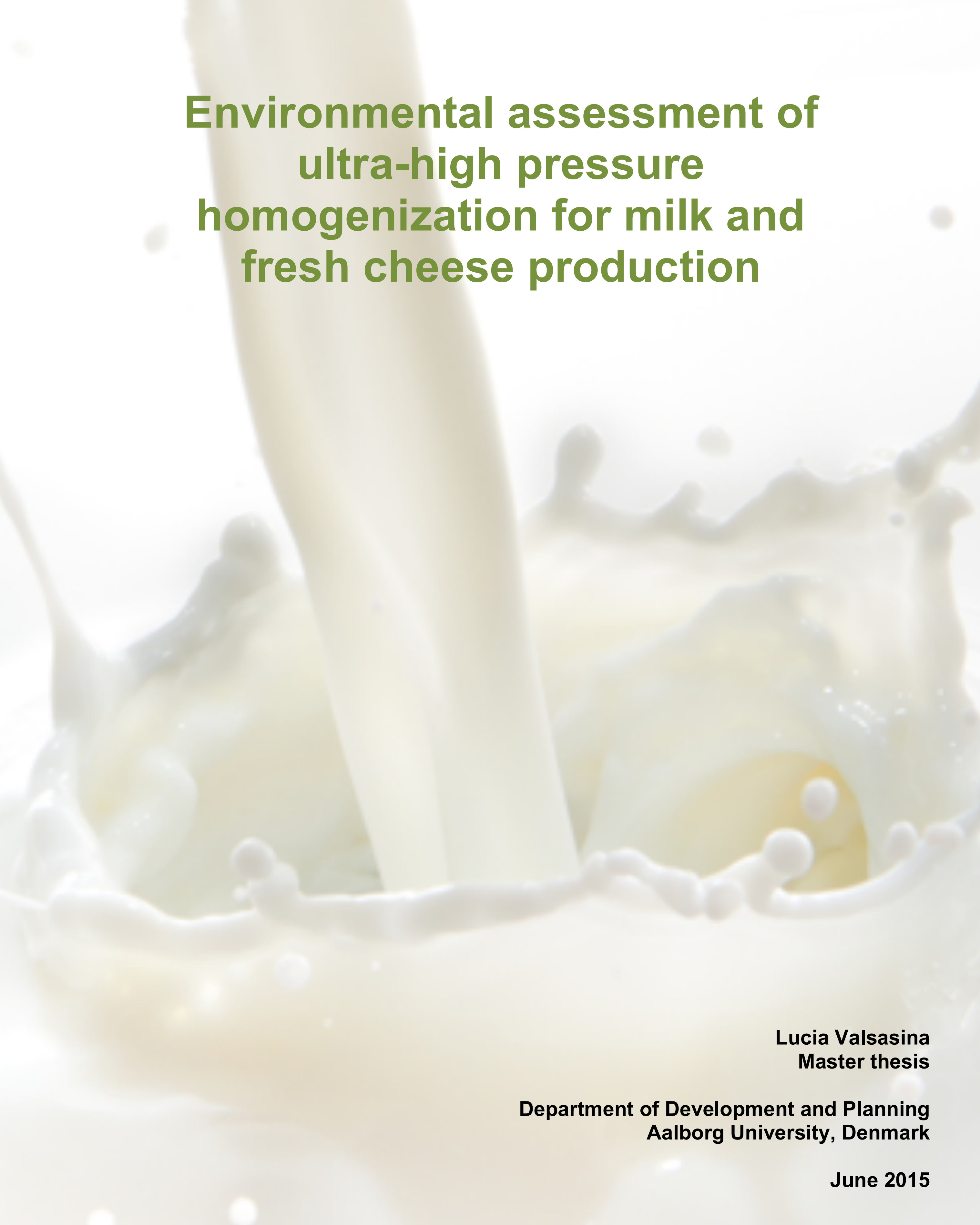

Environmental assessment of ultra-high pressure homogenization for milk and fresh cheese production

Lucia Valsasina
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Department of Development and Planning
Aalborg University, Denmark

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Lucia Valsasina

Aalborg University
Environmental Management and Sustainability Science

School of Architecture, Design and Planning
Department of Development and Planning
Vestre Havnepromenade 5,1.
9000 Aalborg

Supervisor
Assoc. Prof. Massimo Pizzol

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Abstract. Dairy products are responsible for 8 to 10% of environmental impacts of European consumption (Weidema et al. 2009). Businesses have to respond to an increasing pressure for higher quality products, while still maintaining competitive prices.

This study analyses the application of Ultra-high pressure Homogenisation (UHPH), an innovative technology for food sterilisation that relies on pressure up to 400MPa, for the treatment of cow milk. The technology is forseen to provide equal or higher quality products compared to the combination of Ultra High Temperature (UHT) and Homogenisation treatment and, at the same time, to lower energy consumptions through the combination of sterilisation and homogenisation in a single process. Furthermore, the use of UHPH treated milk for the production of fresh cheese has been proven to increase shelf life from ~13 to ~19 days and yield from 11 to 14% (Escobar 2011; Zamora and Guamis 2014). This study provides an LCA of UHPH and UHT processing of milk and fresh cheese production from processing to end-of-life.

Pilot scale data was collected for the following cases: UHPH equipment with capacity of 90l/h was tested with water, buffer, skimmed milk (1.5%) and whole milk (3.5%); UHPH with capacity of 360l/h with water; and an 85l/h indirect UHT system, including upstream homogenisation, tested with water. As the first case showed no difference in energy consumption for the four compounds, only water was used for the following tests.

UHPH is a technology not yet used industrially, power-law relationships were used to model the relationship between the equipment's main variables, such as capacity and energy use, as scale increases.

The results of this study show that UHPH is more environmentally beneficial at pilot scale due to lower water and energy consumptions. Savings of approximately 14% are predicted for electricity alone. However, at industrial scale UHT systems ensure an energy recovery of approximately 90%, which is hardly achieveble with UHPH at current technology development level. On the other hand UHPH has a potential of reaching at least 43% of energy savings and carbon dioxide emission reduction; and further resuctions are possible with a long term perspective. Moreover higer quality milk could result from UHPH treatment. Up scaling of UHPH showed the increase in efficiency for different pilot scale and confirmed the linear relatiosnhip between energy use, capacity and speed for UHPH homogenisers. The increase in shelf life of fresh cheese produced from UHPH milk will bring benefits at larger scale due to reduction in food waste and resource use.

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List of abbreviations

CIP	Cleaning in place
ER	Energy recovery
FU	Functional unit
GHG	Greenhouse gasses
LCA	Life cycle assessment
MSW	Municipal solid waste
UHPH	Ultra-high pressure homogenisation
UHT	Ultra high temperatures

1. INTRODUCTION

The elephant in the room might actually be a cow (Bardnard 2014; Pearson 2014). Popular science adopted this saying to bring attention to the impact of food production, which is responsible for a third of anthropogenic emissions (Gilbert 2012). This issue is central in mitigation as, not only it is one of the main contributors, but it is itself affected by climatic changes, such as variations in rainfall seasonality, temperatures etc. It is therefore vital to invest in increased efficiency and decreased resource use to limit the sector's impact, while at the same time fighting malnutrition and ensuring food safety.

The agricultural industry is vital for many economies, not only for countries that have historically based their trading on primary production but also for the majority of lower income countries. The food market is in constant transformation as population, diets and consumer awareness evolve following globalisation and technological development (Pagan et al. 2005). Milk has gradually become a key commodity on international markets. In the last 50 years worldwide production has increased by 100% as livestock doubled and yield grew by 30%. North America and Europe have seen a reduction in the number of livestock, while increase in production has been ensured by technological advancement and specialization, which result in high yield. Asia has experienced a drastic intensification of rearing in combination with greater yield and the same trend characterised South America and Oceania in a smaller scale. Africa had the highest increase in livestock (293%) maintaining a similar milk production per head (Table 1).

Table 1. Number of milk bovines, yield per bovine and production per geographical area (FAOstats 2015)

	Milk Animals (million head)			**Yield (tonnes/head)**			**Production (million tonnes)**		
Regions	**Year**		**Difference in %**	**Year**		**Difference in %**	**Year**		**Difference in %**
	1961	**2012**		**1961**	**2012**		**1961**	**2012**	
World	177	270	52%	1.77	2.32	31%	25	31	100%
Africa	17	67	293%	0.46	0.51	11%	314	626	338%
Asia	34	105	205%	0.62	1.62	163%	84	182	703%
Europe	83	38	-55%	2.27	5.58	146%	21	170	11%
Germany	8	4	-47%	3.11	7.28	134%	190	210	23%
North America	20	10	-50%	3	10	202%	65	99	52%
South America	14	36	160%	1	2	80%	14	66	367%
Oceania	5	7	32%	2.25	4.38	94%	12	30	157%

Chinese consumers are one of the biggest drivers of increased production of milk. The country's adoption of a more westernized lifestyle is expected to increase imports from 14.3% to 34.5% of total demand (Yaron 2014; Meyer 2014). The consumption per capita is forecasted to double and, as consumers are willing to pay for better quality, prices will be pushed well above worldwide average (Meyer 2014). With the scandals of diseases, local milk is not trusted by consumers leaving the market open for larger companies, which also receive state financial support (Yaron 2014; Meyer 2014). International producers are investing significant amount of capital to win the largest slice of this market. European producers, freed since March 2015 from quotas, are ready to respond to increased demand. Countries that are historically leaders in this market, such as Germany and Denmark, have invested in production and most of it will be redirected to China. The next decades will be decisive as China could overturn the tables in a matter or years becoming the leading producer of milk in the world, if they maintain the same rate of import of Australian livestock (Meyer, 2014).

The market for milk is key as it is interlinked to meat production. The latter market has been characterised by increasing demand as well. Because of higher income rates and the spreading of western culture in developing countries, meat is also taking a larger share in diets. This trend is predicted to continue as developing countries become richer. Growing consumption of these products is contributing to the decrease in malnutrition but they represent a risk for humans, livestock, small farmers and the environment (Muehlhoff et al. 2013).

Environmental issues are increasingly gaining importance in global discourse as non-renewable resources availability is at risk. Yasui (2007) indicates the cause of climate change not to be human activities but the "convenient characteristics of fossil fuels". The food industry represents one of the most demanding sectors, with impact between 20 and 30 % of household consumption, for which meat and dairy are mainly responsible (Flysjö 2012). Dairy accounts for 2.7% of global emissions and of 4% if meat by-products are included (Milani et al. 2011; Flysjö 2012).

The main impacts from agricultural products come from farming activities, which is why carbon dioxide is not the only important gas to consider. Methane, nitrous oxide and biogenic carbon oxide from land use, for example, play a key role in the overall impact. Land use is a crucial issue as biofuels represent a valid alternative to fossil fuels but at the same time represent competition to food. The burden of farming is particularly higher in developing countries where, yield per bovine is lower compared to western livestock. CO_2 becomes the most relevant emission in the stages after farm-gate (Flysjö 2012).

The dairy industry has therefore a great impact globally and given the rising demand and production of developing countries it is necessary to investigate ways to lower the environmental load of the sector. Population growth in developing countries put additional pressure on the development of smart resource management ways (Sakai 2007). This calls for both public and business involvement (Sakai 2007). Life cycle engineering aim is to identify ways to produce effectively keeping in mind the planet's capacity (Yasui 2007) and, for business, also economical feasibility (Sakai 2007).

Most research on food items concentrate only on the farm stage, but process improvements represent an important resource to decrease GHG. This study looks into the assessment of a new food processing technology, which is predicted to decrease energy consumption and provide a better quality product. Ultra-high pressure homogenisation (UHPH) is relatively new equipment that combines homogenisation and sterilisation. The European Union has directed founds to investigate the application in vegetable and animal milk production. The use of UHPH milk is also been analysed for the production of fresh cheese, finding increased shelf life and yield. Given the expected advantages of the technology an LCA is conducted. Moreover the system is compared to an established processing milk treatment, ultra high temperatures (UHT) and to provide an overview of the possibilities of implementation in the industry, power laws are used to predict the scaling behaviour of the equipment.

1.1 Assessing the environmental impact of innovative technologies

1.1.1 Eco-design and life cycle assessment

In order to supply the demand of informed consumers, the research in the food industry strives for innovative solutions for producing safe and high quality food that is also environmentally sound. To achieve these goals investments are directed to the research of processing technologies that deliver higher quality products, increase shelf life, lower resource consumption and decrease costs keeping the prices competitive. This must be integrated with optimised chain management, new business strategies, education and knowledge sharing (Munksgaard 2014). Eco-efficiency is a way to promote these objectives and a better and more competitive production. Technological innovation represents the long-term perspective for successful eco-efficiency, which translates into sustainable development; but moving from an established way of production to a novelty, comes with economic and technological risks (Baroulaki and Veshagh 2007).

Life cycle thinking is key approach for eco-design, encouraging the evaluation of the whole product chain from raw materials to end-of-life. Life cycle assessment can support stakeholders, governments and consumers in their decision-making. Producers not only have the chance of understanding the impact of their activities on the environment, which is becoming a key aspect as "greener" products are demanded, but they are provided with insights on where it is possible to reduce energy consumption, resources use and increase efficiency. So, companies can consider what Beroulaki and Veshagh (2007) define as "hidden costs", which are the ones related to energy and materials that are wasted at production and post-production level. These not only result in economic costs but also in environmental costs. Business should therefore strive for eco-efficiency.

1.1.2 Scaling up environmental impacts

Using life cycle assessment as a tool for eco-design brings one of its current limitation to the surface. Innovative technologies are studied at pilot and laboratory scale to assess their performance, but often when considering the application to industrial scale, the consequences of scaling up are not included or cannot be easily estimated. The impact that a technology has at experimental scale does not necessarily have a linear relationship with size and capacity. Caduff et al. (2011, 2012 and 2014) studied the behaviour of different engines as output increases and found that most equipment showed some economies of scale. Even though pilot simulations provide specific and direct data, Shibasaki et al. (2006) identified three main aspects that should be included in LCA studies: first scaling needs to become a key element of analysis on early stage technologies. Many technical aspects, such as yield and efficiency, and practical aspects, such as legislations and costs, vary with scale. Second, processes should not be looked at singularly but they should be seen as a whole with the system in order to use any possible "synergy". With the term "synergy" the authors refer to the investigation of reusing materials or resources that represent waste in one process but can be a resource for another. Lastly, effective capacity should be a concern, and so the maximum output that could be derived accounting for limits such as quality and time. The efficient output should also be calculated taking into considerations all the processes that contribute to a full-scale production line versus a pilot scale, which is usually more limited (Shibasaki et al. 2006).

In the past two years two studies were published that covered the main literature review for this topic. Arvidsson et al (2013) investigated sixteen LCA studies on nanomaterials, which are mainly immature technologies, finding five predominant approaches. The following year Hummen and Kästner (2014) identified four methodologies, which were classified based on two categories of criteria: data and systematic.

Arvidsson et al (2013) defined the following five approaches: the first approach, *likely scenario*, is based on technical considerations and forecasted development; *extreme scenarios* models the best and the worst case scenario; *sensitivity analysis*, is typically included in LCA studies to account for variations of certain parameters given different scenarios; *exclusion*, the novelty is not included in the calculations; *mature system*, the impact of the new technology is set to be equal to the existing one. The approaches are listed from the most to the least used, even if commonly two or more approaches are combined, but few studies motivate their methodological choice. The authors concluded that *likely scenario* and *sensitivity analysis* are more relevant for more mature technologies as they assume a relative knowledge about the system, while the *extremes scenario* and *mature systems* approaches are a good basis for a very long-term view for innovative technologies.

Hummen and Kästner (2014) identified the following four methods. *Simple reduction factors,* this approach follows step by step the development of the technology gradually increasing the level of detail. The close examination of technological progress is the main positive aspect, giving a complete overview of the system. On the negative side, at the beginning qualitative data is used and only simple reduction factors are applied for each process individually. The second method is the *systematical reduction functions using modular influence estimations*; based on already existing studies reduction functions are derived and integrated with experts' opinions. The combination of extent quantitative data and scenario analysis is a complex task but it does provide a detailed knowledge of the system. The third approach is *systematical reduction functions using economies of scale;* this category includes Caduff's (2012) approach of looking at economies of scale and technological scaling. This method gives a good overview of the system as a whole and its potentials, but at the same time lacks specificity as often data is secondary and needs to be standardised. The last methodology is *systematical with a neuronal network approach and process modelling,* which is based on automatic pattern identification given by a large number of data. The *mature system* mentioned in Advidsson et al. (2013) study is a part of this category. The quality of the results is high as it is based on direct quantitative data but the predictions are made based on similarities to existing technologies. The paper's conclusions identify the second method as a good and easy approach, but the economies of scale methodology is the best performing in terms of scaling-up, even though it makes the use of scenarios more difficult. If scenarios are key to the analysis the fourth approach is the best available.

The common problematic pointed out in literature is data collection and level of detail. Moreover data that is derived from consultation with expert makes the studies' validity questionable (Hummen and Kästner 2014). The main conclusion is the need to develop better methodologies to allow the inclusion of environmental evaluations in the early-stages of technologies for a better forecasting.

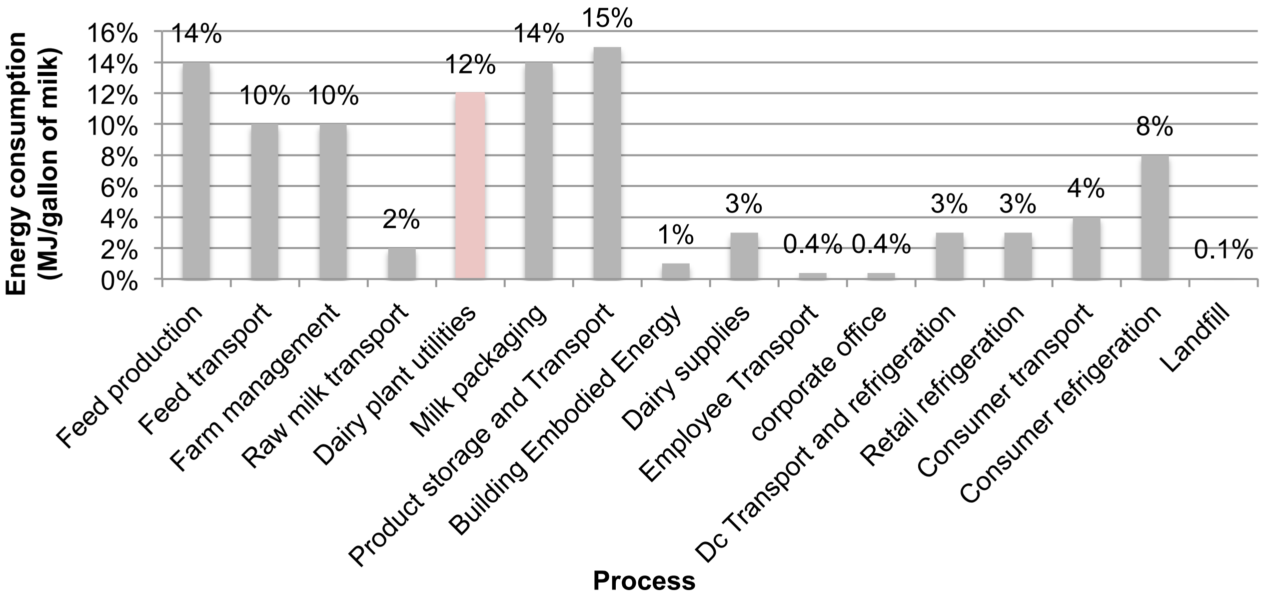
1.1.3 LCA in the milk industry

Dairy products are a hot spot for climate change mitigation. A life cycle approach is relevant in supporting the analysis of emission reduction actions. The majority of research on this sector concentrated on farming, because it is considered the dominant impact for the majority of food products. On the other hand, studies that focused on processing and other stages of the supply chain, found that farming didn't have the highest contribution for all impact categories (Eide 2002; Milani et al. 2011). Because of this it is important not to focalise on a single life cycle stage, but to explore the possibility of more efficient processing technologies and of decreasing losses in production, retail and consumer stages (Milani et al. 2011).

Emissions before farm gate are mainly due to the techniques used in the production of feed, of dairy and manure management. According to Eide's (2002) study of two dairy farms in Norway, 90% of total impact of industrial milk production is due to farming. At the same time packaging, transport to retailers and consumers, and energy use in household are relevant life cycle stages to the overall product's impact. For the climate change impact category, carbon dioxide is the most important gas after farm gate, while methane is dominant in agriculture and waste management. Excluding farming, water consumption mainly derives from cleaning of processing equipment. The author underlines the uncertainties deriving from regional specificities, for example transport distances are on average long in Norway increasing the impact on the photo-oxidant formation category. On the other hand, Norway's electricity mix is constituted by 90% of hydropower lowering the impact share of electricity production. Further sources of uncertainties are the type of wastewater and consumer's behaviour in term of transport and waste production, which is hard to predict and model. The processing stage was one of the major hot spot for the smaller scale farm; Eide, in fact, found the larger scale production to be more environmentally sound (Eide 2002). Nutter et al. (2013) concentrated on post-farm stages and González-García (2013) investigated UHT milk production in Portugal, both found that transport, processing and packaging were the main contributors. In Weidema and Wesæs (2008) food industry represents the sector that has the highest contribution to electricity consumption for dairy products (Table 2) and Cashman (2009) estimated electricity consumption at dairy plant to be 12% of overall requirements (Graph 1).

Table 2. Main electricity consuming processes for meat and dairy products in % of total consumption (Weidema and Wesæs 2008)

Process	Direct	Farming	Food industry	Retail	Other	Sum
Storage of food in household	23.4			0.1	0.6	24
Dairy products		4.1	7.5	1.7	6.2	19
Pork and pork products		1.8	7.9	2.2	7.0	19
Dishwashing in household	7.9			0.04	0.5	8.4
Restaurants and other catering (not incl. food)	6.4			0.1	1.3	7.8
Beef and beef products		0.8	1.9	1.0	3.6	7.2
Cooking in households	7.1			0.1	0.7	7.8
Poultry and poultry products		0.7	0.7	0.4	1.3	3.1
Other					3.3	3.3
Sum	45	7.3	18	5.5	24	100



Graph 1. Energy consumption per gallon of packaged milk for different stages of the life cycle (Cashman 2009)

Kim et al. (2013) investigated the impact of the production of whey and cheese, mozzarella and cheddar. The results are similar to milk production and farming still remains the dominant stage. For this reason the authors, as suggested by Milani et al. (2011), underline the importance of reducing waste at all stages to avoid higher production.

In milk LCA studies the modelling choice between attributional and consequential approach can be important (Milani et al. 2011). Thoma et al. (2013) opted for an attributional approach rather than consequential, because they found that there was not enough data to model substitutes. On the contrary Thomassen et al. (2008) argued that due to the considerable amount of products and activities that are responsible for the impact of dairy production, system expansion provided by the consequential approach is a better approach as it gives a more complete overview, even if it makes for a more complex study. Schmidt and Daalgard (2012) estimated the carbon footprint of dairy farm operations for Denmark and Sweden using different modelling approach. The authors calculated total emissions using consequential and attributional modelling, founding 1.06 and 1.05 kg of CO2 eq. per kg of energy corrected milk (ECM), respectively. Schmidt and Dalgaard, also calculated the carbon footprint following the PAS2050, guidelines of the British Standard institute (BSI), and the methodology of the International Dairy federation (IDF), finding higher results deriving from land use change. The methodological choice results in high emissions as it considers feed production from land that has been redirected in the past 20 years from forest to cultivation.

1.2 Milk as a product

1.2.1 Milk processing

The majority of milk sold today underwent a preservation process (pasteurisation or sterilisation) to ensure its safety and extend its lifetime. Most commonly milk sterilisation is obtained through heat treatments, which consist in subjecting the product to high temperatures for a determinate amount of time. There are different combinations of temperature and time that can result in the production of a commercially sterile product. Higher temperatures and shorter time are preferable to maintain important characteristics of milk, such as pH, colour and taste (APV 2008; Lewis and Deeth 2009). The chemical characteristics of milk and the effect of heat treatments are explained in the following section. There are three main continuous thermal sterilisation processes used at industrial level: UHT and Indirect hydrostatic sterilisation (Georget et al. 2013). The former subjects the product to temperatures that range between 135 and 150 °C for a time of 20 seconds or less (Lewis and Deeth 2009; Bylund 1995); while the latter to temperatures between 115 and 125°C (Georget et al. 2013). The demand for differently treated milk varies for different countries. For example in Germany, consumers' preference tends towards UHT (Lewis and Deeth 2009).

UHT treatment can be achieved through two procedures: indirect or direct heating. In the case of indirect system the heating and processed media never come into contact, hot water or steam passes through a heat exchanger with opposite flow of milk. Direct heating can either be the result of the injection of steam into milk (direct steam injection DSI) or the flow of milk into a steam full chamber (infusion). The main difference between indirect and direct is the relation between temperature and time, the former exposes milk to high temperatures for a longer time, while direct processing reaches the required temperature almost instantaneously (Lewis and Deeth 2009). These differences determine the impact of the two main downsides of thermal processing: the impact on milk characteristics and the demand for energy. Indirect UHT exposes the product to high temperatures for a longer time resulting in, for example, a strong cooked taste in milk and a lower retention of vitamin C. On the other hand indirect processing ensures a 90% energy recovery versus 50% for direct treatment (Lewis and Deeth 2009).

Combined high pressure and moderate to high temperature processes have been identified as having the potential to outperform conventional thermal processing to pasteurise or sterilise food -ie achieving a reduction of the microbial (sporulated) flora - while helping to keep the natural product's qualities. These treatments are already in place for pasteurisation of products ranging from cooked ham to juices. Commonly, isostatic high pressure treatments subject packaged food to pressures between 100 and 1000 MPa. The the process of high pressure high temperature sterilisation has been approved by the FDA for mash potato, no industrial application exist yet due to the unavailability of industrial scale equipment allowing for homogenous temperature conditions during high isostatic pressure processing. Furthermore, the batch nature of this process has high processing costs. On the other hand, the use of continuous, dynamic high pressure processing via ultra-high pressure homogenisation could allow for similar levels of inactivation in pumpable matrices by combining high pressure up to 400 MPa and high temperatures in a continuous process. This technology has been available since the years 2000 and is already to date available at the pilot scale level with the first industrial prototypes coming on the market (Floury et al. 2002; Georget et al. 2014a), but neither isostatic nor dynamic pressure assisted thermally sterilised milk has been commercialised.

1.2.2 Homogenisation

Milk is natural oil (13%) in water (87%) emulsion (Bylund 1995). Proteins create a membrane that surrounds the fat globules giving it stability (Bylund 1995). As fat globules are light they have the tendency to collect at the top when milk is left untouched in a container. For this reason homogenisation is necessary (Bylund 1995). The homogenisation process causes the rupture of fat globules into smaller droplets so to maintain their dispersity and avoid the creation of cream plugs. In the case of milk, droplets' diameter is not superior to 2μm after homogenisation (Brennan and Grandison 2012). In the process of homogenisation pressure is applied to the product from pistons or plungers, which are moved by a crankshaft. The amount of pressure is determined by what is defined as back –pressure, which depends on the gap between the valve seat and the forcer (Bylund 1995). Varying on the product, homogenisation is commonly conducted at temperatures between 60 and 70°C, where the higher the temperatures the higher the dispersion of fat globules, and pressures between 10 and 25 MPa. In the late 1990s high-pressure treatment at 100MPa become common and few year later STANSTED produced a homogeniser that could reach 350Mpa (Floury et al 2000), which was a great step for high pressure and entailed a change in valve and chamber design (Floury et al 2004). Valve design is key to the development of homogenisers that could withstand higher pressures, but measurements become harder to obtain as valves become smaller and pressures higher. Floury et al (2004) creates a model to estimate valve and chamber design for future research. In this study we considered equipment that can reach 380MPa.

There are two main principles working in high pressure homogenisation: turbulence and cavitation. Turbulence is the effect of pressure in homogenisation. The higher the pressure, the higher the velocity and so the smaller the eddies. Eddies are a type or turbulence, so a twisting of the fluid, which cause the separation of fat globules that have the same dimension. The second principle at work is cavitation. Cavitation is the process where steam bubbles form, when these bubbles pass the valve gap they implode separating oil droplets. Homogenisation can happen in a single or two-stages. The former is used for more viscous product, while the latter for fatter products that need a better homogenisation; in fact the second stage serves as a supplier of continuous back-pressure and as a mean to separate agglomerates that form after the first stage. The positive effects of homogenisation are the avoidance of cream formation, stabilisation of the emulsion and better sensory characteristics. On the other hand homogenisation results in higher chances of variations in flavour given by exposure to light, higher sensitivity to heat variations and this type of milk cannot be used for the production of hard cheese

(Bylund 1995). Additionally, high pressure, turbulence and temperature make proteins stabilisation harder (Floury et al. 2004).

1.2.3 Milk properties

Table 3 gives an overview of milk as a product. An important characteristic of milk is its pH values. Milk's pH is in the range of 6.5 – 6.7 when fresh and at a temperature of approximately 25°C. Milk behaves as a buffer, a buffer is a solution for which pH does not drastically change given an addition of alkaline or acidic base (Bylund 1995). As temperatures increase pH decreases. For an increase in temperature form 20 to 120°C, pH will change from a value of 6.5 to 5.9 (Fox and McSweeney 1998). If pH drops below 6.5, becoming more acid, it is the result of bacterial action (Bylund 1995).

Table 3. Quantitative composition and main characteristics of milk (Bylund 1995)

Main constituents	**Range**	**Average (%)**
Water	85.5 – 89.5	87.5
Total solids	10.5 – 14.5	13.0
Fat	2.5 – 6.0	3.9
Proteins	2.9 – 5.0	3.4
Lactose	3.6 – 5.5	4.8
Minerals	0.6 – 0.9	0.8
Characteristics	**Variation**	**Average**
pH	6.5 – 6.7	6.6
Fat globules diameter	0.1 – 20 μm	3 - 4 μm
Fat globules quantity		15 billion per ml

Smaller and disperse globules increase the viscosity of the product (Bakshi and Smith 1984). This increase contributes to the creation of a more stable emulsion (O'Mahony and Fox 2013). Viscosity is defined as a fluid's resistance to motion and shear stress (ELert 2015) Viscosity is one of the parameters that influences consumers' perception (Bakshi and Smith 1984), together with colour, odour etc.

Change of viscosity during storage is considered as one of the main UHT treatment problems, in particular when looking at direct steam injection and infusion. This process is due to the proteolysis, the fragmentation of casein, and it is influenced by: the conservation temperature, the quality of raw milk, the amount of solids present in the product and the type of processing (Chavan et al. 2011). The best conditions to prevent the excessive increase in viscosity is storage either at 4°C or between 35 and 40°C, while a temperature between 25 and 28°C is the most favourable environment for an increase in the gelation rate (Robertson 2013).

An additional parameter considered is the creaming rate. Creaming is the process where fats rise and, for milk, it results in the creation of two emulsions, cream and skimmed milk.

The creaming rate (υ) follows Stokes' equation:

$$\upsilon = 2r^2 (\rho - \rho_o) g / 9\eta$$

where, (r) indicates the globules radius, ($\rho - \rho_o$) is the difference between the globules' and the medium's density, (g) is the gravitational acceleration and (η) is medium's viscosity. From this formula it can be seen how the smaller the droplets are the slower the creaming is, this is therefore important when looking at long-life milk (Floury et al. 2004).

Food processing can have an effect on all above listed characteristics. It is therefore important to assess the extent and the relevance of mentioned effects. In case of indirect UHT treatment in combination with homogenisation and of ultra-high pressure homogenisation, the goal is the formation and stabilisation of a fine emulsion. This emulsion needs to be commercially sterile, have a long-life shelf time and needs to meet the requirements of the consumer. The effects of UHPH and UHT on pH and globules size are summarised in Table 4.

Table 4. UHPH and UHT effect on milk's pH and fat globules diameter (Kietczewska et al 2006; Hassan et al 2009)

Characteristics	UHPH	UHT
pH For milk with 2% fat content	6.72	-
pH For milk with 4% fat content	6.71	6.17 – 6.85
Fat globules diameter	0.1 – 0.3 μm	0.2 – 2 μm

2 PROBLEM FORMULATION & RESARCH QUESTIONS

Pre-treatments of milk for consumption need to inactivate microorganisms including bacterial spores (if ambient storage), in order to prevent safety issues or spoiling; moreover they need to ensure homogenisation of the product to avoid the formation of cream. High temperatures have been used for centuries to make milk safe for consumption for longer periods of time. With ultra high temperatures treatments (UHT), milk does not require refrigeration for storage, but textural characteristics change significantly.

Ultra-high pressure homogenisation (UHPH) could represent a valid alternative to these industrially established treatments. Thanks to high pressures, microbes are eliminated while at the same time a stable emulsion is created. Sensorial characteristics have been investigated conducting tests on experts and non-experts. The product was perceived to have the same or higher qualities then other milk (Guamis 2007 and 2011). Additionally this technology is expected to have lower energy consumption as it sterilises and homogenise in a single step (Zamora and Guamis 2014; Dumay et al. 2013). UHPH milk has also been studied for the production of fresh cheese, for which higher yield and shelf life was found (Escobar 2011; Zamora and Guamis 2014).

Complying with the eco-design and eco-efficiency idea, new technologies need to be assessed under different points of view to optimise efficiency and evaluate benefits and consequences of industrial application. This study wants to provide an environmental assessment of UHPH and give a first input on the scaling behaviour of the equipment. The following research questions were formulated to guide the research:

1) What are the environmental impacts of ultra-high pressure (UHPH) processing for liquid foods? The case of milk production.
   1.1) How does UHPH compare to ultra high temperature (UHT) treatment under the environmental perspective?
2) What are the consequences on the environment of extended shelf life and increased yield in fresh cheese produced with UHPH treated milk?
3) What are the foreseeable environmental impacts of UHPH application at industrial scale?

3 METHODOLOGY

3.1 Life cycle assessment

3.1.1 Goal and scope

Ultra-high pressure Homogenisation (UHPH) is an innovative technology for liquid food sterilisation (e.g. bovine milk) that relies on pressure up to 400MPa. The technology is foreseen to provide equal or higher quality products compared to Ultra High Temperature (UHT) treatment and, at the same time, to lower energy consumptions through the combination of sterilisation and homogenisation in a single process. Furthermore, the use of UHPH treated milk for the production of fresh cheese has been proven to increase shelf life from ~13 to ~19 days and yield from 11 to 14% (Escobar 2011; Zamora and Guamis 2014). This study provides an LCA of UHPH and UHT processing of milk and fresh cheese production from processing to end-of-life.

The study is conducted at the German Institute of Food Technologies (DIL e.V.), a research institution working with innovative food processing technologies. In the context of this study the institute's aim is to compile a full profile of new technologies under the biochemical and environmental prospective to identify potential sustainable benefits of technologies application.

3.1.2 Functional unit

Commonly, the functional unit for milk refers to mass or volume and most studies refer to Energy corrected milk (ECM), where proteins and fat content are specified (Fantin et al 2008). This latter characteristic can be disregarded for this particular case, as the tests showed no difference in energy requirements between whole and skimmed milk (and control with water use). To conform to previous studies (Hospido et al 2003; Heide 2002) and to include the technological function of delivering a commercially sterile product, the following functional unit is set: 1000 litres of commercially sterile milk. Commercial sterility is defined by WHO/FAO (WHO/FAO 1993) as: "*Commercial sterility means the absence of microorganisms capable of growing in the food at normal non-refrigerated conditions at which the food is likely to be held during manufacture, distribution and storage*." In this study commercial sterility is quantified based on logarithmic inactivation of spores. For the EU Council directive 92/46/EEC raw milk produced with heat treatments should meet the following standard: plate count at 30°C ≤ 100 000 cfu/ml.

There are two key studies for identification of commercial sterility parameters of UHPH: Amador-Espejo et al (2014) and Georget et al (2014b). The former study investigates the required pressures and temperatures for the inactivation of *Bacillus cereus, Bacillus licheniformis, Bacillus sporothermodurans, Bacillus coagulans, Geobacillus stear-othermophilus* and *Bacillus subtilis* finding a pressure of 300 MPa and an inlet temperature of 75°C (T_i) to be sufficient to ensure a reduction (of ~5 log CFU/mL), and consequently commercial sterility. This result is valid for all organisms with the exception of *G. stearothermophilus* and *B. subtilis.* For these two spores the same pressure and temperature (T_i = 85°C) was necessary to reach inactivation (~1x10^6 CFU/mL). Georget et al (2014) investigated the effect of different parameters on these spores. The findings of the study point at the relevance of valve temperature for inactivation; the authors identify a pressure of >300Mpa, inlet temperature ~80°C and a valve temperature of >145°C for ~0.24 s to be a successful treatment. Based on these results Georget et al.'s parameters are chosen for UHPH commercial sterility, as they ensure the needed log inactivation for all the mentioned microorganisms.

UHT is a widely used milk treatment, the EU defines the parameters to reach commercial sterility to be: "*UHT treatment is achieved by a treatment: (i) involving a continuous flow of heat at a high temperature for a short time (not less than 135°C in combination with a suitable holding time) such that there are no viable microorganisms or spores capable of growing in the treated product when kept in an aseptic container at ambient temperature, and (ii) sufficient to ensure that the products remain microbiologically stable after incubating for 5 days at 30°C in closed containers or for seven days at 55°C in closed containers or after any method demonstrating that the appropriate heat treatment has been applied*." (Ref: Commission Regulation (EC) No 1662/2006 (amending Regulation (EC) No 853/2004)). Following the EU indications and relying on literature (Triowin n.d.; Bylund 1995), the parameters for UHT treatment are set to be: pre-heating at 80°C, UHT temperature at 145°C for 4 seconds.

To assess the performance of UHPH treated milk for the production of fresh cheese, the chosen reference flow is the yield of 1000 l of milk for fresh cheese production, so that it is in line with the processing inventory.

Yield is here defined as: Yield = 100 x cheese (g) / milk (g) (Escobar 2011)
Knowing that 1000 l of milk = 1033000 g of milk and UHPH yield = 14%

Fresh cheese production per f.u. = 144620 g which results in 578.48 pieces of packaged cheese, given packaging of 250 g (Zamora and Guamis 2014)

3.1.3 System boundaries

Fig. 1 represents the system for the dairy industry. For the LCA study of UHPH and UHT the system boundaries are set at the processing stage plus cleaning. This was chosen, as no foreseeable differences are expected upstream or downstream for drinkable milk. For the production of fresh cheese, on the other hand, the distribution, use and end-of-life stages are included. The increase in yield and shelf life entail changes in the downstream activities.

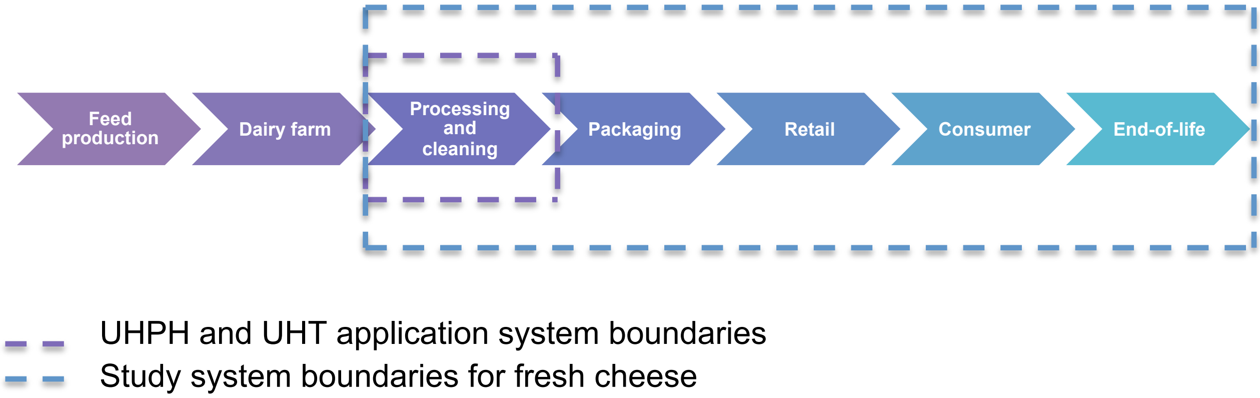


Fig. 3 Dairy industry system

3.1.4 Data collection

In order to assess the impact of technologies' scaling up, data was gathered from multiple sources. The first test was run on a pilot-scale UHPH equipment with capacity of 90 l/h with four different substances: water, phosphate buffered saline (PBS), skimmed milk (1.5%) and whole milk (3.5%). The test was conducted in conjunction with microbiology researchers, investigating the inactivation of *B. amyloliquefaciens* spores in a buffer (solution that withstands changes in pH) and milk (Dong, Georget et al. 2015). Data was collected for water with the purpose of estimating the variation, if any, in energy requirements between different products. No difference in consumption was found for the three different compounds, presumably because of little difference in viscosity. Tests were then conducted using only water, as results did not depend on the substance. Water was used not to waste milk on a larger pilot-scale UHPH, with capacity of 360 l/h, and on an 85l/h Indirect UHT (homogenisation and sterilisation) system, for the identification of up scaling trends and comparison purposes. Data quality for milk production is affected mainly by: pilot scale equipment can behave quite differently than full scale production lines and the means of measurement's accuracy for energy consumption. Data quality for cheese production is characterised by high uncertainty as it is taken from literature.

3.1.5 Modelling approach and LCA tool

Attributional and consequential are the two modelling approaches used in LCA to draw a system's boundaries. Attributional considers the current supplier's share of the market, modelling physical flows. Co-products' impacts are allocated based on, for example, mass or price. Consequential considers the effects on supply of a change in demand, looking at the marginal unconstrained suppliers and it avoids allocation expanding the system boundaries.

This study is based on a consequential approach as it models the consequences of the decision of substituting an already existing technology, UHT treatment, with UHPH. Through system expansion avoided cheese production and avoided waste management, deriving from extended shelf life, are included and are treated as a co-product of UHPH. UHPH is therefore modelled to be a multifunctional activity (Figure 1). The tool used for the LCA is Simapro 8.0.4.30.

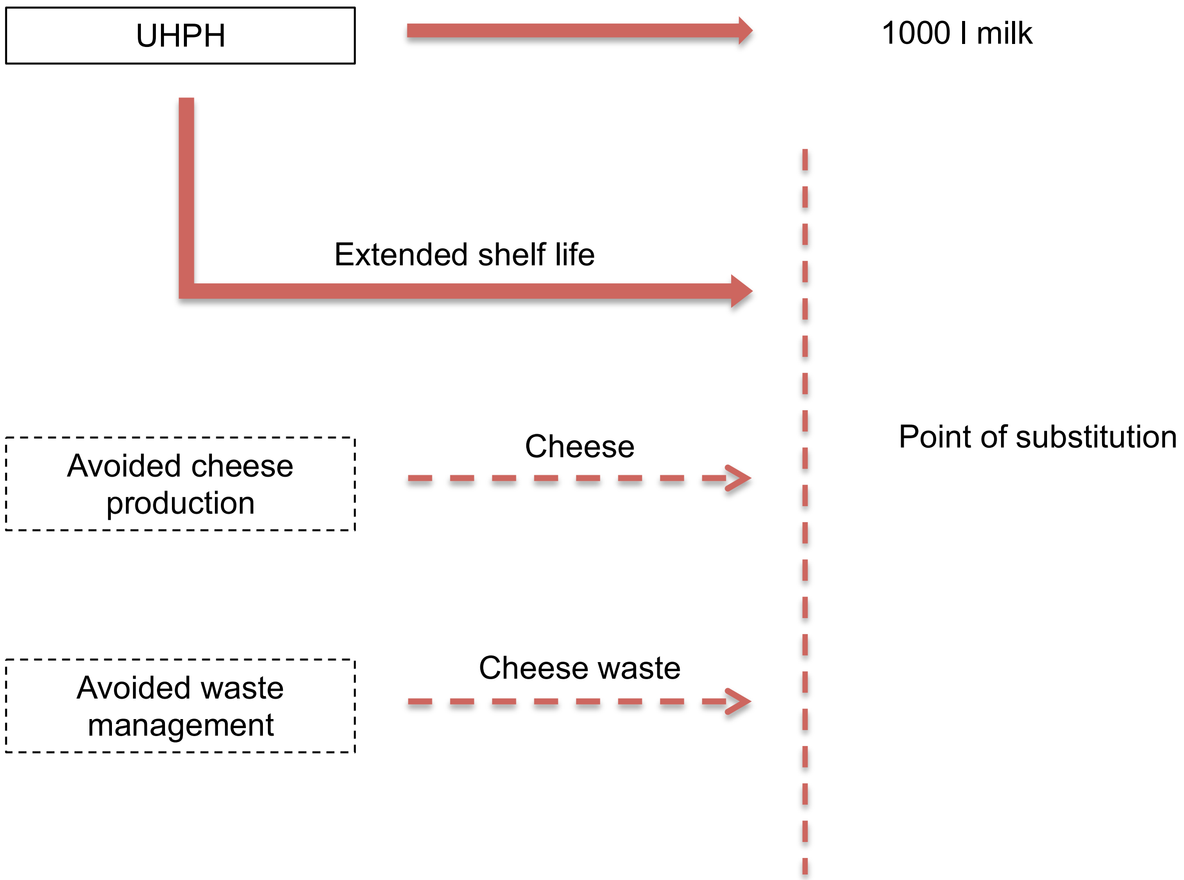


Fig. 1 Consequential modelling for UHPH treated milk for fresh cheese production

3.1.6 Life cycle impact assessment method

Recipe midpoint (E), Europe is relevant for this study as: it is Europe specific; midpoint excludes the uncertainties of predicting the effect of emission on human health, natural environment and resources; and the egalitarian (E) approach provides a precautionary thinking for a long-term perspective. Long term is the needed vision for technological innovation (Acero et al. 2014).

3.1.7 Capital good

Capital goods are excluded from the study for few main reasons: the majority of the equipment is built with stainless steel for both technologies; pilot-scale can be very different from real application, for example, some equipment's was to be adjusted to work at the required flow; and for pilot scale testing some equipment, such as heater and feeding pump, were the same for the two systems. It is acknowledged that the exclusion of capital good can introduce uncertainties.

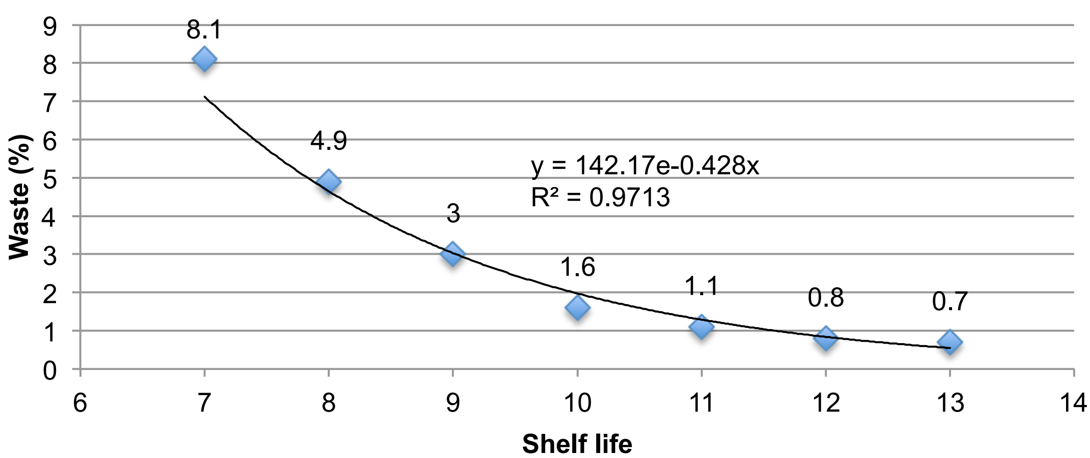
3.1.8 Change in waste production due to increase in shelf life

According to WRAP (2013) no empirical studies exist on the relation between extended shelf life and wastage. Part of the reason relates to the amount of variables that have an influence and the difficulty in collecting empirical evidence on such changes in consumer's behaviour. It is therefore acknowledged that the proposed model is subject to numerous assumptions and it is a simplified representation of reality.

The major assumption made in this study is that the relation between product life and waste percentage for milk can be applied to the study of fresh cheese. According to WRAP (2013) the proposed model can be used as an indication for other products, but it could result in inconsistencies if the considered product has a different shelf life then milk and if the frequency of consumption is different. Fresh cheese durability is close to milk durability, while frequency of consumption is hard to establish as diets vary from country to country. These uncertainties need to be kept in mind when analysing the results. WRAP (2013) calculations are shown in Table 5 and Graph 2.

Table 5. Waste percentage of milk for shelf life in days

Shelf life	7	8	9	10	11	12	13
Waste (%)	8.1	4.9	3	1.6	1.1	0.8	0.7



Graph 2. Percentage of milk waste versus remaining shelf life

From the data provided the following equation was derived: $y = 142.17\ e^{-0.428x}$ with $R^2 = 0.9713$, where y = % waste and x = shelf life. Applying this to the case study the avoided waste is calculated.

Waste for shelf life of 13 days: $y = 142.17\ e^{-0.428 * (13)} = 0.545\%$
Waste for shelf life of 19 days: $y = 142.17\ e^{-0.428 * (19)} = 0.042\%$

The increased shelf life from 13 to 19 days reduces waste in 0.503%. Thus the potential saving is 727.439 g of cheese per 1000 l of processed milk (0.503% x 144620 g), which are approximately 2.91 packages of cheese. This amount corresponds to 5.030 litres of milk (727.439 / 14% = 5195.993 g). These calculations are used to estimate the environmental benefits deriving from increased shelf life.

WRAP's (2013) study recognises the difficulty in determining consumer's behaviour and how this might be influences by changes such as shelf life. It is acknowledged that the derivation of waste equation is a big uncertainty but this is the only model available as today (to the author's knowledge) and it is therefore the best way to estimate the changes of waste at consumer level.

3.1.9 Ultra-high pressure homogenisation

Data is collected for two UHPH scales: a 90l/h two-piston pump and a 360l/h three-plunger pump. Both machineries represent a pilot scale for this technology and for both the pressure equipment is a positive displacement pump of the reciprocating group. The smaller scale runs with two-piston and a needle valve (Figure 2), while the larger scale is a three-plunger pump with a solenoid valve. It is acknowledged that pilot scale equipment can be very different from each other and that there are a number of parameters that considerably change with scale. The biggest commercially available UHPH have capacities of 1000l/h and 1500l/h, but neither of these has yet been applied at industrial scale (Georget et al. 2014a).

Ultra-high pressure homogenisation equipment is very similar to a conventional homogeniser; the main adjustment that needs to be accounted for is the used materials for the valve to withstand pressures up to 400 MPa. The two materials currently used are ceramic and artificial diamond coating (Dumay et al 2013). The process consists of the product storage in a container tank and the preheating of the product, in the case of this work to 80°C. The product then enters the homogeniser where it is pumped from the piston through the narrow valve gap. The product is then cooled by a heat exchanger, with a cooling liquid at a temperature of -10°C able to rapidly drop milk's temperature below 50°C (Figure 2 and 3). Temperature at inlet and temperature at valve are important parameters to assess the inactivation of bacterial organisms and in particular bacterial spores to ensure commercial sterility (Dumay et al 2013; Georget et al. 2014b). The same process applies for the 360l/h UHPH.

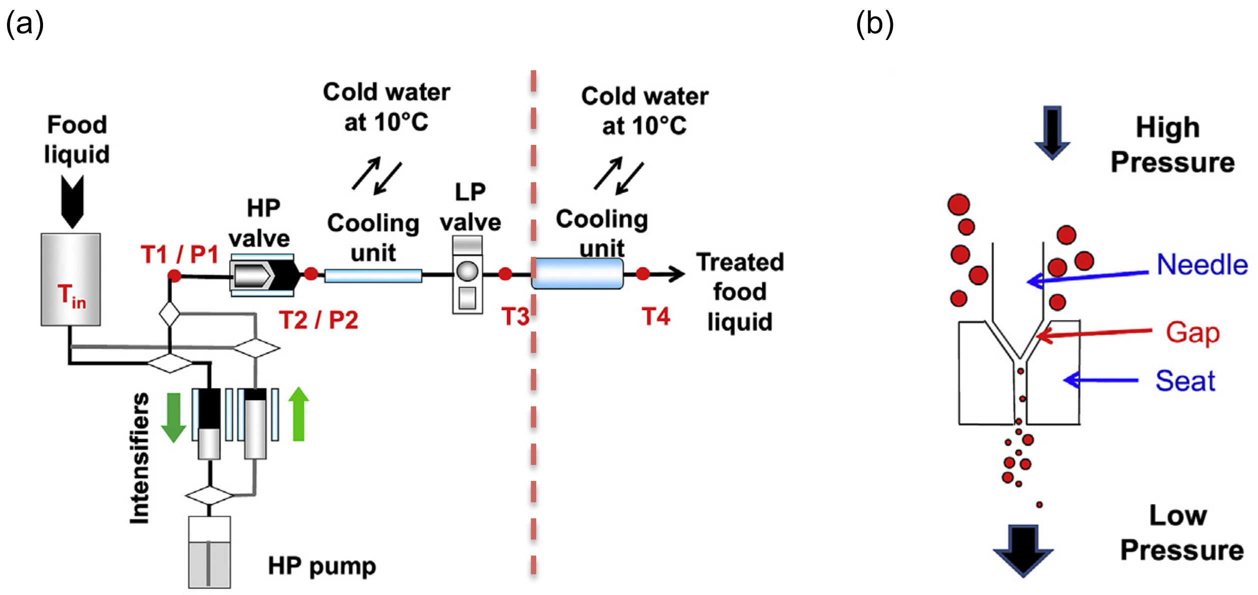


Figure 2. (a) High pressure homogeniser worked by two intesifiers. T_{in} is temperature in feeding tank. P_1 is pressure at valve inlet. T_2 and P2 are temperature and pressure at outlet. T3 and T4 are the temperatures after cooling. The red line is traced to indicate the end of the system used for the test. (b) and Y-shaped valve (Dumay et al. 2013).

Figure 3. UHPH system

3.1.10 Ultra high temperature

The data collected refers to an indirect UHT system with flow rate of 85l/h. The line of production can be built in two different ways; homogenisation can precede or follow sterilisation. In the latter case the homogenisation will have to be conducted aseptically, which is a more expensive procedure but it produces a more stable emulsion. This study considers the case of homogenisation prior to the UHT treatment. Initially the product is pumped from the storing tank and heated to approximately 80°C to be then homogenised (temperature required ranges between 70 and 80°C). The product is then sent for UHT treatment at 145°C for 4 seconds, achieving sterilisation, and cooled.

At industrial scale, there is potential for significant heat regeneration. The product is brought to the first pre-heating temperature (80°C) in a heat exchanger, where the heating mean is already-treated UHT milk, which in the meantime cools down. The heating at sterilisation temperature is achieved through heat exchanger where water circulates in a closed loop, while steam is injected to maintain the required temperature. The product is cooled in heat exchangers, where the counter-flowing liquids are cooling water and incoming raw milk (Figure 4 and 5).

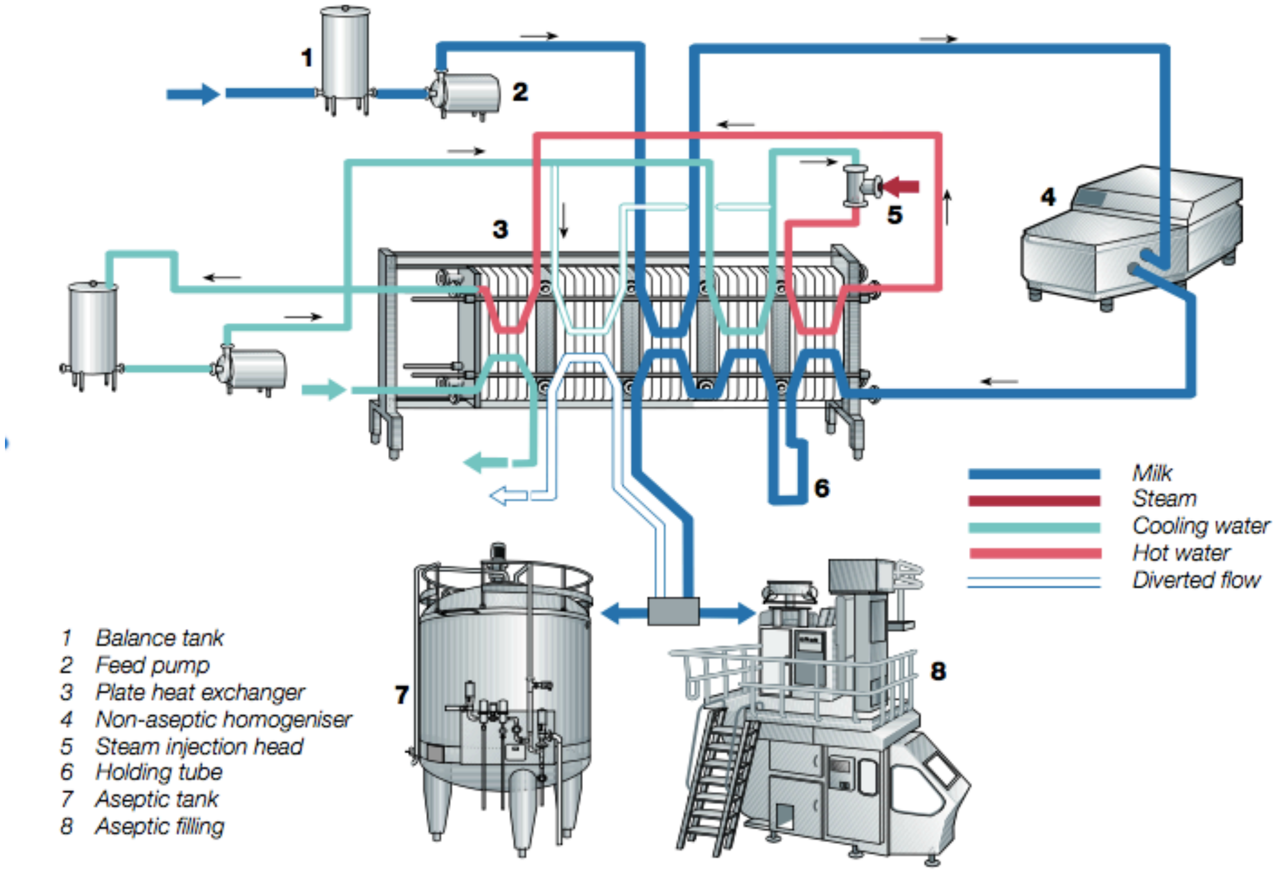


Fig. 4 Indirect UHT production line (Bylund 1995)

Fig. 5 Indirect UHT system without heat regeneration

3.2 Life cycle inventory

First the inventory for UHPH 90l/h and UHT 85l/h is presented; following the requirements for UHPH 360l/h and fresh cheese production are explained.

3.2.1 UHPH 90l/h and UHT 85l/h

Pumping product from tank

The feeding pump runs with a 3-phase engine with power factor (PF) of 0.72. Power factor is defined as: "*In AC circuits, the power factor is the ratio of the real power that is used to do work and the apparent power that is supplied to the circuit*" (RapidTables n.d.). This calculation is valid both for UHT and UHPH. Based on the direct measurement in ampere energy consumption is converted to kW.

Conversion of ampere to kW (RapidTables n.d.):

$$P(kW) = \sqrt{3} * PF * I_{(A)} * V_{L\text{-}L\ (V)} / 1000$$

Where:
PF = power factor
$I_{(A)}$ = current in Ampere
$V_{L\text{-}L\ (V)}$ = line to line RMS (root mean square) in volts

$$kW = \sqrt{3}*0.72*0.3A*400V/1000 = \sim 0.150kW$$

The hourly consumption to process 85l is of 0.150kWh. The energy required for the functional unit of 1000l is therefore equal to 0.150kWh / 85l * 1000l = 1.765kWh.

Table 6. Pumping product from tank (UHPH90l/h & UHT)

	Unit	**Amount**	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	1.765	Electricity, medium voltage {RoW}| market for | Conseq, U

Pre-heating

As for the feeding pump, the same equipment is assumed for UHPH and UHT to pre-heat the product, i.e. the LCI data for this process are identical in the UHPH and UHT alternatives. For both processes it is necessary to reach a temperature of 80°C. Based on the equation to determine heat load (SpiraxSarco n.d.), the energy requirement is calculated.

$$\dot{Q} = \dot{m} c_p \Delta T$$

Where:
$\dot{Q}$ = quantity of heat energy (kW)
$\dot{m}$ = secondary flow rate kg/s
c_p = specific heat capacity of water = 4.19 kJ/kg°C
ΔT = difference in temperature

Given the characteristics of the equipment, assuming an initial temperature (room temperature) of 20°C and heating of the product to 80°C, which requires reaching a 90°C temperature on the heat-exchanger:

$$Q = 90\text{kg/h} * 4.19\ \text{kJ/kg°C} * 70\ \text{°C} = 26397\ \text{kJ/h} \approx 7.333\text{kW}$$

The energy requirement is of 7.333 kWh to process 90l. The consumption for the functional unit is of 7.333kWh / 90l * 1000l = 81.478kWh.

Table 7. Pre-heating (UHPH90l/h & UHT)

	Unit	**Amount**	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	81.478	Electricity, medium voltage {RoW}| market for | Conseq, U

Homogenisation and sterilisation UHPH

Electricity

The UHPH relies on a 3-phase engine with PF of 0.86. At pressure 300MPa the consumption was calculated to be ~14.598 kWh, derived from a mean measurement of 24.5A (kW= √3*0.86*24.5A*400V/1000 ≈ 14.598kWh). For 1000 l the required energy is 14.598 kWh/ 90l * 1000l = 162.197 kWh.

Compressed air

Air supply is connected through a ¼" BSPF (British standard pipe fitting) pneumatic air connection that requires constant pressure supply not below 6 bar. Considering the parameters for 80psig (6.530bar), the air flow is of 10.5 SCFM (standard cubic feet per minute), which correspond to:

CFM = SCFM / [(Work pressure(psig) + 14.7) / 14.7]

Where:
CFM = cubic feet per minute
SCFM = standard cubic feet per minute
psig = pounds per square inch

CFM = 10.5 / [(80psig + 14.7) / 14.7)] ≈ 1.630
1.630 CFM ≈ 2.769 m^3/h

If per hour consumption is 2.769 m^3/h, the total compressed air supply for 1000l is of 2.769 m^3h / 90l/h * 1000l = 30.767 m^3. The existing processes for air do not model for supply below 6 bar. To estimate the consumption for lower pressure the processes for 6, 7 and 8 bar are taken into consideration (*"Compressed air, 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, optimized generation | Conseq, U", "Compressed air, 700 kPa gauge {RER}| compressed air production, 700 kPa gauge, >30kW, optimized generation | Conseq, U" and "Compressed air, 800 kPa gauge {RER}| compressed air production, 800 kPa gauge, >30kW, optimized generation | Conseq, U")*. The only input changing with pressure is the amount of electricity. The data was extrapolated and the relationship between electricity and pressure was found to be linear. Consequently the process *"Compressed air, 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, optimized generation | Conseq, U"* is modified accounting for a lower energy demand. As 6.53 bar is 108.833% of 6 bar, 108.83% of electricity is taken (Appenxid B).

Table 8. Homogenisation and sterilisation UHPH90l/h

	Unit	**Amount**	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	162.197	Electricity, medium voltage {RoW}| market for | Conseq, U
Modified_Compressed air	m^3	30.767	Compressed air, 108.833% 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, optimized generation | Conseq, *U*

Homogenisation UHT

Electricity

For UHT, a two-stage homogeniser was mounted on the production line. Based on the product specifics and on Bylund (1995) equation for electrical effect, the following value is derived:

$$E\ (kW) = Q_{in} \times (P_1 - P_{in}) / 3600 \times \eta_{pump} \times \eta_{el.\ motor}$$

Where:
E = electrical effect (kW)
Q_{in} = feed capacity (l/h)
P_1 = homogenisation pressure (bar)
P_{in} = pressure to the pump (bar)
η_{pump} = pump efficiency coefficient
$\eta_{el.\ motor}$ = motor efficiency coefficient

$$E = 85\ l/h \times (200\ bar – 2\ bar) / (36000 \times 0.85 \times 0.95) = 0.579\ kW$$

Given 0.579 kWh as the energy consumption unit, the following calculation provides electricity consumption per FU: 0.579 kWh / 85l * 1000l = 6.812 kWh.

Compressed air

Airflow depends on the pipe size and on pressure. The homogeniser is connected with a ¼” BSPF pipe and pressure supply is of 2 bar. To calculate the airflow for 29.008 psig (2 bar), an equation was derived from 10 parameters relating SCFM and pressure (EngineersEdge n.d.).

$$y = 0.1296\ x + 0.3284 \text{ with } R^2 = 0.99964$$

Where:
y = SCFM
x = pressure (psig)

For a pressure of 29.008 psig: y = 0.1296 (29.008) + 0.3284 = 4.088 SCFM. SCFM are then transformed to CFM.

$$CFM = SCFM / [(Work\ pressure(psig) + 14.7) / 14.7]$$
$$CFM = 4.088 / [(29.008psig + 14.7) / 14.7)] \approx 1.375$$
$$1.375\ CFM \approx 2.336\ m^3/h$$

Thus 2.336 m^3/h / 90l/h * 1000l = 25.956 m^3 of air pumped for 1000l. The same concept applies here as for UHPH compressed air calculation. The process is modelled as 2 bar *

100 / 6 = 33.333% of "*Compressed air, 33.33% 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, optimized generation | Conseq, U*"

Table 9. Homogenisation UHT

	Unit	Amount	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	6.812	Electricity, medium voltage {RoW}| market for | Conseq, U
Modified_Compressed air	m^3	25.956	Modified_Compressed air, 33.33% 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, optimized generation | Conseq, U

Sterilisation UHT

For UHT, the consumption of energy derives from the pump that drives the product and from the steam injector that supplies vapour at temperature of 175°C. Steam is necessary in order to maintain water temperature elevated to the point of heating milk to sterilisation.

Pump consumption

The UHT relies on a 3-phase engine with PF of 0.76. With a mean measurement of 0.16A, consumption is:

$$kW= \sqrt{3}*0.76*0.16A*400V /1000= \sim 0.084 \text{ kW}$$

Processing 85 l of milk consumes 0.0884 kWh of energy. Referring back to the functional unit of 1000l the requirement is of 0.084 kWh / 85l * 1000l = 0.988 kWh.

Steam injector energy consumption

Based on steam consumption equation (SpiraxSarco n.d.)

$$\dot{Q} = mc_p\Delta T / t$$

Where:
$\dot{Q}$ = quantity of heat energy (kW)
m = mass to be heated (kg)
c_p = specific heat capacity of water = 4.19 kJ/kg°C
ΔT = difference in temperature
t = time in seconds

The amount of water to be heated is known as the flow was calculated during the tests. At pilot scale there is no energy recovery, while in full-scale UHT plants water runs in a closed loop and is used to heat and cool incoming and outgoing product.

$$Q = [87.805 \text{ kg} \times 4.19 \text{ kJ/kg°C} \times (175 – 20)] / (3600) = 15.840 \text{ kW}$$

Per hour the consumption is of 15.840kW processing 87.805 kg (85l). The steam injector's nameplate indicates a consumption of 15 kW; the calculations are therefore close to the standard range. For a 1000l energy needed is: 15.840 kWh / 85l * 1000l = 186.353 kWh.

Steam injector water and air consumption

12kg/h of steam are supplied at pressure of 5.5 bar. The requirement for tap water are of 12 kg/h / 85l * 1000l = 141.176 kg. The amount of compressed air required is of 3.6 bar (52.214 psig). Applying the previously explained equations:

$$y = 0.1296x + 0.3284 \text{ with } R^2 = 0.99964$$
$$y = 0.1296 (52.214) + 0.3284 = 7.095 \text{ SCFM}$$

$$\text{CFM} = \text{SCFM} / [(\text{Work pressure(psig)} + 14.7) / 14.7]$$
$$\text{CFM} = 7.095 / [(52.214 \text{ psig} + 14.7) / 14.7)] \approx 1.559$$
$$1.559 \text{ CFM} \approx 2.649 \text{ m}^3/\text{h}$$

Referring back to the functional unit it is calculated that 2.649 m^3/h / 85l/h * 1000l = 31.165 m^3. Once again the process for compressed air is modelled as 60% of "*Compressed air, 33.33% 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, optimized generation | Conseq, U".*

Table 10. Sterilisation UHT

	Unit	**Amount**	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	(186.353 + 0.988) = 187.341	Electricity, medium voltage {RoW}| market for | Conseq, U
Tap water	kg	141.176	Tap water, at user {Europe without Switzerland}| market for | Conseq, U
Modified_Compressed air	m^3	31.165	Modified_Compressed air, 60% 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, optimized generation | Conseq, U

Cooling

The cooling agent used for ***UHPH90l/h*** is R134a refrigerant, which has a specific heat capacity of 0.239 kJ/kg°C (DuPont 2004). Assuming, the need to cool the product from room temperature to reach the required -10°C, the change in temperature is 30°C. From the given parameters the following is derived: Q = 90kg/h * 0.239 kJ/kg°C * 30°C = 645.3 kJ/h ≈ 0.179 kW. For a 1000l the consumption is 0.179 kWh / 90l * 1000l = 2 kWh.

Table 11. Cooling UHPH90l/h

	Unit	**Amount**	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	2.000	Electricity, medium voltage {RoW}| market for | Conseq, U

The cooling agent for ***UHT*** is water. Assuming to start from room temperature to reach the required 5°C, the required temperature is derived:

$$Q = 85kg/h * 4.19\ kJ/kg°C * 15°C = 5342.25\ kJ/h \approx 1.484\ kW$$

Per hour the consumption is of 1.484 kWh processing 90l. Thus 1.484 kWh / 85l * 1000l = 17.459 kWh for 1000l production.

Table 12. Cooling UHT

	Unit	**Amount**	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	17.459	Electricity, medium voltage {RoW}| market for | Conseq, U
Tap water	kg	85	Tap water, at user {Europe without Switzerland}| market for | Conseq, U

Cleaning90l/h

The inventory shows data for a cycle of cleaning in place (CIP). The capacity of the UHPH and UHT systems are of 90l/h and 85l/h respectively, so to processing of 1000l of milk requires between 11 to 12 hours. CIP is usually performed every 12 to 14 hours (GEA Process Engineering A/S n.d.). One cleaning cycle is therefore assumed per functional unit. The cleaning process depends on the product processed rather than on the machinery; in fact the same procedure is found to be suitable for both technologies. There are different substances and procedures that can be used for this process (Eide et al. 2003). In the cleaning of equipment for milk production caustic, acidic and disinfecting agents are generally used. In this study the following agents are modelled: “BTS 3000” a caustic agent against fat, “Bio Tec Biomelk sauer” acid agent, and “BTS 4000” for disinfection purposes.

The table below represents the calculations for the cleaning procedure. The details regarding calculations and the specifics for the cleaning agents are explained in the following sections. The reference flow is defined as 1 piece (p), which represents one cycle of cleaning per 1000 l of processed product.

Table 13. Cleaning UHPH90

	Unit	**Amount**	
Cleaning	p	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	(5.29 + 0.3) = 5.59	Electricity, medium voltage {RoW}| market for | Conseq, U
Modified_Compressed air	m^3	5.538	Compressed air, 108.833% 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, optimized generation | Conseq, *U*
Heating Biomelk solution	p	1	Table 23
Water	kg	127.5	Tap water, at user {Europe without Switzerland}| market for | Conseq, U
BTS 3000	kg	1.05	Table 18
Bio Tec Biomelk sauer	kg	0.169	Table 22
BTS 4000	kg	0.05	Table 26

Table 14. Cleaning UHT

	Unit	**Amount**	
Cleaning	p	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	1.336	Electricity, medium voltage {RoW}| market for | Conseq, U
Modified_Compressed air	m^3	4.672	Compressed air, 33.33% 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, optimized generation | Conseq, *U*
Heating Biomelk solution	pc	1	Table
Water	kg	191.25	Tap water, at user {Europe without Switzerland}| market for | Conseq, U
BTS 3000	kg	1.05	Table
Bio Tec Biomelk sauer	kg	0.169	Table
BTS 4000	kg	0.05	Table

UHPH cleaning procedure

The specific instructions for UHPH are reported. First the pressure is released and the machine left running with a pressure not superior to 5MPa. As a first step the machine is pre-rinsed to eliminate any product residuals. Following the cleaning agents are circulated. After each agent the machine is rinsed with clear water 5-10 minutes to drain. The water has then to be expelled from the system and the machine has to be checked.

Energy requirements for cleaning UHPH 90

Electricity is calculated given UHPH electricity consumption derived from the equation y = y = 2.4498ln(x) - 0.0463 R^2 = 2.645 kWh (5.29 kWh for cleaning cycle) where the equation is the result of the analysis of the collected data. The energy consumption of the feeding pump (~0.15kWh) is then summed. The machinery is run at pressure 3Mpa. This choice is based on a combination of UHPH instructions, which indicate a maximum pressure of 5Mpa for this operation, and TetraPak (2010) instructions for UHT CIP, which advice for a pressure of 3MPa. TetraPak's instructions were found only for direct UHT and tubular indirect UHT. Since for both technologies a pressure of 3Mpa is suggested, the parameter is assumed to be valid for plate heat exchanger UHT. UHPH compressed air consumption is of 2.769 m^3 per hour, as the cleaning is assumed to last for two hours, 2.769 m^3 *2 h = 5.538 m^3 are needed. The value of two hours was chosen as a combination of literature, first-hand experience and time requirements for all cleaning products.

Energy requirements for cleaning UHT 90

For a UHT system cleaning requires flow rate to be 1.5 times the production's flow rate and the homogenizer needs a pre-charge pressure no less than one-third of the processing pressure (SPX, n.d.). The overall energy is calculated summing the consumption of the feeding pump, homogenizer and pasteurization pump. Compressed air requirement is of 2.336 m^3*2h = 4.672 m^3

Feeding Pump: 0.150 kWh / 85l * 90 * 1.5 = 0.238 kWh

Homogeniser: $E (kW) = Q_{in} * (P_1 - P_{in}) / 3600 * \eta_{pump} * \eta_{el.\ motor}$

$E = 90\ l * 1.5 * (67\ bar - 3\ bar)/(36000 * 0.85 * 0.95) = 0.297\ kW$

Sterilisation pump: 0.084 kWh / 85l * 90 * 1.5 = 0.133 kWh

Total consumption: (0.238 + 0.297 + 0.133) x 2 h = 1.336 kWh

Water UHPH & UHT

According to Tetrapak (2010) a tubular exchange UHT with capacity of 1400l/h would require between 1000 and 2000 l/h for CIP procedure, which in proportion reflects the requirement assumed in this study. The amount of water is calculated based on the time required for the cleaning procedure related to capacity. Pre-rinsing and a rinsing cycle after each agent are also included. A 10 minutes rinsing per cycle is assumed based on average time from literature (Alvarez et al 2010). Including drying time CIP is predicted to last for approximately 2 hours. For water use the chosen process is *"Tap water, at user {Europe without Switzerland}| market for | Conseq, U"*. The Ecoinvent process is modelled based on estimates for Switzerland and energy use for Germany. According to the instruction manual for the pressure pump, the used water does not have to be completely demineralized or desalted. Tap water is chosen for inventory, as local water is moderately soft.

Cleaning agents

BTS 3000

The ingredients that constitute this substance are: Sodium hydroxide (5-15%), potassium hydroxide (1-5%) non-ionic surfactants (1-5%), water hardness stabilizers, active chlorine (ca.3,2%), auxiliaries and builders. BTS 3000 has to be used cold, with concentration between 2 and 5% and used with the foaming method for 20 minutes.

Table 15. BTS 3000

	Unit	**Amount**	
BTS 3000	kg	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Sodium hydroxide (10%)	kg	0.1	Table 19
Potassium hydroxide	kg	0.03	Potassium hydroxide {GLO}| market for | Conseq, U
Chlorine	kg	0.032	Chlorine, liquid {GLO}| market for | Conseq, U
Non-ionic surfactants	kg	0.03	Ethoxylated alcohol (AE7) {GLO}| market for | Conseq, U

Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Conseq, U is modified to account for a concentration of 10% (Table below). According to Ecoinvent3 guidelines (Weidema et al. 2013), to modify the process the percentage of product is considered as a variable and the remaining inputs (transport and water) need to be multiplied proportionally.

According to Tiger Chemical Company (n.d.) Eythoxylated alcohol is one of the most common non-ionic surfactants. Eythoxylated alcohol exists in different concentrations; in fact processes exist for ethylene oxide (EO) concentration 3, 7 and 11. Air Products, chemical manufacturing company, suggests three EO concentrations (2.5, 5 or 7.3) for surfactants for dairy cleaning. According to P&G *AE-7, Alcohol Ethoxylate* and *AE-3, Alcohol Ethoxylate* can both be used for the same function. An EO concentration of 7 is chosen as it compatible with the carbon content of P&G *AE-7, Alcohol Ethoxylate* (P&G n.d. a and b).

Table 16. Modified_Sodium hydroxide, without water, in 10% solution state {GLO}| market for | Conseq, U

	Unit	Amount	
Modified_Sodium hydroxide, without water, in 10% solution state {GLO}| market for | Conseq, U	kg	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Transport, freight, sea,	tkm	3	Transport, freight, sea, transoceanic ship {GLO}| market for | Conseq, U
Transport, freight, inland waterways	tkm	0.123	Transport, freight, inland waterways, barge {GLO}| market for | Conseq, U
Sodium hydroxide, without water, in 50% solution state	kg	1	Sodium hydroxide, without water, in 50% solution state {GLO}| sodium hydroxide to generic market for neutralising agent | Conseq, U
Transport, freight, lorry, unspecified	tkm	1.040	Transport, freight, lorry, unspecified {GLO}| market for | Conseq, U
Transport, freight train	tkm	0.101	Transport, freight train {Europe without Switzerland}| market for | Conseq, U
Transport, freight train {CN}	tkm	0.341	Transport, freight train {CN}| market for | Conseq, U
Transport, freight train {CH}|	tkm	0.002	Transport, freight train {CH}| market for | Conseq, U
Transport, freight train {US}	tkm	0.479	Transport, freight train {US}| market for | Conseq, U
Transport, freight train {RoW}	tkm	0.623	Transport, freight train {RoW}| market for | Conseq, U

Bio Tec Biomelk sauer

Bio Tec Biomelk sauer is a combination of mineral acids (nitric acid) materials and builders. For the cleaning procedure a concentration of 0.5 - 1% is necessary, which has to be circulated at 40-60°C for 10 to 20 minutes.

Table 17. Bio Tec Biomelk sauer

	Unit	Amount	
Bio Tec Biomelk sauer	kg	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Nitric acid	kg	0.5	Nitric acid, without water, in 50% solution state {GLO}| market for | Conseq, U

The percentage of nitric acid is not specified. A 50% solution is chosen because is the most common concentration found on the market and from literature on cleaning in place (CIP) for Norwegian dairy plants (Eide et al. 2002). Therefore the already existing process *"Nitric acid, without water, in 50% solution state {GLO}| market for* | *Conseq, U"* was used.

This cleaning step requires heating of cleaning agent to 50°C (chosen as an average of indicated temperature 40-60°C). The heat load is therefore determined to be:

$$Q = 90 kg/h * 4.19 kJ/kg°C * 30 °C = 11313 kJ/h \approx 3.143 kW$$

Per hour the consumption is of 3.143 kW. Biomelk is circulated for 15 minutes, therefore the consumption is of 3.143 kWh / 4 = 0.790 kWh.

Table 18. Heating Biomelk sauer solution

	Unit	**Amount**	**Source**
Heating Biomelk solution	pc	1	Reference flow
Inputs	**Unit**	**Amount**	**Source**
Electricity	kWh	0.790	Electricity, medium voltage {RoW}| market for | Conseq, U

BTS 4000

BTS 4000 is Active chlorine (the 1% solution contains about 750 mg of chlorine / l), stabilizers and scaffold materials. It has to be used with a concentration of 0.5%, at cold temperatures for 10 minutes.

Table 19. BTS 4000

	Unit	**Amount**	
BTS 4000	kg	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Chlorine	kg	0.008	Chlorine, liquid {GLO}| market for | Conseq, U

Wastewater Treatment

It is assumed that wastewater after cleaning is sent directly for municipal treatment. The amount of water refers to the water used for the cleaning stage. The water used as cooling means in the UHT system is not included as, since it does not come into contact with the product, cleaning is not required.

Table 20. Wastewater treatment UHPH90

	Unit	**Amount**	
Cleaning	p	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Wastewater treatment	m^3	0.128	Wastewater, from residence {RoW}| treatment of, capacity 1.1E10l/year | Conseq, U

Table 21. Wastewater treatment UHT

	Unit	Amount	
Cleaning	p	1	Reference flow
	Unit	**Amount**	**Database entry**
Wastewater treatment	m^3	0.191	Wastewater, from residence {RoW}| treatment of, capacity 1.1E10l/year | Conseq, U

3.2.2 UHPH 360l/h

Pumping product from tank

For 90l/h consumption is of ~0.150kWh. For 360l/h assume: 0.150kWh / 90l * 360l = 0.6 kW. For the functional unit 0.6 kWh /360l * 1000l = 1.667kWh.

Table 22. Pumping product from tank UHPH360l/h

	Unit	Amount	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	1.667	Electricity, medium voltage {DE}| market for | Conseq, U

Pre-heating

Heat load is determined to be Q= 360kg/h * 4.19 kJ/kg°C * 70 °C = 105588 kJ/h ≈ 29.33kW. Thus 29.33kWh/360l*1000l = 81.472kWh.

Table 23. Pre-heating UHPH360l/h

	Unit	Amount	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	81.472	Electricity, medium voltage {DE}| market for | Conseq, U

Homogenisation and sterilisation

Electricity

The UHPH relies on a 3-phase engine with PF of 0.87. Electricity consumption is of 37.6 kWh/ 360l * 1000l = 104.444kWh for 1000l.

Compressed air

Air supply is connected through a ¼" BSPF (British standard pipe fitting) pneumatic air connection that requires constant pressure supply not below 5.5 bar. Because the parameters are similar to the smaller scale UHPH, the same calculations are valid, so the consumption is of 2.769 m^3/h for 360l. For the functional unit of 1000l, the total requirement is of 2.769 m^3h/ 360l/h * 1000l = 7.692 m^3.

Table 24. Homogenisation and sterilisation UHPH360l/h

	Unit	**Amount**	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	104.444	Electricity, medium voltage {DE}| market for | Conseq, U
Modified_Compressed air	m^3	7.692	Compressed air, 108.833% 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, optimized generation | Conseq, *U*

Cooling

Assuming the same parameters than for UHPH90l/h, the following is derived: Q = 360kg/h * 0.239 kJ/kg°C * 30°C = 2581.2 kJ/h ≈ 0.179 kW. For a 1000l the consumption is of 0.717 kWh / 360l * 1000l = 1.992 kWh.

Table 25. Cooling UHPH360l/h

	Unit	**Amount**	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	1.992	Electricity, medium voltage {DE}| market for | Conseq, U

Cleaning

Energy requirement

At pressure 3MPa the consumption is of 0.376 kWh. For a two hours cycle: 0.376 kW * 2h = 0.752 kWh. Two hours of compressed air supply correspond 5.538 m^3.

Table 26. Cleaning UHPH360

	Unit	Amount	
Cleaning	p	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	(0.376 + 1.2) = 1.576	Electricity, medium voltage {DE}| market for | Conseq, U
Modified_Compressed air	m^3	5.538	Compressed air, 108.833% 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, optimized generation | Conseq, *U*
Heating Biomelk solution	pc	(1/90*360) = 4	Table 23
Water	kg	(127.5/90*360) = 510	Tap water, at user {Europe without Switzerland}| market for | Conseq, U
BTS 3000	kg	(1.05/90*360) = 4.2	Table 18
Bio Tec Biomelk sauer	kg	(0.169/90*360) = 0.676	Table 22
BTS 4000	kg	(0.05/90*360) = 0.2	Table 26

Wastewater Treatment

It is assumed that wastewater after cleaning is sent directly for municipal treatment.

Table 27. Wastewater treatment UHPH90

	Unit	Amount	
Cleaning	p	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Wastewater treatment	m^3	0.51	Wastewater, from residence {RoW}| treatment of, capacity 1.1E10l/year | Conseq, U

3.2.3 Fresh cheese

Short product durability is the one of the main reasons for food waste generation. According to an English Waste and Resources Action Programme (WRAP 2014) study, between 1.3 and 2.6 million tonnes of food is thrown away from industries and households. Extending the shelf life of a product, in particular of quickly perishable goods, of a single day, have the potential of saving 0.2 tonnes of food. This estimate corresponds to 5% of what is identified as preventable waste in the UK. The resulting benefits are not only food savings but also increase revenue for retails and increase purchasing possibilities for consumers. To estimate the benefit of increasing shelf life, this study mainly relies on data derived by the UK WRAP's studies.

Avoiding waste is beneficial for manufacturer, retailer as well as consumer. Manufacturers will produce fewer quantities, suppliers will purchase less as more of their stock is sold and consumers will redirect the saved money to the purchase of other products. Generally consumers will switch to the consumption of higher quality and value products, generating profit for retailers (WRAP 2013). There are different ways in which these benefits could be accounted for but problems arise because of lack of data and allocation of the benefit. Two WRAP studies present ways to account for extended shelf-life: "Reducing food waste by extending food life" (2015), in which all benefits are allocate to retailer (including also the manufacturer savings) as it is considered that this positive effect will be transferred to consumers. The second study is "The Milk Model: Simulating Food Waste in the Home" (2013). The report estimates consumers' waste. Because of data availability and modelling problematic, in this study no waste is assumed for manufacturers and retailers and the benefits are estimated solely at consumer level.

Fresh cheese production

Raw milk is processed with UHPH treatment at 300Mpa at 30°C. It is then sent for coagulation, which consists in the collection of milk in a vat where it is warmed and stirred. Salt, calcium chloride and rennet are added. The produced curd is then cut and the grains are packaged. The product is then stored at 4°C (Zamora 2009). Refrigerated transportation is used to deliver the product to retails. Refrigeration at retail, transport to household, refrigeration in household and disposal of product close the system for cheese production.

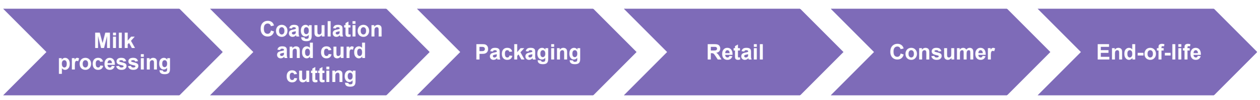


Figure 6. Fresh cheese production system

Processing

For **UHPH90&360l/h** refer to LCI above for 300MPa. The consumption for feeding pump and UHPH processing are the same as the flow and the pressure are the same.

Pre-heating

For **UHPH90l/h**, given the characteristics of the equipment, assuming an initial temperature (room temperature) of 20°C and heating the product to 30°C, which requires reaching a 40°C temperature on the heat-exchanger:

$$Q= 90kg/h * 4.19\ kJ/kg°C * 20\ °C = 7542\ kJ/h \approx 2.095kW$$

The hourly consumption is of 2.095 kWh processing 90l. Referring back to the functional unit of 1000l 2.095kWh / 90l * 1000l = 23.279kWh.

Table 28. Pre-heating fresh cheese UHPH90l/h

	Unit	**Amount**	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	23.279	Electricity, medium voltage {RoW}| market for | Conseq, U

For **UHPH360l/h**

$$Q= 360kg/h * 4.19\ kJ/kg°C * 20\ °C = 30168\ kJ/h \approx 8.38kW$$

The hourly consumption is of 2.095 kWh processing 90l. Referring back to the functional unit of 1000l 8.38 kWh / 360 l * 1000l = 23.278kWh.

Table 29. Pre-heating fresh cheese UHPH360l/h

	Unit	**Amount**	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	23.278	Electricity, medium voltage {RoW}| market for | Conseq, U

Cooling

For fresh cheese production temperature at inlet is of 30°C, at valve approximately 104°C are reached and ≤ 20°C at outlet. The same assumptions made for cooling for milk production apply to cheese making, as the difference between valve and outlet temperature is approximately the same.

Table 30. Cooling fresh cheese UHPH90l/h

	Unit	**Amount**	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	2.000	Electricity, medium voltage {RoW}| market for | Conseq, U

Table 31. Cooling fresh cheese UHPH360l/h

	Unit	**Amount**	
Milk	l	1000	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	1.992	Electricity, medium voltage {DE}| market for | Conseq, U

Fresh cheese production

Coagulation and curd cutting

The data is taken from the technical sheet for a TetraPak's vat *Tetra Damrow ™ Double-O Vat 8 Type DB*. Considering the parameters for the smallest capacity (2000 l/h), the following data is available:

Technical sheet: Tetra Damrow ™ Double-O Vat 8 Type DB		
	Unit	**Amount**
Coagulation and curd cutting of fresh cheese	l/h	2000
Inputs	**Unit**	**Amount**
Electricity	kWh	2.2
Steam	kg/h	190

For the functional unit of 1000l the data of the table above is halved. Moreover the process requires the addition of 1% (v/v) of salt, 35% (w/v) of calcium chloride and 0.03% (v/v) of recombinant rennet chymosin. Rennet was not included due to lack of information (Nigri et al. 2014).

Table 32. Coagulation and curd cutting of fresh cheese

	Unit	**Amount**	
Coagulation and curd cutting of fresh cheese	kg	144.620	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	1.1	Electricity, medium voltage {RoW}| market for | Conseq, U
Steam	kg	80	Steam, in chemical industry {GLO}| market for | Conseq, U
Salt	kg	1.446	Sodium chloride, at plant/RNA
Calcium chloride	kg	50.617	Calcium chloride {GLO}| market for | Conseq, U

Packaging

Packaging material

For fresh cheese, packaging consists in polypropylene (10g) moulds (Anelli n.d.). The moulds are then inserted in a container of the same material, where the container and the cap have a total weight of 24g (16 and 8 g respectively) (Anelli n.d.).

Packaging energy

The data is based on the technical sheet of *XBG50 Shanghai Xiangyi Machinery Co., LTD* filling machine with following characteristics:

Capacity	700-1000cups/h
Power	2kw
Filling volume	300ml
Voltage	AC220V/50HZ
Temperature	0-400centigrade
Machine size	1200*1200*1850
Weight	350-450kg
Air comsumption	0.7M3/MIN

The machine fills 850 cups/h on average. The energy per cup is of 2kW / 850 = 2.353 W. The packaging considered is of 250 g, which are equal to 238.095 ml (given a density of 1.05 g/ml). Assuming a linear relationship between energy requirement and capacity, the consumption per cup is of 238.095 ml * 300 / 0.002. Compressed air requirements are given per minute, knowing that 850 / 60 = 14.167 cups are filled per minute, the consumption is of 0.3 m^3/min / 14.167 = 0.021 m^3 per cup.

Table 33. Packaging of fresh cheese

	Unit	Amount	
Packaging Soft cheese	p	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Polypropylene	g	34	Polypropylene, granulate {GLO}| market for | Conseq, U
Electricity	W	1.961	Electricity, medium voltage {RoW}| market for | Conseq, U
Compressed air	m^3	0.021	Compressed air, 600 kPa gauge {RER}| compressed air production, 600 kPa gauge, >30kW, optimized generation | Conseq, *U*

Storage

Storage at manufacturer and at retailer are assumed to require the same energy. See *Energy in retail* below.

Transport to retail

Transport distance in assumed to be 80 km, which is an average distance for transport to retail for Europe (Cashman 2009). Total weight of the product is 284 g (250g of cheese plus 34 g of packaging). To account for refrigeration an increase in fuel of 0.025 l/km is included (Roibás et al. 2014). The process "Diesel, low-sulfur {RoW}| market for | Conseq, U" is the process for diesel that is included in *Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Conseq, U*. The required increase for the distance travel is of 0.025 * 80 = 2 l = 1.664 kg (density of diesel = 0.832 kg/L).

Table 34. Transport to retail

	Unit	Amount	
Packaged cheese	p	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Transport to retailer	tkm	0.023	Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Conseq, U
Diesel for refrigeration	kg	1.664	Diesel, low-sulfur {RoW}| market for | Conseq, U

Energy in retail

Foster et. al (2006) suggested energy requirements at retail to be of 8.333 kW for 1000l = of milk for a storage time of 18 hours. The consumption equals 11.111 kWh / day for 1000l. 1000l of milk equal to 1 033 000 g so the energy consumption for 250 g is 0.003 kWh / day.

Table 35. Storage energy in retail

	Unit	Amount	
Packaged cheese	p	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	0.003	Electricity, medium voltage {RoW}| market for | Conseq, U

Transport to household

Travel for shopping is assumed to be 10.9 km trip^{-1} with 175 trips per year (Thoma et al. 2013). According to Thoma et al. (2013) 0.307% of consumption for groceries' transport is attributable to dairy products. From Bouamra-Mechemache et al (2008) data on dairy consumption, fresh cheese share is estimated to be of 3.926%.

Table 36. Transport to household

	Unit	Amount	
Trip	p	1	Reference flow
Reference flow	**Unit**	**Amount**	**Database entry**
Transport to household	km	0.001	Transport, passenger car, EURO 5 {RER}| market for | Conseq, U

Energy in household

Relying on Thoma et al. (2012) the estimate for refrigeration energy for households is of 1345 kW h y^{-1}. Per capita consumption of fresh cheese is 5.134 kg y^{-1} or 0.014 kg d^{-1} per capita (Bouamra-Mechemache et al 2008). Considering 4 people household the total amounts to 5.134 kg y^{-1} x 4 = 20.536 kg y^{-1}. Knowing that for 229.2 kg y^{-1} the energy required of total refrigeration is 1.62%, for 20.536 kg y^{-1} it is estimated a consumption of 0.145%, which equals to 1.950 kWhy^{-1}. Energy allocated to fresh cheese per day is therefore calculated to be 1.950 kWhy^{-1} / 365 = 0.005 kWhd^{-1}. 0.005 kWhd^{-1} is required for 0.056 kg, thus for a 250g piece the consumption is 0.022 kW h d^{-1}.

Table 37. Storage energy in household

	Unit	Amount	
Packaged cheese	p	1	Reference flow
Inputs	**Unit**	**Amount**	**Database entry**
Electricity	kWh	0.022	Electricity, medium voltage {RoW}| market for | Conseq, U

Packaging disposal

The process includes transport and disposal.

Table 38. Packaging disposal

Reference flow	Unit	Amount	Source
Packaging disposal	p	1	Reference flow
Inputs	**Unit**	**Amount**	**Source**
Polypropylene disposal	g	34	Waste polyethylene/polypropylene product {GLO}| market for | Conseq, U

Cheese waste disposal

The process includes transport and disposal of cheese waste.

Table 39. Cheese waste disposal

Inputs	Unit	Amount	Source
Cheese waste disposal	g	60.74	Biowaste {RoW}| market for | Conseq, U

Fresh cheese extended shelf life

For **UHPH90l/h** and **UHPH360l/h** extended shelf life and yield are estimated to avoid the production of 5.03 l of milk. To evaluate the environmental benefit the process for fresh cheese production is analysed for the production deriving from (1000 l – 5.03 l) 994.97 l of milk.

3.2.4 The issue of energy recovery

At industrial scale, the energy recovery of an indirect UHT amounts to 88-90% exploiting heat transfer as explained in the relevant section. So the energy required by UHT treatment would be 28.776 kWh per functional unit assuming 90% recovery. As UHPH has not been applied at industrial scale yet, the pilot-scale is a non-insulated system that does not consider possible heat regeneration techniques. According to the possible ways to build the UHPH line, there is the possibility for regeneration; for example the outgoing product could be passed close to incoming milk to produce the same energy exchange as in the UHT line.

Hereafter the calculation of possible heat recovery for UHPH is presented. The energy requirement is of Q= 90kg/h * 3.93 kJ/kg°C * 40°C = 14148 kJ/h ≈ 3.93kW. Where 3.93 kJ/kg°C is the specific heat capacity of milk and 40°C is the difference between of temperature of the outgoing product, which is maximum at 50°C, and 90°C, which is the temperature that needs to be reached at the heat exchanger to ensure a 80°C pre-heating. The consumption for the functional unit is of 3.93kWh / 90l * 1000l = 43.667kWh versus 81.478 kWh without recovery. UHPH could therefore recover minimum 15% of energy. Energy recovery for UHPH could be much higher if temperature at valve (145°C) were to be used so that pre-heating and cooling would require minimal to no energy. In this case energy recovery could get up to 32% for UHPH 90 and 43% for UHPH 360.

3.3 Scaling up methodology

So far the environmental impacts of pilot scale UHPH have been discussed, but if the technology has to be used in industry the consequences of larger scale equipment and production have to be considered. Life cycle assessment is used in Eco-design and on various stages of product development to assess business as usual and consequences of future changes. In order to predict industrial application impacts scaling relationships are used. Scaling relationships are applied in different fields such as economics. An example is the six-tenth rule, which is commonly used for cost estimations (Caduff et al. 2010). Power laws have not been applied to LCA studies extensively. Caduff et al. (2014) derived equations relating power to mass, cost and energy requirement for commonly used engines and found that equipment generally does not linearly scale up and that the six-tenth rule does not always apply. The authors derived the equations through the ordinary least square regression of log10 transformed empirical data for key characteristics of different size equipment. Scaling laws are expressed as $i = a*P^{bi}$, where *i* is a key property, such as energy requirements, *a* is a normalisation constant and *b* is the scaling factor. For application in life cycle assessment, the inventory of the chosen equipment is parameterised so that each element is related to the relevant key property. For example capital good are related to mass, while electricity is related to energy consumption. This way each process is identified as size dependent or indipendent and is expressed in relation to the relevant key property. The same scaling relationship is then applied to environmental impacts (EI) so that $EI_i = a*P^{b_i}$ transformed in log10 $\log(EI_i) = \log(a) + b_i \log(P)$ for simplification (Caduff et al. 2014). This methodology is applied in this study. The two size UHPH data is integrated with empirical evidence and, following power laws for pressure pump, the relationship between key variables is set and then applied to estimate environmental scaling. In total data for 10 machineries are included in the analysis, it is acknowledges that this is a small sample for modelling purposes but it is considered as a valid initial assessment as no data is available in this regards.

UHPH relies on a positive displacement high-pressure pump of the reciprocating group. Fluid is drawn into pump and forced through a discharge valve. Reciprocating pumps work on the principle that a “solid will displace a volume of liquid equal to its own volume” (Evans n.d.). The 90l/h UHPH is a piston pump, while the 360l/h is a plunger pump. The former are commonly used to work at pressures up to 14 MPa, while the latter support pressures up to 207 MPa. Affinity laws are used to theoretically model the behaviour for the main properties of this equipment. Affinity laws mainly refer to centrifugal and rotary pumps, this because the relationship between the key variable for reciprocating positive displacement pumps are fairly straightforward. The key variables for positive displacement pumps are speed, capacity, pressure, power and the net positive suction displacement head required (NPSHr). NPSHr is the pressure required at the inlet for the pump to function avoiding cavitation. Cavitation is the creation of vapour bubbles when the inlet pressure is lower than the vapour pressure of the liquid. The consequences are pitting, noise and decrease in capacity. Pitting damages are responsible for a shorter lifetime of the equipment. For this reason it is important to check the NPSHr indicated by the manufacturer. For displacement pumps NPSH is often referred to as net inlet pressure, which is expressed in psi or bar (Evans n.d.).

Positive displacement pumps are volumetric pumps, which means that regardless the pressure applied, the flow depends directly on speed (hp = (Q*P)/(1714*ME), where hp is break horse power and ME is mechanical efficiency). Flow and power vary directly with a change in speed, while the NPSHr changes as the square of variation in speed (Evans 2014). The equations to determine the scaling up of the technologies are:

Flow: $Q_2 = (N_2/N_1)*Q_1$
Power: $kW_2 = (N_2/N_1)*kW_1$
Head: $NPSHr_2 = (N_2/N_1)^2*NPSHr_1$

Where:
Subscript 1 indicates the values for the known pump, while 2 are the values for the second pump for which a value is unknown
Q: capacity (litres per hour)
N: speed (revolution per minute)
kW: (power)
NPSHr: (net positive suction displacement head required)

Having set the equations they can be applied to the case study.

Table 40. UHPH 90 and 360 l/h parameters

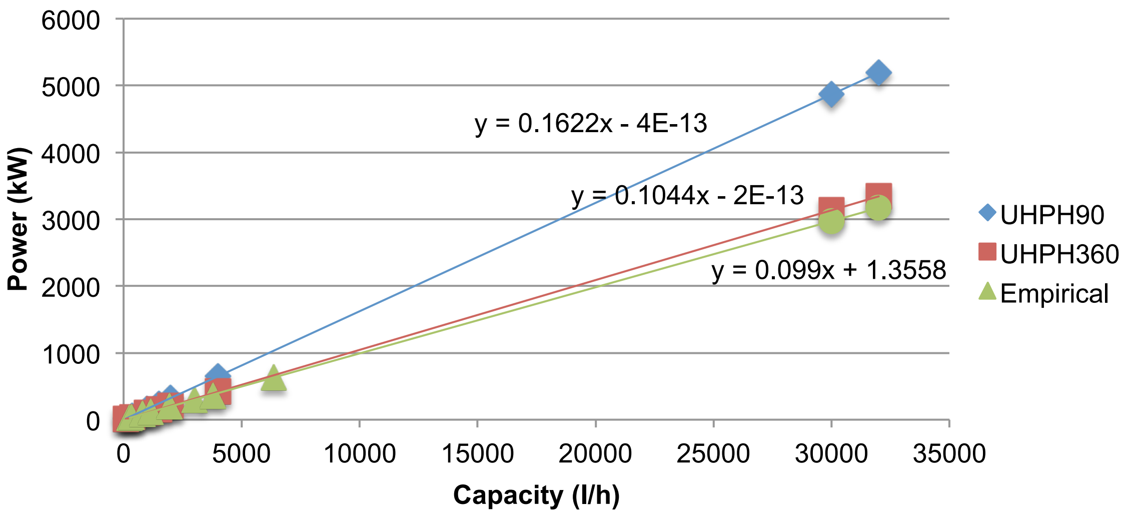
	UHPH90	UHPH360
Capacity (l/h)	90	360
Power (kW)	14.598	37.6
NPSHr (bar)	1	2
Speed (rpm)	234	620

UHPH commercially available have maximum capacities of 1000 and 1500 l/h. UHT capacity at industrial scale varies between 4 000 and 32 000 l/h for indirect and 2 000 and 30 000 l/h for direct steam injection. The revolutions per minute (rpm) to reach these capacities are shown in Table 49.

Table 41. UHPH 90 and 360 l/h rpm versus capacity

Capacity (l/h)	rpm (UHPH90)	rpm (UHPH360)
1 000	2600	1736
1 500	3900	2604
2 000	5200	3472
4 000	10400	6944
30 000	78000	52083
32 000	83200	55556

All the variables are related to speed; in Graph 3 values are shown for the capacity corresponding to the calculated rpm versus energy requirement. To validate the use of affinity laws to model up scaling, the technical sheet of a series of 6 three-plungers and 2 five-plunger pressure pumps were analysed (Hammelmann n.d.). Graph 5 shows the results. The green line represents empirical data, till a capacity of 6360 l/h (triangular shaped indicators), and the projected consumption for capacities of 30 000 and 32 000 l/h (circular indicators). The graph confirms the linear relationship of capacity and power with speed.



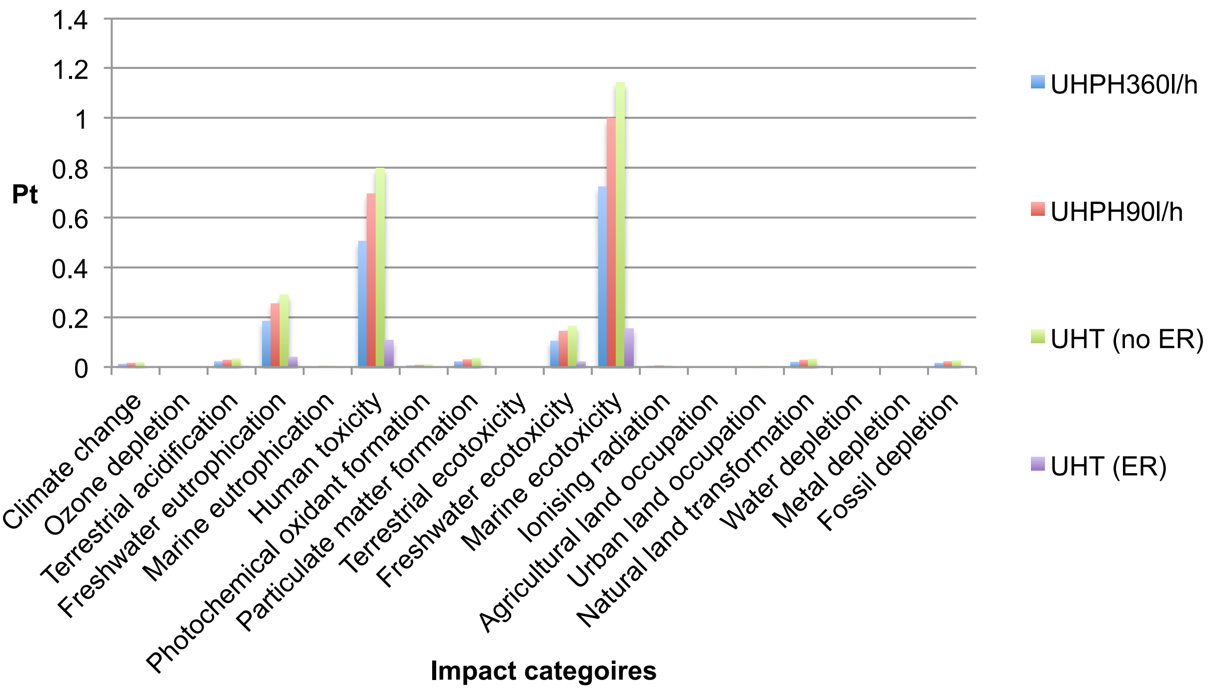
Graph 3. Energy consumption for UHPH equipment with different capacities

In the case of positive displacement reciprocating pump the scaling factor *b* is equal to 1 for most of the key properties. So when applied to life cycle assessment the environmental impacts will scale with constant return and with the same constant variable.

4 RESULTS

4.1 Life cycle impact assessment

For the production of milk only the processing stage is considered in order to compare UHPH and UHT treatments. The results for the impact assessment of the production of milk with two UHPH, with different capacities, and UHT, including and excluding the energy recovery (ER) that this technology ensures at a larger scale, are presented in the following section. Graph 4 shows the normalised results.



Graph 4. Impact assessment of UHPH, 90l/h and 360l/h, and UHT, with and without energy recovery (ER)

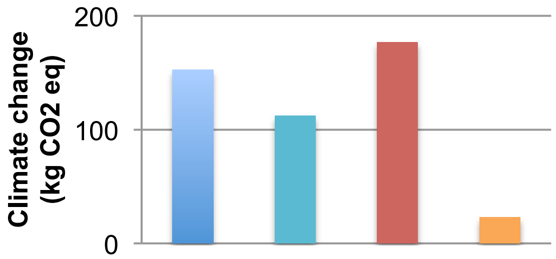
As expected UHPH performs better at bigger scale and outperforms UHT when energy recovery is not included. Including a 90% energy recovery the impact of UHT decreases significantly and outperforms the other systems. The characterised results are shown below (Table 42) for selected impact categories. The categories are chosen based on literature (Kim et al. 2013) and based on the most significant normalised values for this study.

Table 42. Characterised results for UHPH treatment of milk for selected impact categories

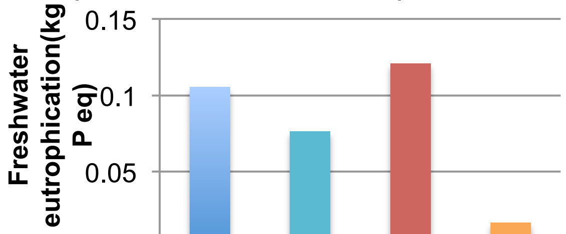
Impact category	Unit	UHPH 90l/h	UHPH 360l/h	UHT (no ER)	UHT (ER)
Climate change	kg CO2 eq	152.464	112.107	176.842	23.033
Freshwater eutrophication	kg P eq	0.105	0.076	0.121	0.017
Human toxicity	kg 1,4-DB eq	3111.198	2254.968	3565.864	484.49
Freshwater ecotoxicity	kg 1,4-DB eq	1.68	1.218	1.926	0.263
Marine ecotoxicity	kg 1,4-DB eq	2527.886	1832.544	2897.94	393.593

Graph 5,6,7,8 and 9 show the characterisation factors for selected impact categories for UHPH 90l/h (blues), UHPH 360l/h (light blue), UHT without (red) and with energy recovery (ER) (orange).

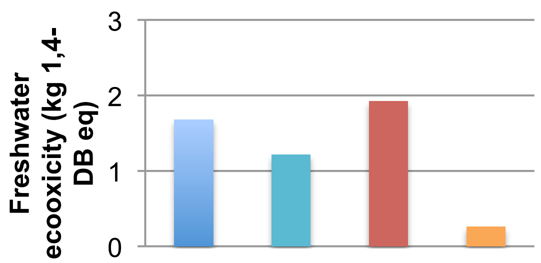
Graph 5. Climate change



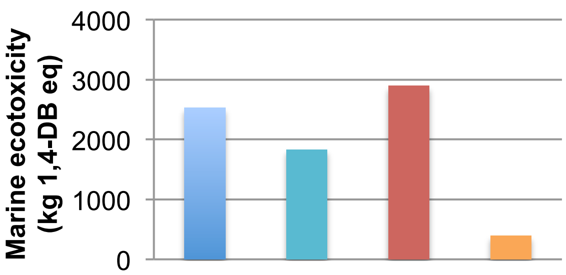
Graph 6. Freshwater eutrophication



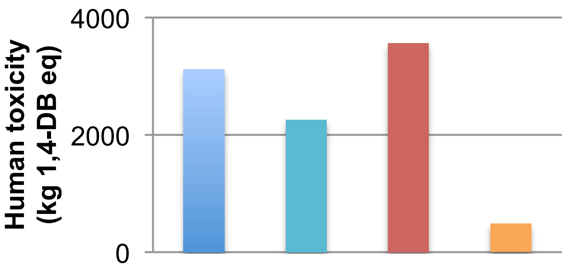
Graph 7. Freshwater ecotoxicity



Graph 8. Marine ecotoxicity



Graph 9. Human toxicity



Climate change

For all four systems electricity from hard coal and lignite are the main contributor to climate change, with exception of UHT with recovery. Given lower energy consumption the main contributor shifts from being electricity production to the ammonia used for the production of nitric acid for Biomealk sauer.

Fresh water eutrophication

The main contributors are treatment of spoil coal mining, lignite mining and wastewater treatment. Mining is part of electricity production life cycle, while wastewater is the handling of water after the cleaning stage.

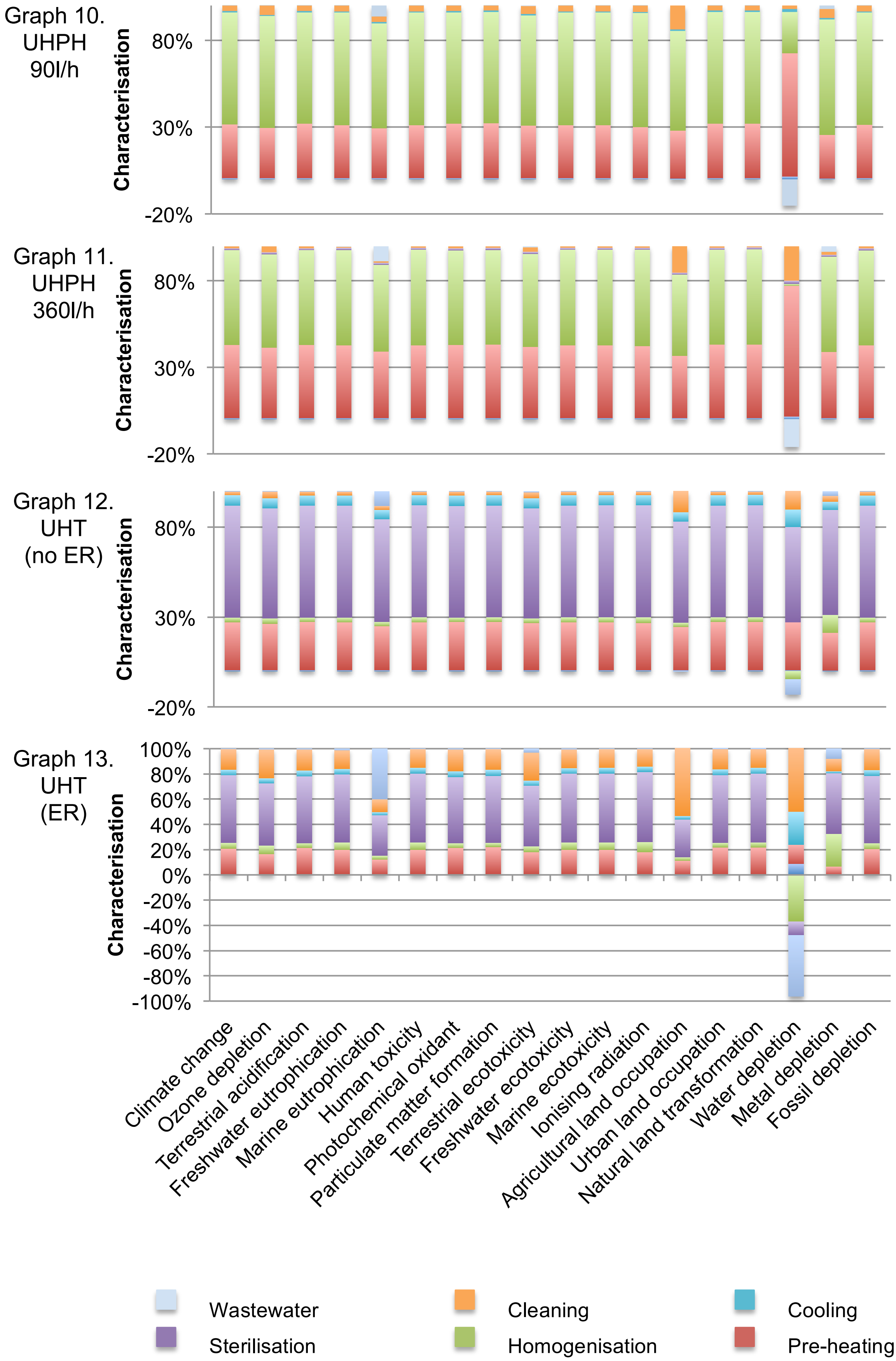
Human toxicity, marine ecotoxicity and freshwater ecotoxicity

All three categories of toxicity depend on three main activities: treatment of coal slurry, treatment of hard coal ash and electricity. Electricity has its highest impacts when it is produced from coal and lignite. Coal slurry accounts for the impact of leaching, while hard coal ash is incinerated in a municipal solid waste facility.

4.1.1 Process contribution

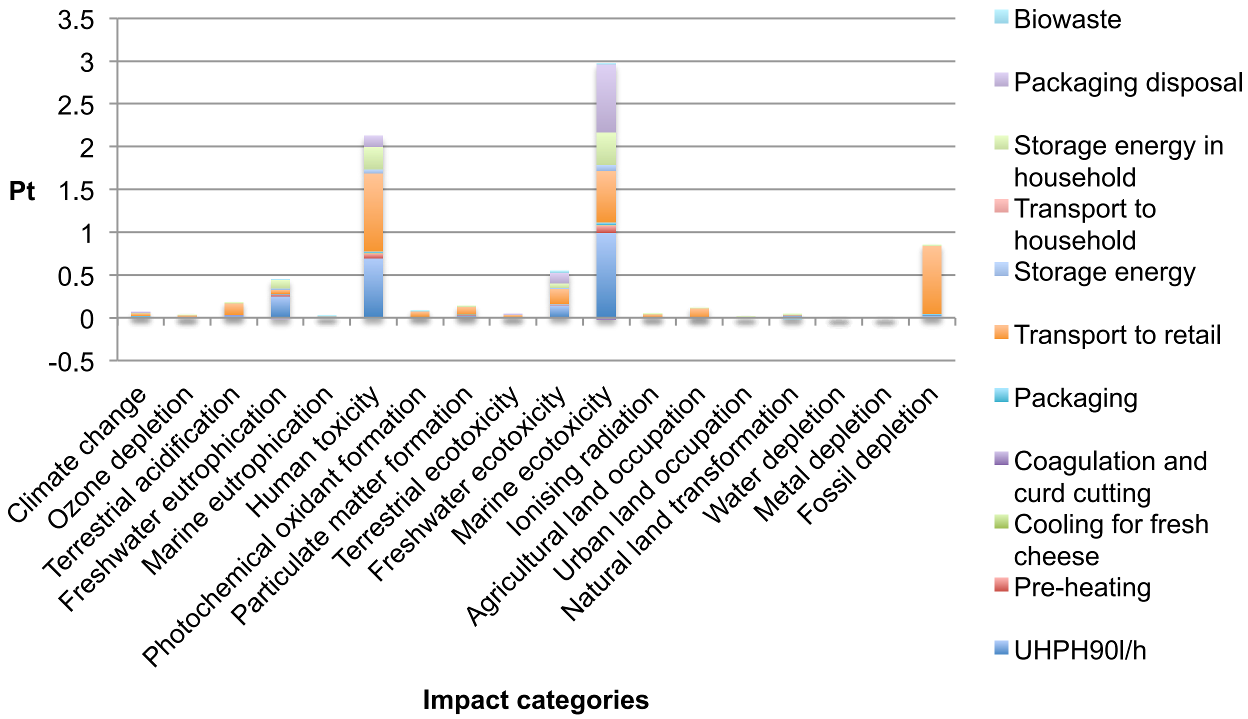
The processes that mainly contribute to UHPH processing are homogenisation and pre-heating. The difference between the two sizes depends on the higher energy efficiency of the larger scale pressure pump, so pre-heating becomes more important. For UHT treatment sterilisation and pre-heating are the most important processes. With the inclusion of energy recovery sterilisation remains one of the main contributors, but the importance of pre-heating decreases. Cleaning becomes relatively more important and consequently so does wastewater. The negative impact of homogenisation derives from the production of electricity from hydro sources and saving of tap water as hydroelectricity plants help conserving water tables (USGS n.d.). The same applies for sterilisation. The changes due to increased importance of cleaning can also be seen in increased marine eutrophication and the impact on agricultural land transformation derived from the use of wood chips in the production of sodium hydroxide. The differences of cleaning can also be seen between the two UHPH systems but the changes are of a smaller magnitude given a lower consumption of water.

Graph 10,11,12 and13 show the process contribution for UHPH 90l/h, UHPH 360l/h, UHT without and with energy recovery (ER).



4.1.2 Fresh cheese production

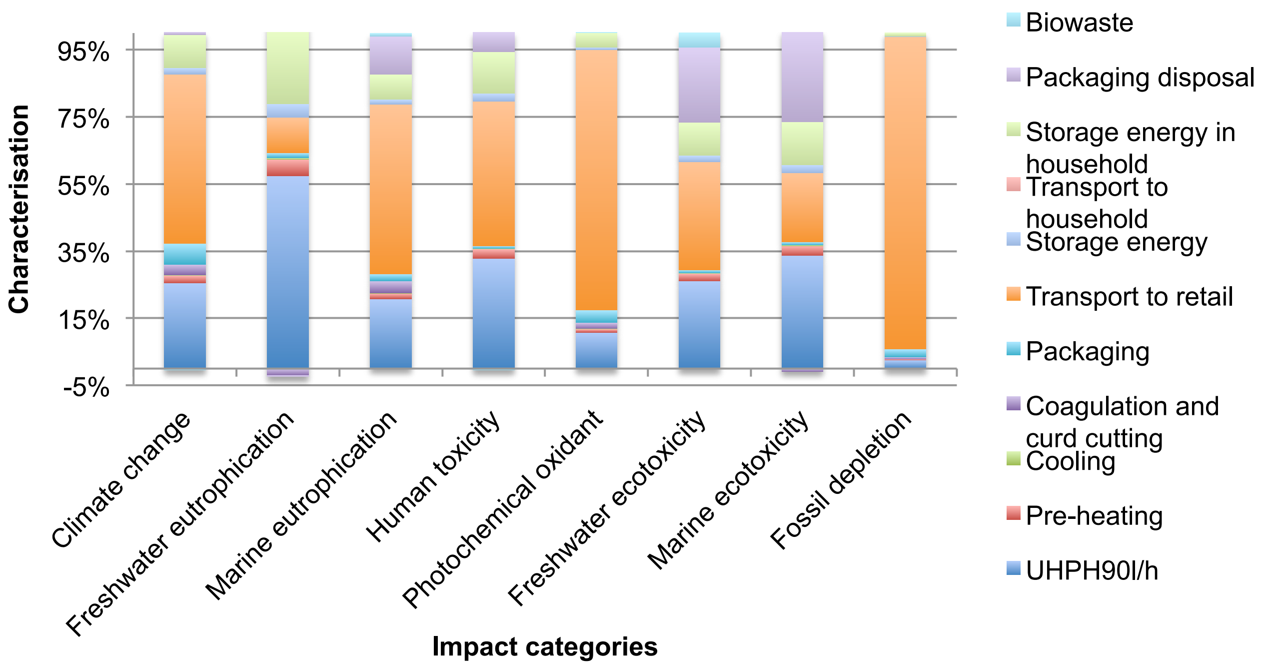
The life cycle inventory for cheese production is compiled based on a number of assumptions and no direct data from manufacturing gate to grave. It is therefore necessary to account for the high uncertainty. According to WRAP (2013) the majority of sold fresh cheese has an 8 days shelf life left out of 13 days in total. Based on this information given 19 days of total shelf life for fresh cheese from UHPH treated milk, the model accounts for 11 days in retail and 8 days of household refrigeration. Kim et al (2013) found the most important life cycle impact categories for the production of mozzarella cheese, which falls in the category of fresh cheese, were: climate change, marine eutrophication, photochemical oxidant formation, freshwater eutrophication, human toxicity and ecotoxicity. Given the correspondence between literature and the normalisation results of this study (Graph 14), the characterisation results for the mentioned categories plus fossil depletion are shown in Table 43 and the relevant process contribution in Graph 15. The normalised results and process contribution are shown for UHPH 90l/h. It was chosen to show the outcomes for only one machine as the relative importance of impact categories and of process are similar between the two.



Graph 14. Fresh cheese production UHPH 90l/h normalisation factors

For climate change, the main activities contributing are transport and processing. The determinant in both cases is the production of diesel, for transportation purposes and as fuel for building machines used in hard coal electricity production. Mining spoils from the cleaning of the desired minable surface, are responsible for the impact of electricity production on eutrophication, human toxicity, marine and freshwater ecotoxicity. The other two determining source of environmental impact for ecotoxicity, fossil depletion and photochemical oxidant formation are petroleum extraction and natural gas production.

These are part of both electricity production and transportation processes. For UHPH 360l/h similar results are obtained, the main difference is a decrease in contribution of the processing stage, given the lower energy consumption, and the relative increase of importance of transport.



Graph 15. Fresh cheese production process contribution for UHPH 90l/h

The impact of avoided production and waste treatment is low as the amount of saved cheese is small. The impact of extended shelf life mainly depends on refrigeration in household. Even though food waste is prevented, the amount of waste after 13 days is low. Consumer's behaviour is affected by multiple variables, in the case of milk WRAP assumed a normal distribution relating amount of milk purchased based on available shelf life. What the authors suggest is that a longer shelf life will decrease waste and a better stock rotation, keeping milk with a life between 5 and 11 days on the shelf, will lead to less waste.

In this case the environmental saving is of approximately 0.05% for all impact categories. The German market, for example, demands 1 387 000 t of fresh cheese (Statistisches Jahrbuch 2012), which would require 9 590 651 l of milk. For climate change, 3 kg of CO_2 would be saved for every 1000 l of processed milk for both UHPH 90 and 360 l/h (Table 50); so the application of UHPH treatment for the production of fresh cheese would have avoided the emissions of 28 772 kg of CO_2 eq.

Table 43. Characterised results for UHPH 90 and 360 l/h fresh cheese production for selected impact categories

Impact category	Unit	UHPH 90l/h (without avoided emissions)	UHPH 90l/h (with avoided emissions)	UHPH 360l/h (without avoided emissions)	UHPH 360l/h (with avoided emissions)
Climate change	kg CO2 eq	521	518	601	598
Freshwater eutrophication	kg P eq	0.125	0.124	0.181	0.180
Marine eutrophication	kg N eq	0.177	0.176	0.197	0.196
Human toxicity	kg 1,4-DB eq	7876	7837	9526	9478
Photochemical oxidant formation	kg NMVOC	4.174	4.153	4.424	4.401
Freshwater ecotoxicity	kg 1,4-DB eq	5.270	5.244	6.161	6.130
Marine ecotoxicity	kg 1,4-DB eq	6133	6102	7474	7436
Fossil deplition	kg oil eq	1312	1305	1330	1323

Dairy plant to grave represents 40% of overall impacts. Schmidt and Dalgaard (2012) studied carbon footprint of Danish and Swedish milk on national and farm level. The authors found using IPCC 2007 (100a) as impact assessment method, emissions of 1.06 kg of CO_2eq, using consequential approach, and 1.05 kg of CO_2eq using attributional approach, per kg of energy corrected milk (ECM). 1.06 kg of CO_2eq are the result of a total impact of 2.26 kg of CO_2eq (including iLUC, services and capital goods) and an avoided beef system of -1.88 kg of CO_2eq. So if the farm stage were included in the assessment of the impact of increased shelf life, the environmental benefits would be considerably higher. For the functional unit of 1000 l, 0.943 kg of CO_2eq / 1.033 *5.03 l = 4.6 kg of CO_2eq, where 1.033 is the kg to litre conversion, would be avoided at cradle to farm gate. Table 44 shows the impact for the overall life cycle of fresh cheese production. This study results have been included and recalculated using the IPCC 2007 (100a) for consistency.

Table 44. Total emissions in kg of CO_2eq for UHPH90 fresh cheese processing including cradle to farm gate activities for functional unit of 1000 l

	Cradle to farm gate	Farm gate to grave	Cradle to grave
Emissions including iLUC			
Total emissions excluding iLUC, excluding services & capital goods	908.4	647	1555.4
Avoided emissions	4.6	3	7.9
Total	913	644	1557
Emissions excluding iLUC			
Total emissions including iLUC, services & capital goods	974.174	686	840.1
Avoided emissions	0.1	3	3.1
Total	193	644	837

On the German market this would translate in 9 590 651 l * 7.9 kg of CO_2 eq / 1000 l = 75 766 kg of CO_2 eq for the overall life cycle the.

4.1.3 Electricity sensitivity

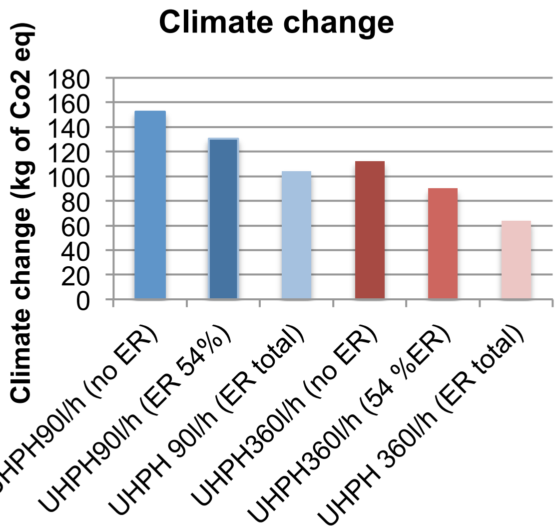
The results for water depletion in the process contribution for milk production are not of big magnitude but it was considered important to further investigate the reason for the negative results for electricity production. To do so the electricity was changed from RoW to the same process but specific for Germany (*Electricity, medium voltage {DE}| market for | Conseq, U*). The difference found was in the contribution of the different activities but the positive affect on water depletion was still great in characterisation terms. The main responsible for this are the processes of electricity production from hydropower, which helps conserving water tables as explained above. Moreover to exclude methodology as a determining factor, the same process has been analysed using a water scarcity method Berger et al. (2014). A positive impact is found for all approaches (Table 45).

Table 45. Water depletion values for different LCIA methodologies in m^3

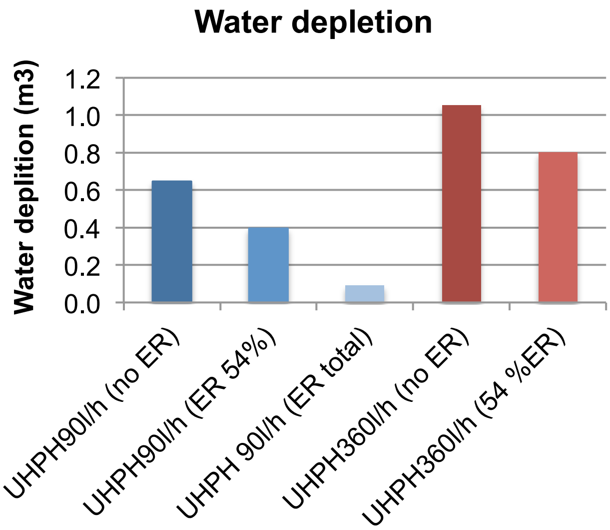
	Recipe RoW	**Recipe DE**	**Berger et al.**
Total	0.013449122	-0.218913443	-3.32E-05
Pumping of product	0.001171978	-2.87E-05	-0.001530351
Pre-heating	0.054102207	-0.001324676	-0.000128684
Homogenisation	-0.133308157	-0.137942143	-0.003520557
Sterilisation	-0.038870131	-0.166312229	-0.000328092
Cooling	0.094588721	0.082711921	-0.001032295
Cleaning	0.208409963	0.176627838	-1.45E-06
Wastewater	-0.172645458	-0.172645458	-3.32E-05

4.1.4 The issue of energy recovery: results

A minimum energy saving of approximately 54% of pre-heating energy consumption has been estimated. Following the savings, for 54% of pre-heating (ER 54%) and savings of pre-heating and cooling (ER 100%), are presented for climate change and water depletion impact categories (Graph 16 and 17). Climate change was chosen as the activity depends on the production of electricity. All impact categories, apart from water depletion, behave as climate change. Assuming a saving of 54%, the impact decreases by between 12 and 14%, for UHPH90, and 16 and 20%, for UHPH 360, of the overall impact. The results for water depletion are shown because of their greater magnitude and different trend. Water depletion decreased impact is of 39% for UHPH 90 and 24% for UHPH360. Assuming a total saving on heating and cooling, the impact decrease by 32 and 43% for UHPH 90 and 360 respectively. Water depletion changes by 86% for UHPH 90 and 36% for UHPH 360. Water depletion impact is lower for UHPH90 because of a greater negative effect of hydropower electricity.



Graph 16. Climate change characterisation results for UHPH 90 and 360 l/h with and without ER.



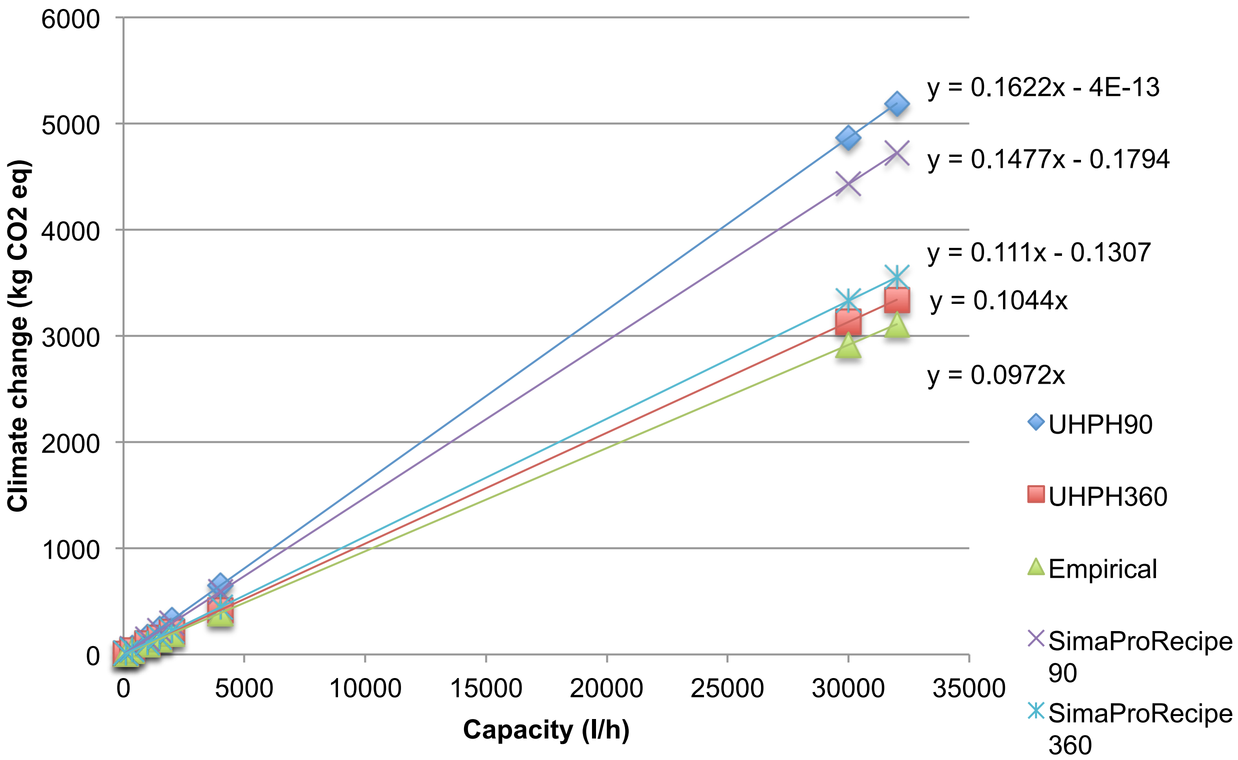
Graph 17. Water depletion characterisation results for UHPH 90 and 360 l/h with and without ER.

Table 46. Characterisation results for UHPH 90 and 360 with and without energy recovery for the selected impact categories

Impact category	UHPH90 (no ER)	UHPH90 (ER 54%)	UHPH90 (ER 100%)	UHPH360 (no ER)	UHPH360 (ER 54%)	UHPH360 (ER 100%)
Climate change (kg of CO_2 eq)	152	131	104	112	90	64
Water depletion (m^3)	0.646	0.395	0.092	1.055	0.804	0.5

4.2 Scaling laws applied to environmental impact assessment

Capacity and energy consumption scale linearly with speed, the equations are shown in the methodology section. The same relationship is applied in the environmental considerations, i.e. the same normalisation constant and power factor are applied (Graph 18). The main impact on the product's life cycle is due to electricity consumption, it was therefore chosen to look at the relationship between the climate change impact category and capacity.



Graph 18. Climate change versus capacity for UHPH 90 and 360 l/h, empirical data and SimaPro Recipe results

The larger pilot scale is similar to empirical data. On the other hand the smaller scale UHPH has a significantly lower efficiency. The difference between UHPH 90 and empirical data is of 40%, while UHPH 360 differs of only 12%. The variance between the two UHPH studied shows how pilot-scale measurements need adjustments and often not reflect performance at larger scale. Compared to the scaling that is obtained in SimaPro the results are similar and there is no variation greater of 9% for UHPH 90 and 6% for UHPH 360. Given the linear nature of the relationship of the key elements the results of the comparison with SimaPro were expected.

5 DISCUSSION

The study was set out to explore the environmental implications of ultra-high pressure homogenization, this processing technique has the aim of creating an emulsion and destroying microbes. The European Union has directed funding to assess this technology performance in the treatment of vegetable and animal milks. Bovine milk was used in this study because of its importance on international markets and its predisposition, as a substance, to behave like a buffer and so representing a good benchmark. To place the technology in today's production context it was compared to one of the most common milk treatments, ultra high temperatures. When evaluating possible improvements at a single stage of production, upstream and downstream consequences need to be explored. No significant change on the supply chain could be forecasted for the use of UHPH processing for the production of drinkable milk but when used for the production of fresh cheese Escobar (2011) and Zamora (2014) found increased shelf life and yield. This study sought to give a comprehensive view of this technology. The importance of including a scaling methodology for environmental impacts is becoming a strong topic in literature (Shibasaki et al. 2006; Arvidsson et al 2013; Caduff et al. 2014; Hummen and Kästner 2014) and so a glimpse into the industrial application was included.

Under the environmental aspect UHPH was predicted to lower energy consumption combining homogenization and sterilisation but at the same time have high heat loss (Zamora and Guamis 2014; Dumay et al. 2013). This study confirms what was expected; UHPH has a lower energy consumption compared to UHT and heat waste is one of the main concerns. High temperatures are reached and, as today, no heat recovery is included in pilot process systems. This last issue is what developers need to address. Technological readiness level cannot be disregarded when comparing novelties and established practices; ultra high temperature treatments have been used in the milk industry for decades having reached a top performance. On the other hand UHPH is a relatively new technology that still needs time to develop. This concept applies to all elements of a technology, for example materials that can withstand high pressures have only recently being discovered and applied. Additionally this study showed that some heat recovery is theoretically possible simply adding heat exchangers to the process line following the UHT example. This is an example of how eco-design can play a role in supporting the development of new technologies and the importance of assessing equipment performance as a single unit and as part of the entire process line.

Lower energy requirements not only bring environmental benefits but it is also an economic advantage. According to Milani et al. (2011) processing is an economic issue rather then technological, as studies have shown possibility of emission reduction through the improvement of the efficiency of established technologies. For this particular study the energetic efficiency of UHT is already very important but UHPH not only could lower the consumption of electricity but also could provide a better product. Milk quality investigation was not in the boundaries of this study, but it is an important element in the evaluation of UHPH. European researches have shown the potential of pressure treatments of producing a safe food item maintaining the nutritional characteristics, which are deteriorated by the exposure to high temperatures. Consumers are increasingly more careful in the choice of their diet composition and require to be more informed about the characteristics of the food items on the shelves. UHT milk cooked taste and nutrient poverty (Clare et al. 2005) have been reason for campaigns against shelf stable milk (Forristal 2004). Consumer acceptance of this product is different depending on countries cultural preferences. European demand for this product is generally strong, while American consumers prefer their milk to be refrigerated. UHPH milk can represent a valid alternative to UHT on European markets, providing higher quality without loosing on shelf life, and could be more easily accepted on the American market if sensory and nutritional values are of better quality.

Under a process contribution perspective the impact categories identified as significant under a normalisation results point of view are similar to what is found in literature (Kim et al 2013). As expected electricity production is the most relevant impact for the climate change category. When energy recovery is included in the results cleaning becomes important; in fact, the production of Biomealk sauer agent is the main impact for UHT with ER. Cleaning requires high energy (Eide et al. 2002) and it is the most water demanding stage, after irrigation, for the overall life cycle of dairy products. Eide et al. (2002) found cleaning to be responsible for 80% of eutrophication and 30% of energy requirements. In this study cleaning (represented by the sum of cleaning and wastewater activities) accounts for 20% of freshwater eutrophication and 50% of marine eutrophication for UHT with energy recovery. The difference in findings might derive partly from the exclusion of product residuals treatment, the inclusion of cleaning in place exclusively and from the pilot scale nature of the system. Product waste gives rise to high chemical oxygen demand (COD), biochemical oxygen demand (BOD), nitrogen (N) and phosphorus (P) (Eide et al. 2002). The influence of waste product on eutrophication can be as high as five times more than cleaning agents' impact, if no treatment is included. Nevertheless efficient cleaning and wastewaters treatments can decrease waste concentration in wastewater and decrease the amount of substances that reach the environment (Eide et al. 2002).

The study of fresh cheese production showed the relevance of the processing stage. UHPH made for a fourth of farm-gate to grave climate change related emissions and for a tenth of the overall carbon footprint of cheese production. Similar results are found in literature (Cashman 2009). Research and technical development can therefore contribute significantly to mitigation. Life cycle stages after farm gate still represent almost half of the overall impact and should not be disregarded. Transport and refrigeration are the other aspects on which research should focus on. This is particularly evident from the evaluation of the effect of extended shelf life. Additionally extended shelf life could also lead to longer transportation distances. The controversy between a more efficient, economically and environmentally, larger production (Eide 2002) versus a more desirable local distribution is not unknown. Further investigation of this issue is needed to support effective decision-making. The results of the modelled fresh cheese production are highly uncertain as built on a combination of literature data and as many values vary between countries, such as transport distances. Moreover the relations between food waste and shelf life can be subjected to high criticisms because modelling consumers' behaviour is a hard task and subject to cultural differences. Initiative such as the recent French legislation (Chrisafis 2015) that bans food waste forcing supermarket to donate unsold food might be an easier and more efficient way to address waste at retail and consumer level. This in combination with good managements practices, such as efficient stock rotation, could give an important contribution to decreasing waste.

Nevertheless the positive effect of extended shelf life shall not be disregarded as, food waste, malnutrition and battle for land are three of the greatest issues faced nowadays. Farming activities are mainly responsible for the impact of food items, as shown in the results for cheese production, the relevance of emissions at farm stage more than doubles the saving of carbon dioxide emissions. Therefore any novelty that can decrease impacts at that stage should be thoroughly investigated. Agricultural emissions not only derive from human activities but an important share is biogenic. The past years the impact of livestock has been extensively addressed as human impact on climate change derives from agriculture and the impact of agriculture is mainly due to livestock's enteric digestion and manure management. Diets need to change and rearing needs better practice. Given these premises stages after farm-gate cannot be ignored.

Moving onto scaling considerations, the chosen method seems the most appropriate at this stage. Caduff's approach gives a projection of what the technology can achieve at the moment, giving insights for further development. For a long-term prospective the exclusion or mature approaches, i.e. not including the novelty in the calculations or assigning it the same impact as the established practice, would be more appropriate (Arvidsson et al 2013). If one of the mentioned approaches were applied to compare UHPH and UHT, the former technology would represent a better solution as it provides higher quality.

Scaling showed linear relationships between the main variables and the environmental impact for UHPH because of the technical characteristics of positive displacement pumps, but revealed the learning through increased efficiency from different pilot scales and empirical evidence. This study showed that even if data is not available for larger scale, a combination of engineering principles and similar equipment forecasting is possible. Moreover the learning effect between the two pilot scale UHPH could be integrated into the scaling equation, as done by Caduff et al. (2012) for wind turbines, to predict the potential future increase in efficiency. There is therefore ground for the development of this technology. Additionally referring back to what Shibasaki et al. (2006) identified as key points to include in this kind of life cycle assessment studies, further considerations should be included. In this study technological aspects have been looked at, but further in depth research needs to be included. For instance research on valve design and materials is key in UHPH scaling. Issues such as legislation and costs can vary with scale, in particular costs can be key as processing is mainly an economic issue (Milani et al. 2011). The lifetime of the equipment will be an important point in feasibility assessments and the saving in terms of energy consumption will be key in determining the advantages of the technology under a cost perspective. The third point raise by Shibasaki et al. (2006) refers to synergies. Heat regeneration has already been mentioned but the equipment has been mainly considered on its own, for a proper exploration of industrial performance the all system should be included in the analysis.

UHPH effects on milk processing needs further research, for example the impact on milk shelf life should be verified as well as consumers' perception of UHPH milk to assess market acceptance of the product. Further research is needed in general on food items processing, as their contribution to mitigation can be significant. Moreover the impact of extending shelf life, integrating retail practices and consumer behaviour, should be investigated in order to take advantage of possible reduction in waste. The application of scaling methodologies to LCA should become a more common practice and therefore there is a need of the validation of existing methods and of new approaches.

Further research: drugs and cosmetics

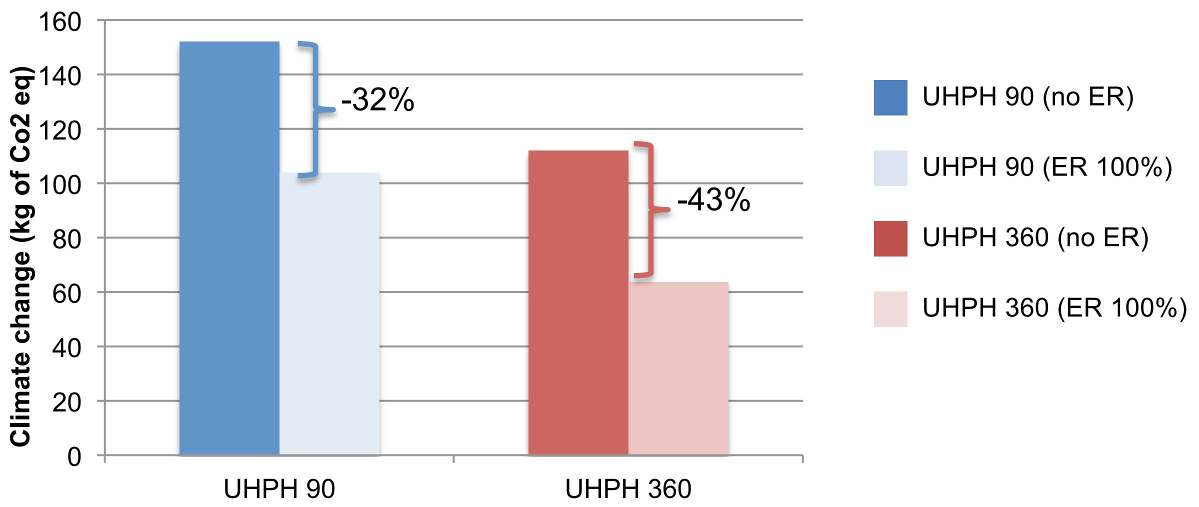
UHPH application is not restricted to the food sector. Emulsion formation is a key process for industries, such as the pharmaceutical and cosmetic. The technology might be more competitive in the processing of non-edible products. Further studies should therefore look into upstream and downstream consequences in other sectors and line of productions. Based on viscosity and other parameters, the energy consumption and the considerations made in this study can be applicable to other products as well.

Limitations

- There are some general limitation of LCA studies, such as the exclusion of capital goods, data reliability and the selection of life impact categories. Additionally the study system boundaries for milk production are set to include only the production line available in the laboratory; the inclusion of other stages of production would contribute to a better overview of the overall production phase.
- Pilot scale production lines are built with equipment of different size. Some equipment had to be readjusted to work at the needed capacity; this can vary the consumption, as the machine is not used at its best efficiency.
- Data reliability for pilot scale tests values is subject to uncertainty given the means of measurement uncertainty.
- Only cleaning in place (CIP) is included in the study and the starting and shutting down phase of the equipment is not included.
- Cheese production is based on theoretical assumptions and many activities such as, transportation, are country specific. The uncertainties are therefore high. However, the insight on cheese production demonstrates the possible applicability of the research results. A further limitation is that waste in only considered at consumer level.
- The scaling up of empirical data is made based on affinity laws and the last empirical data is for equipment of size 3 600l /h versus the assumption a maximum capacity of 32 000l/h.
- Only ten machineries are included in the scaling up.

6 CONCLUSION

Population growth puts pressure on food availability making research in food technologies fundamental for future production. The westernization of diets increasing milk and meat demand threatens the goals to decrease human induced atmospheric emissions. The agricultural sector is the main responsible for anthropogenic impact on the environment. This study aimed at exploring the impact of a new processing technology, ultra-high pressure homogenization. This technology provides emulsion, while destroying microbes. Applied to the production of milk energy consumption is 14% lower than existing technologies at pilot scale, a minimum 15% of energy recovery is achievable. The exploitation of valve temperature could increase energy savings up to reducing by 43% CO_2 emissions (Graph 20 and 21). Additionally UHPH milk can become a potential competitor to UHT if further researches on its properties show higher quality for sensory and nutritional values. There is therefore a large potential market for this product. The technology needs time to develop but there are good basis for a successful application.



Graph 19. Climate change savings given by energy recovery and higher efficiency

The study of fresh cheese production and the calculation on energy recovery showed the relative importance of processing and the benefits that could derive from technological innovation. Even though not a lot of cheese is wasted, extended shelf life has positive effects, reducing waste and increasing yield, and the benefits more than double if the farming stage is included as well. At industrial scale impacts scale linearly but increased efficiency is shown between different pilot scale equipment and empirical evidence. Synergies, economic benefit and the entire product line should be evaluated to have a comprehensive view on industrial application. UHPH is a promising technology but it still is at early stages of development; in particular in the processing of milk, the energy requirements need to decrease compared to existing practices. The investigation of the use of UHPH in other industries is recommended as its performance could bring significant benefits.

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