# Decarbonisation options for the Dutch dairy processing industry

Studying the feasibility of a carbon-neutral dairy processing industry in 2050

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# Preface

Part of the research performed for this thesis was done as part of an internship at the Planbureau voor de Leefomgeving (PBL). For this internship a report has been written, which will be posted online (check https://www.pbl.nl/en/middenweb/publications). Parts of the report for PBL have been used for this study.

# Abstract

The dairy industry is a major part to the Dutch economy, contributing to 7% of the Dutch trade balance. At the same time, the dairy processing industry is a consumer of large quantities of energy, as the production processes of several dairy products are energy intensive. Because of the high energy requirements and the large volume of milk processed by the industry, a large carbon footprint is associated with the production of Dutch dairy products. The dairy processing industry has ambitions to reduce its emissions, which means that novel ways of producing the products are needed, or more sustainable sources of energy should be used.

To analyse the possibilities and difficulties for the Dutch dairy processing industry in realising their ambitions, this study set out to quantify the development of the industry until 2050, looking at possible scenarios regarding volumes and mixes of dairy products. The energy requirements for these products have been determined, and possible decarbonisation options have been found. These options consisted of three energy-efficiency measures, the use of ultra-deep geothermal energy, and the use of electric boilers. The decarbonisation potential of these options has been determined up to 2050, along with their costs, thereby creating a yearly decarbonisation pathway for the different scenarios.

The Dutch dairy processing industry can reach full decarbonisation in 2050 at a cost of between EUR 99 million and EUR 185 million, depending on the development the industry undergoes. Energy-efficiency options with low abatement costs, namely the use of zeolite during spray-drying and the use of mechanical vapour recompression during evaporation, can be utilised first to reduce the overall energy requirements. The remaining heat requirements can then be filled by geothermal energy, and finally by replacing natural gas boilers with electric ones. For the use of geothermal energy to be economically favourable, it is important that the industry can externalise or share the high investment costs. To ensure the increased electricity consumption by electric boilers leads to decarbonisation, the share of renewable electricity used should be high enough. This can either be achieved by increasing the share of renewables in the national grid or using renewable electricity generated by the dairy industry itself.

Uncertainty in the used parameters can have significant impact on the results of this study. Therefore, future research should look at cooperating with the Dutch dairy industry to obtain more accurate values for production volumes and energy requirements.

# Contents

# 1. Introduction

## 1.1 Research background

The growing realisation of the need to reduce carbon emissions globally has led to the adoption of various climate agreements and goals. These agreements set goals regarding energy use and emission reductions, giving specific targets for different sectors. Examples of these targets in the Netherlands include an energy-use reduction of 100 petajoules (PJ) by 2020 (from the 'Energieakkoord voor duurzame groei') and an increase in industrial energy-efficiency of 2% yearly (from the 'MJA3') (RVO, 2008; SER, n.d.). The landscape of climate policies and agreements is not in a standstill however, and new legislation is continuously being drafted. In the Netherlands, the most important of these new additions is 'Het Klimaatakkoord' (Climate Agreement), which aims for a 49% reduction of greenhouse-gas (GHG) emissions as compared to 1990 levels in 2030. For the Dutch industry sector, this means a reduction in emissions of 19.4 million tons (Mt) of GHGs, compared to total industrial GHG emissions of 55.1 Mt in 2015. This is a reduction of 35%, over a period of 15 years (Rijksoverheid, 2019). Reaching these targets will require large efforts and cooperation, and each branch of industry has to set its own goals in accordance with national legislation.

One of the major industries in The Netherlands is the dairy processing industry, which generated a turnover of 7.5 billion euros in 2017, contributing to 7% of the Dutch trade balance together with the dairy farming sector (ZuivelNL, 2019). Not only is it important in economic terms, the sector is also part of Dutch culture, with over 1.6 million cows in The Netherlands in 2017, over 73% of which spent at least 6 hours outside for 120 days per year (ZuivelNL, 2018). This large number of cows leads to a production of around 14 billion kilograms of milk (in 2018), which are processed into a wide variety of products, including consumer's milk, cheese, butter, milk- and whey powders and others (ZuivelNL, 2019). The various steps needed for the processing of milk require large amounts of energy, resulting in direct $CO_2$ emissions at the factory site. Together, all milk processing plants registered under the European Emission Trading System (EU ETS) emitted around 0.468 Mt of $CO_2$, and the entire sector consumed over 20000 TJ of energy in 2018 (NEa, n.d.; RVO, 2019). Companies within the sector, and the trade association for Dutch dairy farmers (NZO) and agriculture (LTO), have put out their own targets regarding energy use and sustainability, aiming at for instance energy-neutrality in 2030 or climate-neutral growth compared to 2010 (FrieslandCampina, 2018; RVO, 2016).

The (Dutch) dairy sector is susceptible to changes in legislation and consumer preferences. For instance, the milk quota system that was established in 1984 was abolished in April 2015, allowing farmers to increase their milk production (Klootwijk, Van Middelaar, Berentsen, & De Boer, 2016). As a result, milk production in The Netherlands increased from below 12 billion kilograms in 2010 to over 13 billion kilograms in 2015 and over 14 billion in 2016 (CBS, 2019). So clearly, external factors influence milk production and thereby milk processing. Even more recently, concerns about the level of nitrogen-emissions from, amongst others, dairy farming were made concrete through the release of the report '*Niet alles kan*', which states that nitrogen-emissions have to be reduced if nature areas are to be conserved (Adviescollege Stikstofproblematiek, 2019).

## 1.2 The Dutch dairy sector

As mentioned above, the Dutch dairy processing sector processes around 14 billion kilograms of milk yearly. A breakdown of the use of this amount of milk is shown in Figure 1. 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 1 below.

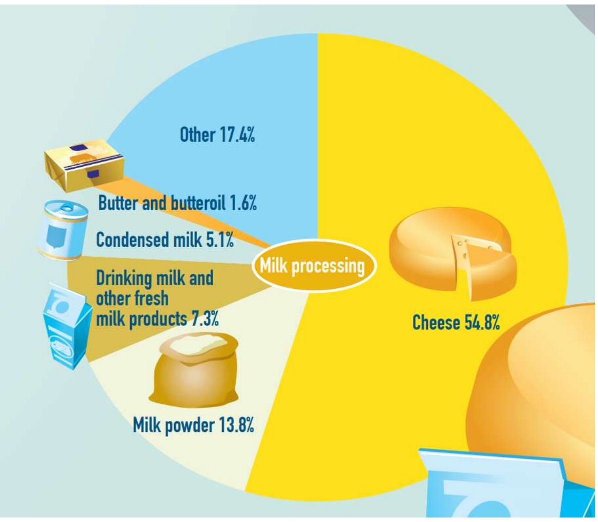


*Figure 1: Use of Dutch milk (ZuivelNL, 2019, p. 4)*

*Table 1: Milk supply and dairy production in The Netherlands (CBS, 2019)*

| 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 | 250.0 | 367.0 |
| **2018** | 13,879 | 140.7 | 880.3 | 231.1 | 344.3 |

The Dutch dairy chain consists of 17,000 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 7.5 billion by the milk processing industry (ZuivelNL, 2019). Of the products, 35% remains in the Dutch market, while 45% is exported to the European Union (mostly Germany and Belgium) and 20% to other countries (mostly China) (ZuivelNL, 2015a). The Netherlands also imports dairy products with a total value of EUR 3.8 billion, mostly from Germany and Belgium (ZuivelNL, 2019).

The dairy sector emitted between 19.84 and 23.07 Mt of $CO_2$-eq in the years 2011–2017, taking into account the entire production chain. Of this amount, over 92% stem from processing at the dairy farm, with the majority of emissions coming from enteric fermentation (in the form of methane) and production of the required feed (in the form of $CO_2$ and nitrous oxide) (Doornewaard, Reijs, Beldman, Jager, & Hoogeveen, 2018). In total, an amount of 1.48 kg $CO_2$-eq is emitted per kg of Dutch milk delivered to the factory (Dolfing, 2017).

Several companies are responsible for processing the Dutch milk into consumer products. The biggest of these companies is FrieslandCampina, which is 5$^{th}$ largest dairy processing company in the world (ZuivelNL, 2019). FrieslandCampina processed over 10 billion kilograms of milk in 2019, generating a turnover of EUR 11.3 billion (FrieslandCampina, 2020).

## 1.3 Problem definition and research question

Most research regarding decarbonisation of the dairy sector has focussed on the production of milk (Knapp, Laur, Vadas, Weiss, & Tricarico, 2014; Weiske, et al., 2006). For instance, Dolfing (2017) looked at the current emission levels of Dutch dairy farmers and investigated different decarbonisation scenarios to find out if they were in line with the Paris agreement.

However, research into the dairy processing sector has been scarce. The research that has focussed on the dairy processing industry has generally taken a wide geographic view. For instance, Xu et al. (2009) investigated the energy requirements for making cheese, including analysis for cheese-making facilities in 4 European countries (among which The Netherlands) and the USA. Their results showed a large difference between countries, with a minimum energy consumption of 4.9 GJ/t cheese and a maximum of 9.6 GJ/t cheese. This shows that for results to be applicable to a certain geographic location, the specific circumstances in that location have to be investigated properly, and that generalisations cannot be made across borders.
Furthermore, many studies looked only at theoretical energy reduction potentials, by comparing specific energy consumptions across geographical locations, or at the impact of a specific decarbonisation option, such as biogas (Gebrezgabher, Meuwissen, & Oude Lansink, 2012; Xu & Flapper, 2011). These studies show in a general way that improvements in energy usage or carbon emissions can be made, but the results do not provide a full overview of the possibilities for a certain geographic location with specific characteristics. Therefore, a study looking at the current situation of dairy processing in the Netherlands is needed, as it will provide concrete decarbonisation options for dairy processing plants with specifically Dutch characteristics.
It is worth noting that many studies regarding energy efficiency or decarbonisation in the dairy sector do not explicitly contain a time-dependent factor. The industrial landscape will change, as will the volume and mixture of consumption of dairy products, and both these developments need to be taken into account if a realistic image of the possibilities for decarbonisation of the sector is to be obtained, since the energy use of the sector will depend on their production mix. Also, technological advancements will be made, so options for energy-efficiency and reduction of emissions will change in the future.

The aim of this research is to get a better understanding of the specific conditions of the Dutch dairy processing sector at the present moment, and to investigate the changes the sector will undergo. In light of these changes, the aim is also to determine the possibilities and difficulties the sector will face regarding their $CO_2$ emissions. By looking at the possible options for decarbonisation in the future, a specific image of the Dutch dairy sector in 2050 can be created, which will also help to better understand its development pathways.

To fulfil the aim set out above, this research answered the following research question:

*'What pathways exist for full decarbonisation of the Dutch dairy processing industry in the year 2050?'*

To be able to answer this question, the following subquestions were answered:

1. *'How much energy do dairy production processes require in The Netherlands at the present moment?'*
2. *'What are the $CO_2$-emissions related to the energy use of the Dutch dairy processing sector?'*
3. *'What scenarios exist for demand for dairy products in the year 2050?'*
4. *'What are the characteristics of the decarbonisation options for the Dutch dairy processing sector up to the year 2050?'*
5. *'What will be the cost for fully decarbonising the Dutch dairy processing sector in 2050?'*

Finally, this report will also look at the possibilities for financing the investments needed for decarbonisation and it will discuss the possible landscape of the dairy industry in 2050 and its pathway to decarbonisation.
This study will only look at the energy consumption and emissions arising from the production processes of the Dutch dairy processing industry. So, energy consumption from elements like transport, waste treatment and housekeeping will be excluded.

# 2. Methodology

To be able to answer the research question and the subquestions, multiple steps had to be undertaken. These steps are shown schematically in Figure 2 below.

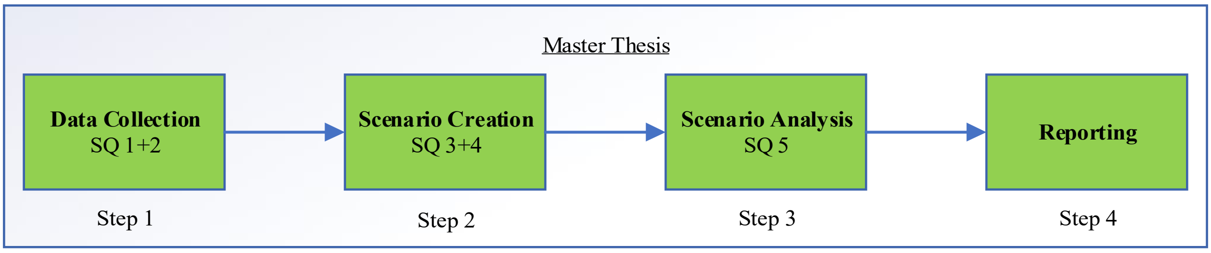


*Figure 2: Steps in research*

## 2.1 Step 1: Current situation of dairy production

The first part of the research consisted of a literature review. The goal was to determine the mass- and energy flows needed to produce the investigated dairy products. The used information was largely collected from scientific articles, reports from engineering firms and milk processing handbooks.

Along with the literature research, process diagrams were reconstructed from relevant sources for those products deemed most important in the portfolios of Dutch dairy processing facilities. Since a wide range of products is made by the dairy processing industry, and since even within a specific group many distinct products with different processing steps can be made (for instance, a large variety of cheeses can be made), these process diagrams were generalised per product group, and did not contain all details for all specific products within the group.

With the process diagrams as a base, mass and energy flows for each product group have been constructed. This has taken the form of a Material- and Energy Flow Analysis (MFA and EFA). This type of analysis shows the in- and outputs for each of the processing steps, thereby creating an overview of the process in terms of material and energy requirements. The analysis also indicated where by-products would leave the process, which could be utilised in some other way. This is especially important for the dairy processing industry, as large volumes of by-products (for instance whey or cream) are created which can still be further processed to increase their value. The information required to perform these analyses, which has been performed in Excel, came from the same sources as used for the literature research on the production processes in the industry.

The energy inputs per ton of product that were determined in this step were compared against values found in scientific literature, to check their validity.

To determine the current $CO_2$-emissions of the dairy processing industry, answering subquestion 2, the EFA was combined with historical production figures and information about emissions from natural gas and electricity use (see Section 2.2.4 for a more detailed explanation).

## 2.2 Step 2: Scenario creation

Subquestions 1 and 2 were answered with the methods as described above. To create the dairy consumption scenarios for 2050, and to answer subquestion 3, another literature review was performed. Literature from trade associations contain ideas about the development of the sector, which were used, in supplement with historical data and literature from other sources, to extrapolate historical trends into the future. Multiple scenarios were created, as a reflection of an uncertain future in which multiple pathways of development may be taken. The scenarios were based on two different pillars: milk production and utilisation of milk.

For milk production, three possible pathways were determined: Business As Usual (BAU), medium demand increase, and low demand increase. For the utilisation of milk two pathways were determined, one in which milk is used in the same way in the future as it is now (called ‘Status Quo’, comparable to

the breakdown shown in Figure 1) and one in which the milk is increasingly used to fill international demand.
These scenarios could also be seen as different storylines for the sector, for instance focussing on maximising profit or reducing energy requirements for production. The scenarios also qualitatively took into account possible new legislation, as the dairy sector is very vulnerable to new additions. Key parameters needed for the evaluation of the decarbonisation options, such as product mix and demand, were determined for the target year of 2050, but also for intermediate years, to be able to create intermediate targets for the sector, and to better analyse the pathway the sector has to take, instead of just looking at the end results.

The methodology used for each of the pillars will be described in the following sections.

### 2.2.1 Milk production

The scenarios for milk production were created by extrapolating historic trends, with data available from CBS (2019). The extrapolation was done using the following formula:

$$P_m(t) = P_m(2018) \cdot (1 + CAGR)^{(t-20\quad)} \qquad (1)$$

Where $P_m(t)$ is the milk production (in kt) in year $t$ and $CAGR$ is the Compound Annual Growth Rate, which was determined using formula 2.

$$CAGR = \frac{P_{m,f}}{P_{m,i}}^{\frac{1}{t_f - t_i}} - 1 \qquad (2)$$

Where $P_{m,f}$ and $P_{m,i}$ are the milk production in the final and initial year used for the calculation respectively, and $t_f$ and $t_i$ are the final and initial year used for the calculation respectively. For the BAU scenario, the entire historical period was taken into account, so the final and initial year were 2018 and 2002 respectively. This scenario includes the relatively strong increase in milk production after the abolishment of the milk quota. This peak was excluded for the other two scenarios, which used final years of 2012 (medium growth) and 2007 (low growth) respectively. These scenarios used 2002 as initial year.

### 2.2.2 Utilisation of milk

Table 2 below shows the historic allocation of Dutch milk for several products. Based on the average over the years shown, a status quo allocation for Dutch milk was determined. This allocation assumes the shares of different products created from Dutch milk don't change in the future, indicating that no significant relative increases in export arise, or that any increases are negated by decreased consumption domestically.
Another possibility is that the dairy sector becomes more international, so that the increased milk production is mostly the result of increased demand for export. For instance, in China and Africa dairy 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).
Also, 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). This trend is shown in Figure 3 below.

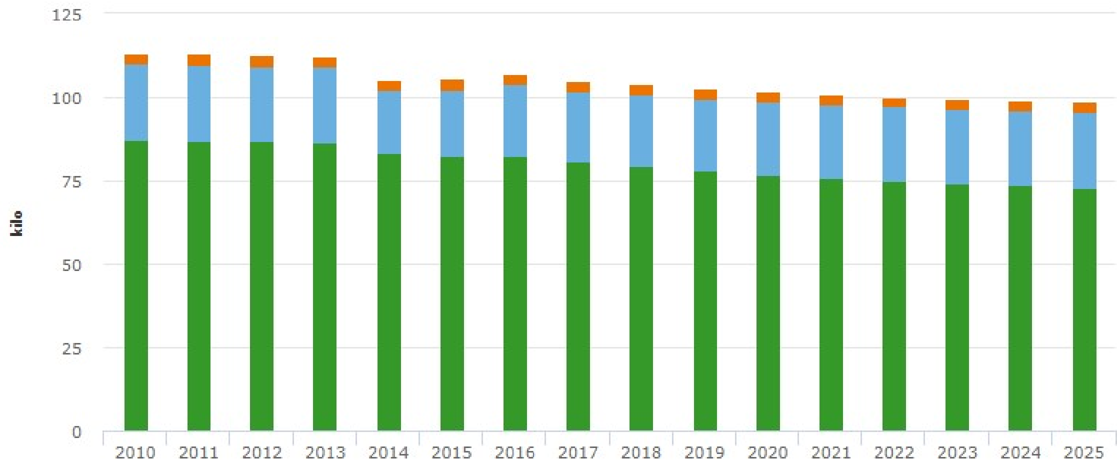


*Figure 3: Per capita consumption of milk (green, bottom), cheese (blue, middle) and butter (red, top) in the Netherlands (Wageningen University and Research, 2019)*

To reflect these changes, it is assumed that for the international demand scenario more milk will be used for dried products ('Milk powder' and 'Other', which is assumed to include whey powder and lactose), while usage for other products declines. The allocation in 2050 is shown in Table 2 below, and linear growth between 2018 and 2050 is assumed for the changes in allocation.

*Table 2: Historic and status quo allocation of Dutch milk*

| Year | 2014 | 2015 | 2016 | 2017 | 2018 | Status Quo | International demand (2050) |
|---|---|---|---|---|---|---|---|
| **Cheese** | 52.40% | 54% | 55.40% | 52.80% | 54.80% | 53.90% | 40.00% |
| **Milk powder** | 13.50% | 13% | 13.70% | 15.10% | 13.80% | 13.80% | 25.00% |
| **Consumer's milk and milk products** | 8.20% | 8% | 7.10% | 7.30% | 7.30% | 7.60% | 5.00% |
| **Condensed milk** | 6.40% | 6% | 5.60% | 5.40% | 5.10% | 5.70% | 5.00% |
| **Butter and butteroil** | 1.60% | 2% | 1.60% | 1.60% | 1.60% | 1.70% | 1.50% |
| **Other** | 17.80% | 17% | 16.60% | 17.80% | 17.40% | 17.30% | 23.50% |

### 2.2.3 Production of dairy products

With the amount of milk produced and its utilisation known, the production of the different dairy products investigated could be determined. This was done using the following formula:

$$P(i,t) = P(i,ave) \cdot \frac{P_m(t)}{P_m(t_{ref})} \cdot \frac{S(i,t)}{S_{sq}(i)} \quad (3)$$

Where *P(i,t)* is the production (in tons) of product i in year t, *P(i,ave)* is the average yearly production of product i over a certain period of time, $P_m(t)$ is the milk production in year t, $P_m(t_{ref})$ is the milk production in a reference year, which is chosen to be the final year of the period of time used for *P(i,ave)*, *S(i,t)* is the share of milk utilised for product i in year t and $S_{sq}(i)$ is the share of milk utilised for product i under the status quo scenario (see Table 2). For the status quo scenarios, *S(i,t)* was assumed to be equal to $S_{sq}(i)$.

To determine *P(i,ave)* historic production figures (from 2002 – 2018) were used, found in CBS (2019). The categories available in their database did not match the product groups shown in Table 2, and for some product groups data were not available for all years. So, some assumptions had to be made.
If available, data from the period 2011–2018 were used for *P(i,ave)*. This was done for cheese, condensed milk, butter and whey powder. For milk, the average was based on the period 2002–2006. The production figures for milk powder included 'other powder products', these were assumed to be protein powders (as lactose and whey powder were mentioned separately). Data was given for 'total milk powder' and 'other powder products' with the remainder assumed to be milk powder. This agreed well with data from ZuivelNL yearly reports on dairy production[1]. This resulted in data for milk powder production during the period 2002–2011, which was used to determine *P(i,ave)*. Production of 'other powder products' (assumed to be 50% whey protein powder and 50% milk protein powder) was determined as the difference between 'total powder production' and milk powder production. 'Total powder production' was determined using formula 3, with the period 2011 – 2018 used for *P(i,ave)*.
Finally, only one datapoint was available for the production of lactose (in 2006). To determine *P(i,ave)* for lactose, first the datapoints for the period 2011–2018 had to be determined. This was done using the following formula:

$$P(lactose,t) = \sum_i \frac{P(i,t)}{P(i,2006)} / 8 \cdot P(lactose, 2006) \qquad (4)$$

Where the summation runs of all products groups i. Since there are 8 product groups, the summation is divided by this number to get the average multiplication of production of all products between year t and 2006. With lactose production in the years 2011 – 2018 determined in this way, formula 3 was used to determine future production figures.

### 2.2.4 Energy use and emissions

Using the constructed energy flows and the amount of product produced as described above, the total energy use of the Dutch dairy processing sector could be determined, and from that its emissions. The total thermal energy use of the sector was determined using the following formula:

$$E_h(t) = \sum_i P(i,t) \cdot E_{hp}(i,t) \qquad (5)$$

Where $E_{hp}(i,t)$ is the thermal energy requirement (in TJ/t product) for product *i* in year *t*. The total electricity requirements were determined likewise, using the electricity requirements per ton product instead of the thermal energy requirements.
By optimising the production process, for instance by improved production scheduling, improved computer control or increased maintenance, small autonomous improvements in energy efficiency can be generated. These improvements generally do not cost a lot of money, but can have a significant effect on energy consumption over a long time period. These improvements have been taken into account using the following formula:

$$E_p(t) = E_p(2018) * (1-\varepsilon)^{t-20} \qquad (6)$$

Where $E_p(t)$ is the energy requirement (in TJ heat or electricity per ton product) in year t and $\varepsilon$ is the autonomous efficiency improvement (in %).

From the energy requirements the emissions could be calculated using the following formula:

[1] See (ZuivelNL, 2015b; ZuivelNL, 2016; ZuivelNL, 2017; ZuivelNL, 2018; ZuivelNL, 2019)

$$CO_2(t) = \frac{\%_{boiler} \cdot E_h(t) \cdot EF_g}{\eta_{boiler}} + \frac{\%_{CHP} \cdot E_h(t) \cdot EF_g}{\eta_{CHP,h}} + \left(E_e(t) - \frac{\%_{CHP} * E_h(t)}{\eta_{CHP,h}} \cdot \eta_{CHP,e}\right) \cdot \frac{EF_e}{1-\%_r(2018)} \cdot (1 - \%_r(t)) \qquad (7)$$

Where $\%_{boiler}$ and $\%_{CHP}$ are the shares of heat produced by natural gas boilers and CHPs respectively, $EF_g$ and $EF_e$ are the emission factors of natural gas and Dutch electricity (using the value of 2018) respectively, $\eta_{boiler}$ is the thermal efficiency of the used boiler, $\eta_{CHP,h}$ and $\eta_{CHP,e}$ are the thermal and electrical efficiency of the CHP respectively, $E_e(t)$ are the electricity requirements per ton product and $\%_r(t)$ is the amount of renewable electricity in the Dutch national grid in year t.

For determining the emissions, four emissions scenarios (ES) have been determined. These are as follows:

- ES1: All heat prior to decarbonisation is supplied by 90% efficient natural gas boilers, and the average Dutch electricity is used.
- ES2: All heat prior to decarbonisation is supplied by 90% efficient natural gas boilers, and 100% of the electricity demand can be met from renewable sources.
- ES3: 75% of the heat prior to decarbonisation is produced by 90% efficient natural gas boilers and 25% by CHPs with 60% thermal efficiency and 30% electrical efficiency. The average Dutch electricity is used.
- ES4: 75% of the heat prior to decarbonisation is produced by 90% efficient natural gas boilers and 25% by CHPs with 60% thermal efficiency and 30% electrical efficiency. Also, 100% of the electricity demand can be met from renewable sources.

## 2.3 Step 3: Decarbonisation and scenario analysis

Three different pathways for decarbonisation were examined: One based on measures aimed at improving the energy efficiency of the production processes of dairy products, one looking at the use of geothermal energy for renewable heat supply, and one looking at the use of electric boilers as a way to electrify the remaining heat supply of the processing facility. In this section the methodology used to calculate the impact and costs of each of these pathways will be discussed.

### 2.3.1 Energy efficiency

Three options regarding improvement of energy efficiency have been investigated, namely the use of zeolite in the spray-drying process, the use of Mechanical Vapour Recompression (MVR) during evaporation and the use of reverse osmosis (RO) membranes to preconcentrate the milk/whey feed before evaporation (see Section 3.2 for an explanation of these techniques). Since MVR and RO target the same production step, namely evaporation, the order in which these techniques are implemented have an impact on the energy efficiency improvement of the technique implemented secondly. Therefore, two pathways need to be investigated separately, one in which the MVR is applied before preconcentrating and vice versa.

First the reduction in thermal energy requirements and increase in electricity use arising from utilisation of these techniques needed to be determined. These were based on scientific literature (see Section 3.2). From these changes, the reductions in $CO_2$-emissions from the production of dairy products could be determined using formula 7, changing all heat and electricity requirements ($E_h$(t) and $E_e$(t)) to the changes in heat and electricity consumption arising from using the decarbonisation options.
Using the $CO_2$ reduction potentials of the options and the costs of decarbonisation, the options were ranked cheapest to most expensive, with the $CO_2$ abatement costs (in EUR/kg $CO_2$) for a decarbonisation option *d* determined using the following formula:

$$C_{CO2}(d,i,t) = \frac{I(d,i,t)+C(d,i,t)-B(d,i,t)}{\Delta CO_2(d,i,t)} \quad (8)$$

Where *I(d,i,t)*, *C(d,i,t)* and *B(d,i,t)* are the investment costs, other costs, and benefits, of decarbonisation option *d* for product *i* in year *t* respectively and $\Delta CO_2(d,i,t)$ is the additional change in $CO_2$-emissions per ton of product when using decarbonisation option *d* for product *i* in year t compared to the previous year. So, the abatement costs look at the yearly costs in a specific year for abating an additional amount of emissions, compared to the situation of the previous year. The average abatement costs are also determined, as the ratio of the total costs and the final yearly abatement in 2050. These costs indicate the average cost of abatement within a year. Finally, the average abatement costs over the entire researched time period were determined as the ratio of the total costs in 2050 and the sum of all yearly abated emissions. These costs indicate the average cost of abating a single unit of emissions over the entire time period.

The costs included in the analysis consist of increased expenditure on electricity, while benefits include reduced expenditure on gas and income from selling carbon credits/reduced need to buy carbon credits. The abatement costs were determined based on a gas price growing linearly from 4664 EUR/TJ in 2018 to 9383 EUR/TJ in 2050, an electricity price growing linearly from 14931 EUR/$TJ_e$ in 2018 to 30000 EUR/$TJ_e$ in 2050, and a price of carbon credits growing linearly from 25 EUR/t $CO_2$ in 2019 to 100 EUR/t $CO_2$ in 2050 (Berenschot, 2016; PBL, 2019).

It was assumed that the options with the lowest abatement costs in a specific year will be the first options to be implemented. The amount of options needed in a year was determined based on a fixed amount of decarbonisation needed in that year. The maximum decarbonisation potential of all options for all products combined (determined using formula 7) in 2050 was used as a target, and linear growth up to that point was assumed to determine the yearly decarbonisation needed. If an option was implemented in a specific year, its decarbonisation potential would have an autonomous development in subsequent years, because the Dutch electricity grid was assumed to contain more renewables, and because the production of a product will change between years. This autonomous change was determined by subtracting the decarbonisation potential in one year with the potential in the previous year. It is possible that the sum of these autonomous increases is greater than the yearly amount of decarbonisation needed. If this is the case, the average yearly decarbonisation needed without the years in which the autonomous increase was greater than this number was determined using the following formula:

$$\Delta CO_{2_{ave}} = \frac{\Delta CO_{2_{tot}} - \Delta CO_{2_{auto}}}{t_{non-auto}} \quad (9)$$

Where $\Delta CO_{2tot}$ is the maximum decarbonisation of all option for all products in 2050, $\Delta CO_{2auto}$ is the sum of all autonomous decarbonisation in years in which the sum of autonomous decarbonisation in a year is greater than the yearly average needed and $t_{non\text{-}auto}$ are the amount of years in which the autonomous increases are not larger than the yearly average needed.

### 2.3.2 Ultra-Deep Geothermal energy

To determine the decarbonisation potential and the costs of using Ultra-Deep Geothermal (UDG) energy, first the amount of heat produced by this source needed to be calculated. A share of the total national heat demand was assumed to be supplied by UDG. To do this, first the national heat demand after decarbonisation through energy efficiency needed to be determined. This was done using the following formula:

$$E_{ht}(t) = E_{hs}(t) + \sum_d \sum_i \Delta E_h(d,i) \cdot P(i,t) \quad (10)$$

Where $E_{ht}(t)$ is the total national heat demand after decarbonisation and $E_{hs}(t)$ is the total national heat demand in the scenario before any decarbonisation. By assuming a share of heat supplied by UDG and an amount of load hours per year, the needed UDG production capacity and the increased electricity consumption could be determined from the data found in literature. With the changes in heat and electricity consumption, the change in $CO_2$-emissions could be determined using formula 7, substituting the changes in energy consumption for $E_h(t)$ and $E_e(t)$ respectively.

The costs were determined using formula 8, using the development of cost elements as described there. For UDG, two scenarios for calculating the costs were taken into account: One in which the UDG project is owned by the dairy processing facilities, and one in which the heat produced by the project is purchased from an outside owner. For the first scenario the costs included investments costs, increased expenditure on electricity and savings on gas consumption and carbon credits. For the second scenario they included the purchasing of the heat, and reduced expenditure on gas and carbon credits only. The costs for purchasing heat were based on Straathof (2012), using a value of EUR 11/GJ heat in 2019. Since UDG is cutting-edge technology, there will be a learning effect which affects the costs of purchasing heat. These have been taken into account for the price of heat using the following formula:

$$p_{UDG}(t) = p_{UDG}(2019) \cdot (1 - \varepsilon_{UDG})^{t-2019} \qquad (11)$$

Where $p_{UDG}(t)$ is the price of the purchased heat from the UDG project in year t and $\varepsilon_{UDG}$ is the percentage decrease in the cost of heat produced by UDG. As a base value, $\varepsilon_{UDG}$ is taken to be 0.1%.

### 2.3.3 Electric boilers

As for UDG, the decarbonisation potential of electric boilers was determined by assuming a certain share of the heat requirements of the dairy processing sector would be supplied by the boilers. This share would only concern the remaining amount of heat needed from non-renewable sources, after the implementation of UDG. By assuming an amount of load hours per year, the total capacity of the needed boilers was determined, which was used to determine the investment costs.

The increase in electricity consumption was determined by assigning a specific thermal efficiency to the boilers. From the decrease in heat supplied by natural gas and the increase in electricity consumption, the change in $CO_2$-emissions was determined using formula 7.
As for the energy-efficiency measures, the costs and benefits included in the cost analysis are investment costs, increased expenditure on electricity, and savings on gas consumption and purchasing of carbon credits.

To test the robustness of the analysis, a sensitivity analysis was performed, in which some of the key parameters used in the research were varied to study their impact on the outcome of the cost analysis, as a reflection of an uncertain future.

# 3. Results

## 3.1 Mass and energy flows dairy products

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 product groups will be discussed. A summary of the mass- and energy in- and outputs is given in Table 3 below. The values shown for the heat- and electricity in- and outputs correspond to the values shown in Figure 4, Figure 5 and Figure 6. The category ‘Other input’ only takes into account inputs that end up in the product itself, while any inputs used only during the process are omitted. The calculations on which these numbers are based can be found in Appendix 1 and Appendix 2.

*Table 3: Energy (final energy) and mass in- and outputs for various dairy products*

| Product | Heat input (GJ/t product) | Electricity input (GJ/t product) | Milk/whey input (t/t product) | Other input (unit input/t product) | Output by-product (t/t product) |
|---|---|---|---|---|---|
| **Milk** | 0.10 | 0.05 | Milk: 1.03 | | Cream: 0.03 |
| **Cheese**[2] | 2.38 | 0.93 | Milk: 9.36 | Water: 1.27 t<br>Salt: 0.05 t<br>Rennet: 2809 ml<br>Lactic acid bacteria: 65.5 kg | Cream: 0.27<br>Whey: 9.36 |
| **Butter** | 1.56 | 0.71 | Milk: 17.90 | | Skimmed milk: 15.89<br>Buttermilk: 1.01 |
| **Milk powder**[3] | 7.40 | 0.95 | Milk: 7.46 | | Cream: 0.22<br>Moisture: 6.24 |
| **Milk protein powder**[4] | 7.66 | 1.74 | Milk: 22.46 | | Cream: 0.66<br>Milk permeate: 17.04<br>Moisture: 3.77 |
| **Condensed milk** | 0.79 | 0.27 | Milk: 2.00 | | Cream: 0.06<br>Moisture: 0.94 |
| **Sweetened condensed milk** | 0.74 | 0.27 | Milk: 2.23 | Sugar: 0.44 t<br>Lactose crystals: 0.005 t | Cream: 0.06<br>Moisture: 1.61 |
| **Whey powder**[5] | 7.64 | 1.07 | Whey: 15.38 | | Cheese fines and whey cream: 0.46<br>Moisture: 13.92 |
| **Whey protein powder**[6] | 11.20 | 2.95 | Whey: 62.59 | | Cheese fines and whey cream: 1.88<br>Whey permeate: 50.38<br>Moisture: 9.32 |
| **Lactose**[7] | 5.35 | 1.14 | Whey permeate: 15.78 | | Cheese fines and whey cream: 0.47<br>Whey concentrate: 0.58<br>Moisture: 13.73 |

In Table 4 the energy inputs as determined in this report (the base values from Figure 4, Figure 5 and Figure 6) are compared against values found in literature. Not all products considered in this research are shown, as the used scientific source did not include these explicitly. There is a significant discrepancy between some of the inputs. A number of possible reasons can be given for this.

[2] Gouda assumed
[3] Whole milk powder assumed
[4] Protein content pf 80% of total dry matter assumed
[5] Non-demineralised whey powder assumed
[6] Protein content of 35% of total dry matter assumed
[7] Lactose produced from whey assumed

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 used. For instance, the energy requirements for evaporation can either be 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, using a value between 76.9 and 600 kJ/kg water evaporated. For milk, 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. These changes have a significant impact on the energy consumption, and even larger changes will occur when also changing other (uncertain) parameters. However, even when taking these possible deviations into account, there is a large discrepancy between the determined energy input for milk and that found in literature. However, different sources report values more in line with those determined here. For instance, Xu & Flapper (2011) found a best-practice energy consumption for fluid milk of 0.2 GJ/t, which is more in line with the value found in this research.
Finally, there is a large heterogeneity in the products that fall under one product-category as those shown in Table 4, 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.

*Table 4: Comparison of determined energy input for different dairy products with values found in literature*

| Product | Energy input determined in report (GJ/t product) | Energy input from literature (GJ/t product)[8] |
|---|---|---|
| **Milk** | 0.1 – 0.2 | 1.1 |
| **Cheese** | 2.9 – 3.7 | 4.3 |
| **Butter** | 1.6 – 2.9 | 2.2 |
| **Milk powder** | 7.4 – 10.7 | 11.1 |
| **Condensed milk** | 0.9 – 1.5 | 2.5 |
| **Whey powder** | 8.0 – 10.1 | 8.2 |
| **Lactose** | 2.9 – 12.3 | 5.6 |

### 3.1.1 General

***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, 2015).
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, 2018). 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

[8] Ramírez, Patel, & Blok (2006)

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, 2015). 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, 2018). 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, 2015).

***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).

***Wastewater treatment***

The dairy industry produces a large volume of wastewater, 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 wastewater 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).

### 3.1.2 Milk

The production process for liquid milk is shown in Figure 4. The milk received from the dairy farm first undergoes thermisation, after which it is cooled and heated up to standardisation temperature. After standardisation the milk is homogenised and finally receives some form of heat treatment. Pasteurisation is the most common, but to produce long shelf-life milk sterilisation can be applied as well.

### 3.1.3 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, 2015).

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, 2015). 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, 2018; Tetra Pak, 2015).

### 3.1.4 Butter

The butter-production process is shown in Figure 4 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, 2015). 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, 2015). The grains are then washed in water, after the left-over liquid, buttermilk, is removed. By kneading and folding the grains (called ‘working’), butter can be formed (European Commission, 2018). If desired, salt can be added during the working stage.

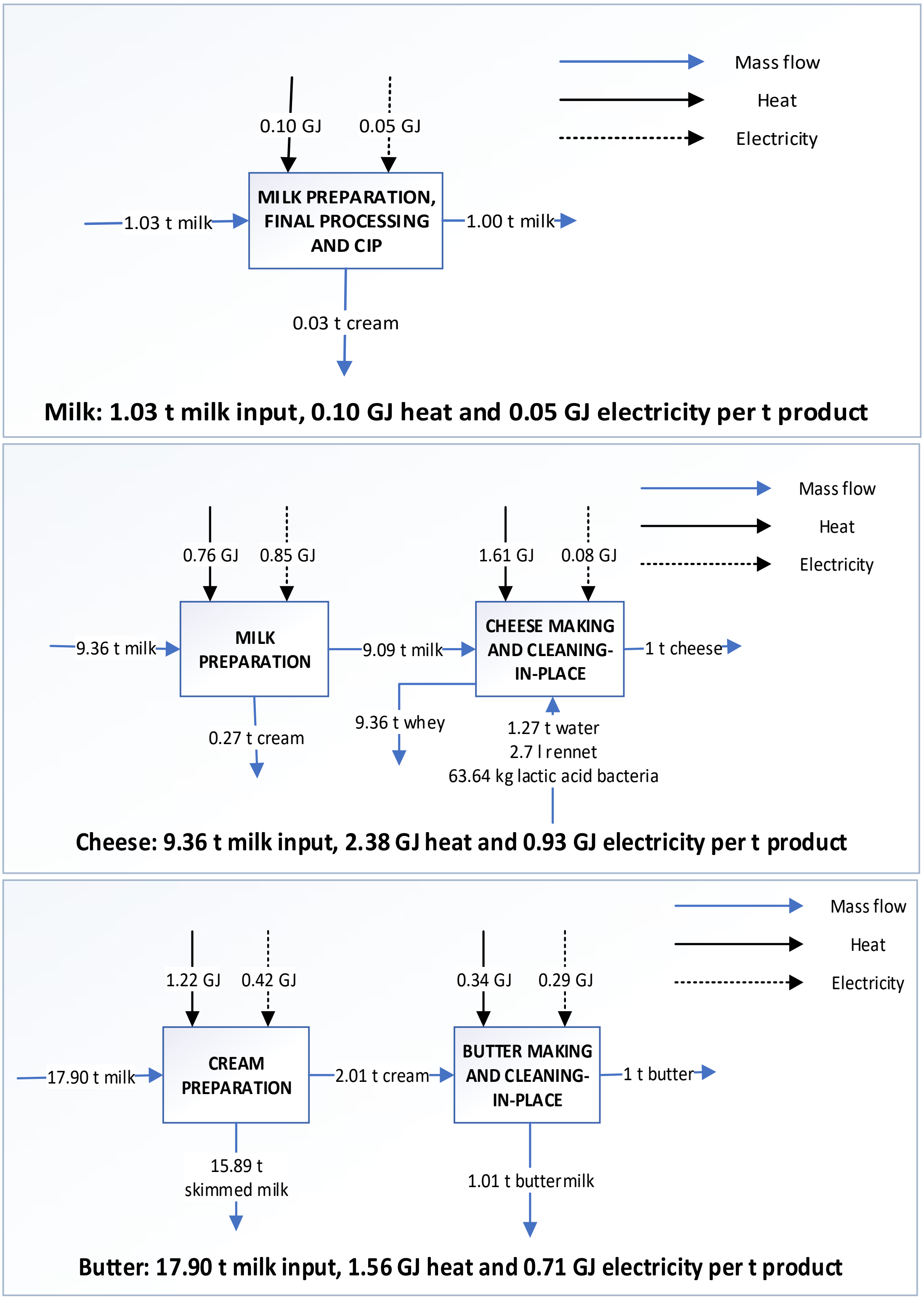


*Figure 4: Production processes for milk, cheese and butter, showing energy and mass in- and outputs*

### 3.1.5 Milk powders and condensed milks

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, 2015; 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 5.

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, 2015). 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)[9], 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; Tetra Pak, 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, 2015).
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)[10] can be homogenised, but this is not always done. The milk is

[9] GEA Process Engineering (2010) states that 375 kg of steam is needed to evaporate 12,300 kg of water
[10] See Appendix 1

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, 2015). 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, 2015).

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, 2015). 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, 2015). 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 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, 2015). This process can yield protein powders with up to around 65–70% protein content in the dry matter (Tetra Pak, 2015; 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.

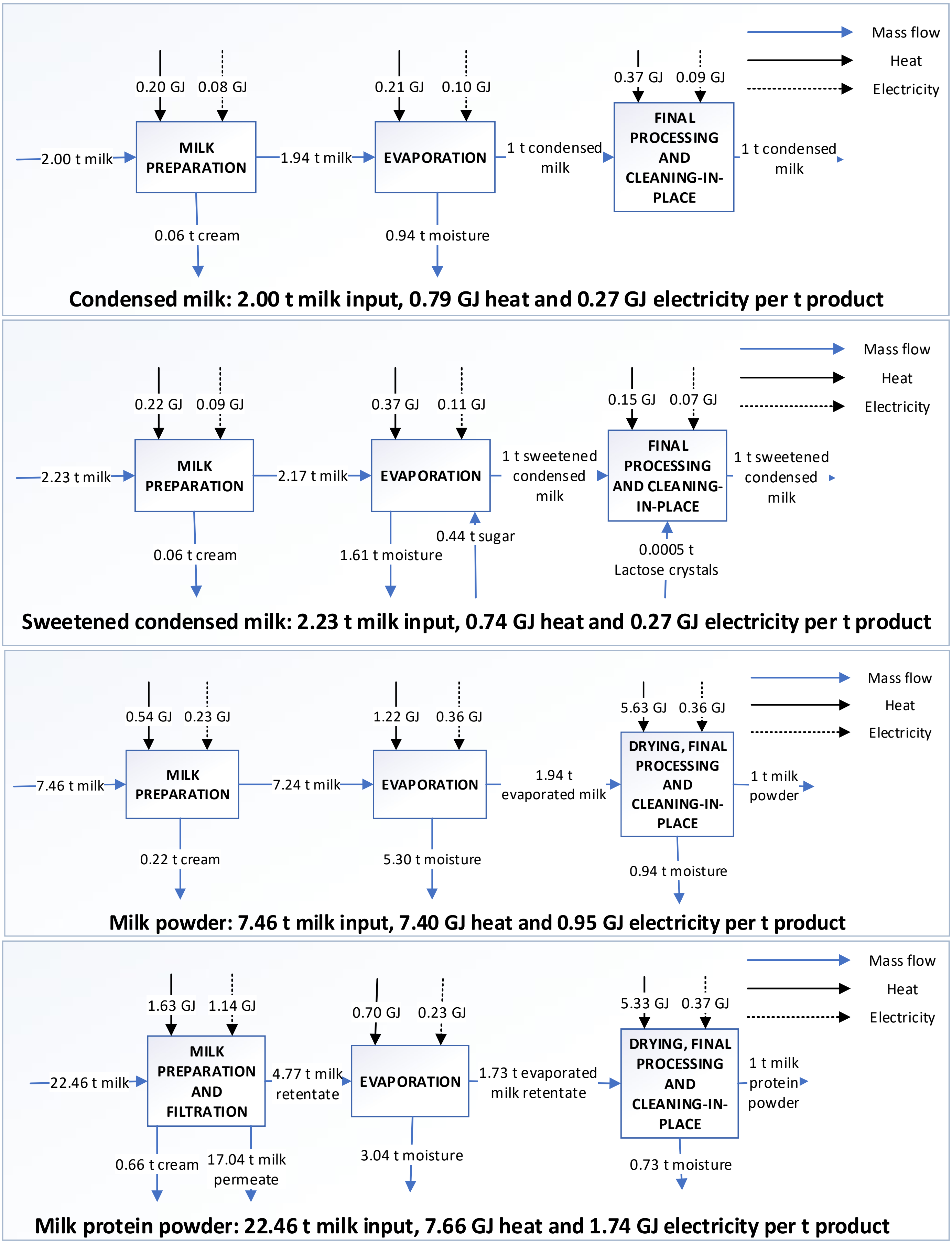


*Figure 5: Production processes for condensed milk, sweetened condensed milk, milk powder and milk protein powder, showing energy and mass in- and output*

### 3.1.6 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, 2015). 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 6 below.

When 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, 2015). 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, 2015). 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, 2015).

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, 2015).

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, 2018). 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, 2015).

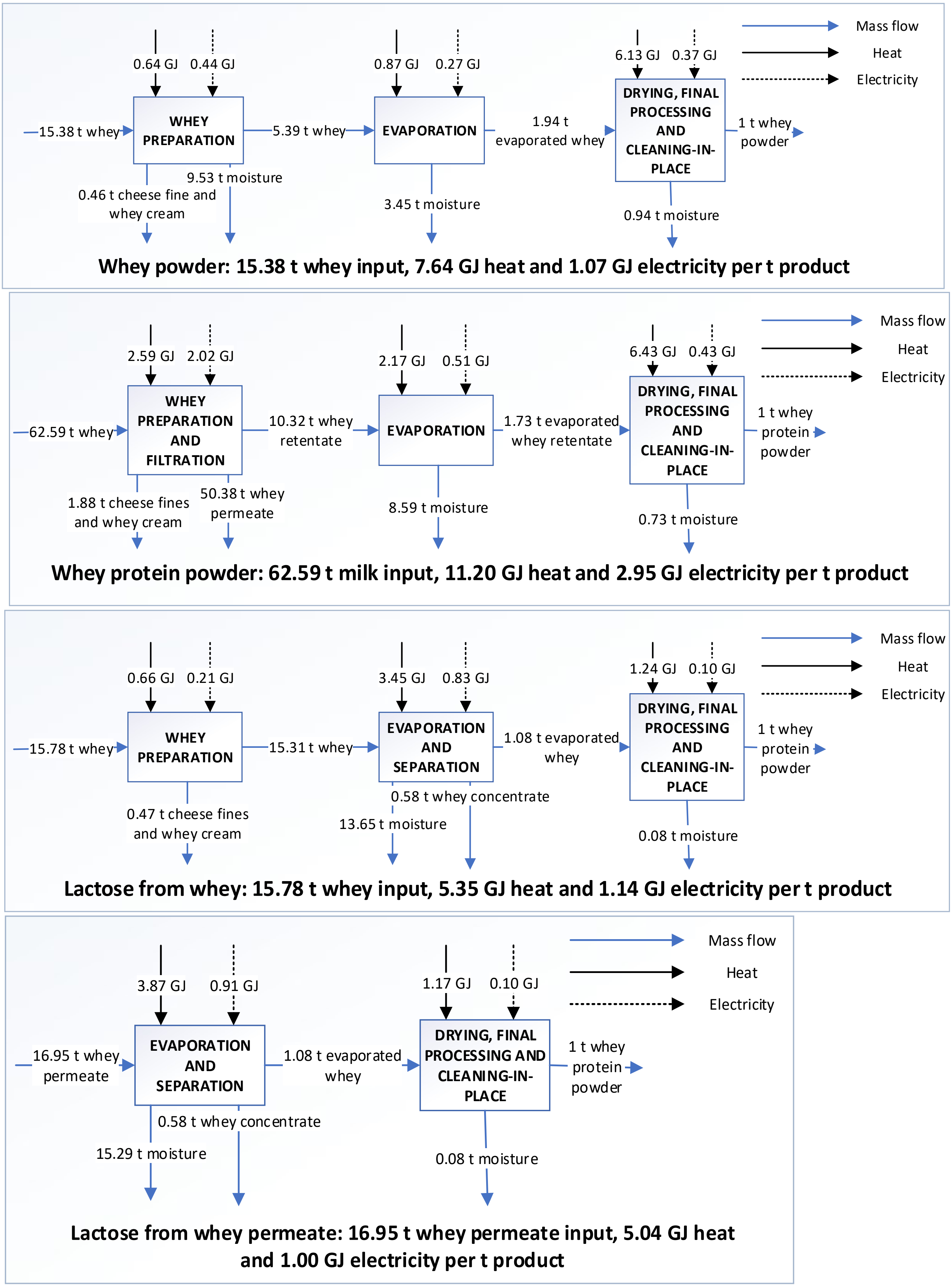


*Figure 6: Production processes for whey powder (non-demineralised), whey protein powder (35% protein in dry matter) and lactose, showing energy and mass in- and outputs*

## 3.2 Decarbonisation options

In this section options for reducing the $CO_2$-emissions of the Dutch dairy processing sector will be discussed. The options that have been included are the use of zeolite during spray-drying, the use of Mechanical Vapour Recompression (MVR) during evaporation, pre-concentration of milk or whey before evaporation using Reverse Osmosis (RO), Ultra-Deep Geothermal (UDG) energy and electric boilers.

### 3.2.1 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, 2019). 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[11]. 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 (van Boxtel, Boon, van Deventer, & Bussmann, 2014).

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%[12], 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 7 below. The costs of such an installation are shown in Table 5 below.

[11] 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).
[12] Other studies state an energy reduction potential of 30–50% (van Boxtel, Boon, van Deventer, & Bussmann, 2014), or 35–45% (Topsector Energie, 2019).

FrieslandCampina 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 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).

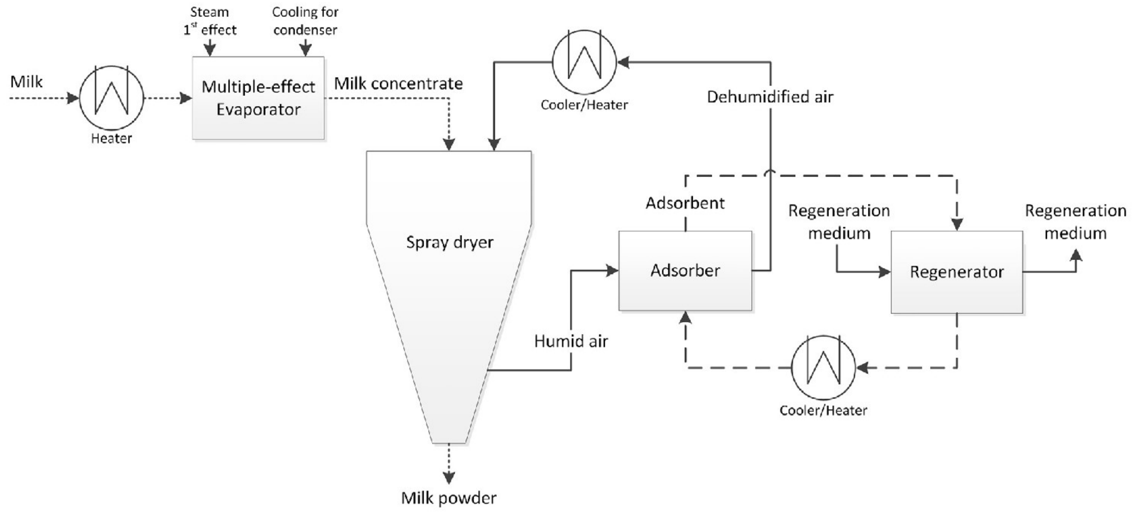


*Figure 7: Process flow for a closed-loop system using a zeolite adsorber for producing milk powder (Moejes, Visser, Bitter, & Van Boxtel, 2018, p. 26)*

*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 [EUR/unit capacity]** | 250,000 | (Moejes, Visser, Bitter, & Van Boxtel, 2018) |

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 |
|---|---|---|---|---|
| **Energy use spray drying without zeolite [GJ/t product]** | 4.38 | 3.92 | 4.82 | 4.31 |
| **Energy use spray drying with zeolite [GJ/t product]** | 2.72 | 2.43 | 2.99 | 2.67 |
| **Total thermal energy use with zeolite [GJ/t product]** | 5.73 | 6.17 | 5.81 | 9.56 |
| **Total electricity use with zeolite [GJ/t product]**[13] | 1.02 | 1.80 | 1.15 | 3.02 |

### 3.2.2 Mechanical vapour recompression

As mentioned in Section 3.1.5, 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, 2020b; Tetra Pak, 2020c). The costs for an MVR are shown in Table 7.

*Table 7: Techno-economic parameters for an MVR system*

| Parameter | Value | Source |
|---|---|---|
| **Capacity [$MW_{th}$]** | 4 – 20 | (TNO, 2018) |
| **Load hours [h/yr]** | 8000 | |
| **CAPEX [million EUR/$MW_{th}$]** | 0.264 – 0.604 | |

In Table 8 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, because of whey's higher heat capacity[14]. An electricity consumption of 200 kW was assumed for the MVR.

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.

[13] Assumed a 25% increase in electricity consumption during the spray-drying process.

[14] Based on TetraPak (2019a), using a steam energy content of 2789 kJ/kg.

*Table 8: Energy saved by application of an MVR in the Dutch dairy sector*

| Parameter | Milk powder | Milk protein powder | Condensed milk | Sweetened condensed milk | Whey powder | Whey protein powder (35%) | Lactose (from whey) |
|---|---|---|---|---|---|---|---|
| **Heat consumption evaporation with TVR [GJ/t product]** | 1.22 | 0.70 | 0.22 | 0.37 | 0.87 | 2.17 | 3.45 |
| **Electricity consumption evaporation with TVR [GJ/t product]** | 0.36 | 0.23 | 0.10 | 0.11 | 0.27 | 0.51 | 0.75 |
| **Heat consumption evaporation with MVR [GJ/t product]** | 0.41 | 0.23 | 0.07 | 0.12 | 0.29 | 0.73 | 1.15 |
| **Electricity consumption evaporation with MVR [GJ/t product]** | 0.57 | 0.38 | 0.16 | 0.18 | 0.43 | 0.82 | 1.21 |
| **Total thermal energy use with zeolite [GJ/t product]** | 6.58 | 7.20 | 0.64 | 0.50 | 7.06 | 9.75 | 3.05 |
| **Total electricity use with zeolite [GJ/t product]** | 1.16 | 1.88 | 0.33 | 0.33 | 1.24 | 3.26 | 1.60 |

### 3.2.3 Pre-concentrating with reverse osmosis

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, so 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[15] (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[16]. The costs of a reverse osmosis installation are shown in Table 9 below.

The effect of using pre-concentrating on the energy requirements for several products is shown in Table 10 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

[15] Assuming an MVR is applied, otherwise the energy-requirements will be even higher.
[16] Assuming 80 kJ/kg water removed for evaporation and 25 kJ/kg water removed for reverse osmosis.

found in Table 26. Only the energy needed for water removal is shown, so the electricity needed for cooling or running the evaporator is excluded.
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 9: 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[17] | (Suárez, Fernández, Iglesias, Iglesias, & Riera, 2015) |
| **Load hours [h/yr]** | 7000 | |
| **CAPEX [$EUR_{2014}/m^2$]** | 1015[18] | |

*Table 10: Energy saved by application of pre-concentrating with membrane in the Dutch dairy sector*

| Parameter | Milk powder | Condensed milk | Sweetened condensed milk | Whey protein powder (35%) | Lactose (from whey) |
|---|---|---|---|---|---|
| **Water removed during pre-concentrating to 18% DM [t/t product]** | 2.01 | 0.54 | 0.60 | 5.02 | 9.78 |
| **Water removed during evaporation to final DM [t/t product]** | 3.29 | 0.40 | 1.00 | 3.57 | 3.87 |
| **Energy use evaporation with pre-concentrating [GJ/t product]** | 0.81 | 0.11 | 0.25 | 1.03 | 1.22 |
| **Energy use evaporation without pre-concentrating [GJ/t product]** | 1.22 | 0.22 | 0.37 | 2.17 | 3.45 |
| **Total thermal energy use with pre-concentrating [GJ/t product]** | 6.93 | 0.66 | 0.60 | 9.93 | 2.87 |
| **Total electricity use with pre-concentrating [GJ/t product]** | 1.00 | 0.28 | 0.28 | 3.08 | 1.38 |

### 3.2.4 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 MWth[19] 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, the two largest dairy companies in the Netherlands, use 100%

[17] 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.
[18] Excludes installation costs on-site.
[19] 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.

renewable electricity in their European production locations (FrieslandCampina, 2019; Vreugdenhil Dairy Foods, 2019).

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. 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 11 below.

*Table 11: Techno-economic parameters for an electric boiler*

| Parameter | Value | Source |
|---|---|---|
| **Capacity [MWe]** | <70 | (Berenschot, Energy Matters, CE Delft, Industrial Energy Experts, 2017) |
| **Efficiency [%]** | <99.9% | |
| **CAPEX [EUR/kWe]** | 150–190[20] | |

### 3.2.5 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, 2018; 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, 2017). The costs for an UDG project are shown in Table 12 below.

*Table 12: Techno-economic parameters for an 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]** | 21.8268 | |
| **CAPEX [EUR/kW]** | 2509[21] | |

## 3.3 Scenarios

As described in the methodology, two pillars were established on which the scenarios were based: milk production and utilisation of milk. These pillars will be discussed in the following sections.

### 3.3.1 Milk production

As the sudden increase of milk production in the Netherlands after abolishing the milk quota in 2015 shows, milk production is volatile and prone to external factors (CBS, 2019). To account for this volatility, three scenarios regarding milk production have been created, reflecting either a Business-As-Usual (BAU) development of the sector, a medium increase in milk production, or a low increase. These scenarios were created through extrapolation of historic trends. The three scenarios are shown in Figure 8 below.

[20] 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).
[21] Does not include costs of geological research and permits. Costs of a heat distribution network of a length of 0.5 km included.

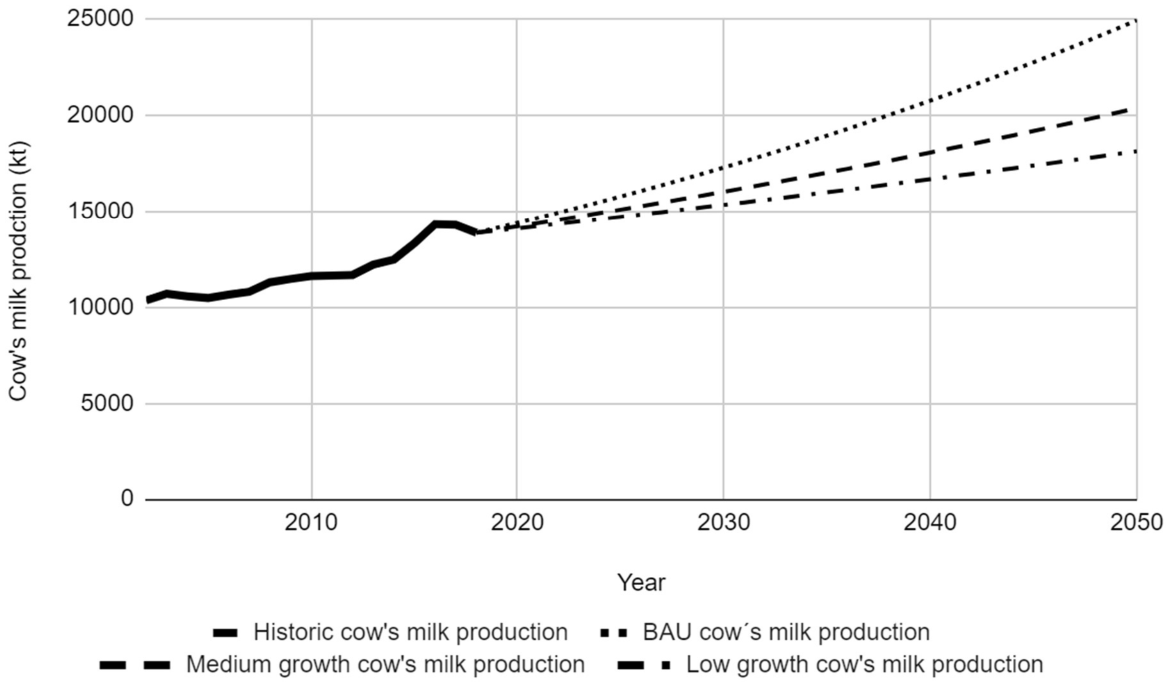


*Figure 8: Milk production scenarios showing the amount of cow's milk produced in the Netherlands*

The BAU scenario extrapolates data from the entire historic period (2002-2018). This results in an increase of around 1.8% per year, which is close to the 1.7% increase expected for global milk production until 2028 (OECD-FAO, 2019). Since this period includes the strong increase after the abolishment of the milk quota, this scenario shows the strongest growth in milk production, and reflects the dairy sector if it undergoes unrestrained growth. However, this growth may not be attainable. In 2015 FrieslandCampina struggled to process the increased milk production from its farmers, even paying a premium if the farmers did not further increase production (Volkskrant, 2015).
Apart from the processing capacities of the processing plants, other factors, such as boycotts (several Dutch dairy companies could not export their products to Russia for several years) or national legislation, can hamper the sector's growth. As mentioned in the introduction, as of early 2020, there is also an ongoing debate around nitrogen emissions, which could have a large impact on dairy farmers, as they are said to be responsible for a large share of these emissions (Adviescollege Stikstofproblematiek, 2019).
Therefore, a medium and low growth scenario have been created. These have been based on an extrapolation of historic production from 2002-2011 and 2002-2007 respectively. This resulted in annual growth rates of 1.2% and 0.8% respectively. The growth in milk production in Europe is expected to be lower than the global average of 1.7% annually, so these growth scenarios might indicate more realistic pathways for the Dutch dairy sector (OECD-FAO, 2019).

### 3.3.2 Utilisation of milk

Two different pathways for the utilisation of Dutch milk have been created. One is based on the historic use of milk in the Netherlands, while the other is based on an increasingly international sector, which shifts the demand to certain dairy products.

To illustrate the impact of the previously discussed choices on the production of dairy products in the Netherlands, an overview of the production in 2050 is shown in Table 13 below.

*Table 13: Production of dairy products in 2050 under different production scenarios*

| Product | Status quo production (kt) | International demand production (kt) |
|---|---|---|
| **Milk** | BAU: 3576 | BAU: 2353 |
| | Low: 2601 | Low: 1711 |
| | Medium: 2921 | Medium: 1922 |
| **Cheese** | BAU: 1476 | BAU: 1095 |
| | Low: 1073 | Low: 797 |
| | Medium: 1202 | Medium: 895 |
| **Butter** | BAU: 397 | BAU: 350 |
| | Low: 288 | Low: 255 |
| | Medium: 324 | Medium: 286 |
| **Condensed milk**[22] | BAU: 664 | BAU: 583 |
| | Low: 483 | Low: 424 |
| | Medium: 543 | Medium: 476 |
| **Milk powder** | BAU: 379 | BAU: 687 |
| | Low: 276 | Low: 500 |
| | Medium: 310 | Medium: 561 |
| **Protein powder**[23] | BAU: 211 | BAU: 382 |
| | Low: 153 | Low: 278 |
| | Medium: 172 | Medium: 312 |
| **Whey powder** | BAU: 251 | BAU: 341 |
| | Low: 183 | Low: 248 |
| | Medium: 205 | Medium: 279 |
| **Lactose**[24] | BAU: 282 | BAU: 383 |
| | Low: 205 | Low: 278 |
| | Medium: 230 | Medium: 313 |

### 3.3.3 Energy consumption and emissions

Combining the energy consumption for the production of dairy products and the production figures of those products from the created scenarios, the total energy consumption of the Dutch dairy industry could be determined. The development of the total energy consumption (heat and electricity combined) for the Dutch dairy processing industry is shown in Figure 9 below, assuming a 0% autonomous efficiency increase. For all energy consumption figures it is assumed that lactose is produced from whey and that the category 'condensed milk' consists for 100% out of unsweetened condensed milk.
The figure shows that the total energy consumption between the different scenarios varies significantly in 2050, as the highest energy consumption (of the BAU international demand scenario) is around 73% higher than the lowest energy consumption (of the low demand status quo scenario). These two scenarios can be seen as the edges of a bandwidth between which the development of the energy consumption of the dairy industry is likely to be in the future.

[22] Assumed 100% unsweetened condensed milk
[23] Assumed 50% milk protein powder and 50% whey protein powder
[24] Assumed to be produced from whey

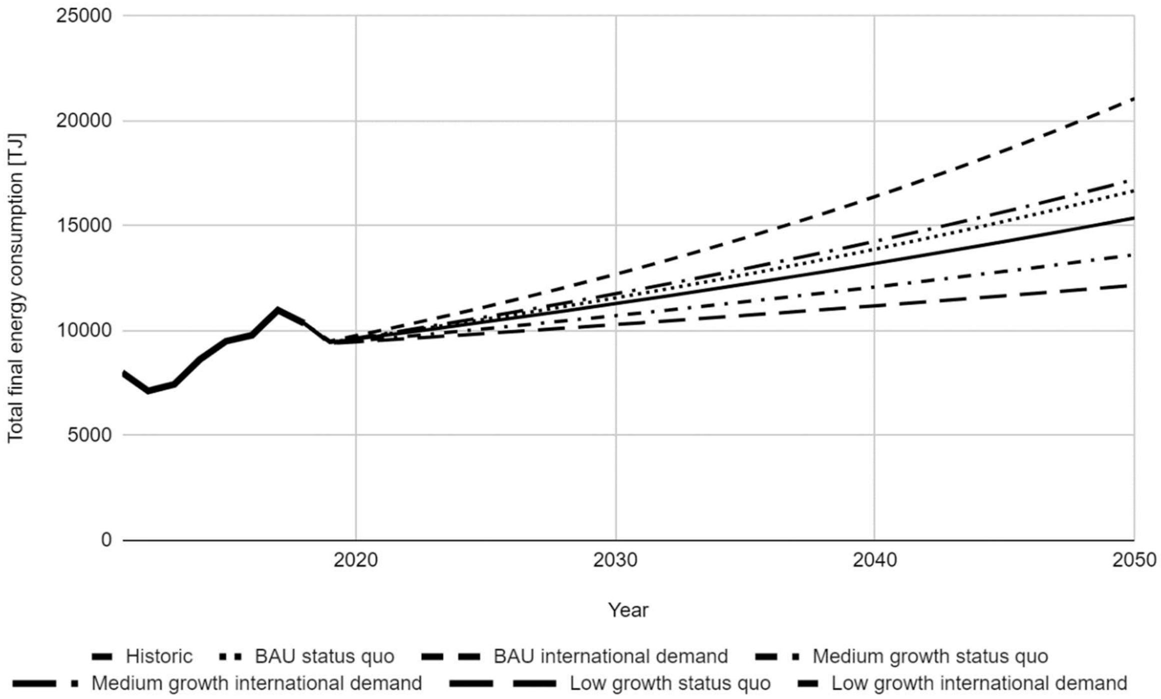


*Figure 9: Development of total energy consumption of the Dutch dairy processing sector for different scenarios*

The total emissions strongly depend on the way the heat and electricity are generated. As an example, the emissions that arise when assuming all heat is produced by 90% efficient natural gas boilers and the average Dutch electricity is used are shown in Figure 10. For this figure, it was assumed that the share of renewables in the Dutch electricity grid would grow linearly from 15.12% in 2018 to 70% in 2030, and then to 98% in 2050, and that the dairy sector does not produce its own renewable electricity (CBS, 2020; Klimaatakkoord, n.d.). The value taken for $EF_g$ was 56,6 kg $CO_2$/GJ gas burned and $EF_e$ was 112.5 kg $CO_2/GJ_e$.

The decrease or relatively slow increase of emissions until 2030 can be explained by the more rapid increase in use of renewable electricity during this period compared to after it. After 2030 the increase in penetration of renewables in the Dutch electricity grid is not large enough to offset the increased electricity and heat consumption.

As for the total energy consumption, the choice of scenario has significant effects on the emissions in 2050. For the emissions, the difference between the scenario with the highest value and the lowest value is around 78%, even larger than the difference in energy. This is because of the differences in utilisation of milk in these two scenarios, as in the international demand scenario more energy-intensive products are produced.

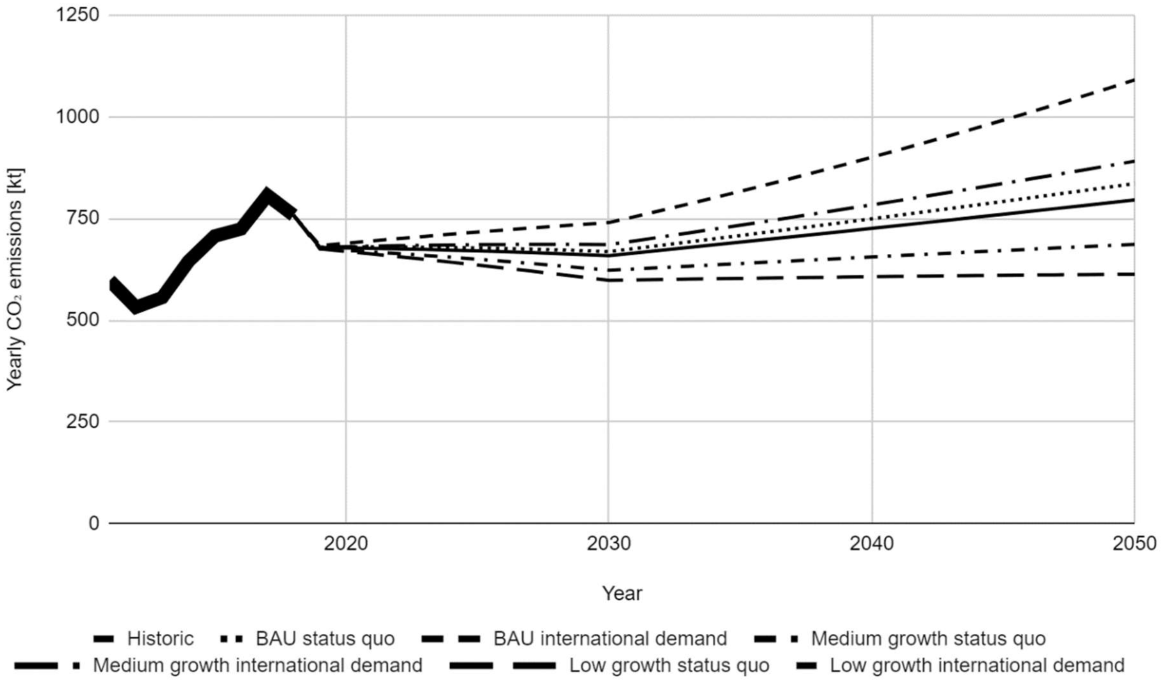


*Figure 10: Development of $CO_2$ emissions of the Dutch dairy processing industry under ES1*

To show the dependence on the way the heat and electricity are generated, Table 14 below shows the total emissions of the sector in 2050, when making different assumptions. The emissions were calculated using formula 7. These assumptions made are as follows:

- All heat is supplied by 90% efficient natural gas boilers, and the dairy processing industry uses no extra renewable electricity (1).
- All heat is supplied by 90% efficient natural gas boilers, and the dairy processing industry uses an extra 25% renewable electricity (2).
- 75% of the heat is produced by 90% efficient natural gas boiler, and 25% by CHPs with 60% thermal efficiency and 30% electrical efficiency (3).
- Same as above, with an extra 25% renewable electricity utilisation by the dairy industry (4).
- 100% of the heat is supplied by CHPs (5).

For all these scenarios, except the base case (which is based on the assumption made for Figure 10), it is assumed the share of renewables in the Dutch electricity mix does not increase, to show the impact of the other parameters. Also, no autonomous energy efficiency developments have been taken into account. Since the only difference between scenario 1 and the base case is the increased penetration of renewables in the Dutch electricity grid, the difference between these two can be attributed to this rise. The table shows that moving to the international demand scenarios from the status quo scenarios has a significantly larger impact on the emissions than moving between emission scenarios. This is reasonable since the difference in energy consumption between the international demand and status quo scenarios is over 26%, leading to similar differences in emissions.

Furthermore, the addition of renewable electricity has a larger impact when all heat is produced by natural gas boilers (resulting in a change of around 8% in the BAU status quo scenario) than when it is done by CHPs (around 4.5%). This is because more electricity has to be purchased from the national grid, so an increase in renewables there will have a larger impact. This difference increases with increased usage of renewable electricity, resulting in lower emissions when using only natural gas boilers with 100% renewable electricity (831 kt $CO_2$ in 2050 in the BAU status quo scenario) compared to 75% boilers and 25% CHPs and 100% renewable electricity (935 kt $CO_2$). This happens since the thermal efficiency of CHPs is lower than that of natural gas boilers, and the decreased electricity consumption does not lead to reduced emissions. This means that the positive effect of CHPs on emissions will decrease over time, since the penetration of renewables will increase.

*Table 14: $CO_2$-emission in 2050 under different emission scenarios*

| Scenario | Emissions 2050 [kt CO2] | | | | | |
|---|---|---|---|---|---|---|
| | BAU status quo | BAU international demand | Low growth status quo | Low growth international demand | Medium growth status quo | Medium growth international demand |
| **Base** | 840 | 1090 | 613 | 796 | 687 | 891 |
| **1** | 1220 | 1518 | 890 | 1107 | 997 | 1240 |
| **2** | 1123 | 1408 | 819 | 1027 | 917 | 1150 |
| **3** | 1138 | 1411 | 830 | 1029 | 930 | 1153 |
| **4** | 1087 | 1362 | 793 | 994 | 888 | 1113 |
| **5** | 1247 | 1620 | 910 | 1182 | 1019 | 1323 |

The emissions under different emission scenarios for the BAU status quo scenarios are shown in Figure 11 below. The figure shows that emissions converge in scenarios in which the heat is produced in the same way (ES1 and ES2, and ES3 and ES4), because of the increase in utilisation of renewable electricity until 2050.

Interesting to note is that the emissions under ES3 are lower than those in its counterpart using only natural gas boilers (ES1) in the early years. However, the emissions end up higher in 2050. This is because, in the early years, the CHPs produce electricity, thereby preventing the relatively high emissions from electricity consumption. These emissions decrease over time because of the increased usage of renewables in the Dutch electricity grid, and finally the emissions from heat consumption overcome the difference because of the lower thermal efficiency of the CHPs. So, the positive effect of using CHPs diminishes over time. When using 100% renewable electricity from the beginning, the emissions using natural gas boilers (ES2) are consistently lower than when using CHPs (ES4).

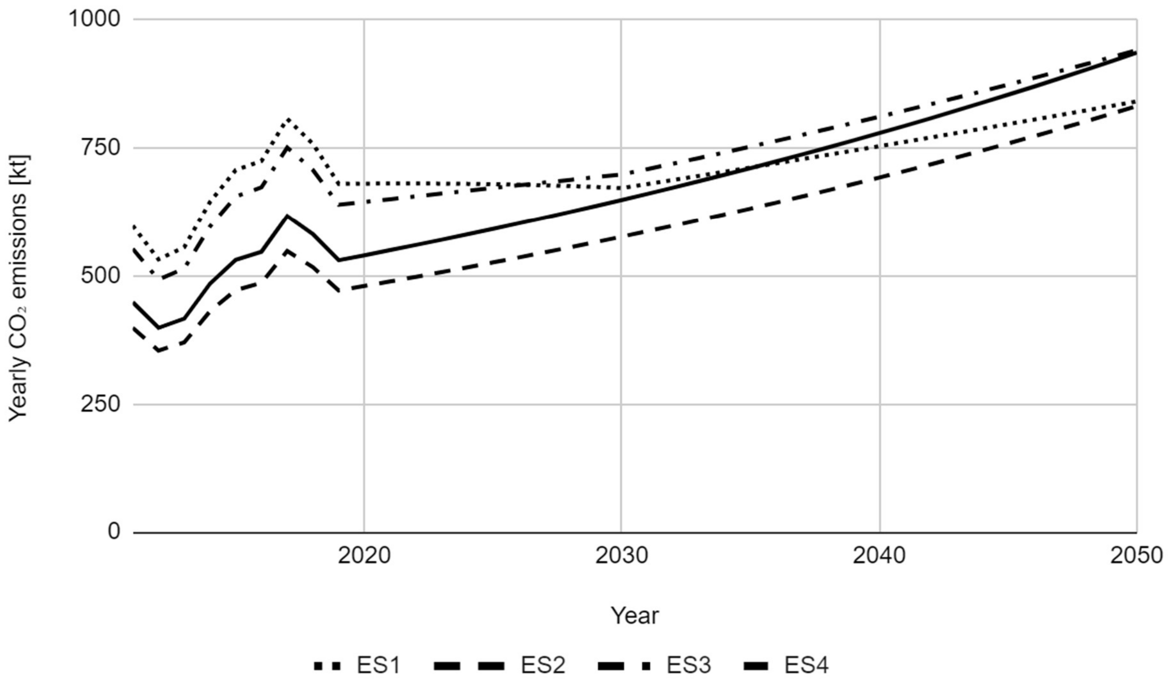


*Figure 11: Development of emissions under different emission scenarios for the BAU status quo scenario*

The effect of adding more renewables to the Dutch electricity grid is further illustrated in Figure 12, where the development of $CO_2$-emissions in the BAU status quo scenario is compared to the development that would occur in this scenario if no renewables are added. The figure also shows the effect of the use of 100% renewable electricity by the dairy sector itself (see Section 2.2.4). The jump in emissions between the historic period and the beginning of the projections stem from the fact that the historic emissions are calculated based on a situation in which no renewables are added by the dairy processing facilities. If these were added to the historic period, emissions would have been lower there as well.

The emissions in both scenarios with renewables converge towards 2050. This is because the dairy sector is assumed to use 100% renewables for the bottom line, while the penetration of renewables increases up to 98% in 2050. So, in 2050, the emissions of these two scenarios will only differ slightly. These scenarios show that using renewable electricity will have a significant effect on the emissions of the sector, as the emissions with renewables are over 30% lower in 2050 than in the scenario without them. This means that emissions from electricity consumption account for around 30% of the total amount.

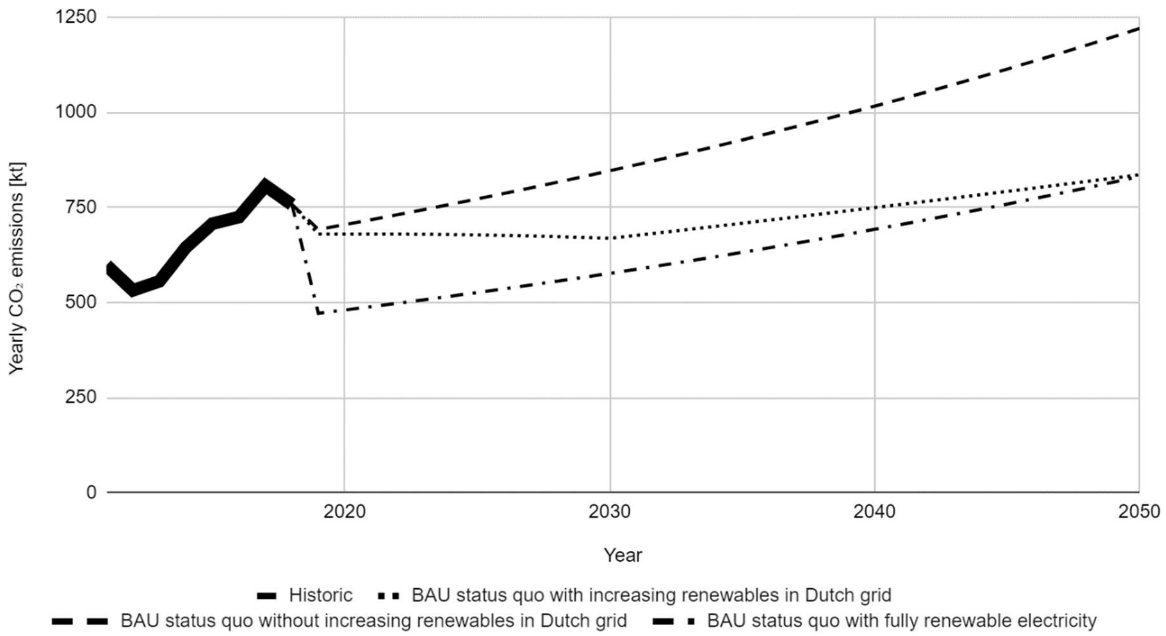


*Figure 12: Comparison of $CO_2$-emissions in the BAU status quo scenario under ES1 with or without increased penetration of renewables in the Dutch electricity grid*

### 3.3.4 Decarbonisation

With the emissions calculated, the effects of decarbonisation have been identified. As mentioned, these fall into three categories: energy efficiency, geothermal energy and electric boilers. In the following sections, the results from each of these categories will be shown. For these results it is assumed that the amount of renewables in the Dutch electricity grid will increase, as described in Section 3.3.3. For a description of the emissions scenarios (ES) used in the following sections, see Section 2.2.4.

***Energy efficiency***

To determine the decarbonisation by energy efficiency measures, the maximum potential in 2050 had to be determined. The results are shown in Table 15 below. As for the emissions before decarbonisation, the effect of changing between milk utilisation scenarios is greater than switching between emission scenarios, indicating that the mix of product made by the dairy processing industry will have a large impact on its decarbonisation.

*Table 15: Maximum decarbonisation potential of energy efficiency measures in 2050*

| Scenario | BAU status quo | BAU international demand | Low growth status quo | Low growth international demand | Medium growth status quo | Medium growth international demand |
|---|---|---|---|---|---|---|
| **Decarbonisation potential in 2050 – ES1 [kt $CO_2$]** | 199 | 311 | 146 | 228 | 163 | 254 |
| **Decarbonisation potential in 2050 – ES2 [kt $CO_2$]** | 200 | 313 | 147 | 229 | 164 | 256 |
| **Decarbonisation potential in 2050 – ES3 [kt $CO_2$]** | 223 | 349 | 163 | 255 | 182 | 285 |
| **Decarbonisation potential in 2050 – ES4 [kt $CO_2$]** | 225 | 352 | 165 | 258 | 184 | 288 |

The yearly emissions that arise when assuming linear growth up to the decarbonisation potential in 2050, for ES1, are shown in Figure 13. Since linear growth of decarbonisation is assumed, the same amount of emissions is abated each year, so the curves in the figure show the same development as those in Figure 10, but at a lower level. Since the decarbonisation potential is lower for the medium- and low growth scenarios compared to the BAU scenarios, the difference between the scenarios decreases compared to Figure 10, as there is only a difference of around 67% between the highest and lowest emission levels in 2050, compared to 78% before decarbonisation through efficiency.

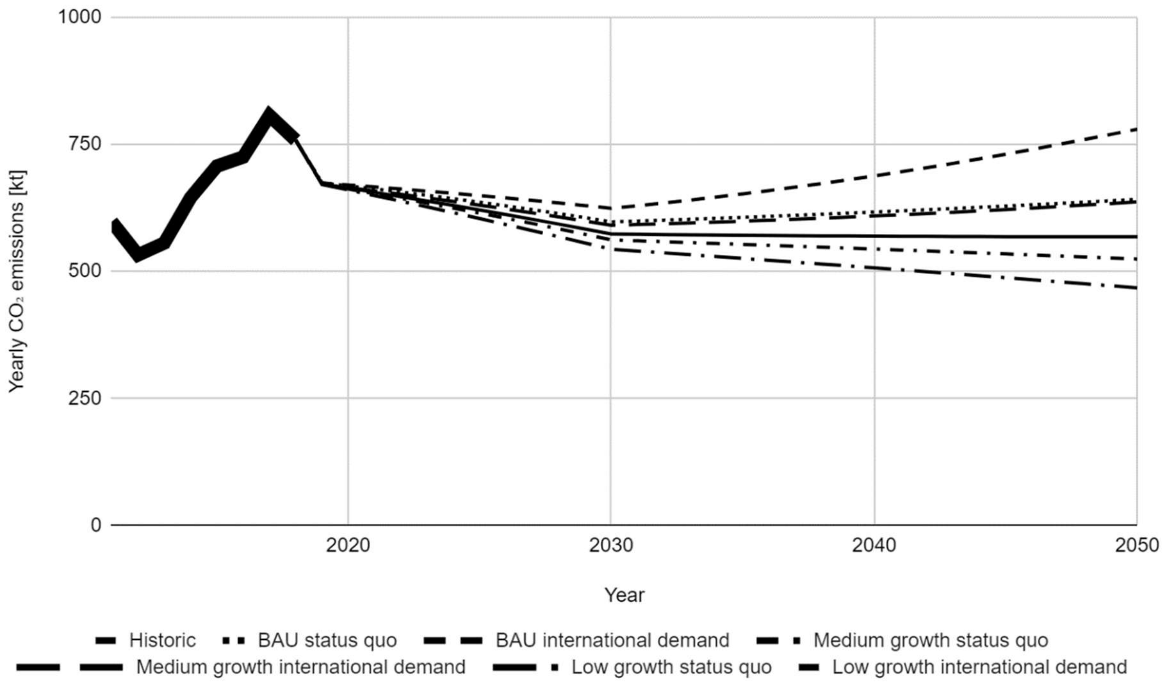


*Figure 13: $CO_2$ emissions after decarbonisation through energy efficiency under ES1*

Next, the abatement costs were determined. The results for the BAU status quo scenario under ES1, assuming no autonomous energy efficiency improvements occur, are shown in Figure 14 below. From the figure it can be seen that there will be sharp increases in the abatement costs. This is because at the

points of increase, there is no additional decarbonisation potential from a cheap option, so a new, more expensive option has to be added. For the BAU status quo scenario under ES1, the first decarbonisation option to be implemented is zeolite for both protein powders. Then in 2029, the MVR option is added, first for lactose. The costs of this option are comparable to those of zeolite, so no sharp increase in abatement costs arise. After implementation of MVR for all products, pre-concentrating starts to be added in 2042. In this year a sharp increase is visible, indicating that the costs of this option are comparatively high. This is indeed the case, as the costs are about four times as high as the next most expensive option. In 2047 and 2048, decarbonisation is achieved by using pre-concentrating on new products (whey protein powder and milk powder respectively) and costs increase again because of the relatively high costs of these products. In all scenarios preconcentrating will be added after implementing the MVRs for all products. The relatively high abatement costs of the additional preconcentrating options can prove to be unfavourable for the sector, which might therefore not be implemented.
In the periods in which no new decarbonisation options are added, costs slope downwards mainly because of the increased savings stemming from the reduced need to buy carbon credits, which get more expensive over time. These patterns largely hold true for other production and emission scenarios. However, the use of 100% renewable electricity by the dairy sector can relatively lower the abatement costs for some MVR options, since the relatively large increase in electricity consumption from this option does not result in a large increase in emissions in this case. Also, for some scenarios there is a drop-off in abatement costs in the final years (for instance, in the BAU international demand scenario under ES3, the peak of EUR 0.43/kg $CO_2$ is reached in 2040 after which the abatement costs drop to EUR 0.07/kg $CO_2$ in 2050). In these cases, the yearly decarbonisation needed can be achieved by the autonomous developments in decarbonisation from previously implemented options, meaning the capacity of these only need to be increased slightly. So, the additional decarbonisation capacity in these cases does not come primarily from new, more expensive options, but from the full portfolio of available options. This does however not mean that the average abatement costs of these scenarios will be markedly lower (see Table 16).

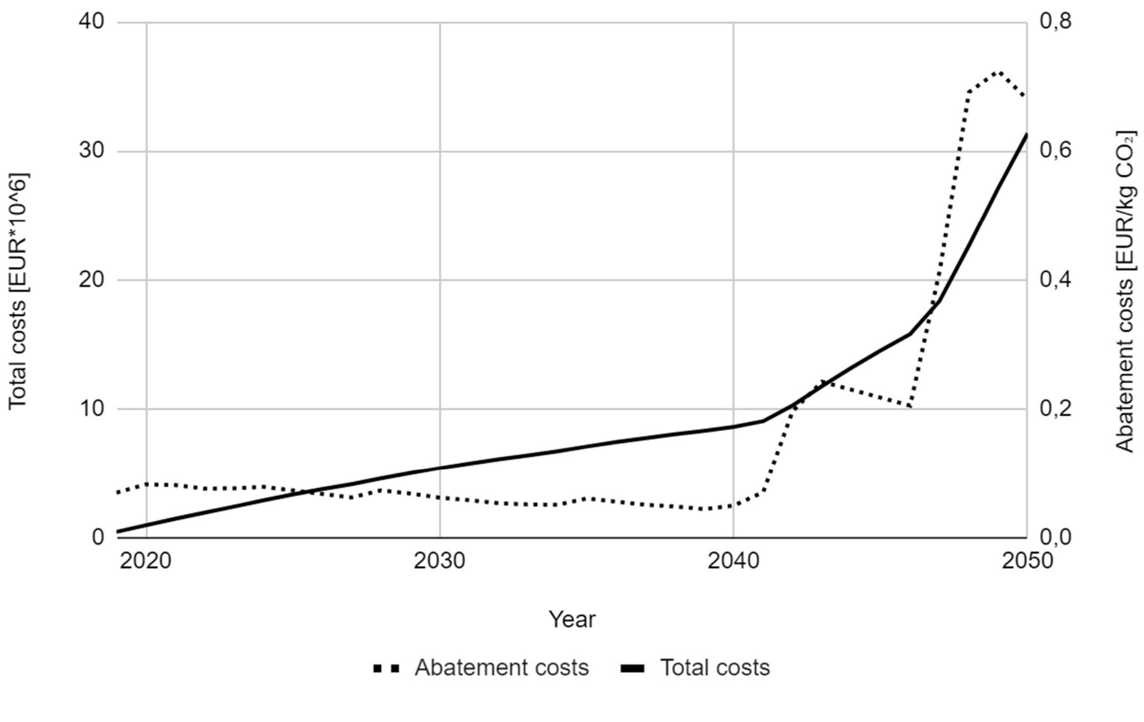


*Figure 14: Yearly and total costs of decarbonisation through efficiency for the BAU status quo scenario under ES1*

Instead of looking at the costs per year, they can also be compared against the amount of decarbonisation reached. This is shown in Figure 15 below. The chart shows that a significant share of the total decarbonisation possible (over 70%) can be achieved at an abatement cost of less than EUR 0.1/kg $CO_2$. The final share of decarbonisation, around 30%, cost around EUR 22 million, thereby accounting for over 70% of the total costs. An option for the dairy industry could be to abate a large share of the total possible abatement at a low price, which will be reached around 2040 according to this research, and then investigate other, less expensive options. Because of the timeframe, namely 20 years, new options will have emerged by then, or the cost profile of existing options will have changed significantly, so a new evaluation of the preferred decarbonisation pathway will be desirable by then.

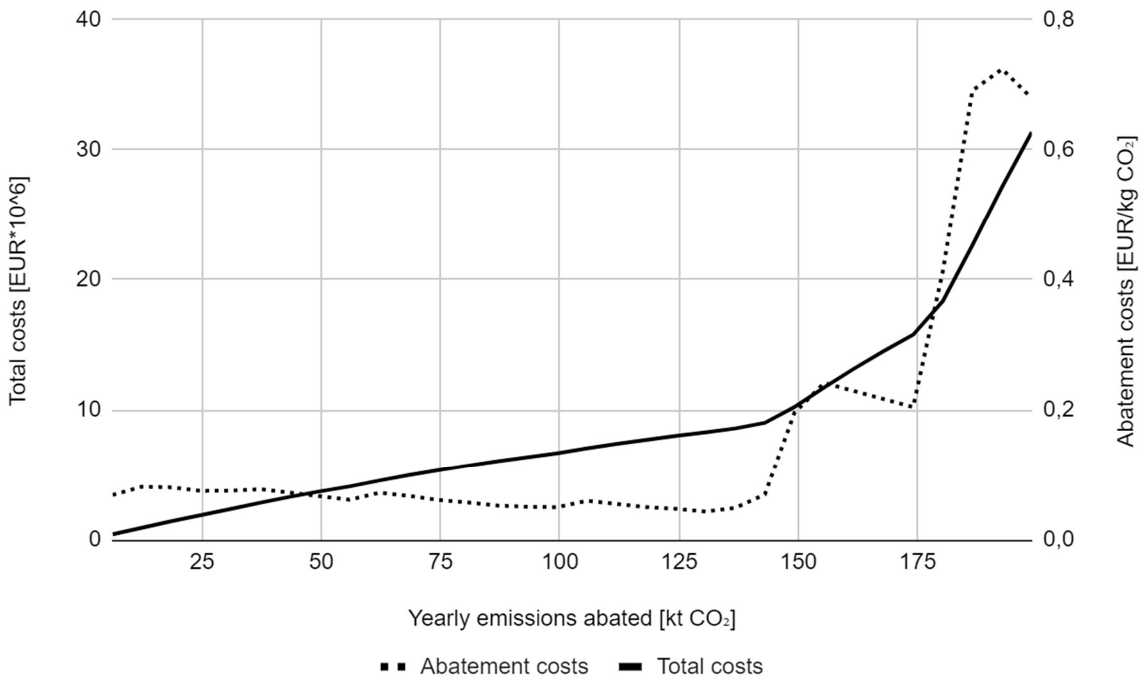


*Figure 15: Yearly and total costs of decarbonisation through efficiency compared against total abatement achieved for the BAU status quo scenario under ES1*

For the BAU status quo scenarios under ES1, the total costs in 2050 are EUR 31.35 million, and the total decarbonisation in 2050 is 198.94 kt $CO_2$, resulting in average abatement costs of EUR 0.16/kg $CO_2$ and remaining emissions of 641.49 kt $CO_2$ in 2050. For all other production and emission scenarios, abatement and total costs are shown in Table 16 below.

The table shows that the use of 100% renewable electricity by the dairy sector has a small effect on the abatement costs if heat is produced by natural gas boilers only (compare ES1 to ES2), and the effect is not consistent when comparing the status quo and international demand scenarios. In the international demand scenarios, a smaller percentage of the energy consumption comes from electricity consumption than in the status quo scenarios because in the international scenarios the product mix shifts towards products with relatively lower shares of electricity requirements. Because of this, the use of 100% renewable electricity by the dairy sector will have a lower effect on the decarbonisation each year, thereby slowly driving up the abatement costs.

In the status quo scenarios the abatement costs consistently go down when switching from ES1 to ES2 or from ES3 to ES4. These changes might be explained by the fact that for a similar amount of investment, more decarbonisation occurs since the increased electricity consumption is produced from more renewable sources. For the international demand scenarios, some increases occur when switching from ES1 to ES2. This happens since, in the international demand scenarios when switching from ES1

to ES2, more yearly decarbonisation is needed, which means that every year a bit of a more expensive option is needed in ES2, driving up the costs slightly.
The shift from ES3 to ES4 results in a significant reduction in abatement costs for all production scenarios. This can be explained by the fact that by reducing the heat consumption by adding decarbonisation options, the electricity consumption is further increased since the CHPs produce less electricity, while also being increased by the decarbonisation options. So, the increase in electricity consumption will be greater than under the ES1 and ES2 scenarios. And since under ES4 this increased consumption can be met by renewables sources, the decarbonisation potential goes up, while the total yearly costs remain similar.

*Table 16: Average abatement costs (AC) in EUR/kg $CO_2$ and total costs (TC) in EUR*$10^6$ for decarbonisation through energy efficiency for different production and emissions scenarios*

| Scenario | BAU status quo | BAU international demand | Low growth status quo | Low growth international demand | Medium growth status quo | Medium growth international demand |
|---|---|---|---|---|---|---|
| **ES1** | AC: 0.16 | AC: 0.16 | AC: 0.16 | AC: 0.15 | AC: 0.16 | AC: 0.15 |
| | TC: 31.35 | TC: 48.63 | TC: 22.86 | TC: 34.59 | TC: 25.49 | TC: 38.84 |
| **ES2** | AC: 0.15 | AC: 0.16 | AC: 0.15 | AC: 0.16 | AC: 0.15 | AC: 0.16 |
| | TC: 29.30 | TC: 49.50 | TC: 21.71 | TC: 35.58 | TC: 24.10 | TC: 39.82 |
| **ES3** | AC: 0.14 | AC: 0.14 | AC: 0.14 | AC: 0.14 | AC: 0.14 | AC: 0.14 |
| | TC: 31.69 | TC: 49.98 | TC: 22.99 | TC: 35.17 | TC: 25.68 | TC: 39.85 |
| **ES4** | AC: 0.12 | AC: 0.12 | AC: 0.12 | AC: 0.12 | AC: 0.12 | AC: 0.12 |
| | TC: 27.74 | TC: 40.95 | TC: 20.56 | TC: 30.43 | TC: 22.82 | TC: 33.75 |

### *Ultra-Deep Geothermal energy*

Using formula 10, the total heat demand of the Dutch dairy processing sector after decarbonisation through energy efficiency could be determined. To determine the impact of UDG, it was assumed that this source would start supplying heat to the industry in 2031. This year was chosen to reflect the fact that UDG is not yet a proven technology, as currently no UDG projects are operational. However, several companies, among which are FrieslandCampina, have joined a programme to examine the potential of this renewable heat source (EBN, 2020).
The potential of UDG is estimated at 30% of the Dutch industrial heat demand (Green Deal, 2018). This was chosen as the target in 2050, and linear growth of the share of heat supplied by UDG was assumed from 2031 onwards. This results in a total heat supply by UDG of just over 3 PJ in 2050 in the BAU status quo scenario.

As mentioned, the UDG project can either be owned by the dairy processing facility or by an outside party. These two scenarios will be discussed here.
If the UDG project is owned by the dairy processing facility itself, the sector itself is responsible for filling the increased electricity demand. Assuming this is done with the average electricity from the Dutch grid, the emissions after implementation of UDG are shown in Figure 16 for ES1. If the project is owned by an outside party, the emissions from the electricity can be excluded. This results in only a very small change in emissions each year, adding up to a reduction of around 20 kt $CO_2$ over the entire period compared to the situation in which the dairy sector has to fill the electricity demand itself. When comparing Figure 16 with Figure 13, it can be seen that adding UDG results in a development of emissions that negates the effect of the lower increase in renewable electricity in the Dutch grid after 2030, since UDG is assumed to become available in 2031. The emissions slope down slightly because an increasing share of an increasing energy consumption is assumed to be supplied by UDG.

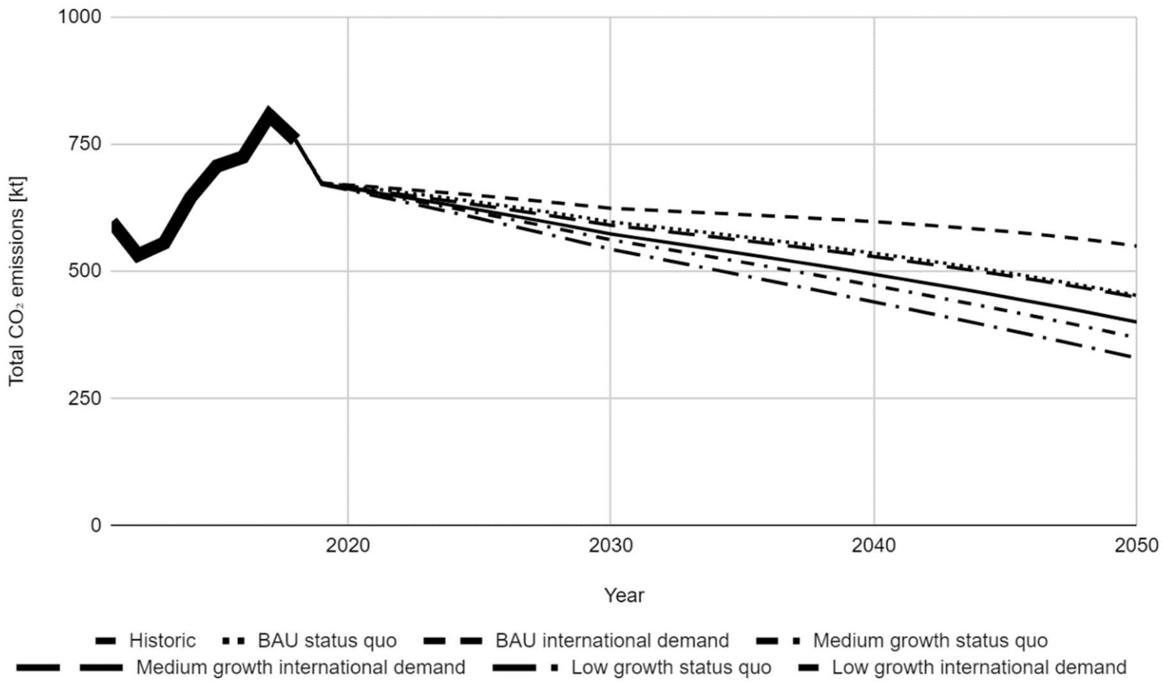


*Figure 16: $CO_2$ emissions after decarbonisation through energy efficiency and UDG under ES1*

The decarbonisation potential of UDG under all production and emission scenarios is shown in Table 17 below. The decarbonisation potential under ES1 and ES3 are the same as those under ES2 and ES4 respectively. This is because the table shows the decarbonisation potentials for UDG projects owned by outside companies, so the emissions from the increased electricity consumption can be negated. Also, heat production happens the same way under ES1 and ES2, and ES3 and ES4, so no differences in decarbonisation will arise from the heat production either. As mentioned above, the decarbonisation potential will only change slightly if the UDG project is owned by the dairy processing facility, so no large changes to Table 17 would occur.

Because of the lower thermal efficiency of CHPs compared to natural gas boilers, the decarbonisation potential of UDG is greater under ES3 and ES4 than under ES1 and ES2, since more emissions can be abated per unit of heat produced.

*Table 17: Decarbonisation potential of UDG in 2050 under different production and emission scenarios, assuming the UDG project is owned by an outside company*

| Scenario | BAU status quo | BAU international demand | Low growth status quo | Low growth international demand | Medium growth status quo | Medium growth international demand |
|---|---|---|---|---|---|---|
| **Decarbonisation potential in 2050 – ES1 [kt $CO_2$]** | 189 | 230 | 138 | 167 | 155 | 188 |
| **Decarbonisation potential in 2050 – ES2 [kt $CO_2$]** | 189 | 230 | 138 | 167 | 155 | 188 |
| **Decarbonisation potential in 2050 – ES3 [kt $CO_2$]** | 213 | 259 | 155 | 189 | 174 | 211 |
| **Decarbonisation potential in 2050 – ES4 [kt $CO_2$]** | 213 | 259 | 155 | 189 | 174 | 211 |

When looking at the costs, the two scenarios yield significantly different results, since the investment costs are high for UDG. The costs included in the scenario in which the UDG project is owned by the dairy sector are the same as for the efficiency measures. If the project is owned by an outside party, the costs do not include investment costs or costs for electricity, but they do include costs for purchasing of the heat. The costs for both situations are shown in Figure 17.
For both scenarios the abatement costs decrease over time as a result of increasing carbon and gas prices offsetting the increasing electricity price or increased expenditure from the purchasing of heat. For the scenario in which the UDG project is owned by the dairy sector, this offset occurs since the increase in electricity consumption by UDG is small compared to the amount of heat produced (around 1/20$^{th}$). In the other scenario, an extra decrease in abatement costs is achieved since the cost of purchased heat is assumed to decrease as well.

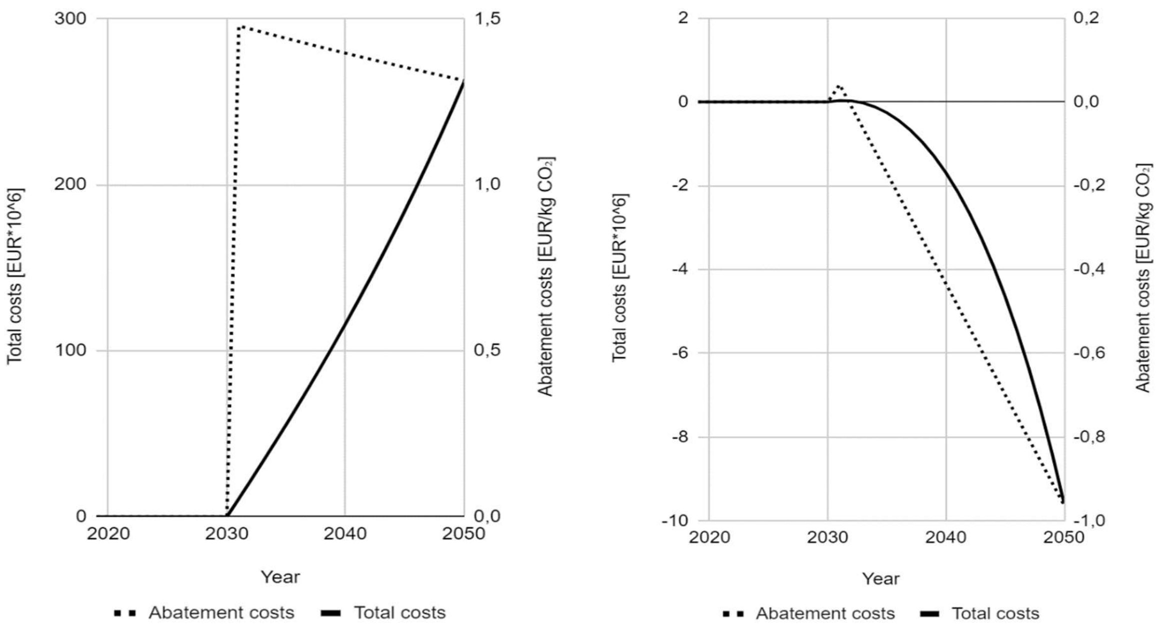


*Figure 17: Yearly and total costs of decarbonisation by UDG for the BAU status quo scenario under ES1, showing costs for assuming the UDG project is owned by the dairy sector (left) or by an outside party (right)*

In Figure 18 below, the abatement costs and total costs of UDG are shown as a function of the amount of emissions abated. Because of the decreasing costs, the first unit of abatement will be the most expensive. In the scenario in which the UDG project is owned by the dairy sector, this makes it so that the initial costs will be significantly higher than those of the other options investigated in this research. This makes it unlikely that the sector will invest in UDG on its own, as the benefits do not outweigh the costs. However, it is possible for the sector to share the investment costs with other companies. Already, FrieslandCampina is looking into the possibilities of using UDG in cooperation with the Dutch government and different consortia of companies (Green Deal, 2018). If the investment costs can be shared among different parties the abatement costs can be decreased, possibly making this scenario financially attractive for the dairy sector.

If the UDG project is owned by an outside company, abatement by UDG is a useful option for the dairy sector, since the abatement costs of this option can be expected to be negative for a long time. It therefore seems reasonable that FrieslandCampina has joined the Green Deal UDG, which aims to identify the potential of UDG in the Netherlands (Green Deal, 2018). If a suitable potential is identified and the investment costs can be shared among different parties, FrieslandCampina can benefit from such a project.

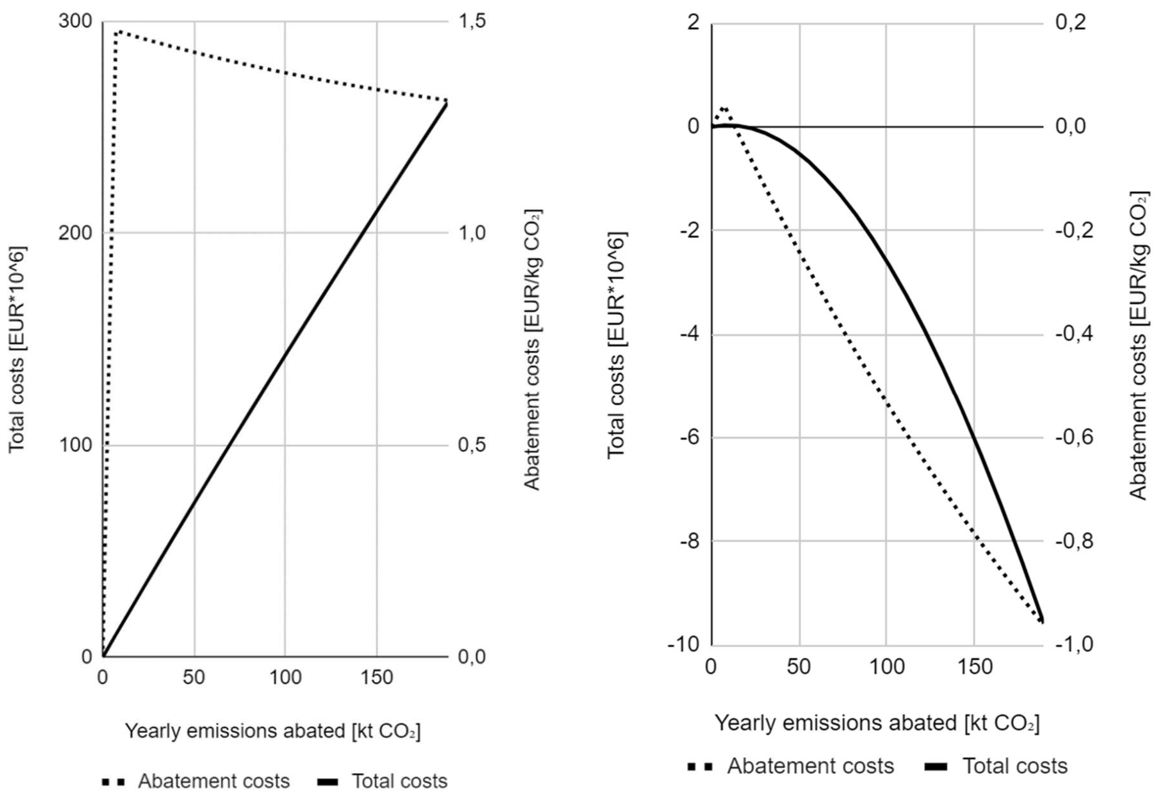


*Figure 18: Yearly and total costs of decarbonisation through UDG compared against total abatement achieved for the BAU status quo scenario under ES1, assuming the UDG project is owned by the dairy sector (left) or by an outside company (right)*

In the BAU status quo scenario under ES1, the total costs in 2050 are EUR 261.67 million, and the total decarbonisation in 2050 is 188.89 kt $CO_2$, resulting in average abatement costs of EUR 1.39/kg $CO_2$ and remaining emissions of 452.61 kt $CO_2$ in that year if the UDG project is fully owned by the dairy processing sector. If the project is owned by an outside party, the total savings are EUR 9.58 million for a total decarbonisation of 189.29 kt $CO_2$ in 2050, resulting in average abatement costs of EUR -0.05/kg $CO_2$ and remaining emissions of 452.20 kt $CO_2$ in that year. For all other production and

emission scenarios, abatement and total costs are shown in Table 18 below, assuming the UDG project is owned by an outside party.
The abatement costs of UDG barely change when switching from status quo to international demand scenarios. Small changes occur because of the different shares of heat and electricity requirements in the two scenarios, but the increases in total costs stem mostly from the absolute increase in heat consumption in the international demand scenarios. When switching to ES3 or ES4, the abatement costs become more negative, meaning more money can be saved through abatement in these scenarios. This is mostly because in ES3 and ES4, less heat has to be purchased per unit of emission abated, since the reference heat production has a lower thermal efficiency. This results in lower expenditure on the heat from the UDG project, lowering the costs.

*Table 18: Average abatement costs (AC) in EUR/kg $CO_2$ and total costs (TC) in EUR*$10^6$ for decarbonisation through UDG for different production and emissions scenarios, assuming the UDG project is owned by an outside party selling the heat*

| Scenario | BAU status quo | BAU international demand | Low growth status quo | Low growth international demand | Medium growth status quo | Medium growth international demand |
|---|---|---|---|---|---|---|
| **ES1** | AC: -0.05 | AC: -0.05 | AC: -0.05 | AC: -0.05 | AC: -0.05 | AC: -0.05 |
| | TC: -9.58 | TC: -12.25 | TC: -6.42 | TC: -8.25 | TC: -7.43 | TC: -9.54 |
| **ES2** | AC: -0.05 | AC: -0.05 | AC: -0.05 | AC: -0.05 | AC: -0.05 | AC: -0.05 |
| | TC: -9.52 | TC: -12.16 | TC: -6.38 | TC: -8.18 | TC: -7.39 | TC: -9.46 |
| **ES3** | AC: -0.07 | AC: -0.07 | AC: -0.07 | AC: -0.07 | AC: -0.07 | AC: -0.07 |
| | TC: -14.88 | TC: -18.73 | TC: -10.21 | TC: -12.93 | TC: -11.75 | TC: -14.82 |
| **ES4** | AC: -0.07 | AC: -0.07 | AC: -0.07 | AC: -0.07 | AC: -0.07 | AC: -0.07 |
| | TC: -14.76 | TC: -18.60 | TC: -10.13 | TC: -12.79 | TC: -11.62 | TC: -14.66 |

### *Electric boiler*

Finally, the impact of electric boilers was determined similarly to that of UDG, by assuming a specific share of the (non-renewable) heat demand would be filled by these boilers. These shares were chosen to be 60% in 2030 and 100% in 2050, and linear growth was assumed between these years, and from the starting year of 2018 (in which it was assumed that no heat was produced by electric boilers). The abated emissions were determined using formula 7, and the yearly development of emissions for the BAU status quo scenario under ES1 is shown in Figure 19. For these results it is assumed that the electric boilers have a thermal efficiency of 99%.
The reason the emissions do not fall to zero in 2050 is that the Dutch electricity mix is not assumed to be 100% renewable-based in that year. The emissions converge since an increasingly small portion of the heat needed, which differs between the scenarios, is produced from natural gas, until all heat is produced by electric boilers in 2050. Then, since the Dutch electricity grid is assumed to consist increasingly out of renewables, the emissions that arise from electricity consumption converge until they almost disappear in 2050, when the share of renewables in 98%. Under ES2 and ES4 the emissions would become zero in 2050, since the dairy sector uses 100% renewable electricity in that year.
It is also interesting to note that in the early years, emissions increase compared to the situation with energy efficiency measures and UDG only. This is because in those years the share of renewables used to fill the increased electricity demand is low, so the emissions from generating the electricity offset the abatement from reduced gas consumption. The boilers start reducing emissions at a share of renewables of around 54%. This increase in emissions might make it unfavourable for the dairy sector to invest in electric boilers early. However, this research has assumed that incremental increases in the heat production capacity of electric boilers are possible. In reality, it makes more sense for a processing facility to buy a boiler based on an expected future demand. So, if the dairy sector wants to be prepared,

they might invest in oversized boilers early, to be able to fill future demand when the share of renewables in the electricity grid is higher. Also, these increases in emissions do not occur under ES2 and ES4, so early investments in electric boilers will result in abated emissions in these scenarios. As of 2018, the dairy processing sector already used 81% of renewable electricity, so it seems likely that investing in electric boilers will not lead to increased emissions (Doornewaard, Hoogeveen, Jager, Reijs, & Beldman, 2019).

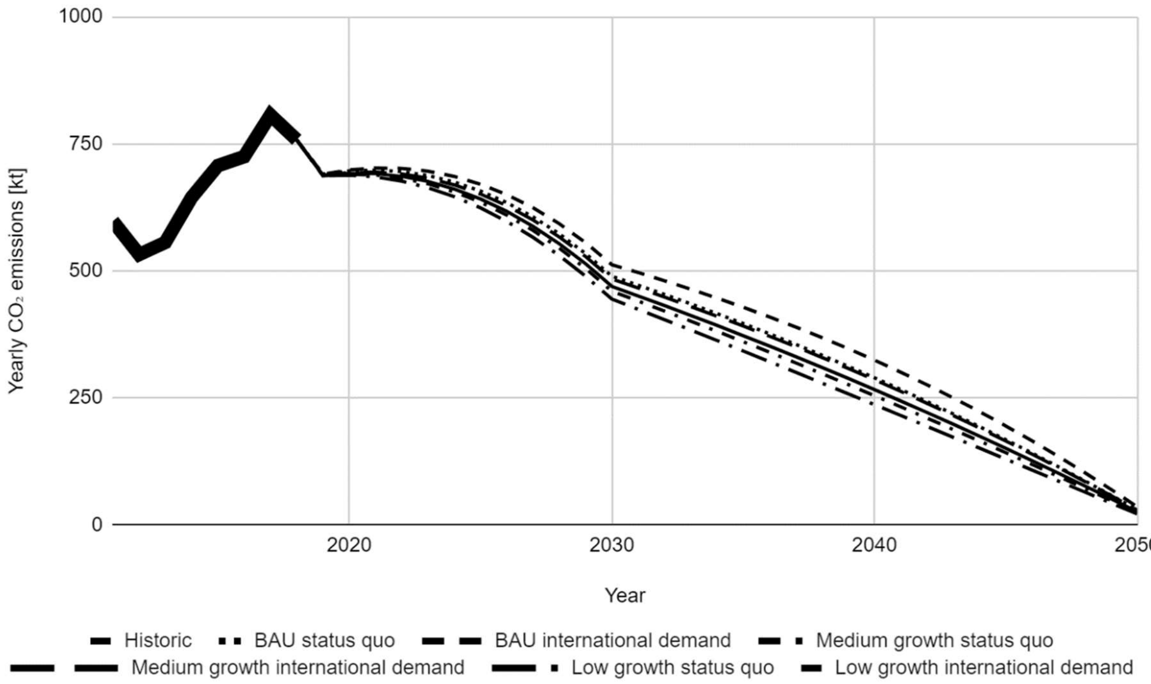


*Figure 19: $CO_2$ emissions after decarbonisation through energy efficiency, UDG and electric boilers under ES1*

The decarbonisation potential of electric boilers under all production and emission scenarios is shown in Table 19 below. As explained above, the use of 100% renewables (in ES2 and ES4) increases the decarbonisation potential, reducing the remaining emissions to zero in 2050. The difference between emissions in ES1 and ES2, and ES3 and ES4, will be the remaining emissions in ES1 and ES3 respectively. Since heat produced with a lower thermal efficiency can be replaced in ES3 and ES4, the decarbonisation potential in these scenarios is higher than in ES1 and ES2.

*Table 19: Decarbonisation potential of electric boilers in 2050 under different production and emission scenarios*

| Scenario | BAU status quo | BAU international demand | Low growth status quo | Low growth international demand | Medium growth status quo | Medium growth international demand |
|---|---|---|---|---|---|---|
| **Decarbonisation potential in 2050 – ES1 [kt $CO_2$]** | 423 | 514 | 308 | 375 | 345 | 420 |
| **Decarbonisation potential in 2050 – ES2 [kt $CO_2$]** | 442 | 537 | 322 | 391 | 361 | 439 |
| **Decarbonisation potential in 2050 – ES3 [kt $CO_2$]** | 476 | 578 | 347 | 421 | 389 | 472 |
| **Decarbonisation potential in 2050 – ES4 [kt $CO_2$]** | 497 | 604 | 362 | 440 | 406 | 493 |

The costs of decarbonisation by implementation of electric boilers are shown in Figure 20 below for the BAU status quo scenario under ES1. The costs include investment costs and increased expenditure on electricity, and the benefits include savings on gas and carbon credits. The decrease in the slope of the total costs after 2030 is a result of the utilisation of UDG, which lowers the additional heat production capacity needed by electric boilers.

The negative abatement costs and sharp positive spike in the early years are a consequence of the abated emissions in those years. First, as explained above, the emissions increase, thereby resulting in negative abatement costs. In this case, these do not mean that the dairy sector will save money by implementing electric boilers, but rather that there will be negative decarbonisation. After a few years the electric boilers start to abate some emissions because of the increased penetration of renewables in the Dutch electricity grid, but since the abated amount if very small, the abatement costs will be very high (since these are the ratio of the yearly costs and the abated emissions). It therefore seems unlikely that the dairy sector will invest in electric boilers in this scenario in the early years. In later years, however, the abatement costs are very low, so investing will be more attractive. It is however not possible to make use of these low abatement costs without having done earlier investments, as the abatement cost-curve is path-dependent. The reason the abatement costs keep decreasing is that only a small additional yearly capacity is needed in the later years because of earlier investments, meaning that the extra expenditure on electricity will be relatively low as well, while decarbonisation increases because of the increased use of renewables. This is however not the case of all investments are done in the later years. In any case (see also Table 20) the average abatement costs will be higher than EUR 0.22/kg $CO_2$.

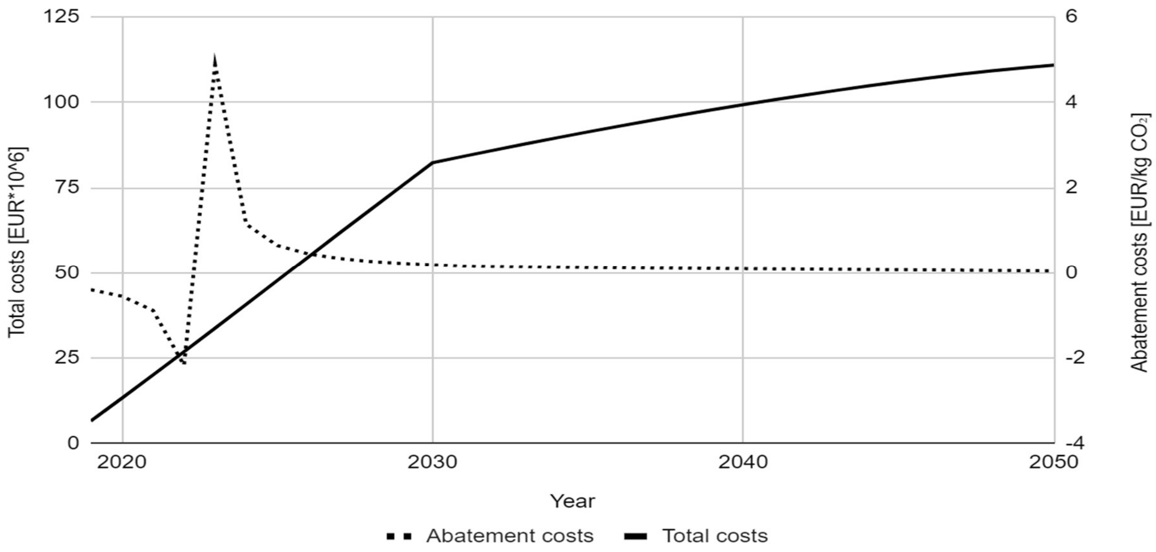


*Figure 20: Yearly and total costs of decarbonisation by electric boiler for the BAU status quo scenario under ES1*

The spikes visible in Figure 20 do not occur under ES2 and ES4, since the early increase in emissions is prevented by the utilisation of 100% renewable electricity by the dairy processing facilities. The cost profile of the BAU status quo scenario under ES2 is shown in Figure 21 below. The figure shows a very different development of the abatement costs, while the total costs develop similarly to those under ES1.

Since the processing facilities use 100% renewable electricity in the scenario, all decarbonisation occurs because of the increased share of heat produced by the electric boilers, thereby preventing consumption of natural gas. However, this increase in decarbonisation is lower than the increase in yearly costs (which increase due to changing electricity prices), so the abatement costs increase.

The abatement costs in Figure 21 underline the explanation from Section 3.2.4, as the abatement costs are quite high as a result of high investment costs and increased expenditure from relatively high electricity costs compared to natural gas costs. By implementing electric boilers as flexible load, they can be utilised at times of low electricity prices, to prevent increased expenditure on fuel and thereby drive down the abatement costs.

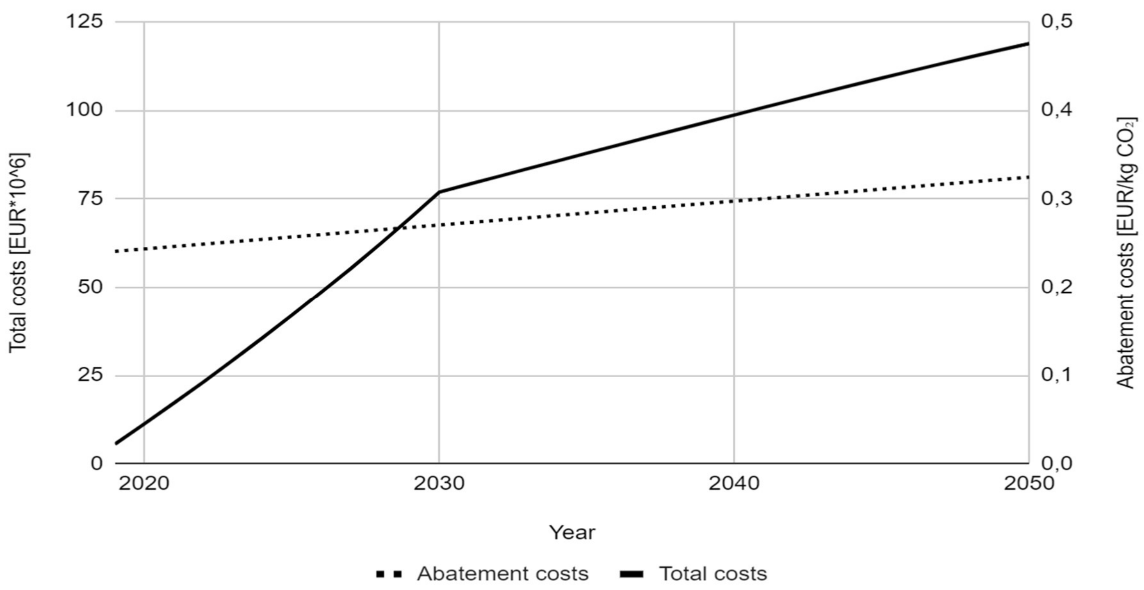


*Figure 21: Yearly and total costs of decarbonisation by electric boiler for the BAU status quo scenario under ES2*

In Figure 22 below, the abatement and total costs of decarbonisation by electric boilers are compared against the total abated emissions for ES1 and ES2. Under ES1, around EUR 55 million has to be invested before any emissions are abated, corresponding to around 50% of the total investment costs in that scenario. After the first EUR 55 million investment, the next 50% result in an abatement of over 440 kt $CO_2$, meaning the average abatement costs are around EUR 0.125/kg $CO_2$ after positive decarbonisation has started.
The bend in the curve of the abatement costs under ES2 occurs in the year 2030, when the increase in renewables in the Dutch electricity grid slows down. This means an additional amount of heat produced will abate less emissions, while its costs increase due to increasing electricity prices, resulting in an increase in abatement costs. Before this bend occurs, around EUR 77 million is invested for an abatement of 300 kt $CO_2$, resulting in average abatement costs of EUR 0.26/kg $CO_2$. The average abatement costs after the bend are EUR 0.30/kg $CO_2$.

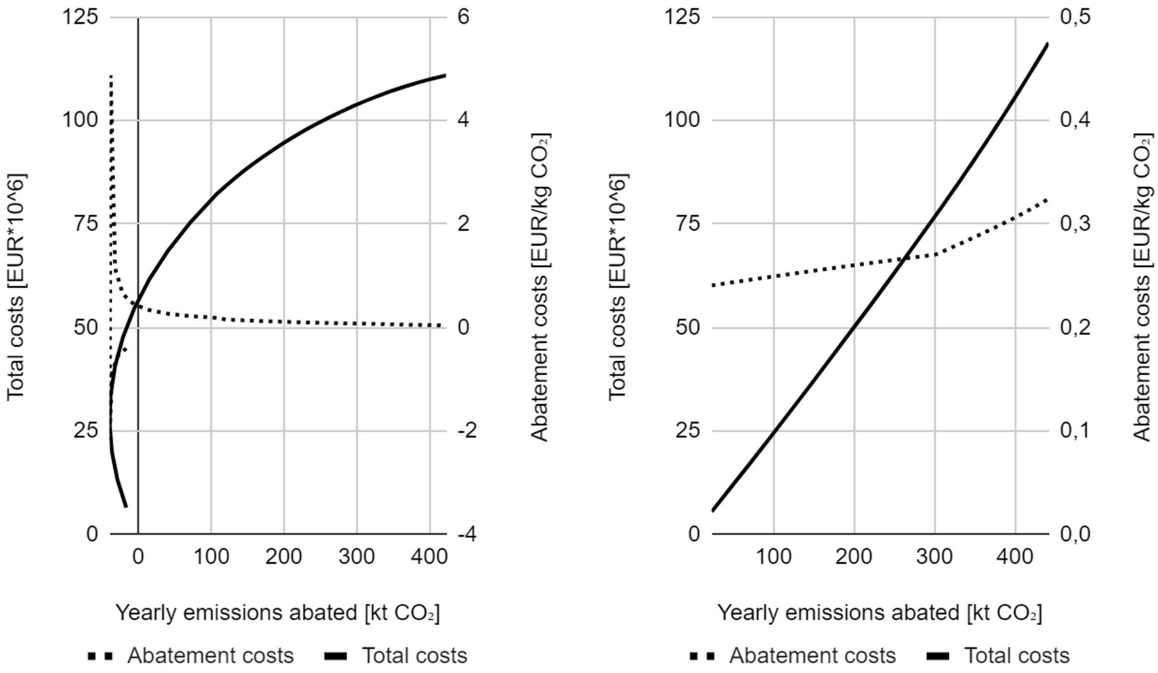


*Figure 22: Yearly and total costs of decarbonisation through electric boilers compared against total abatement achieved for the BAU status quo scenario under ES1 (left) and ES2 (right)*

In Table 20 below, the average abatement and total costs of decarbonisation by electric boilers are shown for all production and emission scenarios. As mentioned, the average abatement costs will always be above EUR 0.22/kg $CO_2$, irrespective of the production and emissions scenario, and the shape of the abatement cost curves. Abatement costs consistently increase when switching from ES1 to ES2 or from ES3 to ES4. This is because in ES2 and ES4 relatively more decarbonisation occurs in early years, since these scenarios already have 100% renewable electricity in the mix then, while the cost of carbon credits is still low, thereby reducing the savings made compared to ES1 and ES2.

*Table 20: Average abatement costs (AC) in EUR/kg $CO_2$ and total costs (TC) in EUR*$10^6$ for decarbonisation by electric boilers for different production and emissions scenarios*

| Scenario | BAU status quo | BAU international demand | Low growth status quo | Low growth international demand | Medium growth status quo | Medium growth international demand |
|---|---|---|---|---|---|---|
| **ES1** | AC: 0.26 | AC: 0.27 | AC: 0.25 | AC: 0.26 | AC: 0.25 | AC: 0.26 |
| | TC: 110.89 | TC: 139.15 | TC: 76.28 | TC: 96.33 | TC: 87.50 | TC: 110.21 |
| **ES2** | AC: 0.27 | AC: 0.27 | AC: 0.26 | AC: 0.27 | AC: 0.26 | AC: 0.27 |
| | TC: 118.91 | TC: 147.25 | TC: 83.80 | TC: 104.08 | TC: 95.20 | TC: 118.07 |
| **ES3** | AC: 0.25 | AC: 0.23 | AC: 0.24 | AC: 0.22 | AC: 0.24 | AC: 0.23 |
| | TC: 118.90 | TC: 134.73 | TC: 81.53 | TC: 93.34 | TC: 93.63 | TC: 106.80 |
| **ES4** | AC: 0.26 | AC: 0.26 | AC: 0.25 | AC: 0.25 | AC: 0.25 | AC: 0.26 |
| | TC: 127.62 | TC: 158.16 | TC: 89.80 | TC: 111.64 | TC: 102.07 | TC: 126.72 |

***Total***

Adding up all costs of the decarbonisation options described above, the total costs of decarbonisation of the Dutch dairy processing industry are shown in Figure 23. On the left the development over the entire time period is shown, while the right graph shows the development from 2024 onwards, to show what happens in the later years with more detail. The figure clearly shows the dependence of the price development on whether the UDG project is owned by the dairy processing facilities or not, as the difference between the two scenarios is close to EUR 300 million in 2050. After the onset of UDG in 2030, the abatement costs increase with around 200% if the project is owned by the dairy sector, or decrease with around 50% if it is owned by an outside company. The figure on the right clearly shows the impact of the increasing abatement costs of decarbonisation through energy efficiency, visible as the stepwise increase in abatement costs from 2040 onwards.

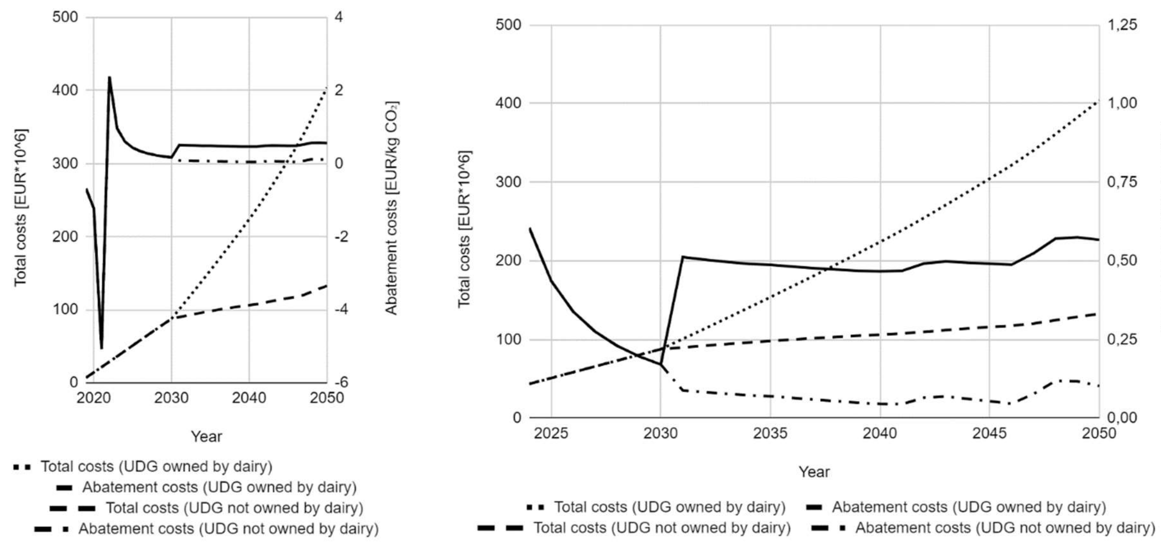


*Figure 23: Yearly and total costs of all decarbonisation combined for the BAU status quo scenario under ES1*

Figure 24 below shows the same development of total and abatement costs when compared against the total amount of emissions abated by the decarbonisation options. In the early years there will still be negative abatement because of the electric boilers, so costs totalling around EUR 40 million have to be invested before emissions start to be abated. This happens sometime between the years 2023 and 2024. After this point over 800 kt of $CO_2$ are abated at a cost of around EUR 360 million if the UDG project is owned by the dairy sector, or EUR 90 million if it is owned by an outside party.

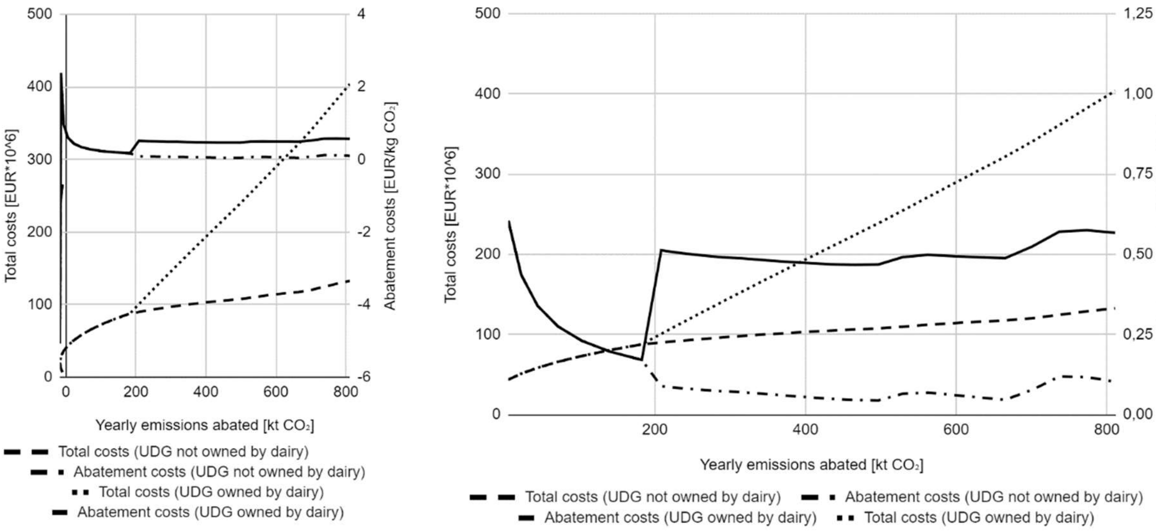


*Figure 24: Yearly and total costs of all decarbonisation combined compared against the total decarbonisation achieved for the BAU status quo scenario under ES1*

Figure 25 below shows the development of the total costs and abatement costs for the BAU status quo scenario under ES2. In this scenario, the peaks in abatement costs from the electric boilers are not present. As is visible for the abatement costs curves for the electric boilers only, the abatement costs under ES2 will end up higher than under ES1, because of the increasing abatement costs of electric boilers. In this scenario, the increases in abatement cost stemming from the energy efficiency measures are large enough to undo the decrease in costs from UDG.

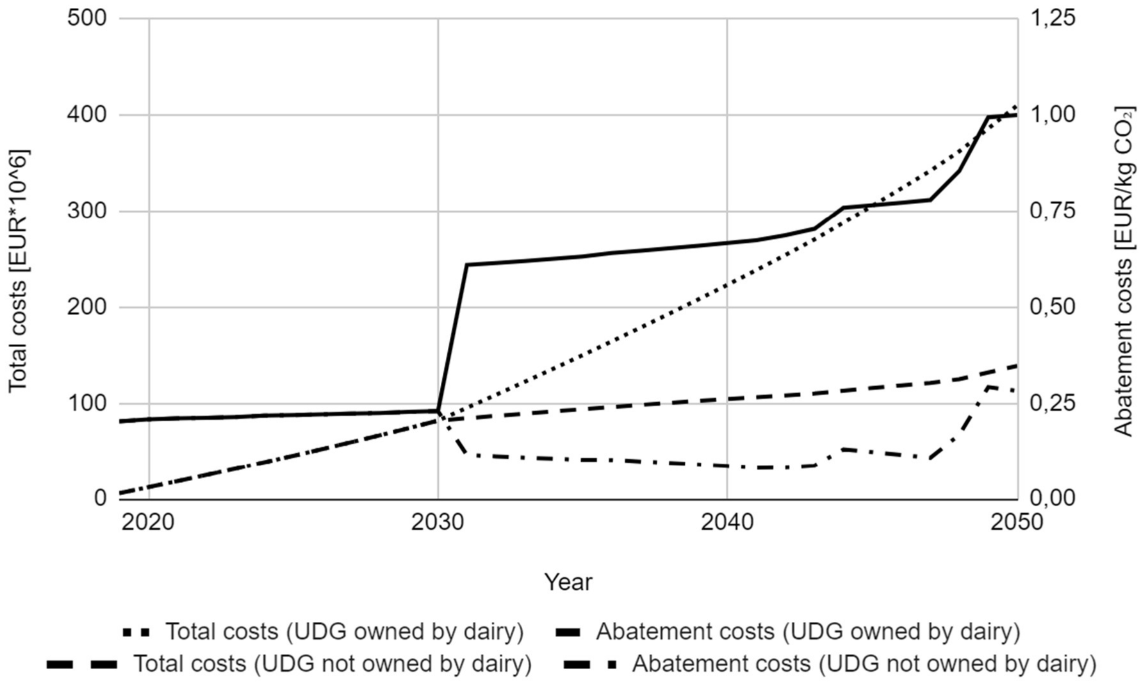


*Figure 25: Yearly and total costs of all decarbonisation combined for the BAU status quo scenario under ES2*

Figure 26 below shows the development of total and abatement costs compared to the total amount of emissions abated. It shows that the amount of emissions abated before UDG starts to play a role (around 375 kt $CO_2$) is significantly higher than under ES1 (where it is around 180 kt $CO_2$). So, under ES2, a larger share of the total abatement (around 45%) happens because of electric boilers and efficiency measures only, while under ES1 only around 23% of the total abatement happens before UDG. Because of this, the relatively high abatement costs after 2030 under ES2 have a less pronounced effect on the total costs, since they act over a smaller amount of emissions abated compared to ES1. This might explain why the average abatement costs under all scenarios are comparable, even if the absolute values differ over time.

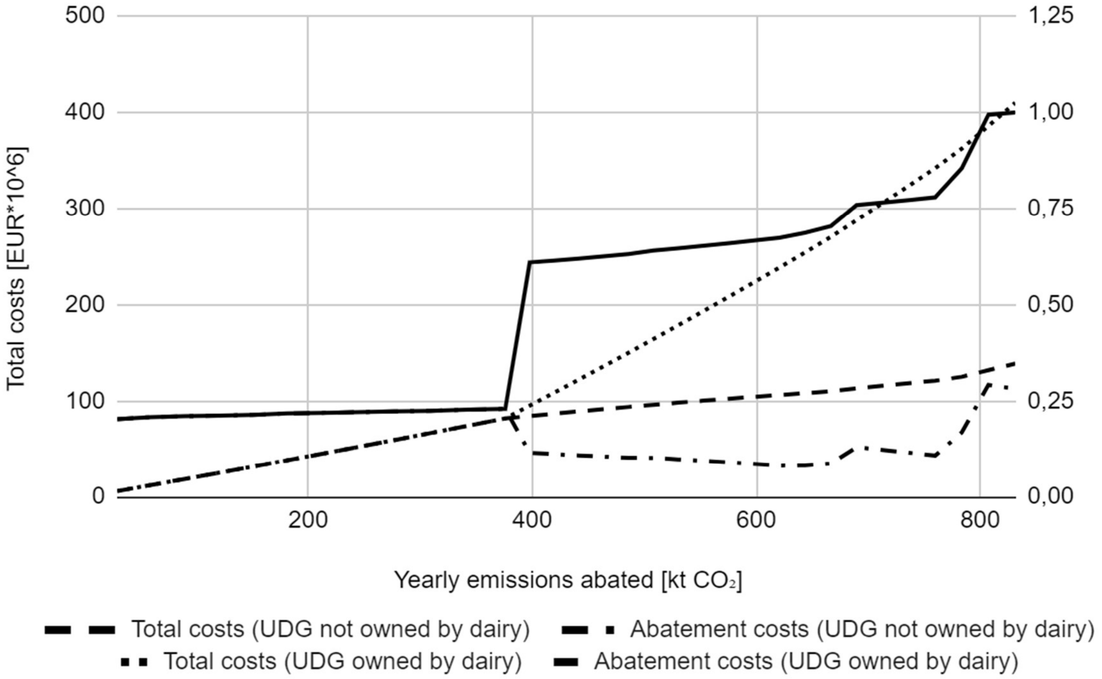


*Figure 26: Yearly and total costs of all decarbonisation combined compared against the total decarbonisation achieved for the BAU status quo scenario under ES2*

Table 21 below shows the average abatement and total costs for all options combined, for all production and emission scenarios, assuming the UDG project is owned by an outside company. The average abatement costs range between EUR 0.12/kg $CO_2$ abated for the low growth international demand scenario under ES4 and EUR 0.17/kg $CO_2$ abated for multiple scenarios. The total costs range between EUR 92.73 million for the low growth status quo scenarios under ES1 and EUR 184.60 million for the BAU international demand scenario under ES2.

*Table 21: Average abatement costs (AC) in EUR/kg $CO_2$ and total costs (TC) in EUR*$10^6$ for all decarbonisation combined for different production and emissions scenarios, assuming the UDG project is owned by an outside party*

| Scenario | BAU status quo | BAU international demand | Low growth status quo | Low growth international demand | Medium growth status quo | Medium growth international demand |
|---|---|---|---|---|---|---|
| **ES1** | AC: 0.16 | AC: 0.17 | AC: 0.16 | AC: 0.16 | AC: 0.16 | AC: 0.16 |
| | TC: 132.66 | TC: 175.53 | TC: 92.73 | TC: 122.67 | TC: 105.55 | TC: 139.51 |
| **ES2** | AC: 0.17 | AC: 0.17 | AC: 0.16 | AC: 0.17 | AC: 0.16 | AC: 0.17 |
| | TC: 138.69 | TC: 184.60 | TC: 99.13 | TC: 131.47 | TC: 111.91 | TC: 148.43 |
| **ES3** | AC: 0.15 | AC: 0.14 | AC: 0.14 | AC: 0.13 | AC: 0.14 | AC: 0.14 |
| | TC: 135.70 | TC: 165.98 | TC: 94.31 | TC: 115.58 | TC: 107.60 | TC: 131.83 |
| **ES4** | AC: 0.15 | AC: 0.13 | AC: 0.15 | AC: 0.12 | AC: 0.15 | AC: 0.13 |
| | TC: 140.59 | TC: 153.80 | TC: 100.24 | TC: 110.10 | TC: 113.27 | TC: 124.20 |

Each year, the total yearly abatement increases, meaning that the total amount of emissions abated increase over time as well. This development of the total amount of emissions abated for all production scenarios under ES1 is shown in Figure 27 below. The figure shows that positive abatement starts between the years 2024 and 2027 for different scenarios, with total abatement between 8775 kt $CO_2$ and 13182 kt $CO_2$ in 2050.

Given these total amounts of abatement, and the total costs given in Table 21, the average lifetime abatement costs (LAC) have been determined, as the ratio between these two. These are shown in Table 22 below, assuming the UDG project is owned by an outside party. The table shows a range of LAC between EUR 6.84/t $CO_2$ and EUR 13.12/t $CO_2$, and a range of total decarbonisation (TD) over the researched time period between 8.02 Mt $CO_2$ and 20.02 Mt $CO_2$. The LAC under ES1 and ES3 are consistently higher than those under ES2 and ES4. This is because for comparable total costs, TD is significantly higher under ES2 and ES4 because of the difference in usage of renewable electricity, especially in early years.

These costs can be compared against the costs of Carbon Capture and Storage (CCS), to understand the relative desirability of abatement by the options researched for this study compared to adding CCS to existing plants. The costs for CCS are between $USD_{2013}$ 53/t $CO_2$ and $USD_{2013}$ 87/t $CO_2$ for natural gas firing plants (Rubin, Davison, & Herzog, 2015). These costs, even after converting to euros, are significantly higher than the LAC shown in Table 22. This means that investing in the decarbonisation options will be a more preferable way to reduce emissions for the dairy industry. Even when considering that the costs for CCS are projected to decrease with between 13% - 60% by 2050, the LAC for decarbonisation with the researched options will be lower, meaning that abating emissions using these options will be preferred over using CCS for the dairy processing industry (Rubin, 2016).

*Table 22: Average lifetime abatement costs (LAC) in EUR/t $CO_2$ and total decarbonisation (TD) in Mt $CO_2$ for all decarbonisation options combined for different production and emissions scenarios, assuming the UDG project is owned by an outside party*

| **Scenario** | **BAU status quo** | **BAU international demand** | **Low growth status quo** | **Low growth international demand** | **Medium growth status quo** | **Medium growth international demand** |
|---|---|---|---|---|---|---|
| **ES1** | LAC: 12.84 | LAC: 13.12 | LAC: 11.56 | LAC: 12.02 | LAC: 12.03 | LAC: 12.48 |
| | TD: 10.34 | TD: 13.18 | TD: 8.02 | TD: 10.20 | TD: 8.77 | TD: 11.18 |
| **ES2** | LAC: 9.49 | LAC: 10.37 | LAC: 8.39 | LAC: 9.19 | LAC: 8.79 | LAC: 9.61 |
| | TD: 14.62 | TD: 17.80 | TD: 11.81 | TD: 14.30 | TD: 12.73 | TD: 15.45 |
| **ES3** | LAC: 11.73 | LAC: 11.28 | LAC: 10.50 | LAC: 10.13 | LAC: 10.95 | LAC: 10.55 |
| | TD: 11.57 | TD: 14.71 | TD: 8.98 | TD: 11.41 | TD: 9.83 | TD: 12.50 |
| **ES4** | LAC: 8.55 | LAC: 7.68 | LAC: 7.54 | LAC: 6.84 | LAC: 7.91 | LAC: 7.15 |
| | TD: 16.44 | TD: 20.02 | TD: 13.29 | TD: 16.09 | TD: 14.32 | TD: 17.38 |

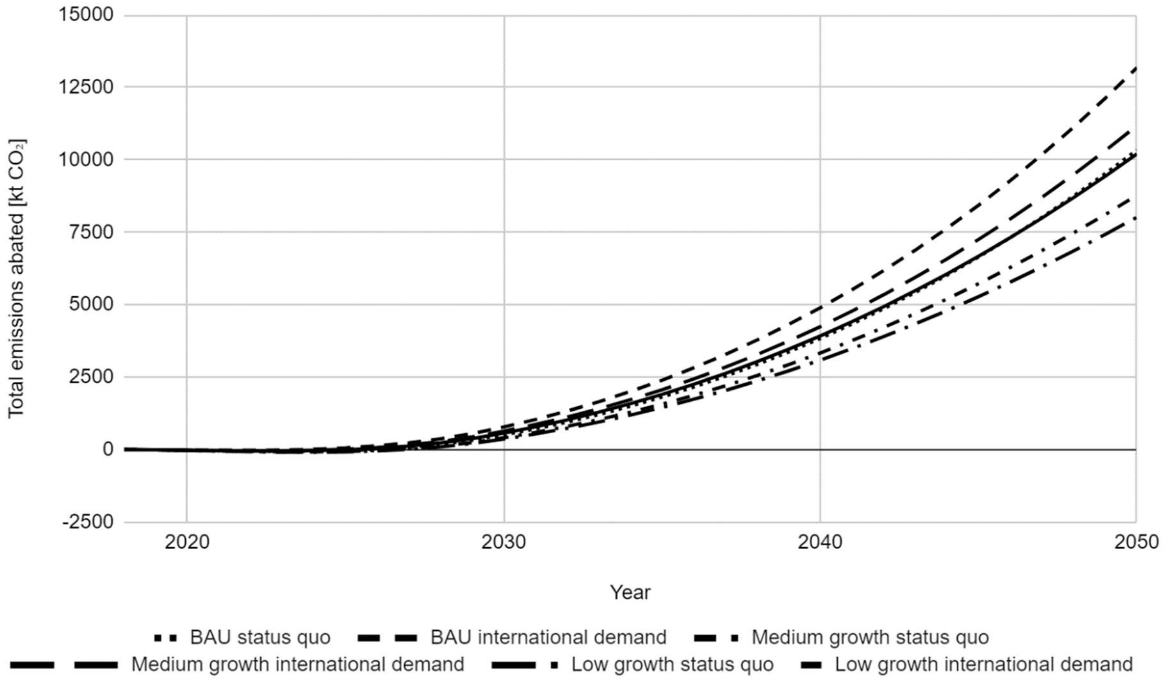


*Figure 27: Total amount of emissions abated under ES1, assuming the UDG project is owned by an outside party*

## 3.4 Sensitivity analysis

For this research many assumptions have been made, and the results depend on a number of parameters which could differ significantly from the values used and shown in this document. To understand the robustness of the results, a sensitivity analysis can show how changes in certain parameters impact the results. Some of the most important parameters used in this study are shown in Table 23 below, with the original value used for the results shown so far. To test the effect of changing these parameters on the results, each of them has been changed to a value 10% higher and 10% lower than its original value, and the effect on various results has been examined. The parameters related to energy consumption of dairy products or the production amounts of these products have been excluded from the sensitivity analysis since the scenarios used already accounted for possible changes in these values.

*Table 23: Parameters used in this study, with the original value used for the results shown so far*

| Parameter | Description | Original value |
|---|---|---|
| **1** | Energy saved during spray drying by zeolite [%] | 38 |
| **2** | Increase in electricity consumption during spray drying by zeolite [%] | 25 |
| **3** | Investment costs zeolite [EUR/unit capacity[25]] | 250000 |
| **4** | Heat consumption MVR [kJ/kg water evaporated] | 76.9/84.59[26] |
| **5** | Power consumption MVR [$kW_e$] | 200 |
| **6** | Investment costs MVR [EUR/$MW_{th}$] | 480000 |
| **7** | Energy consumption pre-concentrating [kJ/kg water evaporated] | 25 |
| **8** | Investment costs pre-concentrating [EUR/$m^2$] | 1015 |
| **9** | Investment costs UDG [EUR/$kW_{th}$] | 2509 |
| **10** | Investment costs electric boiler [EUR/$kW_e$] | 170 |
| **11** | Gas price [EUR/TJ] | Variable[27] |
| **12** | Electricity price [EUR/TJ] | Variable[27] |
| **13** | UDG heat price [EUR/TJ] | Variable[28] |
| **14** | Carbon credit price [EUR/kg $CO_2$] | Variable[27] |
| **15** | Share of heat produced by CHP in ES3 and ES4 [%] | 25 |
| **16** | Thermal efficiency CHP [%] | 60 |
| **17** | Electrical efficiency CHP [%] | 30 |
| **18** | Thermal efficiency natural gas boiler [%] | 90 |
| **19** | Thermal efficiency electric boiler [%] | 99[29] |
| **20** | COP of UDG [$TJ_{th}$ produced/$TJ_e$ consumed] | 19.63 |
| **21** | Autonomous efficiency improvement [%] | 0[30] |

### 3.4.1 Energy savings/consumption energy efficiency measures

First, the effect of changing the decreased and/or increased energy consumption by energy efficiency measures (parameters 1, 2, 4, 5 and 7) was determined. The results are shown in Figure 28 below. The figure shows the effect of changing the input parameter on the average cost of abatement through energy efficiency for the BAU status quo scenario under ES1 (with an original value of EUR 0.16/kg $CO_2$ abated).

The figure shows that the abatement costs are the most sensitive with regard to the percentage energy saved by implementing zeolite during spray-drying. Since this is the most energy-intensive step during the production of dried products this is to be expected, as an increase in savings here will lead to relatively large reductions in carbon emissions. Since scientific studies show an even larger range of possible savings by zeolite than used here (for instance 30% - 50%), the abatement costs of using zeolite for decarbonisation can be said to be highly uncertain (van Boxtel, Boon, van Deventer, & Bussmann, 2014).

The figure also shows the relative unimportance of increases in electricity consumption on abatement costs, since the lines for parameters 2, 5 and 7 are all less steep than their counterparts looking at changes in thermal energy consumption (compare parameters 1 and 2, and 4 and 5). This is because of the relatively small increase in electricity consumption stemming from these options, compared to the decrease in heat consumption. If these changes were comparable, a further increase in electricity consumption would lead to a more significant decrease in emissions abated, and thereby to a more pronounced increase in abatement costs. Also, because of the increasing penetration of renewables in

[25] See Table 5
[26] See Section 3.2.2
[27] See Section 2.3.1
[28] See Section 2.3.2
[29] Only a 10% decrease was used, since an increase would lead to a thermal efficiency greater than 100%
[30] Increased to 1%

the Dutch electricity grid, increasing electricity consumption lead to increasingly smaller carbon emissions, further dampening the effect.
Interesting to note is also the shape of the line for changes in heat consumption by the MVR, as it is not straight as all the other lines. A likely reason for this is that the order of decarbonisation options implemented changes when changing the heat consumption of the MVR, since the abatement costs of the most expensive option with zeolite and the cheapest with the MVR are very close with the original values. A changing order of implementation would have non-linear changes in average abatement costs since the changes in abatement costs are no longer only dependent on the cost of abatement of a single decarbonisation technology, but also on its changing position in the order. Indeed, for some values of heat consumption by the MVR, the position of the decarbonisation options change, as the MVR option for lactose can switch positions with the zeolite option for milk powder.

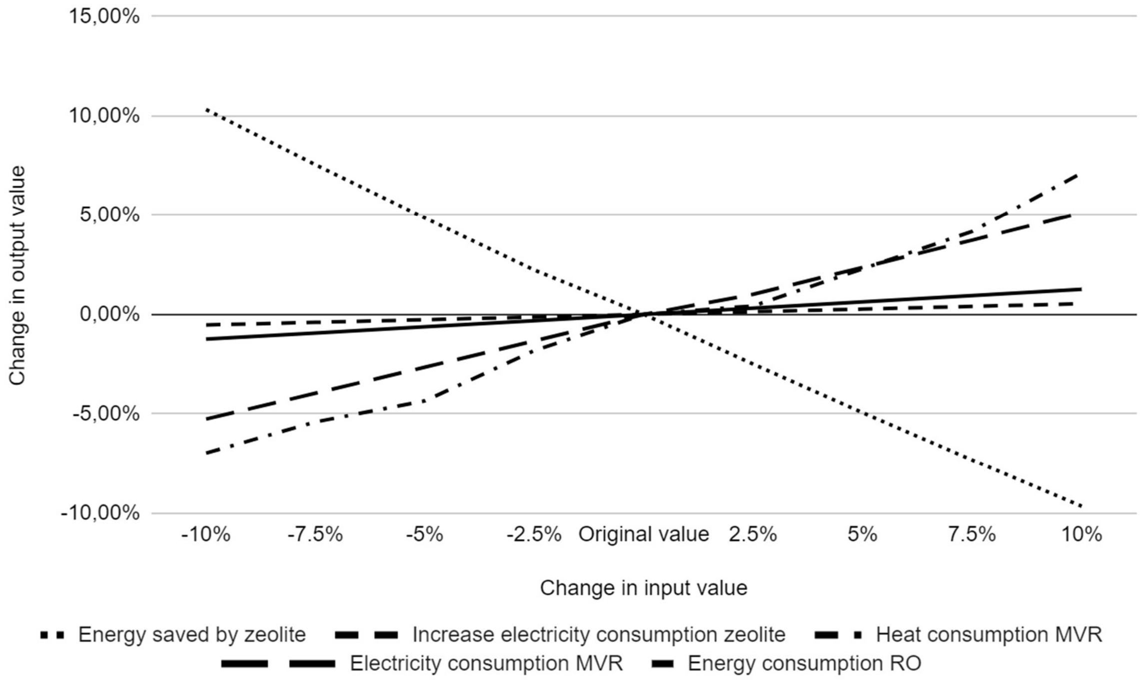


*Figure 28: Sensitivity analysis showing the impact of changing energy savings/consumption by energy efficiency measures on the abatement costs of decarbonisation by energy efficiency for the BAU status quo scenario under ES1*

### 3.4.2 Investment costs

Next, the impact of changing investment costs (parameters 3, 6, 8, 9 and 10) on the total average abatement costs of all options combined was determined. The results are shown in Figure 29 below, for the BAU status quo scenario under ES1. For all lines, except the one showing the investment costs for UDG, the changes in abatement costs for the scenario in which the UDG project is owned by an outside party are shown (with an original value of EUR 0.16/kg $CO_2$ abated). Since in this scenario the dairy sector does not pay the investment costs, changing these costs would have no impact on the abatement costs. So, for changes in the investment costs for UDG the output value is the abatement cost of the scenario in which the project is owned by the dairy sector (with an original value of EUR 0.50/kg $CO_2$ abated).
The figure shows that the impact of changing the investment costs of each energy efficiency measure separately is relatively small. However, if the investment costs of all efficiency measures are changed simultaneously (the line '*Investment costs all efficiency measures*'), the change in abatement costs is comparable to that of the other two options.

The largest uncertainty stems from the investment costs for UDG. This is because these costs are responsible for a large share of the total costs in the investigated scenario (almost 75%), so a change in the investment costs will have a large effect on the total costs, while the amount of emissions abated remains equal. Furthermore, since UDG is not yet implemented in a widespread manner, the actual investment costs might be more than 10% higher or lower than the value used for this research. The investment costs of UDG can therefore be said to be very uncertain and they can have a large impact on the average abatement costs. However, if the UDG project is not (completely) owned by the dairy sector, the increased investment costs will not have an impact on the abatement costs of the sector, since they are externalised. This can be seen as another reason for the dairy sector to try to find partners to raise funds for UDG, so the investment costs can be shared amongst multiple parties, or even externalised completely.

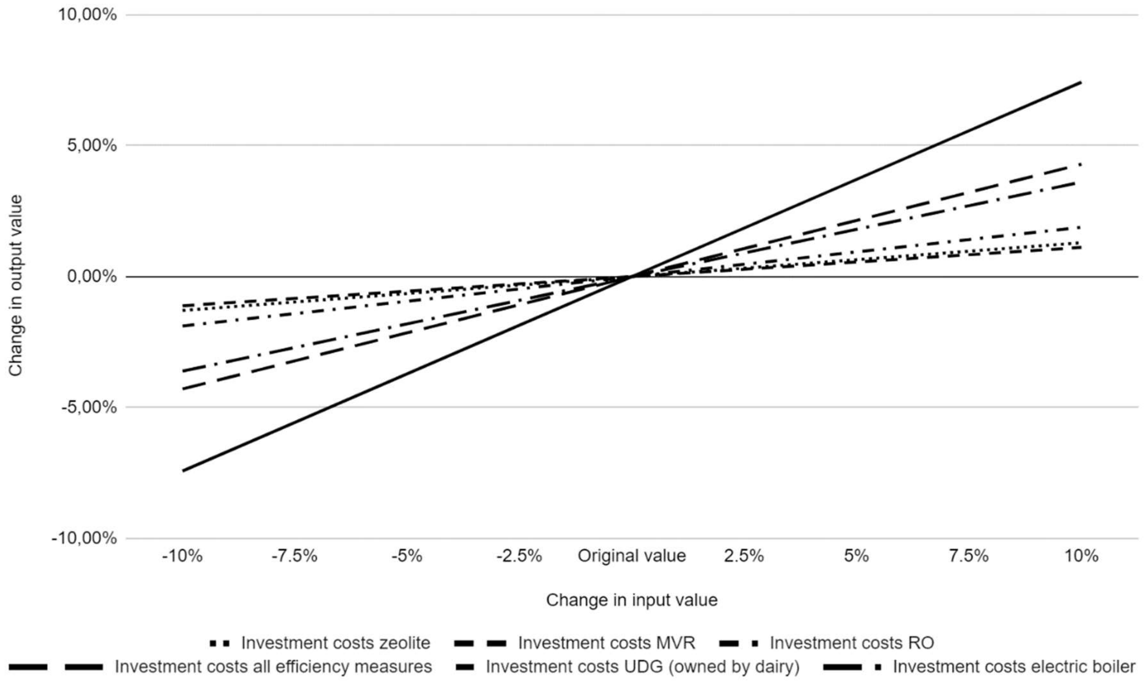


*Figure 29: Sensitivity analysis showing the impact of changing investment costs on the total abatement costs of decarbonisation for the BAU status quo scenario under ES1*

### 3.4.3 Other costs and savings

Apart from investment costs, other costs also arise because of increased expenditure on electricity or heat (parameters 12 and 13). At the same time, savings occur because of reduced expenditure on gas or carbon credits (parameters 11 and 14). The effects of changing these parameters on the total average abatement costs for the BAU status quo scenario under ES1 are shown in Figure 30 below. For this figure the yearly prices of the elements shown were increased or decreased with the same percentage, so they would still change over time. All lines show the effect of changing the impact on the total average abatement costs assuming the UDG project is owned by an outside party (with an original value of EUR 0.16/kg $CO_2$ abated).

The abatement costs are the most sensitive to changes in electricity and gas prices. The reason for this is that these two cost-elements are responsible for a larger share of the total costs than the UDG heat price and the cost of carbon credits. As future gas and electricity prices are difficult to predict, the uncertainty inherent in these parameters can have a significant impact on the choices the industry will make regarding decarbonisation.

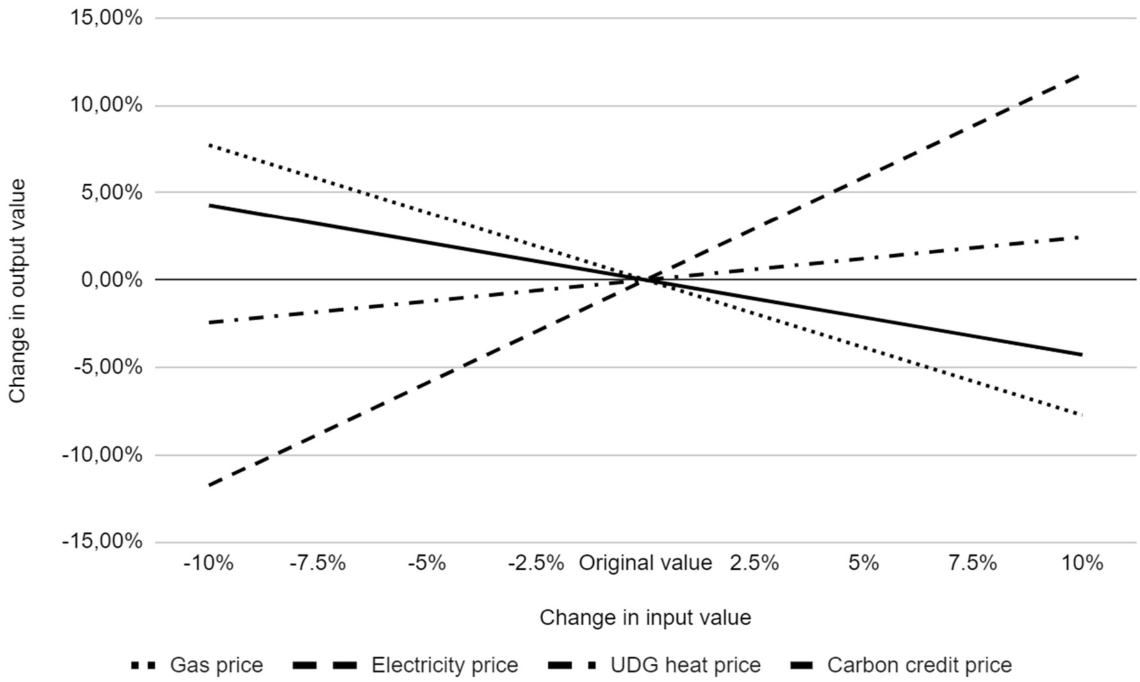


*Figure 30: Sensitivity analysis showing the impact of changing other costs and savings on the total abatement costs of decarbonisation for the BAU status quo scenario under ES1*

### 3.4.4 Heat generation

Next, the uncertainty of parameters related to heat production was researched (parameters 15 through 20). The effect of these parameters on the total average abatement costs are shown in Figure 31 below. For the parameters related to CHP heat production (parameters 15, 16 and 17) the figure shows the effect of changing the input value on the abatement cost of the BAU status quo scenario under ES3 (with an original value of EUR 0.14/kg $CO_2$ abated). The parameters regarding thermal efficiency show the impact on the total average abatement costs of the BAU status quo scenario under ES1, assuming the UDG project is owned by an outside party. The effect of the COP of UDG is in regard to the same abatement costs, but assuming the UDG project is owned by the dairy sector.

The figure shows that the thermal efficiencies of the electric or natural gas boilers have a significant impact on the average abatement costs. For the electric boiler, this is because the required boiler capacity increases with decreasing efficiency, thereby increasing the already relatively high investment costs and the expenditure on electricity, while the total abatement decreases.

For the natural gas boiler, the effect is the opposite, as a decrease in efficiency increases the decarbonisation potential, since replacing one unit of heat leads to a larger abatement of carbon emissions. Also, the total costs decrease because of increased savings on natural gas expenditure.

The other parameters have a significantly smaller effect on the abatement costs, making them less sensitive to the uncertainty of these parameters. The abatement costs are especially insensitive to changes in the COP of UDG. This fact, combined with the small impact of changing the heat price from UDG (see Figure 30), means that the dairy sector can be confident that purchasing heat from a UDG project can benefit their sustainability ambitions.

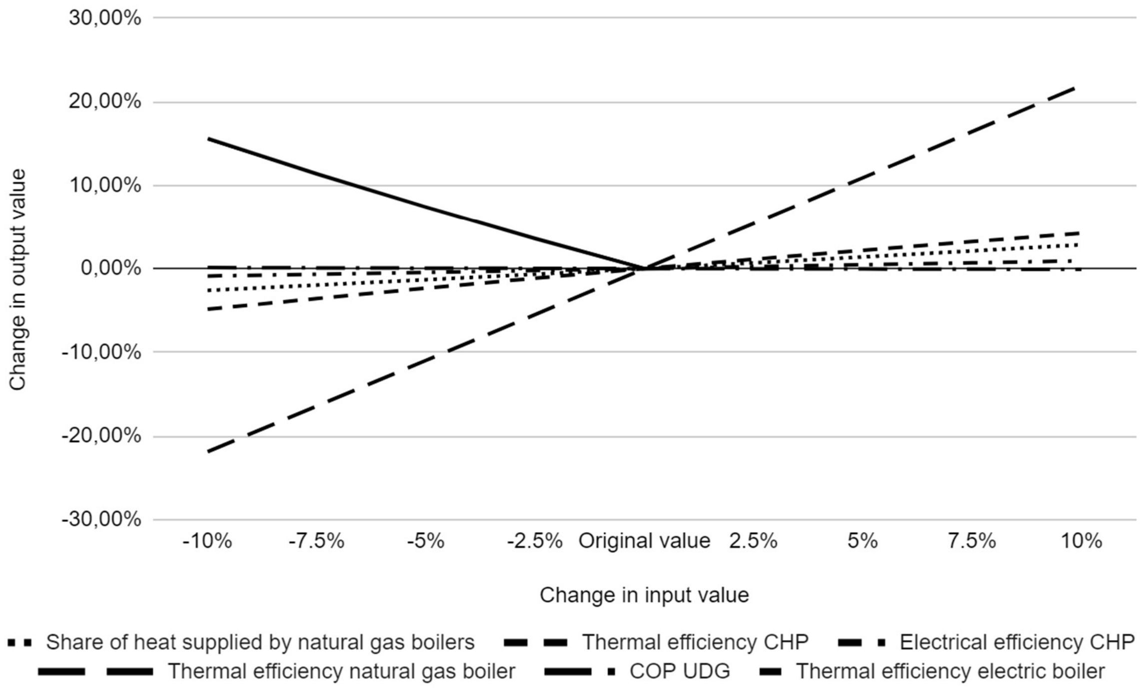


*Figure 31: Sensitivity analysis showing the impact of changing parameters related to heat production on the total abatement costs of decarbonisation for the BAU status quo scenario under ES1 and ES3*

The parameters researched in this section also have a significant impact on the decarbonisation potential in 2050. Figure 32 below shows a sensitivity analysis showing the effect of changing the parameters on the decarbonisation potential on different scenarios as explained above.

Since the figure looks at the impact of the parameters on the decarbonisation potential in 2050, when the Dutch electricity grid consists for almost 100% out of renewables, the effect of the parameters related to electricity (parameters 17, 19 and 20) have a negligible effect on the decarbonisation potential in that year.

The decarbonisation potential is the most sensitive to changes in the thermal efficiency of natural gas boilers. This, coupled with the large sensitivity of the abatement potential, makes it so that the results are strongly dependent on the thermal efficiency of the natural gas boiler being replaced. However, the effects on the abatement costs and on the decarbonisation potential are opposite, so they undo the effect somewhat. Even so, the effect of increasing or decreasing the thermal efficiency of the natural gas boiler with 10% leads to an increase of around 11% or a decrease of 13% in the total costs of decarbonisation respectively.

Changing the heat production from natural gas boilers to CHPs leads to a lower decarbonisation potential and an increase in abatement costs. Still, it seems likely this change will occur in the future, as the benefit of reduced carbon emission from electricity consumption because of electricity production from CHPs will reduce as more renewables are added to the national grid. Also, the dairy sector already uses a large share of renewable electricity and aims to increase this share, so the benefits of using CHPs are small already.

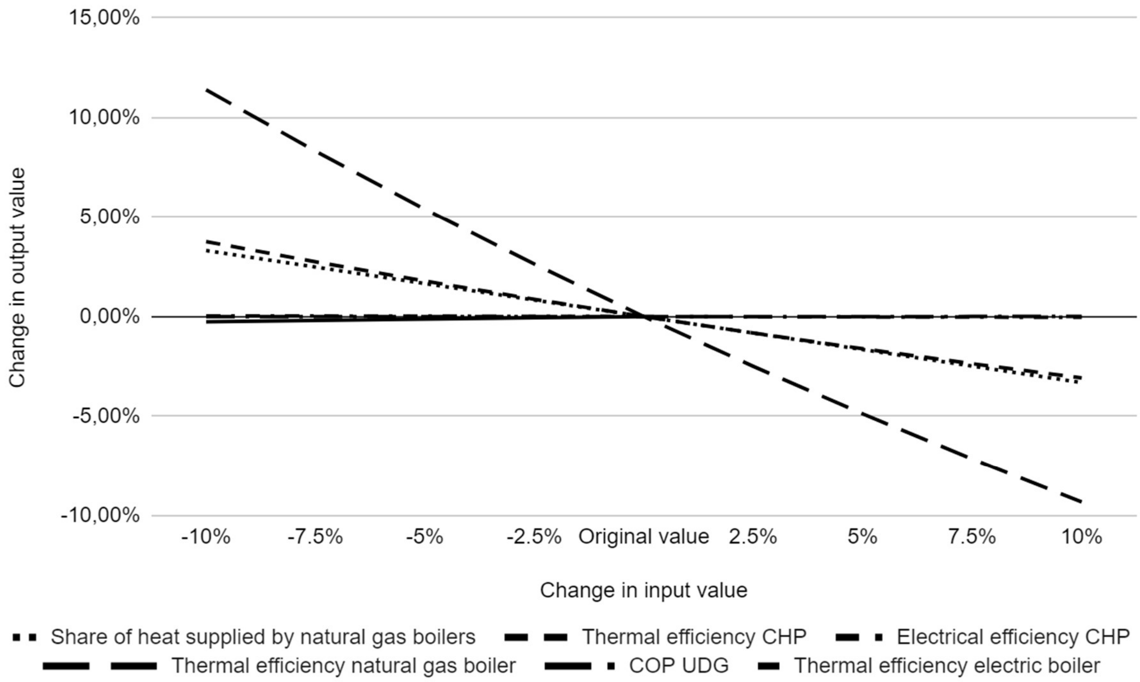


*Figure 32: Sensitivity analysis showing the impact of changing parameters related to heat production on the decarbonisation potential in 2050 for the BAU status quo scenario under ES1 and ES3*

### 3.4.5 Autonomous efficiency improvement

Finally, the impact of autonomous efficiency improvements (parameter 21) has been determined. This parameter was originally set to zero. To determine the impact the parameter was changed to a maximum of 1% efficiency improvement per year. This leads to an energy consumption of 72.5% of the original energy consumption before decarbonisation in 2050. The effect of autonomous efficiency improvements on the average abatement costs and decarbonisation potential for the BAU status quo scenario under ES1 are shown in Figure 33 below.

The figure shows that the impact on the decarbonisation potential is strongly related to the resulting energy consumption by efficiency improvements. The change in decarbonisation potential is exactly the same as the change in the total energy consumption in 2050 compared to 2019. For a 1% yearly autonomous efficiency improvement, the energy consumption is 72.5% of the value without efficiency improvement, decreasing with 27.5%. From the figure it is clear that the decarbonisation potential also decreases with 27.5%. This makes sense, since the amount of decarbonisation needed is directly related to the heat and electricity consumption of the sector before decarbonisation occurs. So, if the total energy consumption goes down, the total amount of emissions to be abated decrease analogously.

The total average abatement costs increase with increasing efficiency improvements. This can be explained by looking at the changing energy consumption over time. In the early years, the energy consumption is still comparatively high, while the monetary savings are relatively low because of the low gas and carbon credit prices. Then, when the prices increase, the decarbonisation potential and decrease in gas consumption are reduced because of the lower energy consumption due to efficiency improvements. This leads to more decarbonisation occurring at times of unfavourable prices, leading to higher costs, and therefore higher abatement costs.

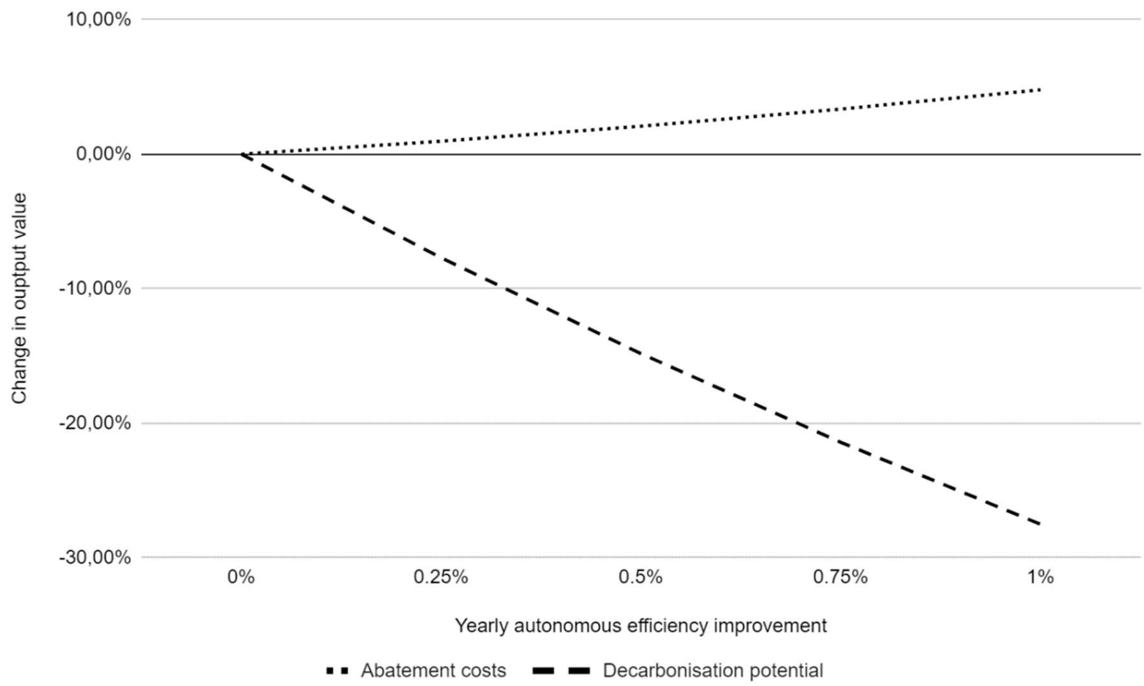


*Figure 33: Sensitivity analysis showing the impact of changing autonomous efficiency improvements on the average abatement costs and decarbonisation potential in 2050 for the BAU status quo scenario under ES1*

## 3.5 Financing possibilities

As the results show, decarbonisation of the dairy industry will cost millions of euros. A large part of the investments will have to be made by the dairy sector itself, but some possibilities exist to shift the capital investments to other parties, or to increase the financial attractiveness of decarbonisation. The possibilities for financing the decarbonisation will be discussed in this section.

### 3.5.1 Subsidies

Most importantly, there is the possibility of receiving subsidies for the decarbonisation technologies. The main subsidy scheme for renewable technologies in the Netherlands is the SDE++ (Stimulering Duurzame Energietransitie), focussing on both options that generate renewable energy and those that lower $CO_2$-emissions. Several options included in this research are eligible for receiving an SDE++ subsidy. An overview of these options and the base value of the subsidy are shown in Table 24 below.

*Table 24: Decarbonisation options eligible for SDE++ subsidy, showing the base subsidy value*

| Decarbonisation option | Subsidy [EUR/TJ$_{th}$ produced] | Source |
|---|---|---|
| **MVR** | 6388.89 | (Marsidi & Lensink, 2019a) |
| **UDG** | 18333.33 | (In 't Groen, De Vries, Mijnlieff, & Smekens, 2019) |
| **Electric boiler** | 12222.22 | (Marsidi & Lensink, 2019b) |

To understand the effect of the subsidy, the costs of heat production by the three decarbonisation options has to be known. This is shown in Table 25 below. Because of changing gas, electricity and carbon credit prices these costs change over time, so a range of costs is shown. The costs shown are for the BAU status quo scenario under ES1. For the MVR, two ranges of costs are shown. The first corresponds to the costs that arise when using the investment costs used for the rest of this research. The cost of heat production found this way is lower than the base value of the SDE++ subsidy. The reason for this is that the subsidy is calculated using higher investment costs (of EUR 0.906 million/MW$_{th}$) (Marsidi &

Lensink, 2019a). When using this value, the cost of heat production between brackets is found, which is higher than the base value of the subsidy. The costs for UDG include the investment costs.
The table shows the share of the cost of heat production that can be supplied by the SDE++ subsidy. For the MVR and electric boiler, this share is significant, meaning a large part of the costs for the dairy sector can be recuperated by applying for this subsidy. For electric boilers, this might stimulate dairy processing facilities to invest in electric boilers early on, even if the relatively high investment costs cannot be offset by savings on gas consumption. For UDG, the share of costs covered by the SDE++ subsidy is quite low, meaning that it is unlikely that the dairy sector will invest in UDG project to be the only owner, as costs for this have been shown to be very high. However, the subsidy can make it easier for multiple parties to invest together.

*Table 25: Cost of heat production for decarbonisation options eligible for SDE++ subsidy*

| Decarbonisation option | Cost of heat production [EUR/TJ$_{th}$ produced] | Share of cost covered by base value SDE++ subsidy [%] |
|---|---|---|
| **MVR** | 3312 – 4263 (11803 – 12754) | 150 – 193 (52 – 57) |
| **UDG** | 86835 – 90116 | 20 – 21 |
| **Electric boiler** | 15789 - 17917 | 68 – 77 |

### 3.5.2 Carbon pricing

To stimulate investments in renewable technologies, the Dutch government can set a price on carbon emissions. If this price is set high enough, companies will choose to decarbonise their production processes, since paying for the emitted carbon would be more expensive. A carbon price has been included in this research, which, at the value used for the results so far, resulted in savings of EUR 58.07 million in the BAU status quo scenario under ES1. However, the price of carbon credits might be further increased in the future, as the Dutch government has set out various climate goals, which might be more easily reached with a high carbon price. So, the carbon price might change significantly from the value used in this research. The effect of this change has already been shown in Figure 30. It showed that a 10% increase in the carbon price results in a decrease in average abatement costs of around 4.3%.

If the price of carbon credits is increased even further, a state of zero costs will be achieved for the dairy sector. For the BAU status quo scenario under ES1, this is achieved at a carbon price of EUR 363.29/t $CO_2$ in 2050, assuming linear growth from a price of EUR 25/t $CO_2$ in 2019. However, the government might also decide to increase the price more rapidly until 2030 or 2040, so that there is an increased incentive to decarbonise for more parts of society, which would otherwise start reducing their emissions in later years, when the price of renewable technologies has decreased. To simulate this situation, a carbon price increasing linearly to 80% of the final carbon price in 2050 was assumed in 2030, growing linearly to the final price in 2050. In this scenario, the total costs for the dairy sector are zero at a carbon price of around EUR 274/t $CO_2$ in 2050, much lower in the scenario with simple linear increase between 2019 and 2050. This shows the significant impact that action taken now, instead of at a later time, can have on the decarbonisation pathway of the dairy industry, and by extension of the Netherlands. If the value of 80% of the final carbon price is assumed to be reached in 2040 instead of 2030, the carbon price needed in 2050 for zero costs for the dairy industry is around EUR 334/t $CO_2$, around 22% higher than if its reached in 2030, further underlining the effect early action will have on decarbonisation and climate change prevention.

### 3.5.3 Production value

Apart from subsidies or carbon pricing, the most important source of funds for investing in renewable technologies is the revenue obtained by selling dairy products. Since the volume, and possibly the mix, of production of dairy products changes over time, the revenue changes as well, especially when also considering changing prices of dairy products. These price developments are very uncertain, as the

international market for dairy products is very volatile, because of the small share of milk production destined for export, the strong position of a few exporters and importers, and the large effect policy can have on its trade (OECD-FAO, 2019). As an indication of this price volatility, Figure 34 below shows the price development of various dairy products in the European Union over the last two decades. Since the Netherlands export a large share of their dairy products, this international price-volatility can make planning for investments difficult.
Figure 34 shows that the price per weight of butter and cheese is consistently higher than that of dried products. This means that in the international demand scenarios, in which less fresh products are produced in favour of dried dairy products, the revenue can be expected to be lower than in the status quo scenarios. On the other hand, the energy consumption in the international demand scenarios will be higher, leading to higher costs of decarbonisation. This divergence between income and costs can prove difficult for the dairy sector when raising the funds necessary to invest in these scenarios.

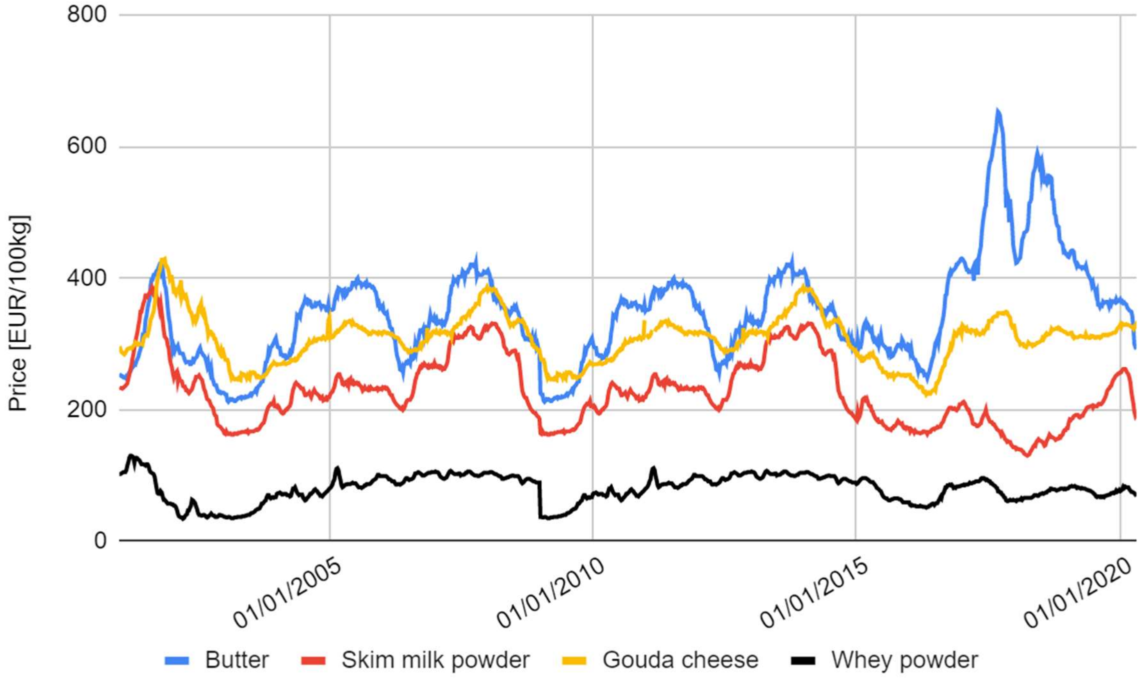


*Figure 34: Price development of various dairy products in the European Union (European Commission, 2020)*

## 4. Discussion

In this section the results shown so far will be discussed, focussing on the uncertainty inherent in scenario-based research, and indicating points of improvement and ideas for future research.

As shown in Section 3.4, the results of this study depend on a large number of parameters, and the effect of changing any of those parameters can be significant. However, some parameters are not as likely to differ significantly from the value used in this study. For instance, the thermal efficiency of natural gas boilers, which is a parameter with a large impact on outcome values, is well known, because of the widespread use of these boilers.
Other parameters, especially those related to decarbonisation options that are not widely used, will be more uncertain. These include the energy savings by zeolite, the investment costs for all options, and future prices of gas, electricity, heat and carbon credits. Especially the latter prices are highly uncertain, as these were assumed to change over time. However, simple linear growth was assumed for their development, which is unlikely to be the case in real life. As described for the price of carbon credits in Section 3.5.2, the timing of these prices can have significant impact on the abatement costs for the

dairy sector. It is unclear what the effect of these changes will be on the average abatement costs, as the parameters will show deviations from the used value in both directions.
Also, investment costs are likely to decrease over time, while they are assumed to remain stable for this research. This decrease will be most noticeable for cutting-edge decarbonisation options, like zeolite and UDG. This decrease of investment costs will lead to decreasing abatement costs, but predicting the price development of these costs is difficult.

Apart from the uncertain parameters, there is also the inherent uncertainty in the created scenarios. These were based on extrapolations of historic data, but many changes may occur in the future. The dairy industry is a highly international industry, and is prone to changes in legislation, both domestically and internationally, so significant differences may occur in the future between the real-life situation and the created scenarios. By creating multiple scenarios, some of this uncertainty has been accounted for, but reality will always differ from what has been calculated for this report.
Also, much of the work of this report is based on energy-consumption figures that were calculated from publicly available sources. These sources do not reflect actual production processes, so the energy consumption of dairy products will differ from the values used here, which will have significant effects on the other results.
This resulted in a total energy consumption (of around 10000 TJ in 2018) that was significantly lower than the figure reported by the Dutch government (over 20000 TJ in 2018) (RVO, 2019). Part of this discrepancy can be attributed to a differing scope, as the figure from the Dutch government includes energy consumption related to transport, housekeeping, and possibly other factors, while this research excluded those segments. (RVO, 2019). Nonetheless, a significant gap between the calculated and reported energy consumption of the sector remains, which will impact the results of this study.

This research also did not take the lifetime of decarbonisation options into account. In reality, the used decarbonisation options will have to be replaced after a couple of years[31]. This will have a noticeable effect on the costs of decarbonisation, as repeated investments will have to be made to ensure enough abatement occurs annually. This also means that there will be more moments for the dairy industry to decide which options to invest in, with favourability changing over time due to changing costs and benefits.

In light of these uncertainties, some recommendations can be made for future research. The largest improvement on this report can be made by cooperating with the dairy sector itself, so that more accurate values can be used for the energy consumption and production of the Dutch dairy industry. This might also make it possible to differentiate between more products, as the product-groups used now likely contain products with strongly different energy requirements. Future research could also use more accurate cost-data, by for instance changing investment costs over time as a reflection of technological advancements, and by including the lifetime of decarbonisation options. Apart from time-dependent cost-data, the results could also explicitly take the time-dependent value of money into account, by looking at the Net Present Value of the decarbonisation options. By doing this, a clearer picture of whether the dairy sector will invest in certain technologies can be created. Finally, more decarbonisation options should be included, to create a better overview of the possibilities for the sector to reduce their emissions.

It is also important to include other factors than economical or technological, since the possibility of decarbonisation will depend on other elements as well. As mentioned, legislation will have a large impact on the dairy industry, so future research could look at policy instruments that can aid the industry with achieving their sustainability goals. Furthermore, since the dairy processing industry is closely related to the developments of the Dutch dairy farmers, possible pathways of change at the farm-level

[31] For instance, the zeolite wheel will have a lifetime of around 15 years (Moejes, Visser, Bitter, & Van Boxtel, 2018)

will have significant impact on the processing needs of the facilities. Therefore, a study researching the development of the entire Dutch dairy industry, from farm to consumer, will yield more realistic and accurate results regarding possible decarbonisation pathways. This is also important since a large share (over 92%) of the emissions related to dairy products come from the production of milk, so reducing the carbon footprint of milk can have a more significant effect than decarbonising the production processes (Doornewaard, Reijs, Beldman, Jager, & Hoogeveen, 2018).

To ensure the described decarbonisation options have the desired effect, some elements will have to be in place. For instance, the capacity of the national electricity grid should be great enough to be able to fill the increased electricity consumption. If the industry cannot obtain guarantees for this, large investments in electrification may become undesirable. Also, the amount of renewables in the Dutch electricity grid should be at such a level that increases in electricity consumption do not lead to increased emissions. Finally, dairy farmers should have enough land to keep the necessary cows. As of 2016, dairy farmers held 28% of the total area of the Netherlands to hold around 1.67 million cows, which produced around 8560 kg of milk per cow per year (van der Peet, et al., 2018; ZuivelNL, 2019). However, since milk production increases in all investigated scenarios, it is likely that the needed area also increases. If not enough land is available the development of the dairy industry as a whole will be markedly different from the scenarios described in this research, with significant effects on its results and conclusions.

# 5. Conclusion

The development of the Dutch dairy industry has been evaluated until 2050, taking into account different possible scenarios regarding milk production and utilisation, to determine its energy consumption and emissions. Several options for decarbonisation have been researched, focussing on their decarbonisation potential and abatement costs.

The research question this study aimed to answer was *'What pathways exist for full decarbonisation of the Dutch dairy processing industry in the year 2050?'*. The results show that full decarbonisation is possible at a price ranging between EUR 99.13 million and EUR 184.60 million, when using three different options aiming at improving the energy-efficiency of the production processes, geothermal heat, and electric boilers. However, some options are more favourable than others, due to differing abatement costs. Between the three energy-efficiency options, the use of zeolite during spray drying is most preferable, which has similar abatement costs as the use of mechanical vapour recompression. The third option, the use of reverse osmosis to preconcentrate the feed before evaporation, is significantly more expensive than the other two, so it seems unlikely that dairy processing facilities will invest in this option given the current prices.

The use of ultra-deep geothermal energy can be a useful source of heat for the dairy industry. However, its usefulness depends strongly on whether the dairy industry has to be the (sole) investor in creating a geothermal energy station. If this is the case, the high investment costs will make it unprofitable, and therefore unlikely to be used by the industry. If the investment costs can be externalised or shared, however, the relatively low costs and large decarbonisation potential can be a source of monetary savings for the industry, making it a suitable option for the abatement of carbon emissions.

The impact of electric boilers depends strongly on the amount of renewables used by the dairy industry, as using the average Dutch electricity will lead to increases in emissions before the penetration of renewables becomes big enough. However, the dairy industry already uses a large share of renewable electricity, indicating that emissions will be saved if electric boilers are used. Because of their high investment cost, and the high average cost of electricity compared to natural gas, the profitability of investing in electric boilers will depend on other factors which might enable the recuperation of these costs. For instance, the boilers could first be used as flexible load, so they can be used at times of lower electricity prices. Another option, which is also available for some of the other decarbonisation options, is applying for the SDE++ subsidy. Carbon pricing can also be used as an incentive to reduce emissions.

These results depend on a large number of parameters, which might vary from the values used for this research. Future research using more accurate data is needed, which might be obtained by cooperating with the dairy industry. The results can also be improved by taking into account time-dependent cost data, and including the time-dependent value of investments. Finally, by including more decarbonisation options a more realistic overview of the possibilities for abatement can be created.

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# Appendices

## Appendix 1: Mass flows 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)):

$$Raw\ milk\ needed\ \left[\frac{l\ raw\ milk}{l\ standardised\ milk}\right] = \frac{F_C - F_N}{F_C - F_D} \quad (12)$$

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, 2015). 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 12 (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:*

Milk: After standardisation, no feed is added/removed, so **1.03** kg of raw milk is needed per kg of end 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, 2015). 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, 2015). The amount of raw milk was calculated using the following formula:

$$W_R\left[\frac{t\ feed}{t\ product}\right] = \frac{DM_F}{DM_I} \quad (13)$$

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 based on 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 13, 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 13, 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, 2015). 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 based on 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 13, 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, 2015).

*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 13, using the dry matter content after the final water removal step as $DM_F$. Results are shown in Table 26 below. The moisture removed in these steps can be determined by subtracting feed flows between the steps. All dry matter contents were found in Tetra Pak (2015), 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 26: 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, 2015). 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, 2015; 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, 2015; 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, 2015). 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, 2015; 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, 2015). 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).

## Appendix 2: Energy flows 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:

$$E_H[J] = c\left[\frac{J}{kg*°C}\right] * M[kg] * \left(T_f[°C] - T_i[°C]\right) * (1 - R[\%]) \qquad (14)$$

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, 2020b). After thermisation, the milk is cooled back to 4°C (Tetra Pak, 2015). The heat removed during refrigeration is determined using formula 14. 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 27 below.

*Table 27: Energy consumption for thermisation*

| Product | **Milk** | **Cheese** | **Butter** | **Milk Powder** | **Milk protein powder** | **Condensed Milk** | **Sweetened Condensed Milk** |
|---|---|---|---|---|---|---|---|
| c [J/kg/°C] | 3770 | 3770 | 3770 | 3770 | 3770 | 3770 | 3770 |
| M [t] | 1.03 | 9.36 | 17.90 | 7.46 | 29.43 | 1.94 | 2.23 |
| $E_{HT}$[GJ] | 0.04 | 0.32 | 0.62 | 0.26 | 1.02 | 0.07 | 0.08 |
| $E_{ET}$[GJ] | 0.02 | 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 14. 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[32] and that of whey is 1.04 kg/l (Tetra Pak, 2015; Tetra Pak, 2019d). Heat ($E_{HS}$) and electricity ($E_{ES}$) requirements for separation are shown in Table 28 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.

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

*Table 28: Energy consumption for preheating*

| Product | Milk | 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 | 3770 | 4018 | 4018 | 4018 |
| M [t] | 1.03 | 9.36 | 17.90 | 7.46 | 29.43 | 2.00 | 2.23 | 15.38 | 187.44 | 15.78 |
| $E_{HS}$[GJ] | 0.03 | 0.30 | 0.57 | 0.24 | 0.93 | 0.07 | 0.07 | 0.53 | 6.43 | 0.54 |
| $E_{ES}$[GJ] | 0.002 | 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 14. Results are shown in Table 29. Except for cheese, all initial and final temperatures were found in Tetra Pak (2015). 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 (Tc) is shown in Table 29, and is used to determine the amount of heat removed, using formula 14. 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 29 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 14, and the electricity requirements using a COP of 2.

*Table 29: Energy consumption for heat treatment*

| Product | Milk | 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 | 3770 | 4018 | 4018 | 4018 |
| M [t] | 1.00 | 9.09 | 2.01 | 7.24 | 28.57 | 1.94 | 2.17 | 14.92 | 181.82 | 15.31 |
| $T_i$[°C] | 60 | 52 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| $T_f$[°C] | 72 | 72 | 95 | 72 | 72 | 120 | 120 | 72 | 72 | 72 |
| $T_c$[°C] | - | 30 | 8 | - | - | 70 | 70 | - | - | - |
| $E_{HH}$[GJ] | 0.01 | 0.10 | 0.04 | 0.05 | 0.20 | 0.07 | 0.07 | 0.11 | 1.34 | 0.12 |
| $E_{EH}$[GJ] | 0.01 | 0.07 | 0.03 | 0.06 | 0.22 | 0.01 | 0.02 | 0.11 | 1.38 | 0.03 |
| $E_{CH}$[GJ] | 0.004 | 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 (Tetra Pak, 2019a). The amount of heat removed could then be determined using formula 14 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 14, 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*
Milk: Milk is homogenised after standardisation, which requires 4.6 kWh/1000 l product (Tetra Pak, 2020a).

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 14, and the electricity requirements based on a COP of 2 (Tetra Pak, 2015). 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 14, 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 14 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, 2015; Tetra Pak, 2020c). 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, 2020c).
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, 2015). The heating requirements for producing this water were determined using formula 14, 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, 2020d).

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

Milk and whey protein powder: 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.

Condensed milk: 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, 2020a).
After homogenisation, the condensed milk is cooled to packaging temperature (14°C) from the temperature after evaporation (50°C) (Tetra Pak, 2015). Electricity requirements for this cooling step were determined using formula 14, 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 14, assuming a heat regeneration of 0%, since the product is already packaged.

Sweetened condensed milk: 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 14 (with an initial temperature of 50°C), and with a COP of 2, the electricity use was determined (Tetra Pak, 2015).

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).