterilised together with the cream (at 120-130 °C). The two streams can then be mixed back together and pasteurised (Tetra Pak, 1995).

After the bacteria reducing treatment a coagulant is added. The type of coagulant used depends on the type of cheese being made. Most often rennet and/or lactic acid bacteria are used (Brush, 2012). By adding lactic acid bacteria, the lactose in milk is converted into lactic acid, lowering the pH of the milk. By doing this the negative charges surrounding the protein are neutralised, allowing for aggregation of protein clumps (Cheese Science, 2019). Rennet then removes the negatively charged kappa casein from the protein particles in the milk, undoing their mutual repulsion so the proteins can start to coagulate (The Courtyard Dairy, 2013). This process takes around 30 minutes, and creates cheese curds, which are then cut. This process occurs at a temperature of around 30-40°C. Afterwards, some of the left-over liquid, called whey, is removed from the curds. Typically around 35% of the whey is removed. Next, the cheese curds are heated. Depending on the temperature, this is called 'cooking' (above 40°C) or 'scalding' (above 44°C). The heating is achieved through the addition of hot water (Tetra Pak, 1995). The curds are then pressed into the desired shape and typically brined (at 12-15°C). Afterwards, the cheese is wrapped and stored, ripening it depending on the cheese variety (European Commission, 2018a; Tetra Pak, 1995).

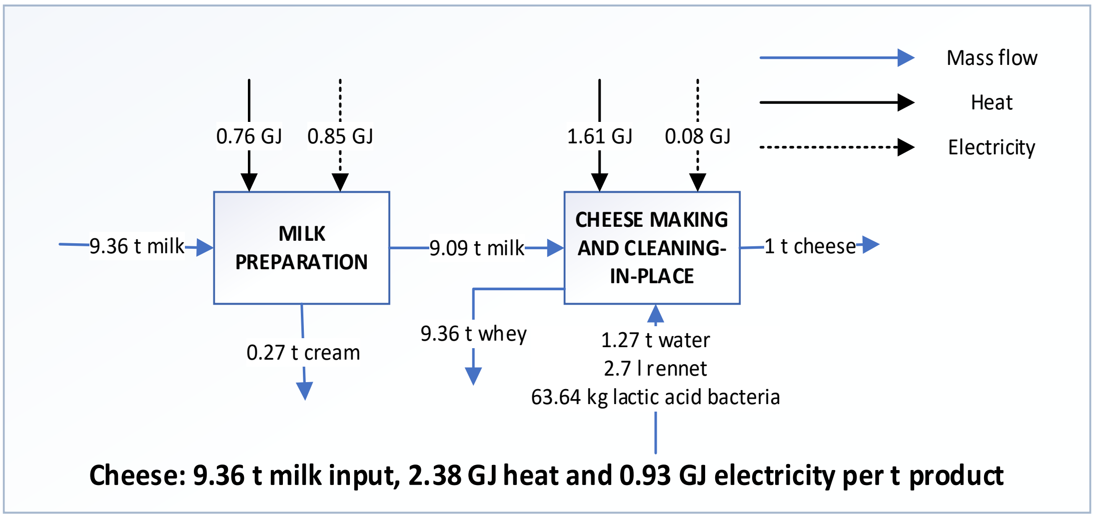

Figure 4 Production processes for cheese, showing energy and mass in- and outputs

2.3 Butter

The butter production process is shown in Figure 2Figure 5 below. Butter (with a fat content of 80-90%) is made by centrifugally separating milk into skimmed milk and cream (Chandan, Kilara, & Shah, 2008). The cream (with a fat content of around 40%) is then pasteurised at a temperature of 95 °C or higher, and chilled to a desired temperature for ripening. During this process the fat content of the cream crystallises, which helps the formation of butter grains during the churning process. Also, it will prevent fat remaining in the buttermilk (Brush, 2012; Tetra Pak, 1995). The cream can then be churned into butter grains. Churning breaks down the fat in the cream, causing globules to stick together. Typically, between 99.55% and 99.30% of the fat content of the cream ends up in the butter grains, while the rest leaves with the buttermilk (Tetra Pak, 1995). The grains are then washed in water, after the leftover liquid, buttermilk, is removed. By kneading and folding the grains (called 'working'), butter can be formed (European Commission, 2018a). If desired, salt can be added during the working stage.

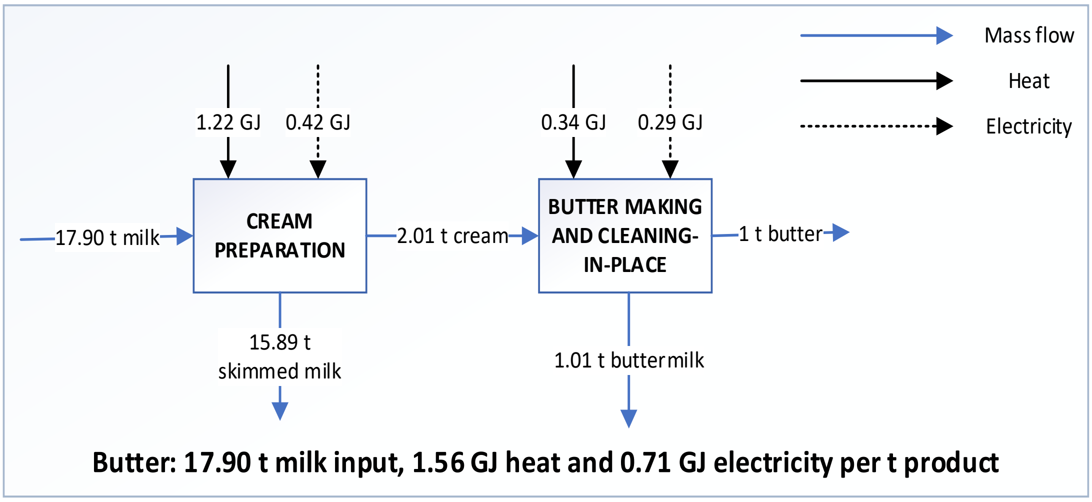

Figure 5 Production processes for butter, showing energy and mass in- and outputs

2.4 Milk powders and condensed milk

Milk consists for approximately 87% out of water. By removing the water content of milk, the solids, such as proteins, fat, lactose and calcium can be obtained as a dry powder. By adding water to this powder, milk can be formed again. Powdered milk has the benefits of reduced transportation costs and an increased shelf-life. The protein content of milk can be concentrated and dried, creating milk protein powder. Milk can also be concentrated through evaporation, resulting in condensed milk, or, if sugar is added, sweetened condensed milk.

For these four products, the milk first undergoes heat treatment. For (sweetened) condensed milk, the milk is heated to 120 °C, which serves not only to kill any microorganisms but also improves the stability of the product later on. To produce milk powder, the milk is generally heat-treated at 95 °C for 1 minute, and for milk protein powder at 72°C (Tetra Pak, 1995; Walstra, Wouters, & Geurts, 2006). Afterwards, the milk undergoes evaporation, after which the concentrated milk can be further processed. The production processes for each product are shown in Figure 6.

During evaporation, the liquid is generally exposed to a heat exchanger in a falling film, causing the moisture in the feed to evaporate up to a dry matter content of around 60% (Tetra Pak, 1995). The milk is often circulated through multiple cycles of falling film evaporation, with the exhaust heat of one cycle (or ‘effect’) being used to heat the next one. Doing this lowers the energy consumption of the process (Brush, 2012). Typically, the pressure between each effect is lowered, resulting in a lower boiling point of the milk, lowering the heating requirement. To heat the effects, steam at a pressure of 10 bar is used. Typically, around 1–1.1 kg of steam is needed to evaporate 1 kg of water if a single effect is used, but if multiple effects are added the steam consumption with 1 effect can be divided by the number of effects (so 0.5 kg for a 2-effect system). Adding effects is also necessary to prevent denaturation of the proteins in the milk, which occurs around 100 °C.

Steam consumption can be further reduced by adding a thermal vapour recompression (TVR) or mechanical vapour recompression (MVR) to the system. In a TVR part of the vapour from an effect is compressed by adding steam of a higher pressure. Doing so means that the vapour from one effect is boosted to a higher temperature resulting in an increase in energy efficiency of the evaporator. Multiple TVRs can be added to an evaporation unit, and adding one TVR has an effect comparable to adding an extra effect, but the costs are typically lower. In an MVR, the total amount of vapour from the evaporator is compressed using a compressor, increasing the temperature of the vapour so it can be reused. Using such a system minimises steam consumption (to around 0.03 kg steam/kg water evaporated)[16], since all the available steam in the system is reused. Only during start-up steam has to be injected into the system, but when the evaporator is running, no additional steam is needed. A trade-off is that using an MVR significantly increases the electricity consumption of the evaporator (to several hundred kW) (GEA Process Engineering, 2010; TetraPak, 2019a). For this report, a value of 230 kJ/kg water evaporated was assumed for milk-based products, corresponding to a 6-effect evaporator with TVR, and a value 10% higher, 253 kJ/kg water evaporated, was assumed for whey products due to their higher heat capacity (Walstra, Wouters, & Geurts, 2006).

To produce condensed milk, the concentrated milk (with a 74% moisture content) is homogenised (at a pressure of 125-250 bar) and cooled for packaging (generally in cans). The packages are then sterilised to ensure a long shelf-life of the product (Tetra Pak, 1995). Sweetened condensed milk is made similarly to unsweetened condensed milk. The sugar (0.44 kg of which is added for 1 kg of sweetened condensed milk) can be added at two stages: after standardisation of the raw milk or during evaporation. After evaporation, the concentrated milk (with a moisture content of around 50%, excluding the sugar)[17] can be homogenised, but this is not always done. The milk is then cooled to allow the lactose in the milk to crystallise. By letting this happen at low temperature, the crystals will be small in size, as to not ruin the texture of the end product (Tetra Pak, 1995). The sweetened condensed milk can then be inspected and packaged. The addition of sugar to the milk creates a high osmotic pressure, causing most of the microorganisms in the end product to be destroyed, removing the need for sterilisation of the packaged goods (Tetra Pak, 1995).

To produce milk powder, the next step after evaporation is to use spray drying to change the concentrated milk into a powder with a moisture content of 2.5-5% (Tetra Pak, 1995). This is done by feeding the milk through an atomiser, which sprays it into the drying chamber as a mist of fine particles. In the drying chamber, the particles come into contact with hot air (typically 175-250 °C), which causes the moisture to evaporate from their surface. This causes the hot air to cool down, which is transported out of the drying chamber (GEA Process Engineering, 2010). The hot powder is then cooled on a fluid bed, where also the final drying occurs on a (often shaking) fluid bed. Shaking the bed ensures proper mixing of the product, and therefore a more homogeneous powder, and it also increases powder contact with air, increasing the drying rate (Tetra Pak, 1995). The final drying occurs on this fluid bed since the final amount of water to be evaporated requires the largest energy input (around 23 kg of steam/kg water evaporated to decrease the moisture content from 6% to 3.5% in the spray drying chamber), and the relatively long residence time allows for a better transfer of heat to the particles in the fluid bed compared to the spray drying chamber, resulting in lower steam consumption (around 4 kg/kg water evaporated) (GEA Process Engineering, 2010). Homogenisation of the evaporated concentrate may occur before drying, but this is not always done, since this will increase its viscosity, which has negative effects on the spray drying process. Additionally, atomisation of the concentrate has a similar effect on the product as homogenisation, so it is not required to homogenise it separately (Walstra, Wouters, & Geurts, 2006).

Finally, milk protein powder can be created. To achieve this, the pasteurised milk undergoes ultrafiltration before being evaporated (Mistry, 2002). In this process, the milk is pumped

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[16] GEA Process Engineering (2010) states that 375 kg of steam is needed to evaporate 12,300 kg of water

[17] See Appendix A.1

over a membrane (with pore size of 10^{-2} to 10^{-1} μm) under a pressure of 20 to 40 bar. Doing so retains the protein content of the milk, but it lets through some of the other dry matter, raising the relative abundance of protein in the retentate (Tetra Pak, 1995). This process can yield protein powders with up to around 65–70% protein content in the dry matter (Tetra Pak, 1995; Walstra, Wouters, & Geurts, 2006). To further increase the protein content the retentate has to undergo diafiltration, a process in which a volume of water is added to the retentate so it can undergo a subsequent step of ultrafiltration, thereby filtering out even more non-protein dry matter (Mistry, 2002). The retentate can then be further processed, undergoing evaporation (to 55% dry matter), spray drying and fluid-bed drying to yield a dried protein powder of around 95% dry matter.

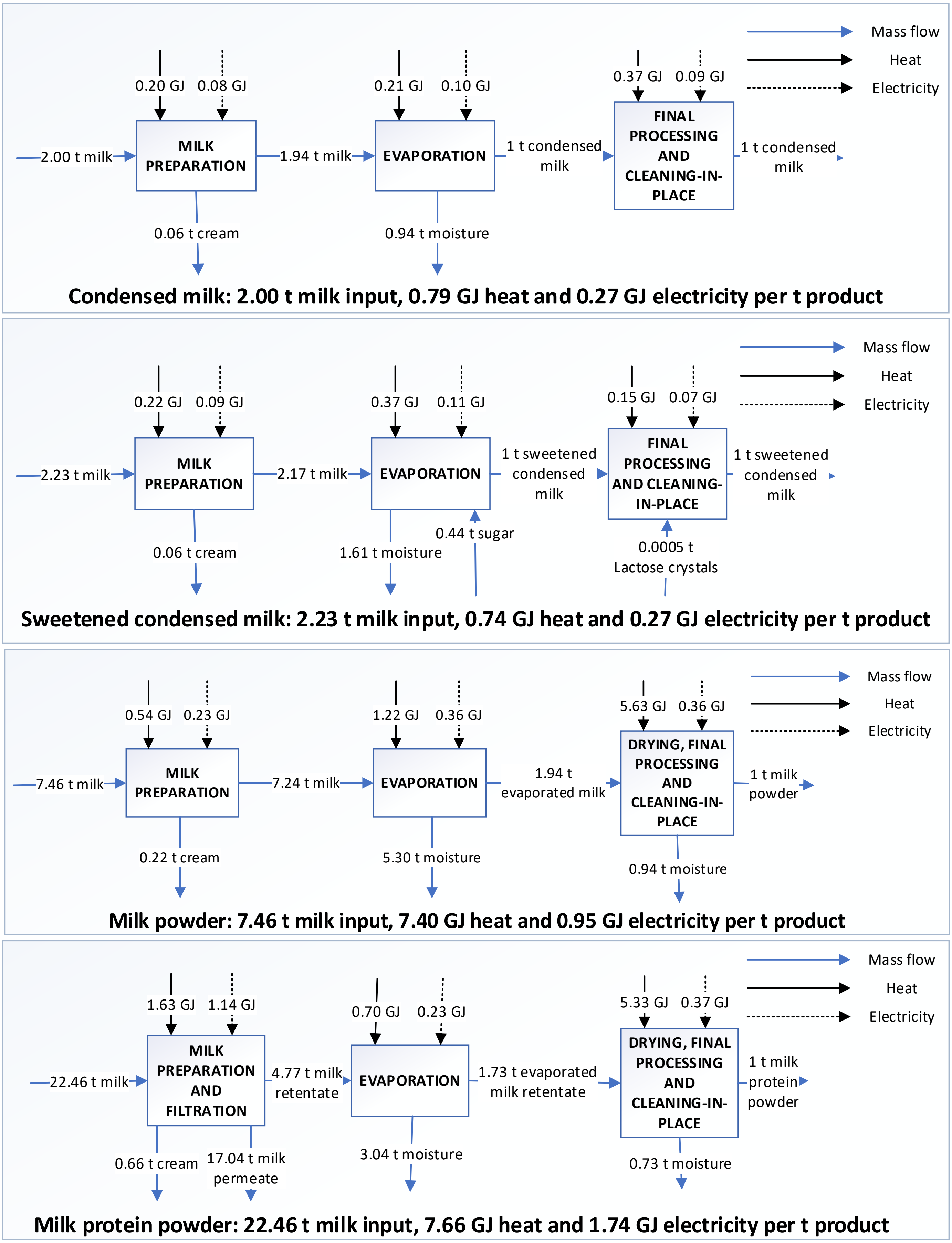

Figure 6 Production processes for condensed milk, sweetened condensed milk, milk powder and milk protein powder, showing energy and mass in- and output

2.5 Whey powder and other whey products

The leftover whey from the cheese-making process can be used to make a wide variety of products, as it still contains proteins, fat, lactose and minerals. As with milk powder production, removing water from the whey is an important step, since whey consists of even more water than milk (around 93%). The first step of whey processing is separation of the fine cheese particles and the free fat content present in the whey (Tetra Pak, 1995). After separation, the whey can be heat treated and subsequently processed into a wide variety of products. The processing steps for whey products are shown in Figure 7 below.

If whey powder is produced, the whey largely follows the same steps as for milk powder processing. Before evaporation the whey is generally cooled to 5-10 °C for preservation, and undergoes reverse osmosis to increase the dry matter content up to 18–24%, decreasing the energy requirements during evaporation (Chandan, Kilara, & Shah, 2008; Moejes & Van Boxtel, 2017). During reverse osmosis, the whey is pumped over a membrane with pore sizes of 10^{-4}-10^{-3} micrometres at a pressure of 30 to 60 bar. The membrane lets water through while retaining the solid components of the whey, thereby concentrating it (Tetra Pak, 1995). Afterwards the whey goes through evaporation (to 40–60% dry matter), spray drying and fluid-bed drying, until the final moisture content of around 97% is reached (GEA Process Engineering, 2010). Whey has a high salt content, which makes it largely unsuitable for direct consumption. Therefore, most often whey is separated into its constituent dry matter, such as whey protein and lactose. These products can then be used for instance as food ingredients or supplements (Tetra Pak, 1995). Whey powder can also be demineralised before evaporation, either through nanofiltration (for low degree demineralisation), electrodialysis or ion-exchange. Electrodialysis makes uses of semi-permeable membranes that selectively let through positively and negatively charged particles, thereby depleting the whey of ions. During ion-exchange, ions are adsorbed by resin beads added to the whey (Tetra Pak, 1995).

Whey protein powder is created analogously to milk protein powder. First the separated and heat-treated whey undergoes ultrafiltration, after which the whey retentate can be further processed, undergoing evaporation (to 55% dry matter), spray drying and fluid-bed drying to yield a dried protein powder of around 95% dry matter. The permeate can be used as fodder for animals, or can further processed, for instance to separate its lactose content (Chandan, Kilara, & Shah, 2008; Tetra Pak, 1995).

Lactose, the main constituent of dry matter in whey, is separated through crystallisation, either from the post-evaporation concentrated whey or permeate left over after ultrafiltration of whey (European Commission, 2018a). Crystallisation occurs by adding seed crystals, after which the lactose crystals (with 92% dry matter) are separated from the remaining concentrate through the use of screw conveyors. The concentrate can be used as animal fodder when dried. The crystals are then dried, generally using fluid bed drying, since the high temperatures used in spray drying would cause the lactose to denaturise. The crystals (with a moisture content of 0.1-0.5%) can then be ground down to the desired size and packaged (Tetra Pak, 1995).

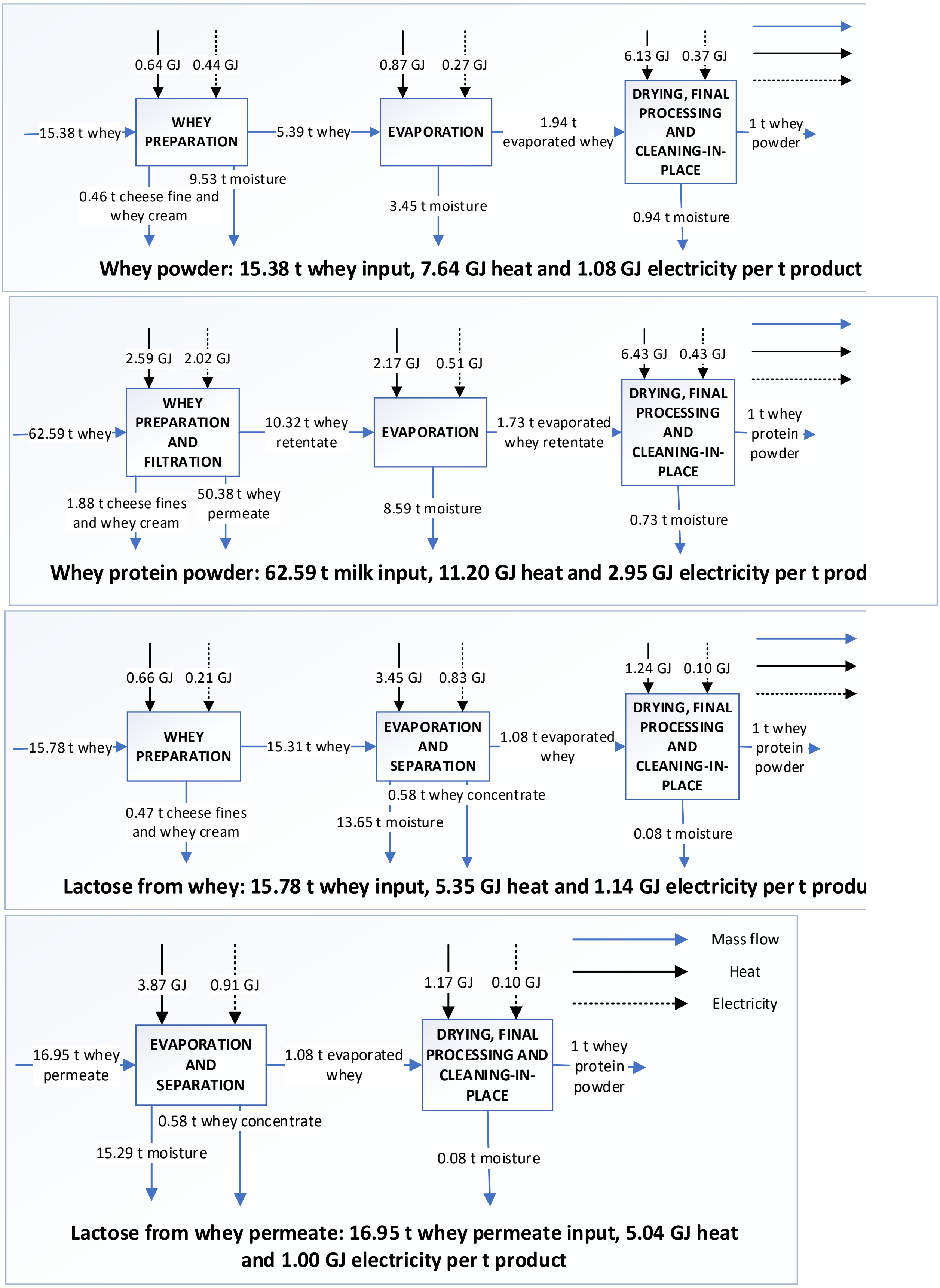

Figure 7 Production processes for whey powder (demineralised), whey protein powder (35% protein in dry matter) and lactose, showing energy and mass in- and outputs

3 Dairy products and application

3.1 Dairy end products

Of the roughly 14 billion kilograms of milk processed yearly, the Dutch dairy processing sector makes a wide variety of products. A breakdown of the use of this amount of milk is shown in Figure 8 below. Since different products require different amounts of milk, the production shares differ from the shares shown in the figure. Yearly milk supply and production of some dairy products in the Netherlands are shown in Table 4. Historical Dutch consumer prices for some of the products are shown in Figure 9 below.

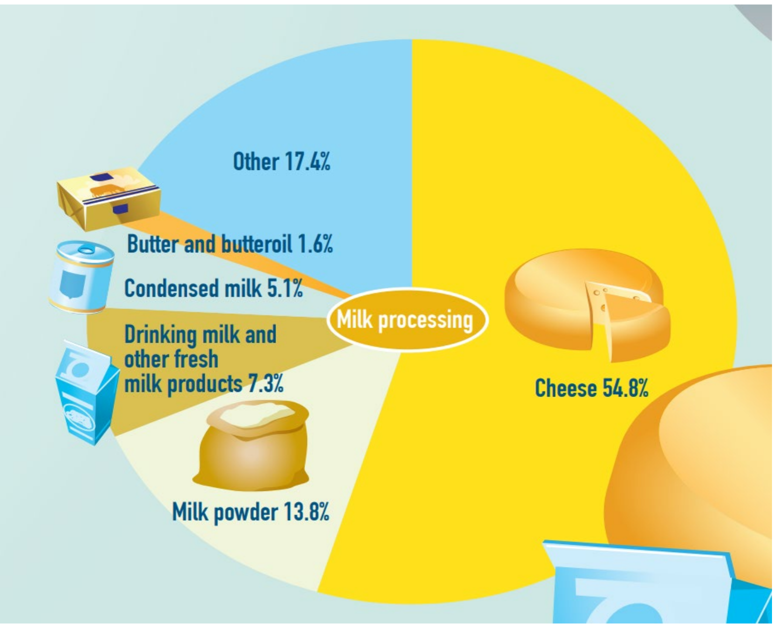

Figure 8 Use of Dutch milk in 2018 (ZuivelNL, 2019a, p. 4)

Table 4 Milk supply and dairy production in the Netherlands (CBS, 2020)

Year	Milk supply (kt)	Production (kt)			
		Butter	Cheese	Milk powders	Condensed milk
2014	12,473	140.5	771.9	204.8	382.2
2015	13,331	147.6	845.0	204.2	407.8
2016	14,324	161.3	887.8	235.9	372.2
2017	14,296	149.0	874.2	249.9	367.0
2018	13,881	153.7	878.9	226.4	344.3
2019 (preliminary)	13,788	137.8	897.4	242.9	382.0

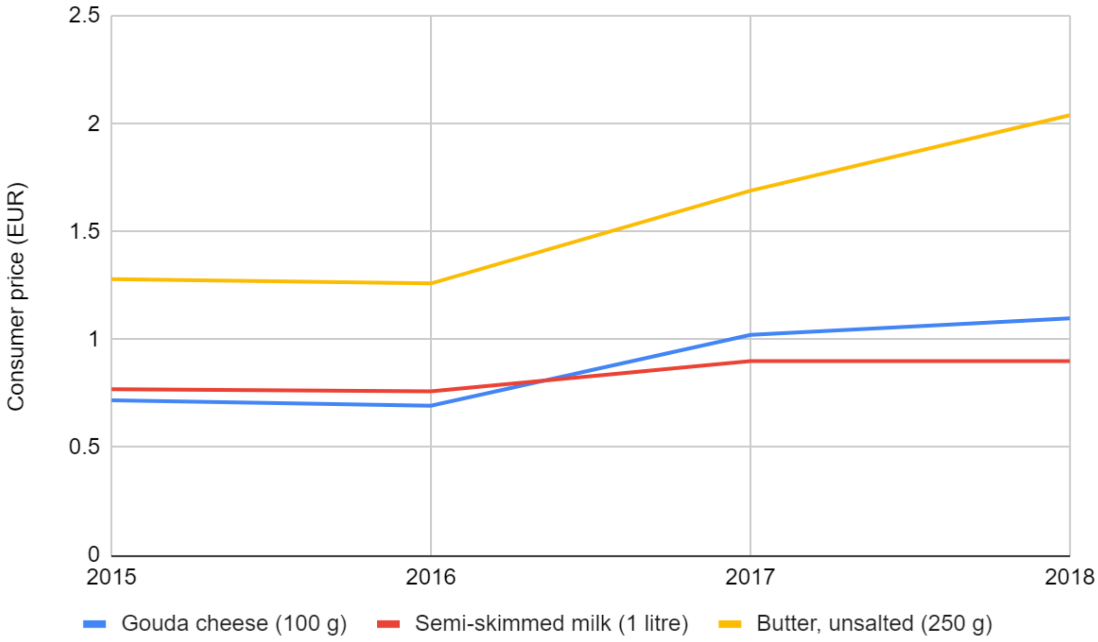

Figure 9 Development of consumer prices for Dutch dairy products (ZuivelNL, 2019b)

Many of the products can be used by direct consumption by the consumer. Other products, such as milk (protein) powders and whey (protein) powders, are mostly used for other purposes. Milk powder can be added to a variety of other foods during their production process. For instance, during chocolate production, addition of milk powder helps to reduce the viscosity of the chocolate, making it easier to process (Sharma, Jana, & Chavan, 2012).
Whey products, especially those further processed to remove or concentrate certain constituents of the original whey, can be used for a wide variety of applications, various of which are shown in Figure 10 below.

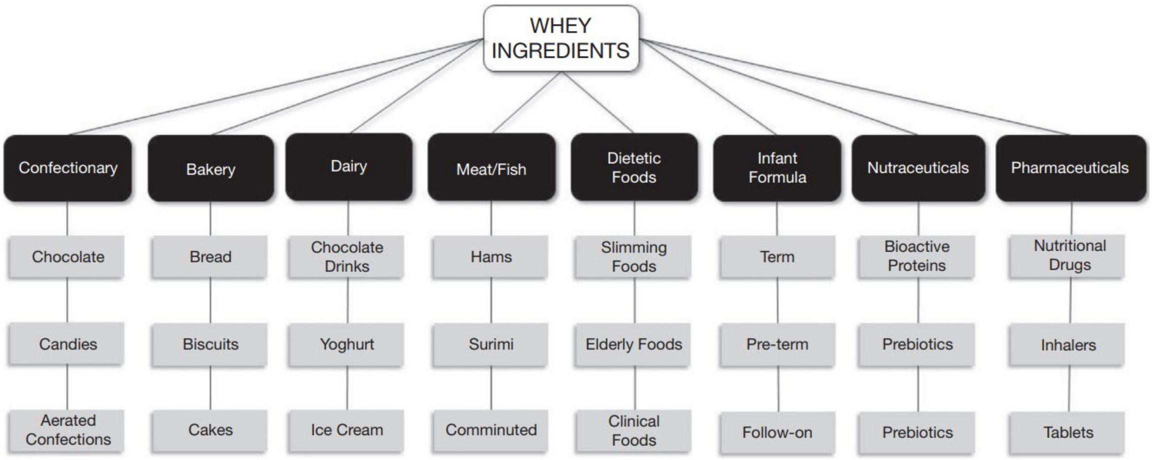

Figure 10 applications of whey ingredients (Ramos, et al., 2016, p. 502)

3.2 Prices and trade

Figure 11 below shows the price development for raw milk in the EU and the Netherlands.

Figure 11 Development of milk prices in European Union and the Netherlands (European Commission, 2019a)[18]

The export value of the Dutch dairy industry equalled EUR 7.7 billion in 2018, 5.7 billion of which was exported to countries in the European Union (mostly Germany (33% of intra-EU trade) and Belgium (22%)) and 2.0 billion to countries outside of the European Union (mostly China (12% of extra-EU trade)). A breakdown of the export value of Dutch dairy products is shown in Figure 12. Cheese and butter exports (over 880 kton and 290 kton respectively in 2018) are mostly destined for the European market (over 84% and 90% respectively), while milk powder (over 320 kton exported in 2018) is mostly exported to countries outside of the European Union (almost 70%) (ZuivelNL, 2019b). The export volume of Dutch dairy products is the 5th highest globally, and the highest of any country in the European Union. At the same time, the Netherlands imports dairy products with a value of EUR 3.8 billion, mostly from Germany and Belgium (ZuivelNL, 2019a).

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[18] European milk price based on weighted average of all milk prices of European countries

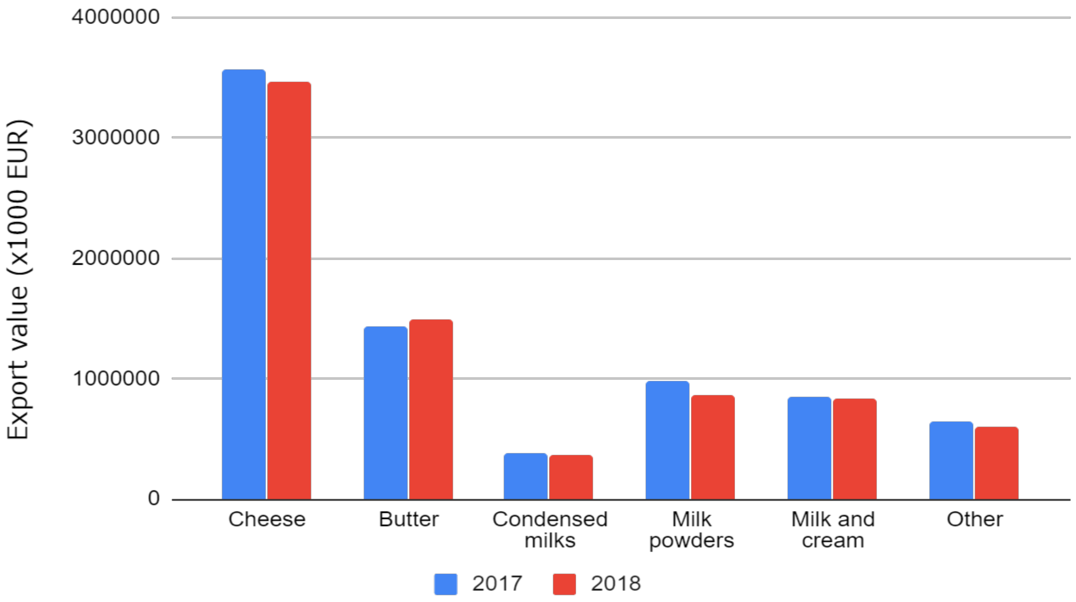

Figure 12 Export value of Dutch dairy products (ZuivelNL, 2019b)

3.3 Consumption and substitution

In the Netherlands, the average yearly dairy consumption was 79 kg of milk[19], 3 kg of butter and 21 kg of cheese per capita in 2018 (Wageningen University and Research, 2019). However, the national level of dairy consumption is decreasing. The National Institute for Public Health and the Environment has undertaken surveys to study the food consumption patterns of Dutch citizens. The surveys showed that the consumption level of dairy products decreased between 3.7% and 19.9% for the researched age groups between the surveys of 2007–2010 and 2012–2014 (National Institute for Public Health and the Environment, 2016). However, more recent figures show a decline of 1.6% and an increase of 11% in the per capita consumption of milk and cheese respectively in the Netherlands between 2017 and 2018 (ZuivelNL, 2019b).

However, as shown in section 3.2, a significant amount of Dutch dairy products is exported abroad, and consumption of dairy products is expected to increase in many regions. For instance, in China and Africa consumption is expected to outpace domestic production, leading to an increase in imports from the European Union, at least until 2028. This increase mostly concerns imports of milk powder, as increases in demand for cheese and fresh dairy products come primarily from domestic consumption. China, for instance, is like to increase its imports with around 400 kt of milk-equivalents per year. This, and increases in other dairy importing countries, will lead to increases in European dairy-exports of around 1.4 million tons of milk-equivalents yearly between 2014 and 2025 (European Commission, 2015).

There is also a growing market for dairy alternatives, such as soy and other dairy-free milk, which accounted for 12% of total fluid milk sales globally. This market had a market share of around 3% of the total dairy market (dairy and dairy alternatives), with a value of USD 18 billion in 2018. And while global dairy demand is expected to grow with 2.5% the coming years, the demand for dairy alternatives is expected to grow twice as fast, with 5%, until 2022 - especially in the Netherlands, a relatively large increase in the retail volume and value of dairy

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[19] This probably includes drinking milk products, since ZuivelNL (2019a) reports a value of 42 kg, but this value explicitly excludes *'other fresh milk products'*.

alternatives has occurred between 2012 and 2017, increasing with around 20% and 25% annually respectively (European Commission, 2018b; Rabobank, 2018).

By (partially) substituting dairy products with a high environmental impact with products with comparable nutritional value or properties the total production of the dairy sector can be lowered, thereby reducing their emissions. The reduction in emissions will mostly stem from the reduced milk production, thereby preventing the relatively high dairy farm emissions (1.48 kg CO_2-eq/kg Dutch milk, see Section 1). The emissions from processing of plant-based products at the factory will typically be higher than those of dairy products, but this is offset by the lower emissions pre-factory gate. Life cycle assessments of plant-based milk alternatives are scarce, but show a carbon footprint that is 2.5-5 times lower for soy and almond milk compared to cow’s milk, based on the volume produced (Henderson & Unnasch, 2017; Poore & Nemecek, 2018; Roos, Garnett, Watz, & Sjors, 2018). As mentioned, substitutes should be found based on nutritional similarity, so comparing plant-based and cow’s milk based on volume can skew the results, as these products generally have different nutritional content, or more plant-based feedstock is needed to produce products with similar nutritional content.

4 Options for decarbonisation

In this section options for reducing the CO_2-emissions of the Dutch dairy processing sector will be discussed. Categories for CO_2-reduction measures are shown in Figure 13 below.
For the dairy processing sector, the main categories of decarbonisation options that apply are those related to fuel substitution and process design. In terms of fuel substitution, alternative methods for producing steam can be applied, such as electric boilers, boilers fuelled with biogas or green gas, and heat pumps or geothermal energy. Process design alternatives are in development and/or partly exist in the form of the use of zeolite in spray drying, membranes for concentration purposes, or implementation of MVRs for evaporation. The decarbonisation options are investigated for the dairy processing sector in general, and not all options may be applicable to specific companies. In the following sections the decarbonisation options will be explained further.

Generally, the decarbonisation options can be considered in two steps: first, increasing energy efficiency by process options, or by re-using the large amount of residual heat, either internally or externally. The second step, fuel substitution, can then be implemented with minimum impact and costs. In this way the entire process is decarbonised an at the same time the energy demand is minimised.

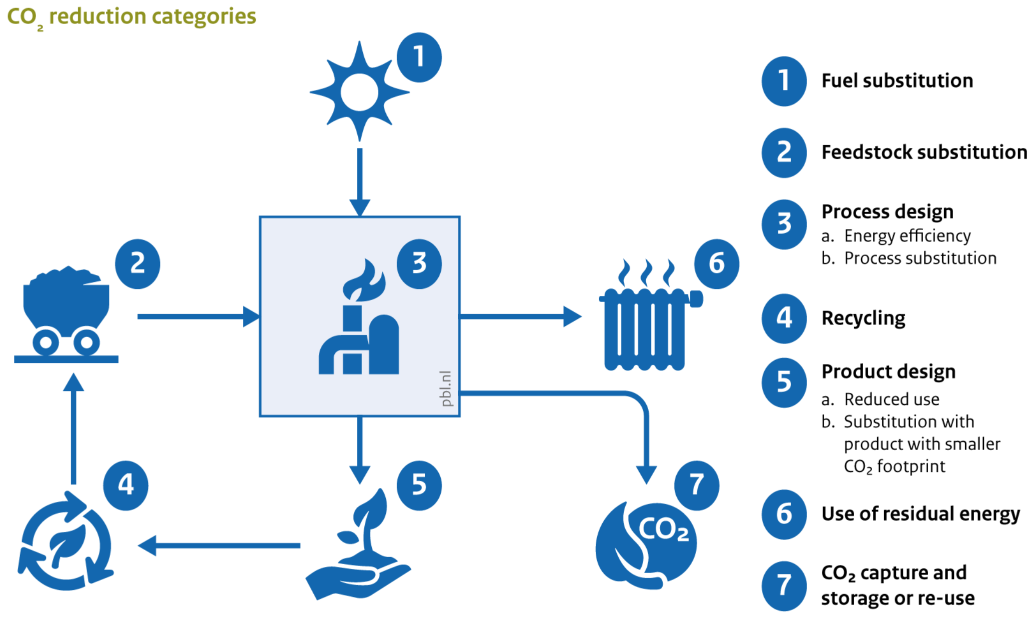

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Figure 13 Categories for reducing industrial CO_2 emissions

4.1 Process design options

4.1.1 Closed-loop spray drying with zeolite

Spray drying is the most energy intensive process used by the dairy processing industry, accounting for 27–55% of the energy requirements for the production of dried products. While the amount of moisture evaporated in a falling-film evaporator is generally much larger than in the spray dryer, energy use in the evaporator is much lower. This is partly because the exhaust heat can be reused in the process. As of 2020, this is not being done for the spray drying process, even though high temperature waste heat is available. This is partly due to the presence of fine powder particles in the dryer exhaust air, which cause fouling of the needed heat exchangers, preventing them from operating correctly, meaning that the sensible heat of the air cannot be recovered. These fines can be prevented through the use of monodisperse droplet atomisers (Moejes, Visser, Bitter, & Van Boxtel, 2018).

Atomisers used in 2020 produce polydisperse droplets, meaning that they are non-uniform in shape and size, resulting in different drying times for each droplet and differing shape and nutrient content in the final product (Wu, Patel, Rogers, & Chen, 2007). Monodisperse droplets can be created using a low-pressure feed paired with a piezo-electric element, which changes shape if an electric current is applied to it, sending a small shockwave through the feed, sending droplets out of the atomiser (European Commission, 2019b). Without the fines, the sensible heat in the dryer exhaust air can be recovered. It also opens up the possibility to recover the latent heat.

To recover the latent heat of the humid air leaving the dryer, a zeolite adsorption wheel can be used. Zeolite is an adsorption material, consisting of crystalline aluminosilicates, which can bind water molecules, thereby dehumidifying the air, making it suitable for reuse as drying air. At the same time, the latent heat present in the exhaust air is released through condensation in the zeolite, thereby increasing the temperature of the air, which can then be used for heating in the production process[20]. Zeolite has a large relative dehumidifying potential when operating in low relative humidity, as compared to other adsorbents, making it suitable for use in the production process of dairy powders.

The zeolite needs to be regenerated after adsorption, a process in which the adsorbed water is released, which requires around 3320 kJ per kg of water to be removed. To ensure the energy efficiency of the drying system is increased when using zeolite, the heat for regeneration needs to be produced efficiently. This can be achieved by using ambient air or steam at high temperatures (van Boxtel, Boon, van Deventer, & Bussmann, 2014). The surplus heat of regeneration can subsequently be used to heat the dehumidified air, reducing the energy use of the spray drying process with 38%[21], if superheated steam at a temperature of 250°C is used for regeneration (Moejes, Visser, Bitter, & Van Boxtel, 2018). By placing the zeolite on a rotating wheel, it can continuously pass between the adsorption and regeneration phase, thereby making continuous production possible (van Boxtel, Boon, van Deventer, & Bussmann, 2014).

The process flow for this option is shown in Figure 14 below. The costs of such an installation are shown in Table 5 below.

Friesland Campina started a pilot program using zeolite wheels for spray drying in 2014, aiming to produce steam at a temperature of up to 350°C at 1 bar, which could then be used in other

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[20] For instance, ambient air at 20°C and 70% relative humidity can be raised to around 60°C and a relative humidity below 1% using zeolite (van Boxtel, Boon, van Deventer, & Bussmann, 2014).

[21] Other studies state an energy reduction potential of 30–50% (van Boxtel, Boon, van Deventer, & Bussmann, 2014), or 35–45% (Topsector Energie, 2019).

industrial processes (possibly after being mixed with steam at a higher pressure). The project finished at the end of 2018, showing that the zeolite-system is reliable, with the next step being the search for the proper conditions for a commercial test (Topsector Energie, 2019).

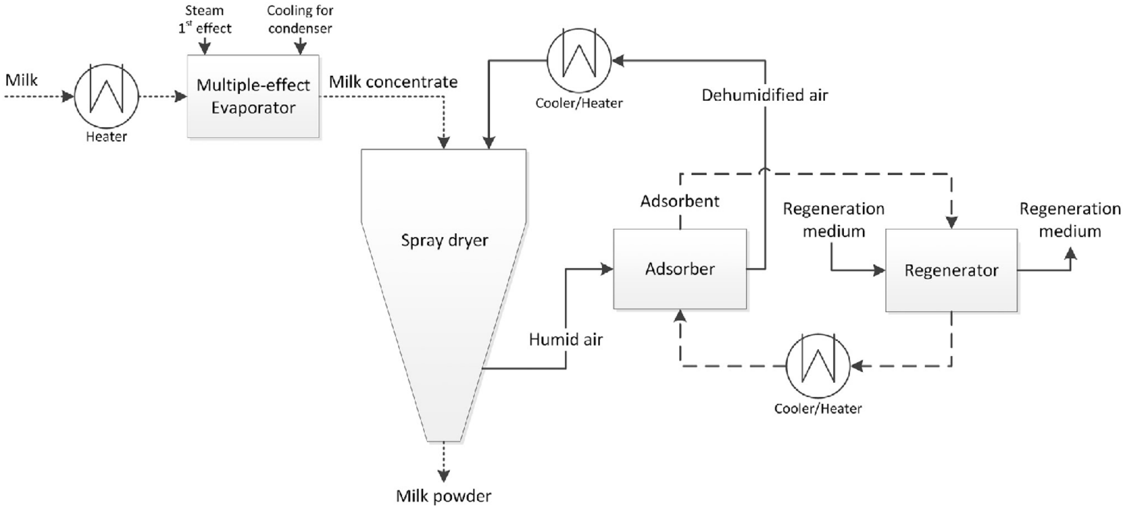

Figure 14 Process flow for a closed-loop system using a zeolite adsorber for producing milk powder (Moejes, Visser, Bitter, & Van Boxtel, 2018, p. 26)

Table 5 Techno-economic parameters for a zeolite wheel for spray drying

Parameter	Value	Source
Capacity [kg water/h]	1400	(Moejes, Visser, Bitter, & Van Boxtel, 2018)
Load hours [h/yr]	8000	Assumption
Electricity use [% increase during spray drying]	25	Assumption
Lifetime [yr]	5	(Moejes, Visser, Bitter, & Van Boxtel, 2018)
CAPEX[22] [EUR/unit capacity]	250,000	(Moejes, Visser, Bitter, & Van Boxtel, 2018)
Fixed OPEX [EUR/yr]	7500	Assumed 3% of CAPEX

Table 6 below shows the amount of energy that can be saved if zeolite wheels are applied in the Dutch dairy processing sector for several products. Energy savings can be significant using zeolite, especially for products where the spray-drying process accounts for a large share of the total energy requirements (mostly milk and whey powder).

Table 6 Energy saved by application of zeolite in the Dutch dairy sector

Parameter	Milk powder	Milk protein powder	Whey powder	Whey protein powder (35%)	Whey protein powder (58%)
Energy use spray drying without zeolite [GJ/t product]	4.38	3.92	4.82	4.31	4.31
Energy use spray drying with zeolite [GJ/t product]	2.72	2.43	2.99	2.67	2.67

4.1.2 Pre-concentrating milk/whey with membrane processes

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[22] Note that CAPEX does not necessarily scale with the capacity; this value is thus applicable for the presented capacity, and may deviate when the capacity is largely different.

By substituting thermal processes for mechanical processes, energy requirements can be lowered, while electrifying the process as well. A good example of this is the use of membranes in the dairy industry. Milk for milk powder production can be preconcentrated using reverse osmosis, thereby lowering the energy needed for the entire process. The limit for concentration through reverse osmosis is around 18–24% dry matter, but typically a maximum of 18% is used. Reverse osmosis is performed by applying a pressure that is greater than the osmotic pressure of the milk, water can be forced through a membrane which retains most of the other constituents of the milk. This is an energetically favourable process compared to thermal concentration, as reverse osmosis requires 14–36 kJ/kg water removed while thermal concentration through evaporation requires at least 55–115 kJ/kg water removed[23] (Moejes & Van Boxtel, 2017; Walstra, Wouters, & Geurts, 2006). To concentrate 1 kg of milk to a dry matter content of 50% from 13% (thereby removing 740 grams of water) would then require 59,200 kJ using only evaporation or 43,922 kJ when first concentrating to 18% dry matter using reverse osmosis (removing 278 grams of water), thereby saving around 26% of energy in the concentrating process, while also switching from steam to electricity[24]. The costs of a reverse osmosis installation are shown in Table 7 below.

The effect of using pre-concentrating on the energy requirements for several products is shown in Table 8 below, assuming evaporation technologies consume 230 kJ/kg water evaporated for milk-based products and 253 kJ/kg water evaporated for whey-based products, and an electricity consumption of 25 kJ/kg water removed for reverse osmosis. The levels of dry matter used after evaporation can be found in Table 20. The impact of implementing the reverse osmosis on both heat and electricity are shown. For the electricity values it is assumed that the electricity use of evaporator is decreased proportional to the decrease in heat consumption by the evaporator.

The table shows that the application of this process yields significant savings during lactose production, but savings are lower for other products. The reason for this is that the initial dry matter content of lactose before water removal is relatively low, meaning that relatively more water can be removed by the more energetically favourable process of reverse osmosis.

Table 7 Techno-economic parameters for a reverse osmosis installation for pre-concentrating of dairy feed

Parameter	Value	Source
Capacity [m^3 feed/h/m^2]	0.047[25]	(Suárez, Fernández, Iglesias, Iglesias, & Riera, 2015)
Load hours [h/yr]	7000	(Suárez, Fernández, Iglesias, Iglesias, & Riera, 2015)
Lifetime [yr]	1[26]	(Suárez, Fernández, Iglesias, Iglesias, & Riera, 2015)
CAPEX[27] [EUR_{2014}/m^2]	1015	(Suárez, Fernández, Iglesias, Iglesias, & Riera, 2015)
Fixed OPEX[28] [$EUR_{2014}/m^2/yr$]	20	(Suárez, Fernández, Iglesias, Iglesias, & Riera, 2015)

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[23] Assuming an MVR is applied, otherwise the energy-requirements will be even higher.

[24] Assuming 80 kJ/kg water removed for evaporation and 25 kJ/kg water removed for reverse osmosis.

[25] Source states that a surface of 426 m^2 is needed to be able to process 20 m^3 wastewater/h. Assumed this is the same for wastewater and product feed.

[26] The membrane itself has to be replaced after 1 year due to fouling. However, this can vary from 1 – 3 years.

[27] Excludes installation costs on-site. This is for an area of about 400 m^2.

[28] Only taking into account maintenance costs, stated as 2% of the CAPEX.

Table 8 Energy saved by application of pre-concentrating with membrane in the dairy sector

Parameter	Milk powder	Condensed milk	Sweetened condensed milk	Whey protein powder (35%)	Lactose (from whey)	Lactose (from permeate)
Water removed during pre-concentrating to 18% DM [t/t product]	2.01	0.54	0.60	5.02	9.78	11.42
Water removed during evaporation to final DM [t/t product]	3.29	0.40	1.00	3.57	3.87	3.87
Heat use evaporation with pre-concentrating [GJ/t product]	0.76	0.11	0.25	1.03	1.22	1.26
Heat use evaporation without pre-concentrating [GJ/t product]	1.22	0.22	0.37	2.17	3.45	3.87
Electricity use evaporation with pre-concentrating [GJ/t product]	0.27	0.06	0.08	0.34	0.46	0.50
Electricity use evaporation without pre-concentrating [GJ/t product]	0.36	0.10	0.11	0.51	0.75	0.83

4.1.3 Mechanical vapour recompression

As mentioned in Section 1, it is possible to reduce steam consumption during evaporation through the application of Mechanical Vapour Recompression (MVR). An MVR reuses the exhaust steam of the evaporator and increases its pressure and temperature by compressing it, thereby making it suitable for evaporation of moisture from the incoming feed. This lowers the steam consumption significantly, to 55–115 kJ/kg water removed (Moejes & Van Boxtel, 2017; Walstra, Wouters, & Geurts, 2006). A trade-off is that an MVR consumes more electricity than an evaporator with TVR, increasing from 50–75 kW to 200–575 kW (GEA Process Engineering, 2010; Tetra Pak, 2020c; Tetra Pak, 2020d). The costs for an MVR are shown in Table 9.

Table 9 Techno-economic parameters for an MVR system

Parameter	Value	Source
Capacity [MW_{th}]	4 – 20	(Marsidi, 2018)
Load hours [h/yr]	8000	
Lifetime [yr]	10	
CAPEX [million EUR/MW_{th}]	0.26 – 0.60	
Fixed OPEX[29] [million EUR/MW_{th}/yr]	0.008 – 0.018	
TRL[30]	9	

In Table 10, the potential energy reduction when implementing MVRs in the dairy processing industry is shown for various products. An energy consumption of 76.9 kJ/kg water removed was used for milk products and a value 10% higher was used for whey products[31]. An electricity consumption of 200 kW was assumed for the MVR.

As for pre-concentrating, the largest energy savings are achieved for lactose, since evaporation accounts for a relatively large share of the total energy requirements, due to the low initial dry matter content of the feed.

Table 10 Energy saved by application of an MVR in the dairy sector

Parameter	Milk powder	Condensed milk	Sweetened condensed milk	Whey powder	Whey protein powder (35%)	Lactose (from whey)	Lactose (from permeate)
Heat consumption evaporation with TVR [GJ/t product]	1.22	0.22	0.37	0.87	2.17	3.45	3.87
Electricity consumption evaporation with TVR [GJ/t product]	0.36	0.10	0.11	0.27	0.51	0.75	0.83
Heat consumption evaporation with MVR [GJ/t product]	0.41	0.07	0.12	0.29	0.73	1.15	1.29
Electricity consumption evaporation with MVR [GJ/t product]	0.57	0.16	0.18	0.43	0.82	1.28	1.34

4.1.4 Heat pumps

Heat pumps are a suitable option for low-temperature heating options, meaning they have a large potential for the dairy processing industry, since the temperature requirements generally fall below 200°C. Heat pumps work analogously to MVRs, as explained in Section 4.1.3, by means of compressing a gas to a higher pressure, thereby increasing its temperature. This requires a heat source and electricity to power the compressor. The most common type of heat pump consists of a closed system, in which heat from the heat source is used to evaporate a refrigerant. Afterwards, the evaporated refrigerant can be compressed to increase its temperature, which can then be used to heat the heat sink through condensation of the

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[29] Excluding energy costs.
[30] TRL = Technology Readiness Level
[31] Based on TetraPak (2019a), using a steam energy content of 2789 kJ/kg.

refrigerant, which can be recirculated. In an open system (such as an MVR) the vapour is compressed directly and used as process heat (RVO, 2016a).
The dairy processing industry creates low-temperature waste heat in several of its processing steps, which can be utilised for process heating in combination with a heat pump. For instance, heat is available at a temperature of 70–90°C as a waste product of CIP systems, and waste heat at a temperature of 60–90°C is available from spray drying (RVO, 2016b; Moejes, Visser, Bitter, & Van Boxtel, 2018). In general, a temperature lift of around 50°C can be deemed profitable for industrial applications, meaning that waste heat from these sources can be used to supply heat to, for instance, pasteurisation (which can be performed using low pressure steam) or evaporation (requiring steam of around 115°C if an MVR is used) (RVO, 2016b; Tetra Pak, 2019b).

The costs for a heat pump are shown in Table 11 below.

Table 11 Techno-economic parameters for an industrial high-temperature heat pump

Parameter	Value	Source
Output capacity [MW_{th}]	<20	(Marsidi, 2019)
COP	3-5	
Temperature heat input [°C]	0-100	RVO (2016a)
Maximum temperature heat output [°C]	140	(Marsidi, 2019)
Load hours [h/yr]	8000	
CAPEX [EUR/kW_{th}]	400-5000	
Fixed O&M[32] [EUR/kW_{th}/yr]	60	
TRL	5	

4.1.5 Water reuse and wastewater treatment

The dairy processing industry creates a large volume of wastewater, around 0.2–10 litres of effluents per litre of milk processed (Vourch, Balannec, Chaufer, & Dorange, 2008). This water has relatively high chemical- and biochemical oxygen demand COD and BOD, meaning a lot of oxygen is required to break down the present effluents, indicating it will have a large impact on its receiving environment if left untreated (Kothari, Kumar, Pathak, & Tyag, 2017). To prevent environmental damage when releasing this wastewater in the environment, and to reduce the water usage of the processing facility, this water can be treated in several different ways. For instance, by applying reverse osmosis, effluents can be removed from dairy wastewater resulting in water of a similar quality to condensate from drying. This water can then be reused as heating, cooling or cleaning water, and by applying further processing steps drinking water can be obtained (Vourch, Balannec, Chaufer, & Dorange, 2008).

This process is already being applied in many dairy processing facilities. For instance, DOC Kaas is totally self-sufficient at its location at Zuivelpark, by treating the produced wastewater with reverse osmosis. The water is then used for washing of cheese curds, as cooling water or for heating purposes, leading to a reduction in water consumption of around 800 million litres of water per year (SenterNovem, 2006; DOC Kaas, 2019d). The costs for a reverse osmosis installation are shown in Table 12 below.

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[32] Excluding electricity costs.

Table 12 Techno-economic parameters for a reverse osmosis installation for dairy wastewater treatment

Parameter	Value	Source
Capacity [m^3 wastewater/h/m^2]	0.047[33]	(Suárez, Fernández, Iglesias, Iglesias, & Riera, 2015)
Load hours [h/yr]	7000	(Suárez, Fernández, Iglesias, Iglesias, & Riera, 2015)
Lifetime [yr]	1	(Suárez, Fernández, Iglesias, Iglesias, & Riera, 2015)
CAPEX [EUR_{2014}/m^2]	1015[34]	(Suárez, Fernández, Iglesias, Iglesias, & Riera, 2015)
Fixed OPEX [$EUR_{2014}/m^2/yr$]	20[35]	(Suárez, Fernández, Iglesias, Iglesias, & Riera, 2015)

Other treatment processes are also possible. Because of its high COD, around 1–10 g O_2/litre, there is a potential to anaerobically treat the wastewater and thereby produce hydrogen (Kothari, Kumar, Pathak, & Tyag, 2017). This is achieved through fermentation, in which carbohydrates are converted into hydrogen (called biohydrogen if this process is applied), thereby simultaneously reducing the COD. Hydrogen production rates are 0.156 m^3 H_2/kg COD when using dairy wastewater, or 0.016–0.493 m^3 H_2/kg COD when using whey wastewater[36] (Karadag, et al., 2014). As of 2020, no dairy processing company seems to be using this technology, but some tests using organic/food wastes in pilot plants have been performed[37]. The produced hydrogen could then be used for heat production. Furthermore, the feed left over after production of hydrogen still contains and appreciable amount of organic material and can therefore be further anaerobically treated, thereby producing methane. This two-stage process can lead to a COD-removal of over 80% and produces an additional amount of methane, around 0.061 m^3 CH_4/kg COD (Zhong, Stevens, & Hansen, 2015).

The potential of hydrogen and methane production from dairy wastewater is shown in Table 13 below[38].

Table 13 Potential hydrogen and methane production from dairy wastewater from a facility processing 1 billion litres of milk annually

Parameter	Value
Milk processed [billion litres]	1
Wastewater produced [billion litres]	0.2 – 10
Hydrogen produced [TJ]	0.4 – 198
Methane produced [TJ]	0.5 – 231

4.1.6 Bactofuges and bactocatch

Part of the heat demand for pasteurization or sterilisation can be replaced by removal of bacteria in a mechanical manner. Two options that are presently available are bactofuges and bactocatch (microfiltration). They were already introduced in section 2.2 since they are already used (at least for cheese production).

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[33] Source states that a surface of 426 m^2 is needed to be able to process 20 m^3 wastewater/h.

[34] Excludes installation costs on-site. This is for an area of 426 m^2.

[35] Only taking into account maintenance costs, stated as 2% of the CAPEX.

[36] Only 1 value was mentioned for hydrogen production using dairy wastewater in the used source, while many values using whey wastewater were reported.

[37] E.g. Jianzheng, Nanqi, Ming, & Yong (2002), Lee & Chung (2010) or La Licata et al. (2011).

[38] Using a hydrogen production rate of 0.156 m^3/kg COD and assuming a hydrogen energy content of 12.7 MJ/m^3 and a methane energy content of 37.8 MJ/m^3.

4.1.7 Implemented energy efficiency improvements

Most of the Dutch dairy processing locations (including all EU ETS registered ones) participate in the MJA3 covenant, which contains the obligation to report advances in energy efficiency. The resulting information on energy-efficiency improvements is shown in Figure 15 below, indicating that the Dutch dairy processing sector has increased its energy-efficiency with around 1.6% annually since 2006 (RVO, 2019). Implemented options include residual heat use and improved monitoring of energy information. A list of companies participating in the MJA3 covenant is shown in Appendix C.

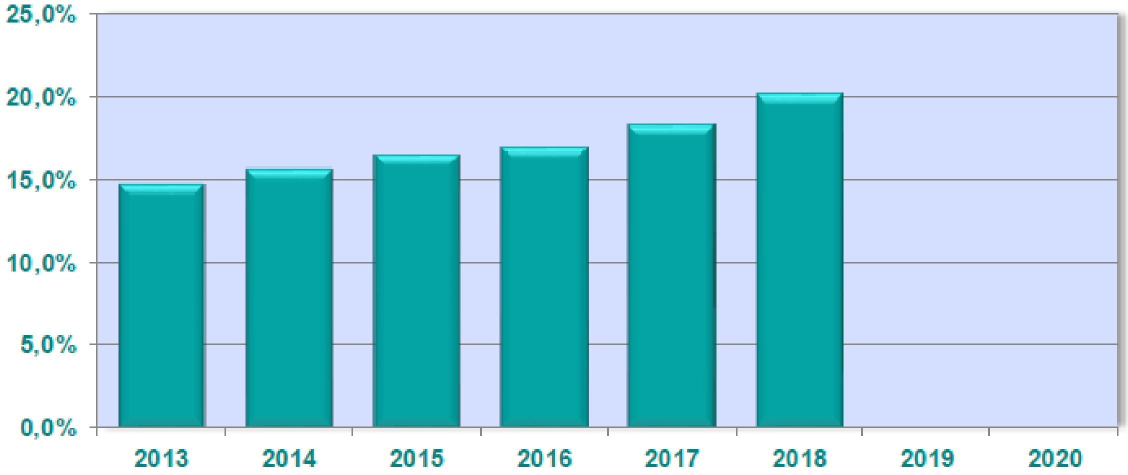

Figure 15 Cumulative energy-efficiency improvements of the Dutch dairy processing sector compared to 2006 (RVO, 2019, p. 6)

4.2 Fuel substitution

4.2.1 Electric boilers

Since typically no CO_2 is emitted from the production processes themselves, steam production can be regarded as the only source of emissions in the dairy processing industry. The highest thermal energy consumption in the dairy processing industry comes from the spray drying process, which requires an input of around 8.5 MW_{th}[39] of steam, which is mostly produced with natural gas. Electric boilers can be used to decarbonise this steam supply. Electric boilers can produce steam of up to 350°C and over 70 bar (Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017). If the used electricity is produced from a renewable energy source, it will be emission-free. Because of the many dairy farmers, who can install solar panels on their properties, delivering milk to the processing facilities, the potential for generation and import of renewable energy by these facilities is high. Already, Vreugdenhil Dairy Foods and FrieslandCampina use 100% renewable electricity in their European production locations (FrieslandCampina, 2019a; Vreugdenhil Dairy Foods, 2019d).

Electric boilers can be implemented both as base and flexible load, since the boilers have a short ramp-up time of around 5 minutes from off to full capacity (Berenschot, CE Delft, ISPT, 2015). FrieslandCampina investigated the use of an electric heater as flexible load for use in a spray dryer, so the process could switch to electrical heating at times of low electricity prices.

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[39] Tetra Pak (2019c) states that the spray dyer uses 11000 kg of steam/h. Assuming this steam has an energy content of 2789 kJ/kg.

The suitability of using electric boilers for flexible heating depends on the price difference between natural gas and electricity, as this is the driving force to recuperate the investment costs. (Berenschot, CE Delft, ISPT, 2015).

The costs for an electric boiler are shown in Table 14 below. It is noted that an electric boiler requires a grid connection and an internal electricity grid with a large capacity, the cost of which may vary depending on the local situation.

Table 14 Techno-economic parameters for an electric boiler

Parameter	Value	Source
Capacity [MW_e]	0.6-70	(Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017; Marsidi, 2019)
Efficiency [%]	95-99.9%	(Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017; Marsidi, 2019)
Lifetime [yr]	15	(Berenschot, CE Delft, ISPT, 2015)
CAPEX [EUR/kW_e]	150–190[40]	(Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017)
Fixed O&M [EUR/kW_e/yr]	1.1	(Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017)
TRL	9	(Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017; Marsidi, 2019)

4.2.2 Hydrogen boilers

Hydrogen (produced without CO_2 emissions) may in the future become available and economically viable as a fuel, depending on the production method and infrastructure. The hydrogen can be supplied through pipelines, trucks and ships, depending on the plant location. In the dairy production plants the natural gas burners need to be substituted by hydrogen burners, which are commercially available (Hart, Howes, & Lehner, 2015). A cost estimate for a 20 MW hydrogen boiler is provided in Table 15. Costs of pipelines are not included in the CAPEX and OPEX.

This option is a true decarbonisation option only if the hydrogen is generated in a carbon-free manner, such as electrolysis powered by green electricity. Alternatively, the hydrogen may be generated in a low-carbon manner from hydrogen with capturing and storing the emitted CO_2 (CCS).

Table 15 Techno-economic parameters of a hydrogen boiler

	Value	Source
Capacity [MW_{th}]	20	(Noothout, de Beer, Quant, & Blok, 2019)
Efficiency [%]	90	(Noothout, de Beer, Quant, & Blok, 2019)
Lifetime [yr]	20	(Van Berkel & Hernandez, 2018)
CAPEX (range) [$kEUR_{2019}/kW_{th}$]	0.14 (0.12-0.16)	(Noothout, de Beer, Quant, & Blok, 2019)

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[40] Typical cost of an electric boiler is EUR 60,000/MWe, the rest of the investment costs stem from the grid connection. These costs are highly site-specific (Berenschot, CE Delft, ISPT, 2015). According to Marsidi (2019), the total costs may be between 100 and 500 EUR/kWe (Marsidi, 2019)

Fixed O&M (range) [$\text{EUR}_{2019}/\text{kW}_{th}/\text{yr}$]	18 (15-20)	(Noothout, de Beer, Quant, & Blok, 2019)
TRL	9	(Van Berkel & Hernandez, 2018)

4.2.3 Biogas/green gas production for biogas boilers

By replacing the use of natural gas as a fuel in boilers by biogas, the heat supply of the dairy production processes can be decarbonised. This option is especially relevant for the dairy processing industry, since the manure produced by the dairy farmers can be utilised to produce biogas, through a process called digestion. In this process, the feedstock is kept under anaerobic conditions at a specific temperature, which allows for bacteria naturally present in the feedstock to digest it, thereby releasing methane (typically a gas with a methane content of 50–65% is produced) and carbon dioxide (Nesir, Ghazi, & Omar, 2012). The feedstock can either be pure manure or a mix of manure and another source of biomass. The former process is called mono-digestion and the latter co-digestion. Typical biogas yield will be around 40–45 Nm^3 per ton of manure processed for mono-digestion. This figure will be considerably higher when using co-digestion, but it depends strongly on the feedstock used. The substance remaining after digestion, called digestate, still contains the same minerals as the original manure and has to be processed further (Piñas, Venturini, Lora, & Roalcaba, 2018). The gas produced from digestion can be used in a boiler or CHP-plant, or it can be upgraded to green gas and sold to the gas grid. Not only is the created biogas a carbon neutral fuel, through digestion the methane released by the manure is processed, thereby preventing it from reaching the atmosphere (Ministerie van Economische Zaken, 2016).

To ensure the financial attractiveness of creating biogas through mono-digestion, it is important that its production costs are comparable to those of other renewable energy options. This can, for instance, be achieved through the availability of subsidies (Ministerie van Economische Zaken, 2016). Another option is stimulation coming from the dairy processing sector itself, which is already being done as of 2020 by FrieslandCampina, by helping with permits and contracts, creating attractive business cases by bundling applications and helping with value-creation for the produced biogas (FrieslandCampina, 2019e). This is an attractive option for the dairy processing sector, since the produced biogas can be used in their processing facilities, which is already being done in Borculo (FrieslandCampina, 2017c). The costs for the biogas boiler used at FrieslandCampina Borculo are shown in Table 16 below, as well as costs for a condensing boiler which is suited for biogas (Danish Energy Agency, 2020).

An alternative way of producing green gas or biogas is by thermal gasification of woody biomass, of which the syngas can be converted to methane. The attractiveness of this option is strongly dependent on the availability and costs of biomass, and also on alternative uses for the biomass supply. Depending on the production process, the gas may have a significant amount of impurities and other unwanted substances, which may require additional treatment of the gas.

Table 16 Techno-economic parameters for the biogas boiler as used at FrieslandCampina Borculo, and generic boiler parameters

Parameter		
Source	FrieslandCampina (2017c)	Danish Energy Agency (2020)
Capacity [t steam/h]	40	26 (between 0,6-65)[41]
Capacity [MW_{th}]	31[41]	20 (between 0.5-50)
Efficiency [%]	103.5	94-105 (LHV)

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[41] Assuming a steam energy content of 2789 MJ/t steam.

Lifetime [years]		25
CAPEX [EUR/kW$_{th}$]	103[42]	60
Fixed OPEX [EUR/kW$_{th}$/yr]	3[43]	2
TRL	9	9

4.2.4 Geothermal energy

Steam for the dairy industry can be produced through the use of Ultra Deep Geothermal (UDG) energy. Holes at a depth of over 4000 metres are drilled for this purpose, which can yield heat at a temperature of around 120 – 140°C, which can then be used for various processing steps in the dairy processing sector. Typically, two holes (called a doublet) are drilled to the desired depth. One of the holes is used to pump cool water into the hole, where it heats up due to the available geothermal energy. The water is then pumped back up, and releases its heat in a heat exchanger at the surface, after which it can be pumped back down (EBN, 2018a; In 't Groen, De Vries, Mijnlieff, & Smekens, 2019).
As of 2020, FrieslandCampina is already looking into the possibility of using UDG at their processing facility in Veghel (FrieslandCampina, 2017b). The costs for an UDG project are shown in Table 17 below.

Table 17 Techno-economic parameters for a ultradeep geothermal energy station

Parameter	Value	Source
Capacity [MW$_{th}$]	17	In 't Groen, De Vries, Mijnlieff, & Smekens (2019)
Load hours [h/yr]	7000	
Electricity use [TJ/yr]	22	
CAPEX [kEUR/kW]	2.5[44]	
Fixed O&M [kEUR/kW/yr]	0.1	

4.3 Other options: CCU/CCS

Carbon capture and utilisation or storage (CCU/CCS) is the technology that captures the CO_2 generated in the processes and prevents it from being emitted. This is a technical possibility, but unlikely to play a considerable role in the dairy sector and therefore not discussed in detail herein. The emission streams of the dairy processing facilities are relatively small-scale and the they are often not located close to potential CO_2 storage (or utilization) sites. Captured CO_2 would then need to be transported by pipeline or by truck to a storage site, for instance offshore in the North Sea. The production locations are also often not located close to other potential carbon capture users (see Figure 1), so there is limited potential for joint carbon capture projects. In summary, it is unlikely to find an economical carbon capture project, unless particular locations will be close to an open-access CO_2 pipeline project or are part of an industrial cluster consortium building CO_2 infrastructure.

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[42] Two boilers, investment 1.6 MEUR each, assuming shared capacity of 31 MW$_{th}$.
[43] Assumed 3% of CAPEX
[44] Does not include costs of geological research and permits. Costs of a heat distribution network of a length of 0.5 km included.

5 Discussion

In this section the previously introduced decarbonisation options will be discussed, focussing on barriers for implementation, infrastructural and other requirements, and other constraints.

Different decarbonisation options require different amount of infrastructural changes. Options with the least amount of changes needed (‘drop-in options’) are those related to the energy supply. Biogas and electric boilers can simply replace the currently existing boilers in the production facilities, but will require some changes to the energy distribution network. This is especially important for electric boilers, as the costs for grid connection are typically very high (see Table 14). Dutch dairy processing facilities are generally not located in dense industrial clusters, but are located close to the dairy farmers, to reduce the need for milk transport. This also means that the facilities are often far removed from the existing high-voltage electricity network, and that long distances need to be bridged for new connections to be possible. So, if electric boilers are placed in these facilities, the costs can be even higher than those shown in Table 14. Additionally, the national electricity transmission grid needs to have sufficient capacity, especially if electricity consumption is going to increase for industrial applications. These uncertainties make it less attractive for companies to invest in electrification options, since it can be unclear whether the required national infrastructure will be in place to support their investment choices.

The same problem can arise for the use of biogas boilers, but this can be prevented by upgrading the produced biogas to green gas, which can then be injected into the national gas grid. However, this will reduce the efficiency of the gas-production, and it will be more costly.

Hydrogen boilers are presently unattractive due to the high cost and low availability of low-carbon hydrogen. On the long term hydrogen may become a viable option, although it will be costly to connect many of the dairy production sites to a separate hydrogen network. This will be no hurdle if the existing gas network will be used for hydrogen distribution. Otherwise, they will rely on supply of hydrogen by truck of ship.

Apart from economic considerations, the dairy processing sector has the technical possibility to fully decarbonise its facilities. This possibility exists because of the low temperatures required for the production processes, meaning that they can be produced from carbon-neutral sources, by using an electric or biogas boiler. To reduce the required size of the boiler installation, energy-efficiency measures can first be taken. The options mentioned in Section 4 can be combined, which will have an impact on their effect. For instance, by applying reverse osmosis and an MVR, the improvement in energy-efficiency will be smaller than the effect of each option added up separately. This is because installing an MVR lowers the energy required for evaporation, thereby reducing the potential energy savings by mechanically concentrating the feed. Similarly, since application of reverse osmosis means that less water is removed in the evaporator, the effect of increasing the energy-efficiency of this step will be less pronounced.

In the light of decarbonisation of the dairy sector as a whole, it is also important to understand the distribution of emissions along the production chain. As mentioned, the emissions up to the farm-gate are much higher than those arising from the processing of the milk[45], and therefore reducing the carbon footprint of milk production itself can have a significant effect. Research regarding this topic is abundant, and a study about the specific Dutch situation has been published as well (Dolfing, 2017; Knapp, Laur, Vadas, Weiss, & Tricarico, 2014; Weiske, et al., 2006).

The large number of dairy farms in the production chain of the dairy companies can be a source of sustainable energy. As mentioned, biogas can be produced from manure. In 2019, this process has a potential of 2 – 3 PJ of biogas, with increased potential after 2020 (Ministerie van Economische Zaken, 2016). Another option is the generation of electricity from renewable sources. This is an attractive option because of the large amount of land that dairy farmers hold (around 28% of total area of the Netherlands), resulting in a large potential for electricity from solar panels and wind turbines (van der Peet, et al., 2018). A potential of 361 MW_{peak} is estimated to be available from solar panels on roofs of dairy farmers, thereby generating 285 GWh (=1026 TJ) (Krebbekx, Lambregts, de Wolf, & van Seventer, 2011). Already 25% of the dairy farms have solar panels (ZuivelNL, 2020).

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[45] Over 92% of emissions stem from processing at the dairy farm (Doornewaard, Reijs, Beldman, Jager, & Hoogeveen, 2018).

References

Andritz. (2018a). *HIGH THROUGHPUT AND EFFICIENT SEPARATION FOR VEGETABLE MILK PRODUCTION.* Retrieved January 6, 2020, from https://www.andritz.com/resource/blob/284078/44b9f0e43b9014a2b7ef7768b39326d5/se-f-decanter-for-vegetal-milk-data.pdf

Andritz. (2018b). *EFFICIENT SEPARATION AND HYGIENIC PROCESSING IN THE DAIRY INDUSTRY.* Retrieved January 6, 2020, from https://www.andritz.com/resource/blob/13690/ac8d2306ebd040a1d3b090c666a3f674/se-f-decanter-dairy-brochure-en-data.pdf

Arcadis. (2013). *MILIEUEFFECTRAPPORTAGE UITBREIDING FRIESLANDCAMPINA DOMO TE BORCULO SAMENVATTING.* Retrieved from http://www.commissiemer.nl/docs/mer/p27/p2740/2740-012mer_sam.pdf

Berenschot, CE Delft, ISPT. (2015). *Power to products.* Retrieved from https://www.topsectorenergie.nl/sites/default/files/uploads/Eindrapport_Power_to_Products_externe_link.pdf

Berenschot, Energy Matters, CE Delft, Industrial Energy Experts. (2017). *Electrification in the Dutch process industry.* Retrieved from https://www.ce.nl/publicaties/download/2278

Bijloo, J. (2015, February 10). *BESCHERMDE GEOGRAFISCHE AANDUIDING VOOR GOUDA HOLLAND.* Retrieved September 24, 2019, from http://www.eu-streekproducten.nl/sites/default/files/Productdossier%20BGA%20Gouda%20Holland%20gewijzigd.pdf

Birgersson, S., Karlsson, B., & Söderlund, L. (2009). *Soy Milk: an attributional Life Cycle Assessment examining the potential environmental impact of soy milk.* Retrieved from https://pdfs.semanticscholar.org/58ef/a4a24e6647fd82fed065bb36f7a18217f416.pdf?_ga=2.170319776.1252264485.1575368161-1210742412.1566287622

BlueTerra. (2019). *Masterplan Energie 2020 bij FrieslandCampina Leeuwarden*. Retrieved August 9, 2019, from https://blueterra.nl/project/masterplan-energie-2020-bij-frieslandcampina-leeuwarden/

Boerderij. (2015, February 4). *Kaasfabriek A-ware in Heerenveen schaalt stapsgewijs op*. Retrieved from https://www.boerderij.nl/Rundveehouderij/Nieuws/2015/2/Kaasfabriek-A-ware-in-Heerenveen-schaalt-stapsgewijs-op-1698676W/

Britz, T. J., Van Schalkwyk, C., & Hung, Y. (2004). Treatment of dairy processing wastewaters. In L. Wang, Y. Hung, H. Lo, & C. Yapijakis, *Waste Treatment in the Food Processing Industry* (pp. 1-28). Boca Raton: CRC Press .

Brush, A. (2012). Energy Efficiency Improvement and Cost Saving Opportunities for the Dairy Processing Industry.

CBS. (2019b). *Dierlijke mest; productie, transport en gebruik; kerncijfers, 1950-2017*. Retrieved from CBS Statline: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82504NED/table?fromstatweb

CBS. (2020). *Melkaanvoer en zuivelproductie door zuivelfabrieken*. Retrieved from CBS Statline: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/7425ZUIV/table?fromstatweb

Chamberland, J., Mercier-Bouchard, D., Dussault-Chouinard, I., Benoit, S., Doyen, A., Britten, M., & Pouliot, Y. (2019). On the Use of Ultrafiltration or Microfiltration Polymeric Spiral-Wound Membranes for Cheesemilk Standardization: Impact on Process Efficiency. *Foods, 8*(6), 198.

Chandan, R., Kilara, A., & Shah, N. (2008). *Dairy Processing & Quality Assurance.* John Wiley & Sons, Inc.

Cheese Science. (2019). *Coagulation*. Retrieved October 7, 2019, from https://www.cheesescience.org/coagulation.html#acid

Dagblad van het Noorden. (2017). *Zuivelfabriek Bedum grootste van Nederland*. Retrieved from Dagblad van het Noorden: https://www.dvhn.nl/economie/Zuivelfabriek-Bedum-grootste-van-Nederland-22023412.html

Dagblad van het Noorden. (2019, October 31). *FrieslandCampina Bedum ziet af van omleiding Boterdiep*. Retrieved 2019, from https://www.dvhn.nl/groningen/FrieslandCampina-Bedum-ziet-af-van-omleiding-Boterdiep-24774921.html

Danish Energy Agency. (2020). *Technology Data for Industrial Process Heat.* Retrieved from https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-industrial-process-heat

Daufin, G., Escudier, J. P., Carrere, H., Berot, S., Fillaudeau, L., & Decloux, M. (2001). RECENT AND EMERGING APPLICATIONS OF MEMBRANE PROCESSES IN THE FOOD AND DAIRY INDUSTRY. *Food and Bioproducts Processing, 79*(2), 89-102.

DOC Kaas. (2016). *JAARVERSLAG 2015.* Retrieved from https://www.dockaas.nl/nl/doc-kaas/jaarverslagen/

DOC Kaas. (2019a). *Jaarverslag coöperatie DOC Kaas B.A. 2018.* Retrieved from https://www.dockaas.nl/nl/doc-kaas/jaarverslagen/

DOC Kaas. (2019b). *Missie*. Retrieved October 31, 2019, from https://www.dockaas.nl/nl/

DOC Kaas. (2019c). *Historie*. Retrieved November 12, 2019, from https://www.dockaas.nl/nl/doc-kaas/historie/

DOC Kaas. (2019d). *Duurzaamheid*. Retrieved November 12, 2019, from https://www.dockaas.nl/nl/doc-kaas/duurzaamheid/

Dolfing, A. (2017). *Scenarios for reducing the greenhouse gas emissions of the Dutch dairy sector.* Master Thesis. Retrieved from https://dspace.library.uu.nl/bitstream/handle/1874/352967/Masterthesis%20-%20Lex%20Dolfing.pdf?sequence=2&isAllowed=y

Doornewaard, G., Hoogeveen, J., Jager, J., Reijs, J., & Beldman, A. (2019). *Sectorrapportage Duurzame Zuivelketen; Prestaties 2018 in perspectief.* Wageningen: Wageningen Economic Research. Retrieved from https://library.wur.nl/WebQuery/wurpubs/fulltext/508871

Doornewaard, G., Reijs, J., Beldman, A., Jager, J., & Hoogeveen, M. (2018). *Sectorrapportage Duurzame Zuivelketen.* Retrieved from https://edepot.wur.nl/466401

Dutch Emissions Authority. (2014). *Emissiecijfers over 2008-2012.* Retrieved from https://www.emissieautoriteit.nl/onderwerpen/rapportages-en-cijfers-ets/documenten/publicatie/2014/11/28/co2-emissiecijfers-2008-2012-per-bedrijf-15-05-2013

Dutch Emissions Authority. (2019). *Emissiecijfers over 2013-2018.* Retrieved from https://www.emissieautoriteit.nl/documenten/publicatie/2019/04/04/emissiecijfers-2013-2018

Dutch emissions authority. (2020). *Emissiecijfers 2013-2019*. Retrieved from NEa: https://www.emissieautoriteit.nl/documenten/publicatie/2020/04/16/emissiecijfers-2013---2019

EBN. (2018a). *Focus energie in beweging.* Retrieved from https://www.ebn.nl/wp-content/uploads/2018/06/EBN_Focus2018.pdf

EBN. (2018b). *Masterplan aardwarmte in Nederland.* Retrieved from https://www.ebn.nl/wp-content/uploads/2018/05/20180529-Masterplan-Aardwarmte-in-Nederland.pdf

EEA. (2019). *Reported data on large combustion plants covered by the Industrial Emissions Directive (2010/75/EU).* Retrieved from https://www.eea.europa.eu/data-and-maps/data/lcp-9

European Commission. (2015). *EU Agricultural Outlook: Prospects for EU agricultural markets and income 2015-2025.* Retrieved from https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/farming/documents/agricultural-outlook-report-2015_en.pdf

European Commission. (2018a). *Best Available Techniques (BAT) Reference Document in the Food, Drink and Milk Industries.*

European Commission. (2018b). *EU commodity market development: Medium-term agricultural outlook.* Retrieved from http://publications.jrc.ec.europa.eu/repository/bitstream/JRC113987/outlook2018_wsproceedings_final_online.pdf

European Commission. (2019a). *Milk market observatory: EU historical prices per Member State*. Retrieved October 11, 2019, from https://ec.europa.eu/info/food-farming-fisheries/farming/facts-and-figures/markets/overviews/market-observatories/milk

European Commission. (2019b). *Final Report Summary - ENTHALPY (Enabling the drying process to save energy and water, realising process efficiency in the dairy chain)*. Retrieved November 25, 2019, from https://cordis.europa.eu/project/rcn/110707/reporting/en

Evmi. (2016). *88 banen weg bij reorganisatie FrieslandCampina*. Retrieved October 31, 2019, from https://www.evmi.nl/nieuws/88-banen-weg-bij-reorganisatie-frieslandcampina

FAO. (1988). *Accounting and equipment costs.* Retrieved September 24, 2019, from http://www.fao.org/3/T0045E/T0045E05.htm#ch5

Finnegan, W., Goggins, J., Clifford, E., & Zhan, X. (2017). Environmental impacts of milk powder and butter manufactured in the Republic of Ireland. *Science of the Total Environment, 579*, 159-168.

FrieslandCampina. (2013a). *FrieslandCampina Member Council approves investment of 245 million euros to expand Borculo and Leeuwarden*. Retrieved August 9, 2019, from https://www.frieslandcampina.com/en/news/2013-08-29-ledenraad-frieslandcampina-stemt-in-met-investering-uitbreiding-borculo-en-leeuwarden/

FrieslandCampina. (2013b). *FrieslandCampina Open Dagen Workum - juni 2013*. Retrieved October 31, 2019, from https://www.youtube.com/watch?v=q_AySnUv1os

FrieslandCampina. (2016). *route2020 strategy: sustainable growth and value creation.* Retrieved from https://www.frieslandcampina.com/app/uploads/sites/2/2016/08/FrieslandCampina-Strategy-route2020-2016-Eng.pdf

FrieslandCampina. (2017a). *Jaarverslag 2016.* Retrieved from https://www.frieslandcampina.com/app/uploads/sites/3/2017/03/FrieslandCampina-Jaarverslag-2016.pdf

FrieslandCampina. (2017b). *Zoeken naar aardwarmte voor Veghel*. Retrieved November 22, 2019, from https://www.frieslandcampina.com/nl/nieuws/zoeken-naar-aardwarmte-veghel/

FrieslandCampina. (2017c). *ERVARINGEN MET GROENE STOOM.* Retrieved from http://www.biowkk.eu/wp-content/uploads/2017/05/FrieslandCampina-Ervaringen-met-groene-stoom.pdf

FrieslandCampina. (2018). *Jaarverslag 2017.* Retrieved from https://www.frieslandcampina.com/app/uploads/sites/3/2018/02/FrieslandCampina-Jaarverslag-2017.pdf

FrieslandCampina. (2019a). *Jaarverslag 2018.* Retrieved from https://www.frieslandcampina.com/app/uploads/sites/3/2019/02/Jaarverslag-2018-FrieslandCampina-NV-WEB.pdf

FrieslandCampina. (2019b). *Nieuwe energievoorziening FrieslandCampina Veghel*. Retrieved August 8, 2019, from https://www.frieslandcampina.com/nl/nieuws/nieuwe-energievoorziening-frieslandcampina-veghel/

FrieslandCampina. (2019c). *FrieslandCampina timeline*. Retrieved November 12, 2019, from https://www.frieslandcampina.com/en/organisation/our-heritage/frieslandcampina-timeline/

FrieslandCampina. (2019d). *Contact*. Retrieved November 12, 2019, from https://www.frieslandcampina.com/en/contact/

FrieslandCampina. (2019e). *Cooperative Jumpstart*. Retrieved November 26, 2019, from https://www.frieslandcampina.com/en/cooperative-jumpstart/

FrieslandCampina. (2019f, April 1). Van wei van kaasfabrieken tot ingrediënten voor kindervoedingsindustrie. Short Twitter video with interview Michiel de Rooij (plant director). Retrieved from https://twitter.com/MinisterieEZK/status/1112735679237287938

FrieslandCampina Butter. (2019). *Plants*. Retrieved August 9, 2019, from https://www.frieslandcampinabutter.com/nl/fabrieken/

GEA Process Engineering. (2010). *Milk Powder Technology Evaporation and Spray Drying.* Retrieved from https://www.gea.com/en/binaries/Milk%20Powder%20Technology%20-%20Evaporation%20and%20Spray%20Drying_tcm11-33784.pdf

Gedeputeerde Staten van Drenthe. (2011). *BESLUIT VAN GEDEPUTEERDE STATEN VAN DRENTHE INGEVOLGE DE WABO VOOR FRIESLANDCAMPINA DOMO TE BEILEN*. Retrieved October 31, 2019, from https://docplayer.nl/32238138-Besluit-van-gedeputeerde-staten-van-drenthe-ingevolge-de-wabo-voor-frieslandcampina-domo-te-beilen.html

Gemeente Gorinchem. (2013). *Uitbreiding Promelca bestemmingsplan*. Retrieved from Gemeente Gorinchem: https://www.planviewer.nl/imro/files/NL.IMRO.0512.BP2013138-4001/t_NL.IMRO.0512.BP2013138-4001.html

Green Deal. (2018). *Green Deal ultradiepe geothermie (UDG).* Retrieved from https://www.greendeals.nl/sites/default/files/downloads/GD217-dealtekst-Ultradiepe-Geothermie.pdf

Groninger Internet Courant. (2017). *Uitbreiding moet van FrieslandCampina Bedum grootste zuivellocatie van Nederland maken*. Retrieved August 8, 2019, from https://www.gic.nl/economie/uitbreiding-moet-van-frieslandcampina-bedum-grootste-zuivellocatie-van-nederland-maken

Hart, D., Howes, J., & Lehner, F. (2015). *Scenarios for deployment of hydrogen in contributing to meeting carbon budgets and the 2050 target.* E4Tech, UCL Energy Institute, University College London, Kiwa Gastec.

Henderson, A., & Unnasch, S. (2017). *Life Cycle Assessment of Ripple Non-Dairy Milk .* Retrieved from https://www.ripplefoods.com/pdf/LIfe%20Cycle%20Assessment%20of%20Non-Dairy%20Milk.pdf

In 't Groen, B., De Vries, C., Mijnlieff, H., & Smekens, K. (2019). *CONCEPTADVIES SDE++ 2020 Geothermie.* Retrieved from https://www.pbl.nl/sites/default/files/downloads/pbl-2019-conceptadvies-sde-plus-plus-2020-geothermie_3692.pdf

Jianzheng, L., Nanqi, R., Ming, L., & Yong, W. (2002). Hydrogen bio-production by anaerobic fermentation of organic wastewater in pilot-scale. *Acta Energiae Solaris Sinica, 23*, 252-256.

Karadag, D., Köroglu, O., Ozkaya, B., Cakmakci, M., Heaven, S., & Banks, C. (2014). A review on fermentative hydrogen production from dairy industry wastewater. *Journal of Chemical Technology & Biotechnology, 89*(11), 1627-1636.

Knapp, J. R., Laur, G. L., Vadas, P. A., Weiss, W. P., & Tricarico, J. M. (2014). Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. *Journal of Dairy Science, 97*(6), 3231-3261.

Kothari, R., Kumar, V., Pathak, V., & Tyag, V. (2017). Sequential hydrogen and methane production with simultaneous treatment of dairy industry wastewater: Bioenergy profit approach. *International journal of hydrogen energy, 42*, 4870-4879.

Krebbekx, J., Lambregts, E., de Wolf, W., & van Seventer, M. (2011). *Melk, de groene motor.* Retrieved from https://www.rvo.nl/sites/default/files/bijlagen/Routekaart%20zuivelindustrie%20-%20rapport%20-%20april%202011_0.pdf

La Licata, B., Sagnelli, F., Boulanger, A., Lanzini, A., Leone, P., Zitella, P., & Santarelli, M. (2011). Bio-hydrogen production from organic wastes in a pilot plant reactor and its use in a SOFC. *International Journal of Hydrogen Energy, 36*(13), 7861-7865.

Lee, Y. W., & Chung, J. (2010). Bioproduction of hydrogen from food waste by pilot-scale combined hydrogen/methane fermentation. *International journal of hydrogen energy, 35*(21), 11746-11755.

Leeuwarder Courant. (2019, October 9). *FrieslandCampina laat bij A-ware in Heerenveen mozzarella maken*. Retrieved October 14, 2019, from https://www.lc.nl/friesland/FrieslandCampina-laat-bij-A-ware-mozzarella-maken-24905876.html

Marsidi, M. (2018). *Technology Factsheet: Industrial Mechanical Vapour Recompression (MVR).* Retrieved January 23, 2020, from https://energy.nl/wp-content/uploads/2019/06/Industrial-mechanical-vapour-recompression-1.pdf

Marsidi, M. (2019). *Technology Factsheet: Electric Industrial Boiler.* Retrieved from energy.nl: https://energy.nl/wp-content/uploads/2018/12/Technology-Factsheet-Electric-industrial-boiler-1.pdf

Marsidi, M. (2019). *Technology Factsheet: Industrial High Temperature Heat Pump.* Retrieved from energy.nl: https://energy.nl/wp-content/uploads/2019/06/Industrial-high-temperature-heat-pump-2.pdf

Marsidi, M., & Lensink, S. (2019). *CONCEPTADVIES SDE++ CO2-REDUCERENDE OPTIES Grootschalige warmtepompen.* Retrieved from https://www.pbl.nl/sites/default/files/downloads/pbl-2019-conceptadvies-SDE-plus-plus-grootschalige-warmtepompen_3746.pdf

Melkvee. (2014, December). *Ambitieus A-ware blijft familiebedrijf.* Retrieved from http://edepot.wur.nl/330735

Melkvee. (2016, December). *Passie voor poeder.* Retrieved from http://edepot.wur.nl/404223

Ministerie van Economische Zaken. (2016). *Aankondiging regeling voor monomestvergisting.* Retrieved from https://groengas.nl/wp-content/uploads/2016/10/Kamerbrief-Aankondiging-regeling-voor-monomestvergisting.pdf

Mistry, V. (2002). Manufacture and application of high milk protein powder. *Le Lait, 82*(4), 515-522.

Moejes, S., & Van Boxtel, A. (2017). Energy saving potential of emerging technologies in milk powder production. *Trends in Food Science & Technology, 60*, 31-42.

Moejes, S., Visser, Q., Bitter, J., & Van Boxtel, A. (2018). Closed-loop spray drying solutions for energy efficient powder production. *Innovative Food Science & Emerging Technologies, 47*, 24-37.

National Institute for Public Health and the Environment. (2016). *The diet of the Dutch.* Retrieved from https://www.rivm.nl/bibliotheek/rapporten/2016-0082.pdf

Nesir, M., Ghazi, T., & Omar, R. (2012). Anaerobic digestion technology in livestock manure treatment for biogas production: A review. *Engineering in Life Sciences, 12*(3), 258-269.

Noothout, P., de Beer, J., Quant, M., & Blok, K. (2019). *erkenning uitbreiding SDE+ met industriële opties; Inschatting van subsidie-intensiteit van geselecteerde technologieën en evaluatie van knelpunten.* Navigant.

Nutricia. (2020). *Onze Geschiedenis*. Retrieved from Nutricia Voor Jou: https://www.nutriciavoorjou.nl/over-nutricia/onze-geschiedenis/

Omroep Brabant. (2019). *Nieuwe fabriek babymelkpoeder in Haps kan dagelijks 3,5 miljoen baby's gaan voeden*. Retrieved from Omroep Brabant: https://www.omroepbrabant.nl/nieuws/2967687/Nieuwe-fabriek-babymelkpoeder-in-Haps-kan-dagelijks-3-5-miljoen-baby-s-gaan-voeden

Piñas, J. A., Venturini, O. J., Lora, E. E., & Roalcaba, O. D. (2018). Technical assessment of mono-digestion and co-digestion systems for the production of biogas from anaerobic digestion in Brazil. *Renewable Energy, 117*, 447-458.

Poore, J., & Nemecek, T. (2018). Reducing food’s environmental impacts through producers and consumers. *Science*, Vol. 360, 987–992.

Provincie Noord-Brabant. (2015). *Danone Nutricia Early Life Nutrition - Haps - omgevingsvergunning* . Retrieved from Provincie Noord-Brabant:

https://www.brabant.nl/loket/vergunningen-meldingen-en-ontheffingen/vergunning-detail?id=5c0a7977-c646-4946-b7b4-2d638a872a2a

Provincie Noord-Brabant. (2019). *Nutricia Cuijk BV - Haps - omgevingsvergunning* . Retrieved from Provincie Noord-Brabant: https://www.brabant.nl/loket/vergunningen-meldingen-en-ontheffingen/vergunning-detail?id=071dffa9-e3b9-4079-88e1-1ff9ed40c996

Rabobank. (2018). *Dare Not to Dairy.* Retrieved from https://services.rabobank.com/publicationservice/download/publication/token/tRJL6VMr6xTTT5eFd6m0

Ramírez, C., Patel, M., & Blok, K. (2006). From fluid milk to milk powder: Energy use and energy efficiency in the European dairy industry. *Energy, 31*, 1984-2004.

Ramos, O., Pereira, R., Rodrigues, R., Teixeira, J., Vicente, A., & Malcata, F. (2016). Whey and Whey Powders: Production and Uses. *Encyclopedia of Food and Health, 5*, 498-505.

Roos, E., Garnett, T., Watz, V., & Sjors, C. (2018). *The role of dairy and plant based dairy alternatives in sustainably diets.* Swedish University of Agricultural Sciences, the research platform Future Food .

Royal A-ware. (2012, May 29). *REALISATIE KAASFABRIEK IN NEDERLAND MET ZUIVELGIGANT FONTERRA*. Retrieved from https://www.royal-aware.com/nl/over-royal-a-ware/nieuws/realisatie-kaasfabriek-in-nederland-met-zuivelgigant-fonterra/7

Royal A-ware. (2018, July 19). *ROYAL A-WARE BOEKT IN 2017 WEER EEN PRIMA RESULTAAT*. Retrieved from A-ware Food Group: https://www.royal-aware.com/nl/over-royal-a-ware/nieuws/royal-a-ware-boekt-in-2017-weer-een-prima-resultaat/115

Royal A-ware. (2019a). *History*. Retrieved November 12, 2019, from https://www.royal-aware.com/en/about-royal-a-ware/history

Royal A-ware. (2019b). *Activities*. Retrieved September 18, 2019, from https://www.royal-aware.com/en/about-royal-a-ware/activities

Royal A-ware. (2019c, October 9). *ANNOUNCEMENT CONTRACT ACQUISITION SALES OF MOZZARELLA*. Retrieved October 14, 2019, from https://www.royal-aware.com/en/about-royal-a-ware/news/announcement-contract-acquisition-sales-of-mozzarella/148

RTVDrenthe. (2015). *Meer dan tweehonderd banen weg bij FrieslandCampina in Beilen*. Retrieved October 31, 2019, from https://www.rtvdrenthe.nl/nieuws/95936/Meer-dan-tweehonderd-banen-weg-bij-FrieslandCampina-in-Beilen

RVO. (2016a). *Industriële Warmtepompen.* Retrieved from https://www.rvo.nl/sites/default/files/2016/02/140220-01%20RVO_Warmtepompen_04.pdf

RVO. (2016b). *BEST PRACTICE INDUSTRIËLE WARMTEPOMPEN.* Retrieved from https://www.rvo.nl/sites/default/files/2018/02/Best%20Practice%20Industriele%20Warmtepompen%20januari%202016.pdf

RVO. (2019). *MJA-Sectorrapport 2018 Zuivelindustrie.*

SenterNovem. (2006). *Leven met Water: 49 waterprojecten in Nederland binnen LIFE-Milieu (1992-2006).* Retrieved from https://ec.europa.eu/environment/archives/life/publications/otherpub/documents/waternl_nl.pdf

Sharma, A., Jana, A., & Chavan, R. (2012). Functionality of Milk Powders and Milk-Based Powders for End Use Applications—A Review. *Comprehensive Reviews in Food Science and Food Safety, 11*(5), 518-528.

Suárez, A., Fernández, P., Iglesias, J. R., Iglesias, E., & Riera, F. A. (2015). Cost assessment of membrane processes: A practical example in the dairy wastewater reclamation by reverse osmosis. *Journal of Membrane Science, 493*, 389-402.

Tauw. (2014). *Aanvraag revisievergunning FrieslandCampina Cheese & Butter Lochem .* Retrieved from https://repository.officiele-overheidspublicaties.nl/externebijlagen/exb-2014-20824/1/Bijlage/exb-2014-20824.pdf

Tetra Pak. (1995). *DAIRY PROCESSING HANDBOOK.* Retrieved from https://dairyprocessinghandbook.com/

Tetra Pak. (2019b). *Tetra Pak® Pasteurizer D Base.* Retrieved November 20, 2019, from https://assets.tetrapak.com/static/documents/processing/tetra-pak-pasteurizer-d-base.pdf

Tetra Pak. (2019c). *Tetra Pak® Spray Dryer Wide Body.* Retrieved November 22, 2019, from https://assets.tetrapak.com/static/documents/processing/spray-dryer-wb-pd10224.pdf

Tetra Pak. (2019d). *TETRA PAK® SEPARATOR H80.* Retrieved November 28, 2019, from https://assets.tetrapak.com/static/documents/processing/separator-h80.pdf

Tetra Pak. (2020). *Tetra Pak® Homogenizer 250.* Retrieved January 6, 2020, from https://assets.tetrapak.com/static/documents/processing/tetra-pak-homogenizer-250-pd-leaflet.pdf

Tetra Pak. (2020a). *TETRA PAK® EVAPORATOR FALLING FILM TVR.* Retrieved January 23, 2020, from https://assets.tetrapak.com/static/documents/processing/evaporator-falling-film-tvr.pdf

Tetra Pak. (2020b). *TETRA PAK® EVAPORATOR FALLING FILM MVR.* Retrieved January 23, 2020, from https://assets.tetrapak.com/static/documents/processing/evaporator-falling-film-mvr.pdf

Tetra Pak. (2020c). *Tetra Pak® Indirect UHT unit DE*. Retrieved January 6, 2020, from https://www.tetrapak.com/processing/uht-treatment/tetra-pak-indirect-uht-unit-de

Tetra Pak. (2020d). *Tetra Pak® Cheese Vat OST CH5.* Retrieved January 6, 2020, from https://assets.tetrapak.com/static/documents/processing/cheese-vat-pd41189.pdf

Tetra Pak. (2020e). *Tetra Pak® Casomatic system SC7.* Retrieved January 6, 2020, from https://assets.tetrapak.com/static/documents/processing/casomatic-sc7-pd10246.pdf

TetraPak. (2019a). *Tetra Pak® Evaporator Falling Film MVR.* Retrieved November 12, 2019, from https://assets.tetrapak.com/static/documents/processing/evaporator-falling-film-mvr-pd10220.pdf

The Courtyard Dairy. (2013, June 12). *Rennet in cheese – the science: how does rennet work?* Retrieved from https://www.thecourtyarddairy.co.uk/blog/cheese-musings-and-tips/rennet-in-cheese-the-science-how-rennet-works/

Topsector Energie. (2019). *Hergebruik van latente warmte van (sproei)drogers m.b.v. innovatieve zeoliet warmtepomp.* Retrieved from https://projecten.topsectorenergie.nl/projecten/hergebruik-van-latente-warmte-van-sproeidrogers-mbv-innovatieve-zeoliet-warmtepomp-00018966

Van Berkel, A., & Hernandez, J. (2018). *Taking the C out of steam.* Lux Research.

van Boxtel, A. J., Boon, M. A., van Deventer, H. C., & Bussmann, P. J. (2014). *Zeolites for Reducing Drying Energy Usage.* doi:doi:10.1002/9783527631728.ch25

van der Peet, G., Leenstra, F., Vermeij, I., Bondt, N., Puister, L., & van Os, J. (2018). *Feiten en cijfers over de Nederlandse veehouderijsectoren 2018.* Retrieved from https://edepot.wur.nl/464128

Veeteelt. (2015). *Fonterra-fabriek in Heerenveen uit de startblokken*. Retrieved from https://veeteelt.nl/nieuws/fonterra-fabriek-heerenveen-uit-de-startblokken

Veldhuisen, C. (2016). *Benefits and costs of a company dedicated transportation network.* Master Thesis. Retrieved from https://pure.tue.nl/ws/files/46946483/855861-1.pdf

Vourch, M., Balannec, B., Chaufer, B., & Dorange, G. (2008). Treatment of dairy industry wastewater by reverse osmosis for water reuse. *Desalination, 219*(1-3), 190-202.

Vreugdenhil Dairy Foods. (2015, May). *Growing responsibly together: CSR report 2014.* Retrieved from https://www.vreugdenhildairyfoods.com/globalassets/corporate/contact/downloads-pers/csr-report-2014_en.pdf

Vreugdenhil Dairy Foods. (2019a). Retrieved from Vreugdenhil Dairy Foods zet groei in volume door: https://www.vreugdenhildairyfoods.nl/globalassets/corporate/nieuws/persbericht-2019.pdf

Vreugdenhil Dairy Foods. (2019b). *Gezonde en betrokken medewerkers*. Retrieved October 31, 2019, from https://www.vreugdenhildairyfoods.nl/duurzaamheid/gezonde-en-betrokken-medewerkers/

Vreugdenhil Dairy Foods. (2019c). *https://www.vreugdenhildairyfoods.nl/over-vreugdenhil/ons-verhaal/*. Retrieved November 12, 2019, from https://www.vreugdenhildairyfoods.nl/over-vreugdenhil/ons-verhaal/

Vreugdenhil Dairy Foods. (2019d, April). *Creating Shared Value: Overview 2018.* Retrieved from https://www.vreugdenhildairyfoods.nl/globalassets/corporate/duurzaamheid/jaarverslag-2018/samenvatting-jaarverslag-vreugdenhil-2018-nl-digitaal-def.pdf

Vreugdenhil-online. (2013, December 22). *Vreugdenhil Dairy Foods laat nieuwe fabriek bouwen*. Retrieved from http://www.vreugdenhil-online.com/index.php/vreugdenhil-dairy-foods-laat-nieuwe-fabriek-bouwen/

Wageningen University and Research. (2019). *De vraag naar zuivelproducten blijft wereldwijd groeien door stijgende importvraag vanuit Azië en Afrika*. Retrieved January 21, 2020, from https://www.agrimatie.nl/themaResultaat.aspx?subpubID=2232&sectorID=3309&themaID=2276&indicatorID=3460

Walstra, P., Wouters, J., & Geurts, T. (2006). *Dairy Science and Technology.* Taylor & Francis Group, LLC.

Weiske, A., Vabitsch, A., Olesen, J. E., Schelde, K., Michel, J., Friedrich, R., & Kaltschmitt, M. (2006). Mitigation of greenhouse gas emissions in European conventional and organic dairy farming. *Agriculture, ecosystems & environment, 112*(2-3), 221-232.

Wu, W., Patel, K., Rogers, S., & Chen, X. (2007). Monodisperse Droplet Generators as Potential Atomizers for Spray Drying Technology. *Drying Technology, 25*(12), 1907-1916.

Xu, T., & Flapper, J. (2011). Reduce energy use and greenhouse gas emissions from global dairy processing facilities. *Energy Policy, 39*(1), 234-247.

Zhong, J., Stevens, D. K., & Hansen, C. L. (2015). Optimization of anaerobic hydrogen and methane production from dairy processing waste using a two-stage digestion in induced bed reactors (IBR). *International Journal of Hydrogen Energy, 40*(45), 15470-15476.

ZuivelNL. (2015). *Nederland Zuivelland.* Retrieved from https://www.zuivelnl.org/wp-content/uploads/2015/11/the-netherlands-land-of-dairy.pdf

ZuivelNL. (2019a). *Zuivel in Cijfers 2018*. Retrieved from ZuivelNL: https://www.zuivelnl.org/wp-content/uploads/2019/07/ZIC2018-ENG.pdf

ZuivelNL. (2019b, July). *Zuivel in cijfers: brochure en folder.* Retrieved October 30, 2019, from https://www.zuivelnl.org/wp-content/uploads/2019/07/Tabellen-Zuivel-in-cijfers-2018.xlsx

ZuivelNL. (2020). *Zuivel in cijfers 2020.* Retrieved from https://www.zuivelnl.org/wp-content/uploads/2020/01/ZIC2020.jpg

Appendix A: Production capacity estimates of the Dutch dairy processing locations in EU ETS

This appendix provides an overview of the Dutch dairy production locations registered in EU ETS. The production capacities of the different products is estimated based on the best available public sources and on the analyses and generic processes as described in this report. Table 18 provides a list of the sites belonging to FrieslandCampina and Table 19 shows a list of other sites. The production capacities are not all from the same year and are not confirmed by the companies.

Table 18 Overview of the ETS registered production locations of FrieslandCampina in the Netherlands, including employee information and production capacity estimates based on available information and considerations in this report. Numbers are not all for the same year and serve to get a general idea of the size and type of the production location.

Producer/ETS registration	Main products	Milk/whey input capacity	Production capacity (kton/yr)	Number of employees
Friesland Campina Bedum	Cheese, ingredients for infant food	1.0 Mt milk (2017)[46]	Cheese: 87 (2016)[47] Whey powder (estimate): 53[*]	350[48]
Friesland Campina Beilen	Milk powders	1.3 Mt milk[*]	178 (2011)[49]	537-557[50]
Friesland Campina DMV B.V., location Veghel	Ingredients	1.5 Mt milk, 1.0 Mt of whey[51]	Milk protein powder (estimate): 67[*] Whey protein powder (estimate): 16[*]	454[52]
Friesland Campina Domo location Borculo	Milk powders, lactose[53]	1.1 Mt milk[*][54]	Milk powder: 150 (2013)[55] Lactose: 60 (2013)[55]	-
Friesland Campina Leeuwarden	Milk powders, condensed milk	1.0 Mt milk[56]	Milk powder (estimate): 40-100[57][*] Condensed milk (estimate): 150-350[57][*]	707-727[58]
Friesland Campina Lochem	Butter, Milk powders	1.2 Mt milk, 55% of all cream of FrieslandCampina[59]	Butter: 130[60], Milk powder: 102.5[60], Milk prism: 26.5[60], Butter oil: 60[60]	184[52]
Friesland Campina Workum	Cheese, Whey powders	1.1 Mt milk[*][62]	Cheese: 120 (2013)[61], Whey powder (2013, estimate): 50[62], Whey protein powder (2013, estimate): 5[62]	187[63]

* Calculated based on input/production, see Table 3.

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[46] Annual capacity (Dagblad van het Noorden, 2017).
[47] Annual capacity (Veldhuisen, 2016).
[48] Dagblad van het Noorden, 2019.
[49] Maximum capacity (Gedeputeerde Staten van Drenthe, 2011).
[50] RTVDrenthe, 2015.
[51] FrieslandCampina, 2019b.
[52] Evmi, 2016.
[53] Galacto oligo saccharide.
[54] Only for milk powder. Total capacity is 1.25 Mt milk (Arcadis, 2013).
[55] Annual production capacity (Arcadis, 2013). Original lactose production capacity was estimated 30 kton.
[56] Annual capacity (BlueTerra, 2019). Processing capacity will grow by 50% towards 2020, because of extension of both the condensed milk production facility and the milk powder production facility.
[57] No information about the relative production capacity of condensed milk and milk powder. These numbers are estimations based on the process inputs of Table 2 and the total Dutch condensed milk production; the total milk input needed for these products corresponds to the known input capacity.
[58] RTVDrenthe, 2015.
[59] 10% of all milk processed by FrieslandCampina in 2018 is about 1.2 Mt (FrieslandCampina Butter, 2019). The amount of cream and other milk products is 0.3 Mt (Tauw, 2014).
[60] Maximum annual production capacities according to permit, based on average maximum input capacity expected for 2014-2017 (Tauw, 2014).
[61] Annual production capacity (FrieslandCampina, 2013a).
[62] Milk supply 'over 1 billion kg' and production of about 55 Mt total whey powder in 2013 (FrieslandCampina, 2013b).
[63] For 2013 (FrieslandCampina, 2013b).

Table 19 Overview of ETS registered dairy producers in the Netherlands, including employee information and production estimates based on available information and considerations in this report. Numbers are not all for the same year and serve to get a general idea of the size and type of the production location.

Producer/ETS registration	Main products	Milk/whey input capacity	Production capacity (kton/yr)	Number of employees
DOC Kaas BV, location Zuivelpark	Cheese	0.9 Mt milk*	100 (2014)[64]	230[65]
Cheese- and wheypowder factory A-ware and Fonterra H.	Cheese, whey protein, lactose	0.9 Mt milk*	Cheese: 100 (2015)[66] Whey protein powder (2015, estimate): 17[67] Lactose (2015, estimate): 28[67]	-
Promelca Dairy Foods	Milk powder	0.9 Mt milk*	120 (2015)[68]	220[69]

* Calculated based on input/production, see Table 3.

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[64] Production in 2015 was 90 kt cheese for location Zuivelpark only (DOC Kaas, 2016). Production at 90% utilisation is assumed.

[65] For entire company (DOC Kaas, 2019b).

[66] Expected for end of 2015 (Boerderij, 2015)

[67] Annual production of 5 kt whey protein and 25 kt lactose (Veeteelt, 2015). Assuming all whey protein powder has 35% protein in the dry matter. Production at 90% utilisation is assumed.

[68] Annual production capacity after adding new facility in 2015 (Gemeente Gorinchem, 2013).

[69] For 2018, only location Gorinchem (Vreugdenhil Dairy Foods, 2019b)

Appendix B: Mass and energy calculations on dairy processes

B.1 Mass flow dairy products

Raw milk needed for standardised milk:
To calculate the amount of Dutch milk needed to produce standardised milk the following formula was used (taken from FAO (1998)):

$$Raw\ milk\ needed\ \left[\frac{l\ raw\ milk}{l\ standardised\ milk}\right] = \frac{F_C - F_N}{F_C - F_D} \qquad (1)$$

Where F_c, F_D and F_N are the fat content of the cream in milk (assumed to be 400 g/l), the Dutch milk (45 g/l) and the needed fat content of the standardised milk. The fat content needed for cheese, (sweetened) condensed milk and milk powder are assumed to range from 26–39 g/l, yielding raw milk requirements of 1.02 – 1.05 litres of raw milk per litre of standardised milk (Tetra Pak, 1995). A value of **1.03** was used for all milk-based products, except butter. This means that also 0.03 kg of cream is produced per kg of standardised milk.

For butter cream is needed instead of standardised milk. The amount of cream that can be produced from Dutch milk was determined as the remainder of milk without skimmed milk, the amount of which was determined using formula 1 (with a skimmed fat content of 0.1g/l for F_N and the fat content of Dutch milk for F_D), yielding 0.89 kg skimmed milk and **0.11** kg cream per kg of raw milk.

Milk/whey input per product:
Cheese: Cheese yield is 0.11 kg cheese/kg standardised milk, so **9.09** kg standardised milk and **9.36** kg of raw milk is needed for 1 kg of cheese (Walstra, Wouters, & Geurts, 2006).

Butter: The butter yield from cream was determined by assuming that the fat content of butter is 800 g/l, so the fat content needs to be concentrated twice, and assuming a churning yield of 99.50% (meaning that 99.50% of the fat content of the cream ends up in the butter) (Tetra Pak, 1995). This results in a butter yield of 0.056 t of butter per ton of raw milk, or **17.9** kg raw milk needed per kg of butter.

Milk powder: The raw milk needs to be concentrated from a moisture content of 87% to a final moisture content of 3% (Tetra Pak, 1995). The amount of raw milk was calculated using the following formula:

$$W_R\left[\frac{t\ feed}{t\ product}\right] = \frac{DM_F}{DM_I} \qquad (2)$$

Where W_R is the weight of the feed needed and DM_F and DM_I are the final dry matter content of the product and the initial dry matter content of the feed respectively. This yields a milk requirement of **7.46** kg raw milk/kg milk powder.

Milk protein powder: the amount of standardised milk required was determined on the basis of the amount of milk protein, not the amount of product. This was calculated by dividing the amount of protein needed by the amount of protein present in the original milk (3.5%), yielding 28.57 kg of milk per kg of milk protein. This could then be converted to amount of milk per amount of milk protein powder by dividing it by the amount of powder needed to contain a kg of whey protein. This was determined by multiplying the amount of protein with the dry matter content and the protein content in the dry matter of the protein powder (95.4% dry matter and 80% milk protein in DM were assumed) (Walstra, Wouters, & Geurts, 2006). This yields an amount of 21.81 kg standardised milk per kg of protein powder. Then, since 1.03 kg of milk is needed for 1 kg of standardised milk, the raw milk requirements were calculated to be **22.46** kg raw milk per kg of milk protein powder, and **29.43** kg raw milk per kg milk protein.

Condensed milk: Using formula 2, a final and initial moisture content of 74% and 87% respectively, an amount of **2.0** kg raw milk/kg condensed milk is needed.

Sweetened condensed milk: to produce 1 kg of sweetened condensed milk, only 0.56 kg evaporated milk is need, since 0.44 kg sugar is added. The amount of raw milk needed to produce this amount of evaporated milk was determined using formula 2, multiplying the result with 0.56, and a final and initial dry matter content of 48.21% and 13% (sweetened condensed milk is assumed to have a moisture content of 27%, dividing this by one minus the sugar content (44%) yields the final dry matter content on a no-sugar basis) (Tetra Pak, 1995). This yields an amount of **2.23** kg raw milk per kg sweetened condensed milk.

Whey powder: Whey is concentrated from 6.5% to 97% dry matter, yielding 14.92 kg of whey needed before evaporation. It is assumed that 3% of the feed is lost as cheese fines and whey cream during separation, resulting in **15.38** kg of whey needed per kg of whey powder.

Whey protein powder: the amount of whey required was determined on the basis of the amount of whey protein, not the amount of product. This was calculated by dividing the amount of protein needed by the amount of protein present in the original whey (0.55%), yielding 181.82 kg of whey per kg of whey protein. This could then be converted to amount of whey per amount of whey protein powder by dividing it by the amount of powder needed to contain a kg of whey protein. This was determined by multiplying the amount of protein with the dry matter content and the protein content in the dry matter of the protein powder (95.4% dry matter and 35% and 58% whey protein in DM for the investigated products) (Walstra, Wouters, & Geurts, 2006). This yields amounts of 60.7 kg whey for 35% protein powder and 100.6 kg whey for 58% protein powder per kg of protein powder. Finally, a loss of 3% was assumed during separation, resulting in **62.6** kg and **103.7** kg of whey needed per kg of 35% and 58% whey protein powder respectively, and **187.44** kg whey per kg whey protein.

Lactose: If lactose is produced from whey, the amount needed is **15.8** kg per kg lactose. This was found using formula 2, with a final and initial dry matter content of 99.5% and 6.5% respectively, and assuming 3% loss during separation. If whey permeate is used, the amount is **16.95** kg per kg lactose (since initial dry matter content of whey permeate is 5.87%) (Tetra Pak, 1995).

Other mass flows:
Moisture: during three steps (reverse osmosis, evaporation and spray drying (which also contains the fluid-bed drying step, which lactose undergoes)), moisture is removed from a

product flow. The amount of product leaving these steps is determined using formula 2, filling in the and filling in the dry matter levels, using the dry matter content after the final water removal step as DM_F. Results are shown in the table below. The moisture removed in these steps can be determined by subtracting feed flows between the steps. All dry matter contents were found in Tetrapak (1995), Walstra, Wouters, & Geurts (2006) and Chandan, Kilara, & Shah (2008). The row 'Feed into first step' shows the amount of feed flowing into the first moisture-removal step, after standardisation (for milk-based products) or separation of cheese fines and whey cream (for whey-based products).

Table 20: kg of product leaving several moisture-removal steps per kg of final product

Product	Milk powder	Milk protein powder	Cond. milk	Sweet cond. milk	Whey powder	35% whey protein powder	58% whey protein powder	Lactose from whey	Lactose from permeate
DM before reverse osmosis [%]	13	20	13	13	6.5	9.24	20	6.5	5.87
DM after reverse osmosis [%]	-	-	-	-	22	-	-	-	-
DM after evaporation [%]	50	55	26	52	50	55	55	60	60
DM after spray drying [%]	97	95.4	-	-	97	95.4	95.4	99.5	99.5
Raw feed needed [kg]	7.5	22.5	2.0	2.2	15.4	62.6	103.7	15.8	17.0
Feed into first step [kg]	7.2	4.8	1.9	2.2	14.9	10.3	4.8	15.3	17.0
Product leaving reverse osmosis [kg]	-	-	-	-	4.4	-	-	-	-
Product leaving evaporation [kg]	1.9	1.7	1	1	1.9	1.7	1.7	1.7	1.7
Product leaving spray drying [kg]	1	1	-	-	1	1	1	1	1

Cheese: All cream present in standardised milk and 5% of the skimmed milk content (microfiltration permeate) is fed into the sterilisation section after microfiltration (Tetra Pak, 1995). The amount of cream (at 400 g fat/l) was determined by assuming it makes up the entire fat content of the standardised milk, which is 26g/l. So, per litre standardised milk there are 26g/400g/l=0.065 litres cream present and 0.935 litres of skimmed milk.

Since 0.11 kg cheese is produced from 1 kg of standardised milk, it is assumed that 0.89 kg of whey is created as well. Then, since the total amount of whey created was assumed to be the same as the original raw milk input, the remainder was added as water during washing/heating of the curds. 35% of the whey is drained before heating of the cheese curds. 30 ml of rennet is added per 100 kg of milk and 0.7% by weight lactic acid bacteria are added (Tetra Pak, 1995; Walstra, Wouters, & Geurts, 2006).

Butter: from the 0.11 kg of cream produced per kg of raw milk, 0.056 kg of butter is produced. The rest, another 0.056 kg, is buttermilk.

Milk protein powder: The amount of ultrafiltration-retentate needed was determined based on its protein content (retentate with 20% dry matter and 80% protein in the dry matter was assumed, resulting in 16% protein in the retentate), resulting in 6.25 kg needed per kg of protein produced (Tetra Pak, 1995; Walstra, Wouters, & Geurts, 2006). This was then converted to kg retentate needed per kg of protein powder as described for the milk input needed above, resulting in 4.77 kg of retentate needed per kg protein powder.

Sweetened condensed milk: 0.44 kg of sugar is needed for 1 kg of sweetened condensed milk (Tetra Pak, 1995). Also, 0.0005 kg of lactose crystals are added for 1 kg of sweetened condensed milk (Chandan, Kilara, & Shah, 2008).

Whey protein powder: The amount of ultrafiltration-retentate needed was determined based on its protein content (3.23% for 35% protein powder and 11.6% for 58% protein powder), resulting in 30.9 kg needed for 35% protein powder and 8.6 kg for 58% protein powder per kg of protein produced (Tetra Pak, 1995; Walstra, Wouters, & Geurts, 2006). This was then converted to kg retentate needed per kg of protein powder as described for the whey input needed above, resulting in 10.3 kg and 4.8 kg of retentate needed per kg of 35% and 58% protein powder respectively.

Lactose: During lactose production, whey concentrate is removed by a screw conveyor, increasing the dry matter content of the feed from 60% to 92% (Tetra Pak, 1995). This means an amount of 1.1 kg of lactose feed enters spray drying (=99.5%/92%), and the amount of concentrate removed can be found by subtracting this amount from the amount leaving the evaporator, resulting in 0.6 of concentrate removed per kg of lactose produced (from whey or permeate).

B.2 Energy flow dairy products

All reported numbers are for energy requirements per ton of product, except for milk- and whey protein powder, where it is for ton of protein.

General processing steps:

Thermisation, preheating and separation: The used milk is thermised before further processing. Energy consumption for thermisation is calculated using the following formula:

$$E_H[J] = c\left[\frac{J}{kg*°C}\right] * M[kg] * \left(T_f[°C] - T_i[°C]\right) * (1 - R[\%]) \qquad (3)$$

Where E_H is the energy needed for heating, c is the heat capacity of the substance being heated (3770 J/(kg*°C) and 4018 J/(kg*°C) for milk and whey respectively), M is the mass of the substance being heated, T_f and T_i the final and initial temperature of the substance and R the heat regeneration.

For all products, the initial temperature is assumed to be 4°C and final temperature is 65°C. Heat regeneration is assumed to be 85% for all products (Tetra Pak, 2019b; Tetra Pak, 2020c). After thermisation, the milk is cooled back to 4°C (Tetra Pak, 1995). The heat removed during refrigeration is determined using formula 3. It is assumed that all cooling is achieved using a cooler with COP of 2. Using this COP, the electricity consumption for thermisation can be determined. Heat (E_{HT}) and electricity (E_{ET}) requirements for thermisation are shown in Table 21 below.

Table 21: Energy consumption for thermisation

Product	Cheese	Butter	Milk Powder	Milk protein powder	Condensed Milk	Sweetened Condensed Milk
c [J/kg/°C]	3770	3770	3770	3770	3770	3770
M [t]	9.36	17.90	7.46	29.43	1.94	2.23
E_{HT}[GJ]	0.32	0.62	0.26	1.02	0.07	0.08
E_{ET}[GJ]	0.16	0.31	0.13	0.51	0.03	0.04

After thermisation, flows are preheated prior to separation. Energy consumption for preheating is calculated using formula 3. Lactose, if produced from whey permeate, is not preheated, since it does not undergo separation. Final temperature after preheating was assumed to be 60°C, and initial temperature 4°C, for all products. Heat regeneration was assumed to be 85% for all products. Electricity consumption for separation is assumed to be 0.46 kWh/1000 l milk or whey. The density of Dutch milk is 1.03 kg/l[70] and that of whey is 1.04 kg/l (Tetra Pak, 1995; Tetra Pak, 2019b). Heat (E_{HS}) and electricity (E_{ES}) requirements for separation are shown in Table 22 below. The energy requirements for whey protein powder of 35% and 58% are the same, since the same amount of whey is processed in this step.

Table 22: Energy consumption for preheating

Product	Cheese	Butter	Milk Powder	Milk protein powder	Condensed Milk	Sweetened Condensed Milk	Whey Powder	Whey Protein Powder	Lactose from whey
c [J/kg/°C]	3770	3770	3770	3770	3770	3770	4018	4018	4018
M [t]	9.36	17.90	7.46	29.43	2.00	2.23	15.38	187.44	15.78
E_{HS}[GJ]	0.30	0.57	0.24	0.93	0.07	0.07	0.53	6.43	0.54
E_{ES}[GJ]	0.02	0.03	0.01	0.05	0.003	0.003	0.02	0.30	0.03

Heat treatment: Energy requirements for heat treatment are determined using formula 3. Results are shown in Table 23. Except for cheese, all initial and final temperatures were found in Tetrapak (1995). For cheese, the initial temperature is the temperature after microfiltration. This will be explained in the 'cheese'-section below. After heat treatment, heat is removed while cooling the product to the temperature needed for further processing. The cooling temperature (T_c) is shown in Table 23, and is used to determine the amount of heat removed, using formula 3. Power consumption for pasteurisation is assumed to be 11 kW, and the pasteuriser has a capacity of 5000 l milk or whey input/h or 2500 l cream/h input (for butter) (Tetra Pak, 2019b). Then, using a COP of 2, the electricity needed for cooling was determined. Heat (E_{HH}), electricity for processing (E_{EH}) and electricity for cooling (E_{CH}) are shown in Table 23 below. It is assumed that the whey permeate needed for lactose production is not heat treated, since this already happens before the creation of the permeate.

For certain products no cooling temperature could be found. The cooling requirements for these products were based on an ice water consumption of 2200 l/h, entering the pasteuriser at 2°C and leaving it at 7°C (Tetra Pak, 2019b). The heat removed was found using formula 3, and the electricity requirements using a COP of 2.

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[70] CBS (2019a) states that 971 litres weigh 1000 kg.

Table 23: Energy consumption for heat treatment

Product	Cheese	Butter	Milk Powder	Milk protein powder	Condensed Milk	Sweetened Condensed Milk	Whey Powder	Whey Protein Powder	Lactose from whey
c [J/kg/°C]	3770	3770	3770	3770	3770	3770	4018	4018	4018
M [t]	9.09	2.01	7.24	28.57	1.94	2.17	14.92	181.82	15.31
T_i[°C]	52	60	60	60	60	60	60	60	60
T_f[°C]	72	95	72	72	120	120	72	72	72
T_c[°C]	30	8	-	-	70	70	-	-	-
E_{HH}[GJ]	0.10	0.04	0.05	0.20	0.07	0.07	0.11	1.34	0.12
E_{EH}[GJ]	0.07	0.03	0.06	0.22	0.01	0.02	0.11	1.38	0.03
E_{CH}[GJ]	0.11	0.05	0.03	0.13	0.03	0.03	0.07	0.80	0.07

Evaporation: It was assumed that all facilities use a 6-effect evaporator with TVR, with a heat consumption of 230 kJ/kg water removed for milk products and 253 kJ/kg water removed for whey products (Walstra, Wouters, & Geurts, 2006). Electricity consumption for evaporation was determined assuming a power rating of 75 kW and a capacity of 15000 kg feed/h for the evaporator. The amount of heat removed was based on a cooling water consumption of 32 m^3 per hour, which enters the evaporator at 28°C and leaves at 35°C (TetraPak, 2019a). The amount of heat removed could then be determined using formula 3 and using a COP of 2, the amount of electricity needed was determined.

Spray drying: For spray drying, a heat consumption of 11000 kg steam/h was assumed for milk products, and 12100 kg steam/h for whey products (because of their higher heat capacity). The energy content of the used steam was assumed to be 2789 kJ/kg steam. The capacity of the spray dryer was assumed to be 13580 kg feed/h, and the power consumption 570 kW. Cooling for spray drying was assumed to be provided by ice water entering at 2°C and exiting the dryer at 8°C, at a consumption rate of 11 m^3 per hour. The heat removed by this ice water was determined using formula 3, and electricity consumption was then determined using a COP of 2 (Tetra Pak, 2019c).

Packaging: It is assumed that the electricity requirements for packaging equal 5% of the total electricity use.

Cleaning-In-Place: It is assumed that CIP requires a negligible amount of electricity, and the heat requirements are assumed to be 15% of the total energy requirements.

Product-specific energy requirements

Cheese: After separation for standardisation, the skimmed milk part of the cheese milk undergoes bacteria treatment. Here microfiltration and sterilisation are assumed. To achieve this, the milk is cooled to 50°C from standardisation temperature (60°C), and the amount of heat removed was determined using formula 3, and the electricity requirements based on a COP of 2 (Tetra Pak, 1995). Electricity use for microfiltration was determined based on an electricity consumption of 10.81 Wh/kg permeate created (Chamberland, et al., 2019).

After microfiltration, the permeate is mixed back together with the cream, which is still at 60°C, thereby increasing the temperature of the mix. Since almost equal parts of cream and permeate are mixed together, this temperature is assumed to be 55°C. Due to the mixing, the heat capacity of the mix will also change. A value was chosen that is in between the heat capacities of skimmed milk and cream (4000 J/(kg*°C) and 3770 J/(kg*°C) respectively), that is 3885 J/(kg*°C). The heat consumption for sterilisation was then determined using formula 3, with an initial temperature and heat capacity as described, a final temperature of 120°C, and heat regeneration of 85%. After sterilisation, the mix is cooled to 70°C, and using formula 3 and a COP of 2 the electricity requirements for this step were determined. The permeate-cream mixture is the mixed back with the rest of the skimmed milk before heat treatment. This temperature was assumed to be 52°C, based on the fact that a relatively large share of skimmed milk at 50°C is used in the mix, and that therefore it's temperature will only increase slightly.

After heat treatment, the milk goes through the cheese-making process. Electricity consumption for this process is assumed to be 4 kW, at a renneting time of 4 hours per load of the cheese-making vat (Tetra Pak, 1995; Tetra Pak, 2020d). The capacity of the cheese vat is assumed to be 5.5 t of milk.

Heating requirements are based on a low-pressure steam consumption of 300 kg/h, and an energy content of 2748 kJ/kg steam (Tetra Pak, 2020d).

Afterwards, the cheese curds are heated using hot water. The temperature of this water was assumed to be 90°C, as this temperature will increase the temperature of the cheese to around 42°C, which is the desired heating temperature (Tetra Pak, 1995). The heating requirements for producing this water were determined using formula 3, with an initial temperature of 4°C and a heat regeneration of 0% (assuming this water is produced in a boiler and not using a counter-current flow).

The curds are then pressed into the desired shape. An electricity consumption of 5.6 kWh/t cheese is assumed for this process (Tetra Pak, 2020e).

<u>Butter:</u> The electricity requirements for butter churning were assumed to be 0.07 kWh/kg butter (Finnegan, Goggins, Clifford, & Zhan, 2017).

<u>Milk and whey protein powder:</u> Electricity requirements for ultrafiltration were assumed to be 25 kJ/kg water removed (Ramírez, Patel, & Blok, 2006). The amount of water removed was determined based on the mass flows and moisture content of the feeds before and after filtration.

<u>Condensed milk:</u> After evaporation, the condensed milk is homogenised. It is assumed this process consumes 4.6 kWh/1000 litres of product, and that condensed milk has a density of 1.295 kg/l (Tetra Pak, 2020).

After homogenisation, the condensed milk is cooled to packaging temperature (14°C) from the temperature after evaporation (50°C) (Tetra Pak, 1995). Electricity requirements for this cooling step were determined using formula 3, a heat capacity of 3560 J/(kg*°C) and a COP of 2. Then, after packaging, the product is sterilised at 110°C. Heat requirements were determined using formula 3, assuming a heat regeneration of 0%, since the product is already packaged.

<u>Sweetened condensed milk:</u> The product is homogenised, with the same electricity consumption as condensed milk, but a density of 1.319 kg/l.

After homogenisation, the product is cooled to crystallisation temperature (30°C), and to 15°C after that. Using a heat capacity of 2350 J/(kg*°C) for sweetened condensed milk, the heat removed can be found using formula 3 (with an initial temperature of 50°C), and with a COP of 2, the electricity use was determined (Tetra Pak, 1995).

Whey powder: Electricity requirements for reverse osmosis were assumed to be 25 kJ/kg water removed (Moejes & Van Boxtel, 2017). If demineralised powder is produced (through ion-exchange), the electricity consumption for this step was assumed to be 0.15 kWh/m^3 of whey processed.

Lactose: Electricity use during separation of the lactose crystals was determined based on a centrifuge with a power consumption of 18 kW, with a capacity of 1250 l feed input/h (Andritz, 2018a; Andritz, 2018b). The density of the feed was assumed to be 1.2 kg/l, higher than that of whey due to the higher dry matter content.

Lactose does not undergo the full spray drying process, but only fluid-bed drying. Steam consumption for this step was assumed to be 167 kg/h, with an energy content of 2748 kJ/kg steam, at a production capacity of 1745 kg product per hour. The power consumption of the fluid-bed dryer was assumed to be 22 kW (GEA Process Engineering, 2010).

Appendix C: List of dairy producers in MJA3 covenant

The MJA3 covenant is an agreement in which dairy producers agree to increase their energy efficiency. In 2018 46 companies participated, which are shown in Table 24.

Table 24 MJA3 participants dairy sector in 2018

Name	Location	In EU ETS
Arla Foods B.V.	NIJKERK GLD	no
A-ware Zaandam B.V.	ZAANDAM	yes (location Heerenveen)
Bel Leerdammer BV Dalfsen	DALFSEN	no
Bel Leerdammer BV Schoonrewoerd	SCHOONREWOERD	no
Cono Kaasmakers	WESTBEEMSTER	no
De Graafstroom	BLESKENSGRAAF CA	no
De Zuivelhoeve	HENGELO OV	no
DOC Kaas BA Zuivelfabriek	HOOGEVEEN	no
DOC Kaas BA Zuivelpark	HOOGEVEEN	yes
Friesland Campina Maasdam	MAASDAM	no
Friesland Foods Western Europe Riedel B.V.	EDE GLD	no
FrieslandCampina	WORKUM	yes
FrieslandCampina (Ecomel)	LIMMEN	no
FrieslandCampina (Leerdam)	LEERDAM	no
FrieslandCampina Balkbrug	BALKBRUG	no
FrieslandCampina Bedum	BEDUM	yes
FrieslandCampina Born	BORN	no
FrieslandCampina Butter Noordwijk	NOORDWIJK GN	no
FrieslandCampina Butter 's- Hertogenbosch	S HERTOGENBOSCH	no
FrieslandCampina Cheese	MARUM	no
FrieslandCampina Cheese	LUTJEWINKEL	no
FrieslandCampina Cheese & Butter	WOLVEGA	no
FrieslandCampina Cheese Steenderen	STEENDEREN	no
FrieslandCampina DMV Friesland Coberco Butter products	LOCHEM	yes
Frieslandcampina DMV Veghel	VEGHEL	yes
FrieslandCampina Domo Borculo	BORCULO	yes
FrieslandCampina DOMO BV Friesland Coberco Dairy Foods BV Beilen	BEILEN	yes
FrieslandCampina Dronrijp	DRONRIJP	no
FrieslandCampina Gerkesklooster	GERKESKLOOSTER	no
FrieslandCampina Kievit BV Meppel	MEPPEL	no
FrieslandCampina locatie Eindhoven	EINDHOVEN	no

Name	Location	In EU ETS
FrieslandCampina locatie Leeuwarden	LEEUWARDEN	yes
FrieslandCampina locatie Rijkevoort	RIJKEVOORT	no
FrieslandCampina Professional	NUENEN	no
FrieslandCampina Rotterdam	ROTTERDAM	no
Hochwald Nederland B.V.	BOLSWARD	no
Hyproca Dairy BV	OMMEN	no
Koninklijke Eru Kaasfabriek BV	WOERDEN	no
N.V. Nutricia	ZOETERMEER	no
Nestle Nederland BV (Nunspeet)	NUNSPEET	no
Nutricia Cuijk BV	CUIJK	yes
Phoenix B.V.	SCHARSTERBRUG	no
Promelca BV	GORINCHEM	yes
Rouveen Kaasspecialiteiten	ROUVEEN	no
Vika BV	EDE GLD	no
Yakult Europe B.V.	ALMERE	no