Mapping energy consumption in food manufacturing

Ladha-Sabur, Alia; Bakalis, Serafim; Fryer, Peter J.; Lopez-Quiroga, Estefania

DOI:
10.1016/j.tifs.2019.02.034

Trends in Food Science & Technology 86 (2019) 270–280

Contents lists available at ScienceDirect

Trends in Food Science & Technology

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

Review

Mapping energy consumption in food manufacturing

Alia Ladha-Sabur[a], Serafim Bakalis[a,b], Peter J. Fryer[a], Estefania Lopez-Quiroga[a,*]

[a] *School of Chemical Engineering, The University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK*
[b] *Faculty of Engineering, The University of Nottingham, Nottingham, NG7 2RD, UK*

ARTICLE INFO

Keywords:
Energy demand
Food manufacturing
Sustainability
UK

ABSTRACT

Background: The food industry is heavily dependent on fossil fuels and significantly contributes to GHG emissions. The global population is also growing and food demand is expected to increase a 60% by 2050. To combat environmental pollution and create a more sustainable food sector, energy use during manufacturing needs to be reduced.
Scope and approach: To gain a better understanding of the energy employed in manufacturing and distribution of foods - within the UK and globally - energy usage within the food industry has been collected from literature and clustered by product, processing technique and transportation method.
Key findings and conclusions: Energy figures show that instant coffee, milk powder, French fries, crisps and bread are among the most energy intensive food products. The thermal processes involved in their manufacturing consumed large proportions of the total processing energy. In the meat and dairy processing sectors, energy and water use have increased due to a rise in hygienic standards and cleaning requirements. Additionally, meat products are processed - and sometime over processed - to a higher degree for consumer convenience, all this increasing the associated energy usage for manufacture. Regarding food transportation, more than 98% of all foods within the UK are transported by road, and the distances travelled have increased in recent years. Tertiary distribution using rigid vehicles was the most energy intensive transportation method, while primary distribution at ambient temperature was the least. Refrigerated transportation, which is more intensive than stationary refrigerated systems, has also increased during the past years.

1. Introduction

The food sector consumes globally approx. 200 EJ per year (FAO, 2017; EIA, 2017), of which a 45% corresponds to processing and distribution activities (FAO, 2011; Sims, Flammini, Puri, & Bracco, 2015). In the UK, the food processing industry is the largest single manufacturing sector, with an annual turnover of £97.3bn and 400 k employees (Food and Drink Federation, 2018). It is also the fourth largest industrial energy user: 117 petajoules (PJ) consumed in 2017 (Department for Business, Energy and Industrial Strategy, 2018a).

This energy intensity is linked to large levels of greenhouse gas emissions (GHGEs) and depleting resources (FAO, 2017). While the use of solid fuels has steadily declined, the food industry is still reliant on other fossil energy sources (FoodDrinkEurope, 2015; Department for Business, Energy and Industrial Strategy, 2018a,b) like natural gas and petroleum, so current practices in food manufacture are considered unsustainable (EEA, 2015; FAO, 2017). The environmental impact of food distribution also needs to be considered. The amount of food transported by heavy goods vehicles (HGVs) in the UK has increased by 23% since 1978 - 287 Mt only in 2017 (Department for Transport, 2018) - and distances travelled have increased by more than 50% (DEFRA, 2005). The globalisation of the food industry has caused concerns over food security and an increasing gap between suppliers and consumers. It has also initiated a debate over the environmental impacts and cost of food miles (Coley, Howard, & Winter, 2009; Pretty, Ball, Lang, & Morison, 2005).

In response to environmental policies and rising social concerns, the food manufacture sector has already undertaken important transformations to meet long-term reduction goals on energy and water demand (e.g. fuel switching, investment in new energy efficient equipment and low carbon technologies). Initiatives like the “Five-Fold Environmental Ambition” promoted by the UK Food and Drink Federation have led to a 44% reduction (by 2014 from the 1990 baseline) in CO_2 emissions from energy used in manufacturing (FDF, 2016). However, in a global scenario of growing population and food demand – the food industry will have to meet the demands of 9 billion

* Corresponding author.
E-mail addresses: ladhaa@adf.bham.ac.uk (A. Ladha-Sabur), serafim.bakalis@nottingham.ac.uk (S. Bakalis), p.j.fryer@bham.ac.uk (P.J. Fryer), e.lopez-quiroga@bham.ac.uk (E. Lopez-Quiroga).

https://doi.org/10.1016/j.tifs.2019.02.034
Received 5 June 2017; Received in revised form 31 December 2018; Accepted 6 February 2019
Available online 08 February 2019
0924-2244/

people by 2050 (FAO, 2017) – additional efforts (Gowreesunker, Mudie, & Tassou, 2017) are required to meet the 2050 sustainability goals (80–95% energy reduction from the 1990 baseline) (European Commission, 2012).

To achieve further reductions on energy demand during food manufacture and distribution, hotspots must be first identified. Energy data corresponding to different food processes can be found in a number of handbooks providing a general overview of food systems (Arendt & Zannini, 2013; Singh, 2013; Smith, Cash, Nip, & Hui, 1997; Van Alfen, 2014) or focusing on food and energy (Klemes, Smith, & Kim, 2008; Morawicki & Hager, 2014; Pimentel & Hall, 1984; Stanhill, 1984; Wang, 2008) and on climate change (Paloviita & Järvelä, 2016). On the other hand, detailed, comprehensive surveys compiling energy consumption data for a variety of food products are scarce. One of the most complete surveys on energy use within the food sector was conducted by Carlsson-Kanyama and Faist (2000). A large amount of data on food processing was collected, and details about the products, processes and energy sources were often specified. Similarly, Foster et al. (2006) analysed the life cycle of many food products in a report produced for DEFRA (Department of Environment, Food and Rural Affairs, UK Government) to provide UK-specific information. Energy use across stages of the life cycle of products was clearly shown and the most energy intensive stages were easy to identify. The analysis undertaken attempted to identify activities that were energy intensive, but data was predominantly reported in terms of primary energy use, making it more difficult to compare the energy efficiency with other literature. Analogous studies focused on energy consumption in the U.S. food system were conducted by Hendrickson (1996), who summarised energy data by food sub-sectors and also provided a deep analysis on potential reduction measures to be adopted, and more recently by Compton, Willis, Rezaie, and Humes (2018), who updated processing energy use data and reported more efficient processes.

Typically, studies reporting data on energy use focus on foods grouped by chain/sub-sector (e.g. cereals, confectionary products, etc). For example, energy use data for different dairy products has been reported by Cox and Miller (1986), Briam, Walker, and Masanet (2015), Ramirez, Patel, and Blok (2006a), Xu and Flapper (2009; 2011) and Xu, Flapper, and Kramer (2009). Similarly, Therkelsen, Masanet, and Worrell (2014) focused on reporting efficiency opportunities in the U.S. baking sector, Özilgen (2016) calculated energy consumption in snacks and Wojdalski et al. (2015) evaluated energy efficiency in the manufacture of confectionary products. Processors can also be useful sources of data (e.g. British Sugar) as well as LCA studies - for example works by Braschkat, Patyk, Quirin, and Reinhardt (2003) on bread, Del Borghi, Gallo, Strazza, and Del Borghi (2014) on tomato products, Pardo and Zufía (2012) on food preservation technologies, Rivera and Azapagic (2016) on ready meals or Konstantas, Jeswani, Stamford, and Azapagic (2018) and Konstatas, Stamford, and Azapagic (2019) on chocolate and ice cream, respectively. Energy use data of single foods products is often paired with specific processes, particularly for emerging technologies. Examples can be found in Jindarat, Sungsoontorn, and Rattanadecho (2014) for microwave assisted drying of coffee beans, in Sharma and Prasad (2006) for microwave drying of garlic cloves, in Atuonwu et al. (2018) for pasteurisation of orange juice using high pressure, ohmic and microwave processes, or in Moejes and van Boxtel (2017) for the manufacture of milk powder. Information on energy consumption for indivual processes is sparse. For example, Pathare and Roskilly (2016) investigated meat cooking; Liu, Zhao, and Feng (2008) studied freeze-drying; Swain (2006) assessed energy consumption in refrigeration processes; Motevali, Minaei, and Khoshtagaza (2011) focused on drying; while Li, Ziara, Dvorak, and Subbiah (2018) provided energy data for packing (meat).

Overall, available energy use data for food manufacture is very fragmented, and a single comprehensive database is lacking. To address this and update previous work, energy use for the processing and transportation of food goods was obtained from the literature to isolate energy intensive activities and provide starting points for energy reduction measures. This data can be also used to feed sustainability analysis tools such as Life Cycle Assessment (LCA) and carbon or water footprint, helping to assess and secure the environmental performance of the whole food chain. Processing energy use figures were clustered both by product (Section 3 and Appendices A-G in the Supplementary Data) and by technique (see Appendix H, Supplementary Data). Data collected for transportation methods was analysed in terms of distances and product carried (Section 4 and Appendix I in the Supplementary Data). Packaging, the retail sector and consumer activities were outside the scope of this study. General and UK specific trends were identified where possible (Section 5). The survey also exposed areas where data is not available.

2. Methodology framework

A literature survey was carried out to collect energy consumption for the food manufacturing sector for the time period 1980 to 2015. ScienceDirect was the main source for published papers, and Knovel was used for online access to books. Full access to some publications was obtained from the authors (Carlsson-Kanyama & Faist, 2000; Van Alfen, 2014)). Specific energy consumption (SEC) data for products, processes and food distribution was collected based on *product-based energy intensity* (PEI) metrics (Briam et al., 2015), where energy input in megajoules (MJ) was divided by product output in kilograms (kg) - energy intensity expressed in different units was converted when possible. This format was chosen to provide a consistent comparative basis. Data was manipulated as little as possible to minimise errors as SEC values were collected for a large range of products, processes, locations and dates. LCA (Life Cycle Assessment) studies reporting lumped SEC values were not considered for this analysis. Nor were energy audits that reported overall energy use from processing plants. This search yielded a total of 44 publications, with the Netherlands, New Zealand and Sweden being the countries where most studies were found.

Energy studies used different accounting methods and system boundary conditions when quantifying a product or activity. This resulted in a large range of SEC values where the steps and processes involved were unknown. The accuracy of data was also often not mentioned. Different energy sources were reported, and these were kept in their original format to analyse the ratio of each type used for a given activity. Equipment details were rarely provided and often details like the location of the study, the processes included, the production scale and the energy sources were not specified, as also observed by Xu and Flapper (2011). Energy intensities of products and processes obtained by studying the total energy consumed by processing plants (Xu & Flapper, 2011) did not always account for differences in product mixes, locations, energy sources, production scale and equipment age (Carlsson-Kanyama & Faist, 2000; Van Alfen, 2014). These factors could have a large impact on SEC values obtained. Allocating SEC values for multi-product activities was also particularly complex; as an example, whey production shares processes with cheese making. To quantify SEC values for whey production, some researchers included energy consumed by those shared operations while others excluded them (Foster et al., 2006).

Once the data set was collated, the following information was recorded: the date and location of the study, product description, processes involved, energy sources, and bibliographic reference. Before analysis, the data was sorted into the following groups: prior to 2000, 2000–2004, and 2005–2015, to account for changes in technologies, processing and fuel efficiencies, and structural changes within the sector. A large number of energy studies were conducted in the 1970's and 1980's - Berry and Makino (1974); Beech (1980); Cleland, Earle, and Boag (1981); Slesser and Wallace, (1982); Stanhill (1984); Pimentel and Hall (1984); Cox and Miller (1986) - and it is noteworthy that recent publications, such as Ramirez et al. (2006a), Van Alfen (2014) or Xu et al. (2009), still report those figures due to the lack of

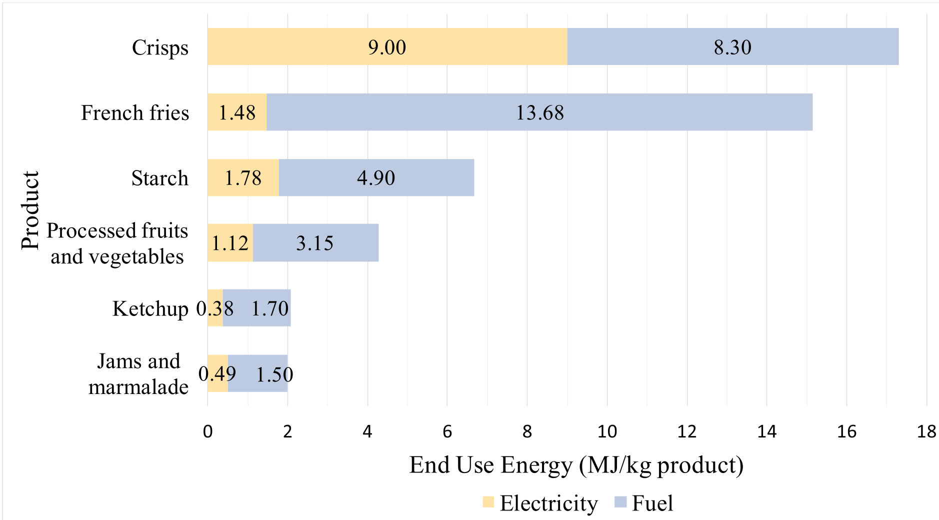

Fig. 1. Energy consumed to process fruits and vegetables (Source: Appendix C).

more recent data. Average energy consumption values for processes and products were only calculated when more than two replicates were obtained from literature. Additionally, only energy expressed in its final form was analysed as conversion efficiencies can vary. For example, the efficiency of electricity production can differ based on the type of fuel, the power plant capacity and the technology employed for production (OECD, 2012). Finally, food products were clustered in seven categories: grains and oilseed milling, sugar and confectionary, fruit and vegetable, dairy, bakery, meat and others - SEC values are shown in Appendices A-G. Energy use figures organised by process are listed in Appendix H, while transportation data is presented in Appendix I. All the Appendices are available as Supplementary Data.

3. Energy consumption by product

Total energy consumption data in the literature was reported with different combinations of energy sources. In some cases, the energy source was not specified. Therefore, results are presented in three different formats to allow for comparison:

- Electricity and thermal energy
- Electricity, fuel and steam energy
- Total energy, source unspecified

Unless stated otherwise, all energy consumption figures in this work do not include packaging.

3.1. Grains and oilseed milling - Appendix A

Apart from flour milling, energy consumption data in this sector was very sparse. Between 2005 and 2015, an average of 0.42 MJ/kg of electricity and 0.03 MJ/kg of fuel was reported for the milling process (Appendix A). Rice required the least amount of energy and was quoted to consume 0.43 MJ/kg in 2013. Data from multiple sources from 1975 to 1996 reported 66 MJ/kg was used for manufacture of breakfast cereals (Appendix A), including grinding, milling, wetting, drying and baking. Aguilera, Simpson, Welti-Chanes, Aguirre, and Barbosa-Cánovas (2011) confirmed the findings on breakfast cereals and discussed milling of flour as an energy intensive process. Three milling methods are commonly used: wet, semi-dry and dry. Dry milling is the most energy efficient process while wet milling is energy intensive (Arendt & Zannini, 2013). This suggests that the low SEC values obtained from literature might be for dry milling.

3.2. Sugar and confectionery - Appendix B

SEC data for popular confectionery products like chocolates and sweets is lacking. Average SEC values for the production of sugar from beets and sugar cane are presented in Appendix B. No data prior to 2005 was found. The average fuel consumption appears to decrease over time while slightly more electricity is used. As data shows, the average total energy (6.90 MJ/kg) was higher than the sum of average electricity and fuel use within the same time frame (3.26 MJ/kg). Sugar extraction data from 1986 ranged from 2.3 to 26 MJ/kg.

In 2010, 160 million kg of sugar was produced globally, with 20% produced from sugar beets. A Japanese sugar factory reported that 65% of its thermal energy was used by the evaporative crystalliser. Melting and centrifugal drying consumed 25% and 22% of total electricity, respectively (The Energy Conservation Centre, 2016). However, this energy demand might be decreased by using multi-stage evaporation and heat exchanger networks. An alternative energy-reduced sugar manufacturing process also exists: the juice purification step is removed and evaporative crystallisation of sugar is replaced by cooling crystallisation from concentrated raw juice (Klemes, 2013). Energy can also be recovered by using biofuels like bagasse, the lignocellulose residue obtained from sugar cane post extraction (Singh, 2013).

3.3. Fruits and vegetables - Appendix C

From data collected, potato-based products consumed the most energy (Fig. 1). No data for crisps and French fries were found later than 1998. These values, when compared to other products within the same time frame, were significantly higher.

Drying potatoes consumes large amounts of energy due to the high initial water content of the raw material (Wu, Tassou, Karayiannis, & Jouhara, 2013). Crisps are dried until a 2% water content is achieved, and since potato flakes have a lower final water content than French fries, their production is much more energy intensive (Foster et al., 2006). Single and double-drum dryers are typically used (Mujumdar, 2014) to dehydrate potato-based products. Increasing the drying air temperature can increase the drying rate, however the product quality might be damaged. The use of ultrasound to improve water mobility has been proposed, with experimental results showing that the drying time can be shortened by 40% compared to experiments where ultrasound was not used (Ozuna, Cárcel, García-Pérez, & Mulet, 2011). The energy consumed to produce vegetable oil was not included in any of the literature discussing these products. Energy studies on multi-ingredient products were rarely found.

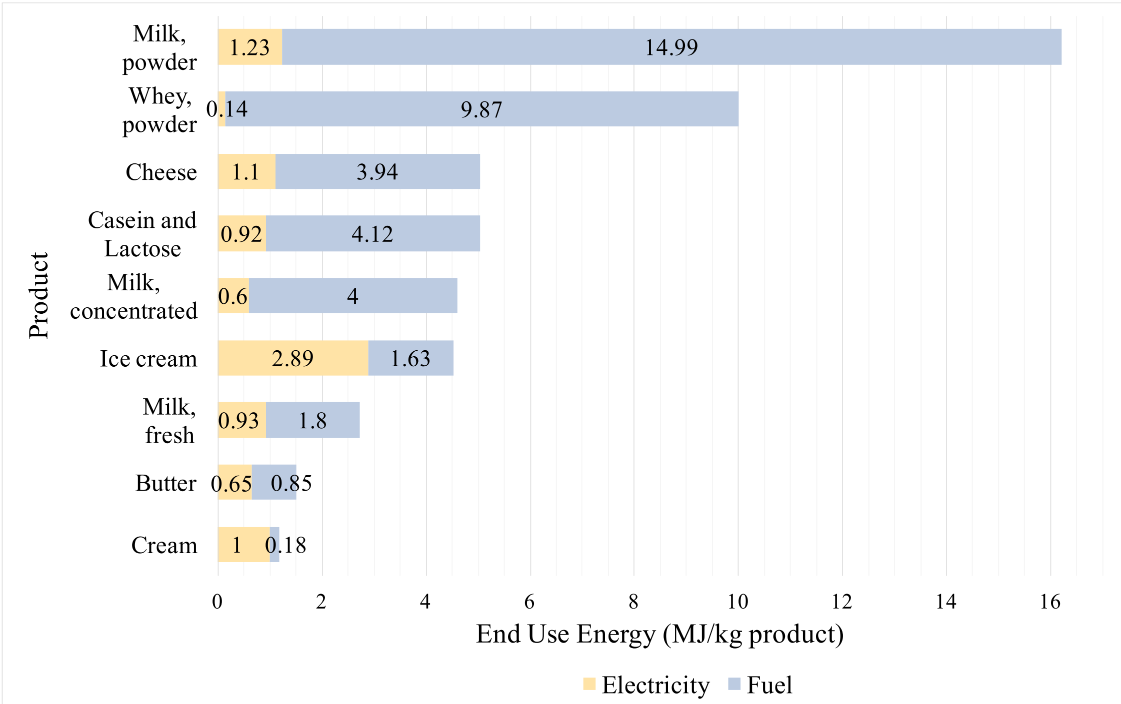

Fig. 2. Average final electricity and fuel energy consumed to produce dairy products (Source: Appendix D).

3.4. Dairy - Appendix D

Dairy processing is considered one of the most energy intensive sectors within the food industry (Briam et al., 2015). Many dairy products are manufactured by concentrating raw milk and separating solids to varying degrees. Electricity is typically used for pumps, refrigeration, control and separation while thermal energy is employed for cleaning, evaporation and pasteurisation (Xu & Flapper, 2011). Daily cleaning-in-place (CIP) operations consume large amounts of energy (Xu et al., 2009), since raw milk is highly perishable and strict hygiene standards must be followed. Fig. 2 summarises the energy used by dairy products, where concentrated milk includes evaporated and condensed milk. Milk powder requires significantly more energy than cheese, since both drying and evaporation steps are required (Ramirez et al., 2006a). However, when SEC data reported as total consumption values were analysed, cheese was the most energy intensive (13.85 MJ/kg), followed by powdered milk (10.30 MJ/kg) (Appendix D). More data for processed milk and cheese were found, perhaps due to the size of the market and the milk quota system that resulted in close monitoring of milk production in Europe (Ramirez et al., 2006a). On the other hand, data for butter, cream, ice cream and yoghurt were scarce.

Milk pasteurisation can consume 17%–26% of the total energy (Van Alfen, 2014). This process can be optimised by recovering 90%–94% of heat input (Ramirez et al., 2006a). Ultra-high temperature (UHT) and sterilisation processes are more energy intensive as higher temperatures are required. Most data collected did not specify the type of treatment employed to process the milk (Appendix D). For the production of milk powder, the concentration and drying steps were the most energy intensive, accounting for 45% and 51% of primary energy respectively (Appendix E). Spray drying is the most common drying process used, requiring 10 to 20 times more energy per kg of water evaporated compared to drying using evaporators. To reduce energy use, evaporators are used to pre-concentrate prior to drying (Ramirez et al., 2006a).

Compared to processed milk, cheese requires over nine times more water, four times as much raw milk and electricity, and three times more fuel (Foster et al., 2006). The energy required can vary significantly depending on the type of cheese, process conditions, and the plant age and size (Xu et al., 2009). Cheese typically needs to be ripened in a controlled environment. If cheese needs to be ripened for more than 14 days, this can increase the specific energy demand by 9–65% (Van Alfen, 2014).

Differences in raw material and final product characteristics, processes involved and operating conditions can affect the energy consumed by dairy products. For example, cheese plants may supply liquid whey that needs further concentration prior to drying (Xu & Flapper, 2011). Additionally, soya milk is produced using soybeans and requires significantly more processing than cow's milk such as peeling, grinding, filtering, adding sugar and flavours (Foster et al., 2006). Dairy industries in Canada, Norway, the Netherlands and the United States use heat pumps to reduce energy use in processes like pasteurisation, evaporation and drying.

The dairy processing industry needs more tools and programs to reduce energy demands. However, many dairy organisations may not have the resources to undertake thorough assessments that would hasten energy reductions in this sector (Xu & Flapper, 2011).

3.5. Bakery - Appendix E

Energy studies in this sector focused on baking and bread manufacturing. The average SEC value obtained was 5.21 MJ/kg (Appendix E). Less than 1% of bread in the UK is imported, and it is regularly consumed by 96% of the population. Three quarters of sold bakery goods are produced by large-scale plant bakeries, and the remainder is made by smaller in-store and craft bakeries (Foster et al., 2006). However, bakeries can consume twice as much energy as large bread factories (Braschkat et al., 2003).

A US study conducted by Therkelsen et al. (2014) was used to compare bread production to other bakery goods. Four products undergoing similar processes were examined, and average SEC for each product reported. Baking and freezing constituted the most energy demanding steps (see Fig. 3), while biscuits, breads and rolls required longer baking times than cakes and pies - their SEC values were therefore higher than the 2.50 MJ/kg consumed by cakes (Fig. 3).

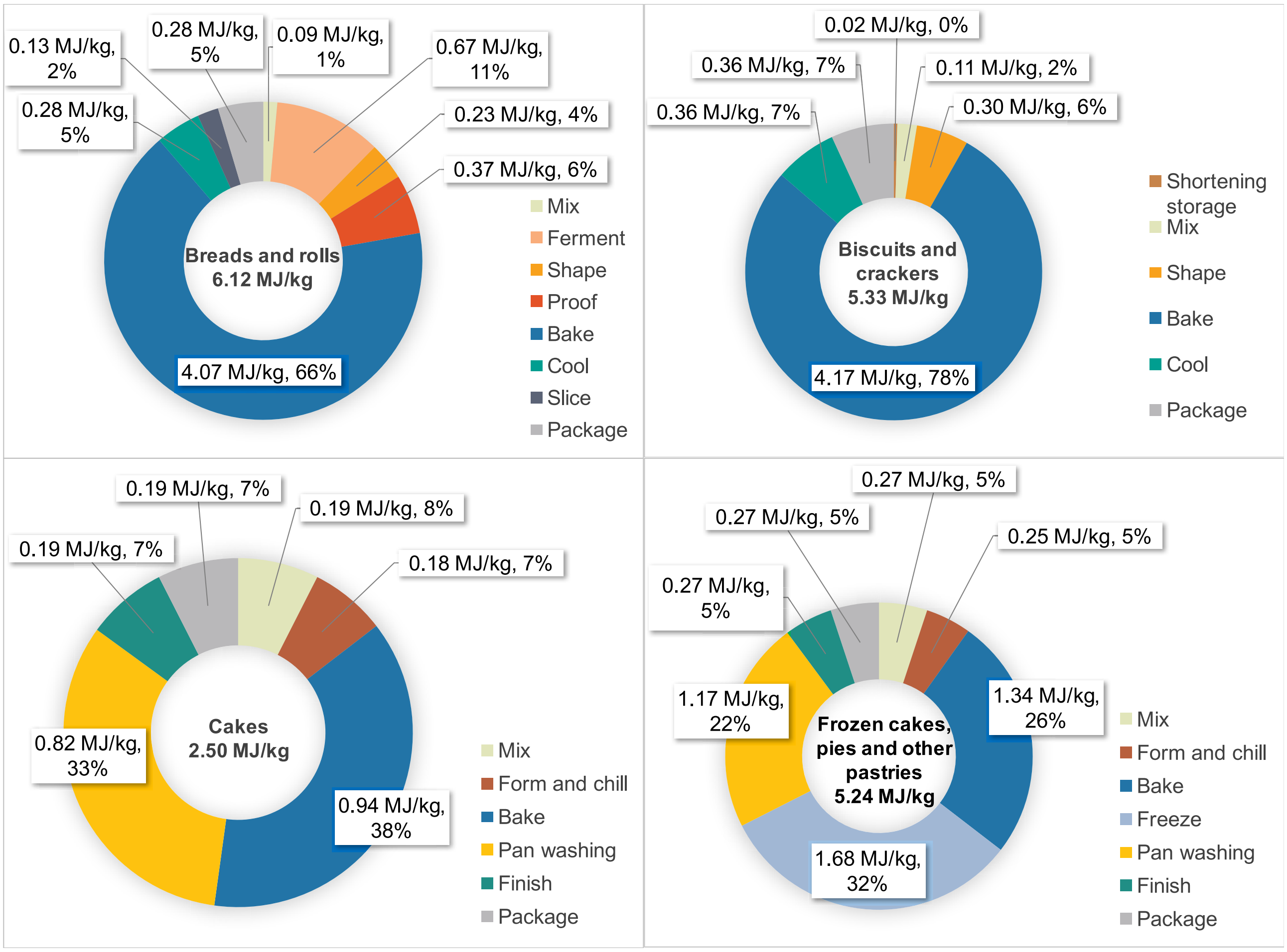

Fig. 3. Energy consumed to produce bakery products (Adapted from: Therkelsen et al., 2014).

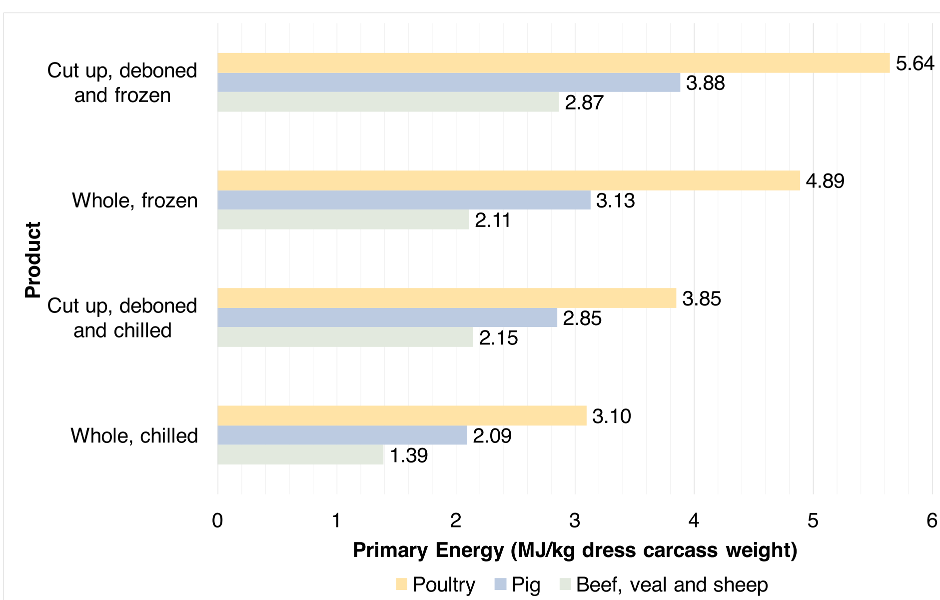

Fig. 4. Average primary SEC values for meat processing (Source: Appendix F).

Energy intensity of baking processes is related to the low values of convective heat transfer coefficients through air (approx. 30 W/m^{2}K) (page 508, Klemes et al., 2008). Direct-fired natural gas ovens are often used, although electric ovens appear to be more efficient (page 508, Klemes et al., 2008). In continuous gas fired ovens, large amounts of heat are dissipated through exhaust gases (page 508, Klemes et al., 2008). Such percentages can vary significantly depending on the operating conditions, which suggest ovens can be optimised to increase

Table 1
Thermal energy required to produce instant coffee (Adapted from: Okada et al., 1980).

Process	Units	Thermal energy
Roasting	MJ/kg product*	3.73
Extraction	MJ/kg product*	8.50
Concentration	MJ/kg product*	7.45
Spray drying	MJ/kg product*	21.10

* Instant coffee.

energy efficiency (Khatir, Paton, Thompson, Kapur, & Toropov, 2013; Therdthai, Zhou, & Adamczak, 2002), e.g. by recirculating part of the oven exhaust gas. However, this should be done without impeding the product safety and quality. Large amounts of hot water and steam are also consumed in baking plants. Steam is used for temperature and humidity control in fermentation boxes and rooms, and cleaning equipment. Boiler systems can be optimised using different measures such as proper sizing and process control.

3.6. Meat and fish - Appendix F

In 2001, the UK meat sector consumed 32 petajoules (PJ) of primary energy. UK electricity usage increased by 2.9% annually from 1990 to 2001 from increased demands for refrigeration and motor drive power (Ramirez, Patel, & Blok, 2006b). An increase in the consumption of poultry and processed meat products has been observed also in Europe - 9% rise from 2007 to 2014 according to (Marquer, Rabade, & Forti, 2015). Processes that use large proportions of electricity and fuels in different meat sectors were reported by Ramirez et al. (2006b): poultry slaughtering consumes more energy than other meats due to hair and feather removal, and singeing operations. An increase in the use of automated equipment, temperature control and hot cleaning water has raised energy consumption in slaughterhouses.

Meat products are frozen, cut and deboned more often to provide convenient products for consumers. These processes are compared in Fig. 4. There was a lack of SEC data in this sector so primary energies were employed. Final energy values could not be calculated as the study was carried out in different countries.

Typically, meat frozen products consumed more energy than chilled ones (Fig. 4). Poultry products were the most energy intensive while beef, veal and sheep were the least. Greater refrigeration requirements and higher temperatures during hard scalding make poultry products more energy demanding. Conversely, to produce 1 kg of broiler meat, poultry feeding requirements are 3.1 kg of dry matter feed, compared to 6.3 kg for pigs and 24 kg for beef cattle (Ramirez et al., 2006b). Vacuum packed and ready-to-eat products are also raising energy use. As this sector is largely influenced by consumer preferences, they must be considered when analysing energy consumption to better understand the progress made in energy efficiency. Also, life-cycle studies rarely focus on meat processing, as stated by Roy et al. (2009).

Energy studies on seafood processing were scarce. Average SEC values for fish processing were 0.38 MJ/kg electricity and 1.87 MJ/kg fuel (Appendix F), although the accuracy of the analysis is uncertain due to the limited data found.

3.7. Others - Appendix G

Coffee was the most energy intensive product in this category. The UK, with a preference for medium roasted and instant coffee (Chanakya & De Alwis, 2004), consumes approximately 95 millions of coffee cups per day (The Bristish Coffee Association, 2018). Coffee beans, obtained from primary processing, are sent for secondary processing, which includes dehulling, roasting and grinding. Roasted coffee consumes an additional 0.4 MJ/kg of electricity and fuel compared to non-roasted coffee (Wang, 2014). A continuous roaster consumes approximately 0.5 MJ/kg green coffee compared to a batch roaster that uses 1.84 MJ/kg (Okada, Rao, Lima, & Torloni, 1980). While these energy figures do not appear significant, data collected in 2013 reported a total of 23.24 MJ/kg for the processing of coffee (Lillywhite, Sarrouy, Davidson, May, & Plackett, 2013). Instant coffee, produced from tertiary processing, consumed 2.70 MJ/kg of electricity and 45 MJ/kg of fuel in 1980 (Cleland et al., 1981), while a more recent study (Morawicki & Hager, 2014) reported 8.3 MJ/kg of electricity and 30.2 MJ/kg of fuel. Processing coffee requires a much larger quantity of thermal energy compared to electricity. The thermal energy used by each unit operation to produce instant coffee as reported by (Okada et al., 1980) is shown in Table 1. Instant coffee is more energy intensive due to the spray drying process. Freeze-drying is also used for instant coffee production and it can consume 0.42 MJ/kg to freeze and as much as 31 MJ/kg to dry (Appendix H). A combined microwave-hot air spouted bed was recently explored as a novel drying method and produced good quality coffee (Jindarat et al., 2014). Developing good flavour is crucial in the coffee industry, however, energy reductions must be made during the extraction, concentration and drying steps.

4. Transportation

Most of the research found focused on the transportation of unprocessed goods. Centralised and local food systems were also often compared to determine the validity of food miles. While reducing food miles lowers transport-related energy consumption, Carlsson-Kanyama (1998) showed that food miles may be irrelevant, in that farm-gate emissions for the production, storage and transportation of tomatoes from Israel to Sweden were lower than those for local production in UK glasshouses. According to this, the supply chain might be better evaluated as a whole. Tassou, De-Lille, and Ge (2009) summarised the average energy consumed at different stages of food distribution in the UK. Articulated vehicles (32t to 44t) are typically used for primary and secondary distribution, and account for 80% of the tkm of all good movements in the UK. Rigid vehicles up to 32t transport goods in tertiary distribution and are the most energy intensive. Mixed temperature distribution is energy intensive as heat transfer between different compartments must be controlled. Additionally, refrigeration systems must be designed to minimise disruptions from activities like loading products and opening doors (Tassou et al., 2009).

The energy consumed during temperature-controlled distribution varied with the distance, type of vehicle, distribution, and product (chilled or frozen). While a higher temperature difference is needed for frozen products, chilled foods can consume more energy. Higher air flows are needed for uniform temperature distribution, products respire and temperature control requirements are tougher. The varied environmental conditions and vibrations from the road were also found to result in higher emissions for transportation refrigeration systems compared to stationary systems. As major retailers in the UK are making more home deliveries and quality expectations are increasing, light vehicle refrigerated transportation must be optimised (Tassou et al., 2009). More than 98% of all foods within the UK are transported by road. Regional distribution centres (RDCs) are therefore often located next to a motorway (Jones, 2002).

Data corresponding to energy intensity of road transportation alongside other common modes of transport can be found in Van Hauwermeiren, Coene, Engelen, and Mathijs (2007). According to this source, air transportation was the most energy intensive while inland bulk transportation by vessel was the least. The transportation distance was also compared to model transportation between neighbouring countries, continental and international transport. Transportation by electric freight train was more energy intensive than by truck, however, SEC values are dependent on factors like the transportation speed, load factor and weather condition (Van Hauwermeiren et al., 2007). Transportation to and from the loading points was not included.

The energy use of railroad transportation has decreased significantly over the years. Road freight vehicles are now considered more energy intensive, and the number of electric freight trains in the EU is rising. GHG emissions are lowered by the reduction of road traffic and the use of electric powered vehicles (Gazzard, 2014).

5. UK energy consumption trends

Consumer preferences and regulations have influenced the energy requirements, structure and level of concentration of the UK processing industry. For example, through market reform, the number of sugar factories in Europe has decreased and the processing capacity of beets has increased. The UK is one of the top producers of sugar beet, growing around 8 million tonnes per year (British Sugar, 2018). As beets have a water content of 75% by mass, significant amounts of energy are needed to produce dry crystalline sugar (Appendix B).

Potatoes are important vegetables in the UK food market and approximately 6 million tonnes are processed each year (Foster et al., 2006). As previously mentioned, drying potatoes is energy intensive. In terms of dairy products, cheese is the second most consumed product after milk, particularly cheddar, and cheese production continues to increase (Foster et al., 2006). In 2000, 30% of the net fuel use in the UK dairy processing sector was consumed by drying and concentration processes (Ramirez et al., 2006a). The UK sector was less energy intensive in 2005 compared to Netherlands, Denmark and Norway, partially due to a lower production of energy-intensive products. However, UK GHGEs were the highest, probably due to different shares of energy sources (Xu et al., 2009).

In the 2017, energy used in food processing was mainly obtained from natural gas (58%) and electricity (34%) (Department for Business, Energy and Industrial Strategy, 2018a), accounting petroleum and coal for the rest.

The relationship between the energy density, the weekly UK consumption and processing energy use for different products were compared in Fig. 5 and Fig. 6. Consumption data were obtained from DEFRA (2015) and average energy densities were calculated from a nutrient database produced by the US Department of Agriculture (USDA, 2016). There were no clear trends between the variables, although this may be due to a lack of data for diverse products. The modern diet in developed countries consists of more energy-dense foods that can prompt weight gain. Food processing can increase the energy density as the water and fibre content are often reduced. The addition of sugar, fat and salt can enhance palatability, which may lead to overconsumption (Webb, 2012) and non-communicable diseases (Augustin et al., 2016) like diabetes. Relatively large volumes of soft drinks are consumed (Fig. 6), which are energy dense due to the high sugar content (Bagchi, 2010). Processed foods with low nutritional value are not considered part of a sustainable diet according to the Food and Agriculture Organisation of the United Nations, although they may have lower associated GHGEs (Drewnowski et al., 2014). Approximately 25% of adults and 20% of children in the UK are obese, and reducing the energy density of processed foods could have an impact on lowering these figures (Cunningham & Harney, 2012).

6. Discussion and remarks

6.1. Limitations of the study

Identifying energy consumption trends is difficult as the food processing industry is very fragmented, products are processed to varying degrees and production is not always continuous (Preface, Klemes et al., 2008).

This survey has collated data that gives a better understanding of energy consumption across different food processing sectors. While the accuracy of reported data could not be determined, i.e. error measurements or uncertainties are rarely reported in energy accounting studies (Paoli, Lupton, & Cullen, 2018), general trends in processing can be identified as well as hot spots. There is a lack of comprehensive and up to date data, and many recent sources still reported dated figures. Estimation and reporting of energy consumption data did not follow a standard methodology, and there were large variations in the estimated energy used for the same food products or processes. Consequently, SEC values could only be assigned to general food groups rather than specific food products. In addition, some energy studies quantified energy consumed by individual plants, however a wide range of SEC values were often reported due to differences in product mixes and equipment condition. The level of capacity utilisation would also affect the SEC values assigned to products (Ramirez et al., 2006a). To ease future investigations and increase the level of accuracy, standardised accounting methods for energy use during food processing that include estimation and propagation of uncertainty must be developed. Paoli et al. (2018)

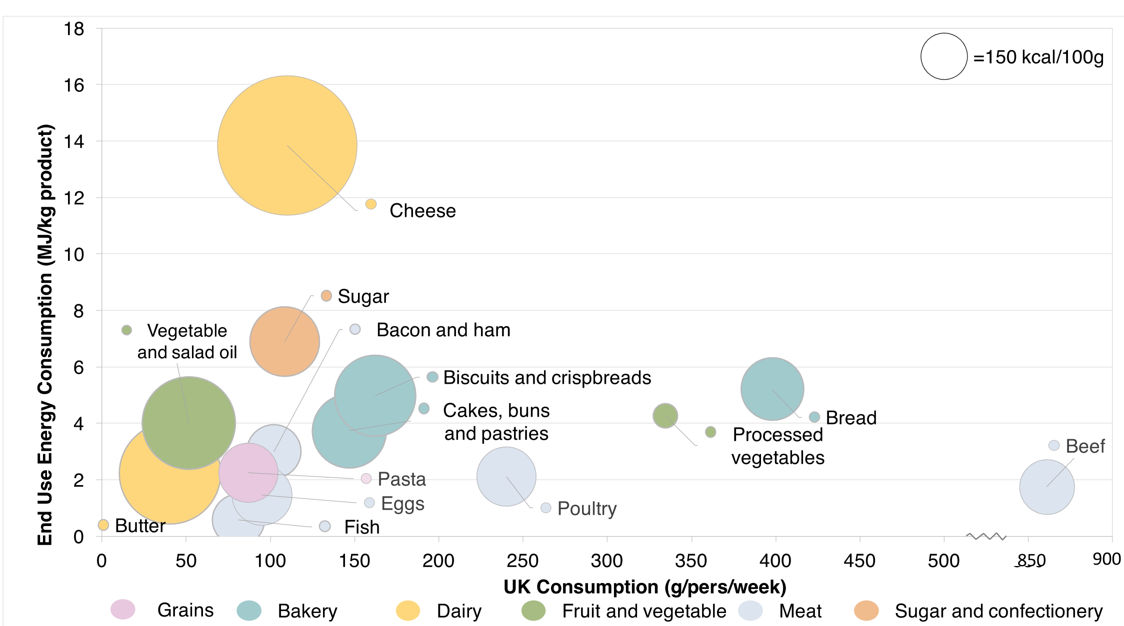

Fig. 5. The energy density, UK consumption and final processing energy use (as end use energy consumption) of solid food products. The sizes of the circles represent the energy densities.

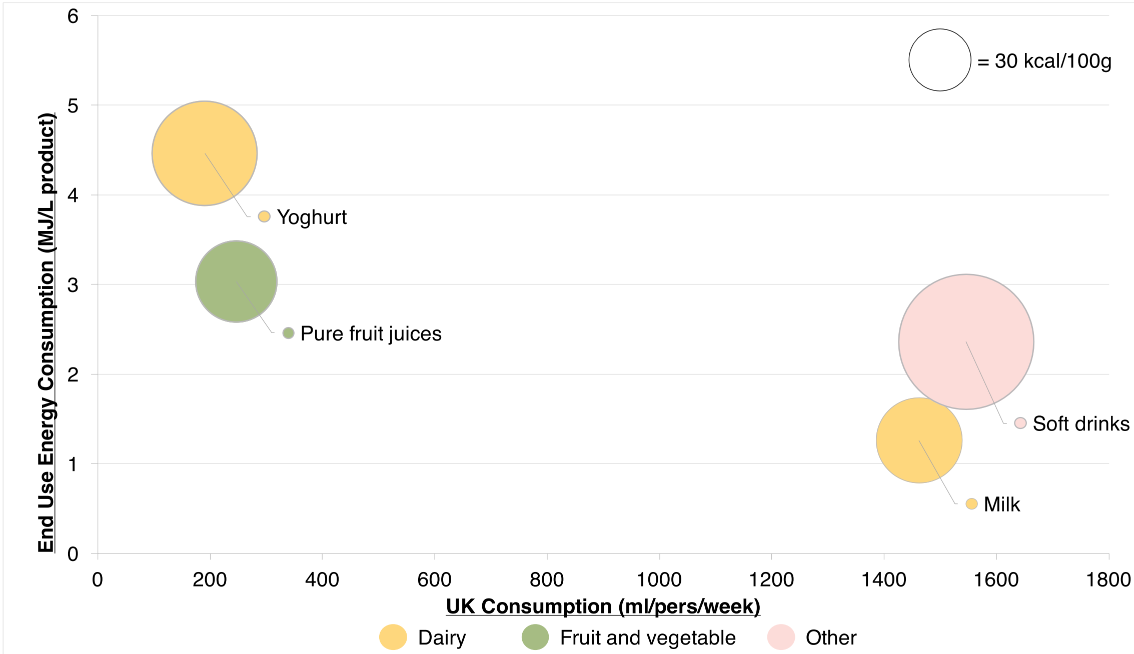

Fig. 6. The energy density, UK consumption and processing energy use (as end use energy consumption) of liquid food products. The sizes of the circles represent the energy density.

has allocated a 25% uncertainty to useful energy demand of the UK industrial sector – this needs to be broken down for the food industry sector.

No account has been taken on the fuel mix for energy generation. This can vary widely between countries: Swedish electricity is almost entirely generated through hydropower and nuclear energy (Foster et al., 2006). In contrast, the UK food manufacturing sector heavily relies on fossil fuels – natural gas accounts for 58% of energy consumed in 2017, with coal and petroleum representing a 6% (Department for Business, Energy and Industrial Strategy, 2018a) - and in consequence it generates more GHGEs (a total of 23 Mt CO_2e in 2015 (DEFRA, 2018a)). Figs. 2, 3 and 5 also reflect this strong dependency on fossil fuels. While more energy intensive activities may not necessarily result in higher levels of GHGEs, effective energy management is also important to reduce costs and alleviate risks associated with changes in energy prices and supply shortages (Briam et al., 2015).

Little data has been found on ready-to-eat meals that are increasingly popular and typically need to be cooked, preserved, and chilled or frozen (Pardo & Zufía, 2012). The meat industry produces a wide variety of products, however a detailed analysis was not possible due to the lack of data. While some data was available for meat and poultry, little data on seafood products was found. Similarly, food products within the grain and oilseed milling, and sugar and confectionery categories were difficult to find. To better understand how resources are used in the food processing industry, more support is needed from producers to allow site-specific data to be obtained (Andersson, Ohlsson, & Olsson, 1998). The energy consumed to manufacture more complex meals also needs to be quantified.

6.2. Phase change processes

Thermal processes are energy intensive and responsible for a large proportion of the energy consumed in food processing. According to Klemes et al. (2008), p. 140, the US food and drink industry consumes 647 PJ for process heating and 73 PJ for refrigeration. In the UK, it has been estimated that about 68% of the energy is used for process and space heating, 8% is electric heating and 6% corresponds to refrigeration (AEA Energy and Environment, 2007). Heat is extensively used in heat preservation techniques (i.e. sterilisation and pasteurisation, see Appendix H).

Many other food thermal processes require first the addition of water to the product followed by its removal, which usually involves a phase change. For example, baking, drying and freeze-drying are energy intensive (see Appendix H) operations due to the high latent heat of vaporisation and sublimation of water present in the raw material or added in during processing (freeze-drying involves both phase changes). Consequently, products that are freeze-dried - like instant coffee (average of 50.20 MJ/kg, Appendix H) or milk powder (average of 16.22 MJ/kg, Appendix E) - or dried - such as French fries (average of 15.16 MJ/kg, Appendix D) and crisps (average of 17.30 MJ/kg, Appendix D) - consume significant amounts of energy. The thermal efficiency of industrial dryers is also low, so large amounts of energy are wasted (Wang, 2008). Commonly this energy is supplied by fossil fuels rather than electricity, as indicated in Fig. 1. Although electricity and gas show very similar high performance in terms of efficiency and flexibility of use, the lower price of gas might explain its preferred use - average prices of 1.8 pence/kWh and 8.3 pence/kWh for gas and electricity, respectively in 2017 as reported by the UK Department for Business, Energy and Industrial Strategy (2018b).

6.3. Energy - efficient processes

Energy reductions can be made through process optimisation, technological and manufacturing behavioural changes (Tassou et al., 2014). The food industry could use methodologies employed in other industries like pinch analysis, where minimum process heating and cooling needs are determined prior to design (Ahmed & Rahman, 2012). An example of the potential reductions of this approach is given in Walmsley, Atkins, Walmsley, Philipp, and Peesel (2018), where savings up to 51% in thermal energy were estimated for production of milk powder. However, small food producers and processors are implementing energy optimisation strategies at a slower rate than their counterparts in other similarly sized industries (page 144, Klemes et al., 2008). For example, *ca.* 2300 small and medium sized enterprises produce bakery products in the UK (DEFRA, 2018b), and producing at a smaller scale is more energy intensive. Baking accounts for the majority of the energy consumed in this sector, and direct-fired natural gas ovens are still popular. Replacing them with electric ovens could help to reduce energy use. A rise in hygiene standards and cleaning requirements has increased energy use in the dairy and meat processing sectors. The dairy industry continues to be energy intensive due to the thermal processes employed to ensure microbial safety, however the use of falling film evaporators, heat recovery systems (Ramirez et al., 2006a) or process integration and optimisation (Fritzson & Berntsson, 2006) can significantly reduce energy demand.

More energy efficient process technologies can also provide energy savings. For example, supercritical extraction can replace concentration through boiling (Fellows, 2009), the use of membrane filtration (Ramirez et al., 2006a) can increase efficiency of dairy processes and osmotic pre-treatments can help to decrease the heating loads and times in drying processes (Prosapio & Norton, 2017). Emerging technologies, e.g. high pressure processing (HPP) (Juliano et al., 2012), ohmic (OH) (Barba et al., 2016) or microwave heating (MWH) (Jindarat et al., 2014), might increase the efficiency of food processes, while reducing the use of non-renewable resources (Barba et al., 2016). Their wide-scale application in the industry is limited by investment costs (Barba et al., 2016; Jermann, Koutchma, Margas, Leadley, & Ros-Polski, 2015), although they are slowly replacing and complementing conventional preservation technologies (Barba et al., 2016). For instance, microwave is used for drying, thawing or pasteurising (Barba et al., 2016; Atuonwu et al., 2018), an it is used as part of hybrid processing technologies too, e.g. or microwave -assisted freezing (Xanthakis et al., 2018, pp. 176–181). Non-thermal processes, like HPP, typically need less water and heat and could have a lower environmental impact (Atuonwu et al., 2018). Furthermore, the required energy source is electricity that could be generated from renewable resources, like biomass from food wastes (Pardo & Zufía, 2012). According to Jermann et al. (2015), ultraviolet light (UV) (Koutchma, Popović, Ros-Polski, & Popielarz, 2016), MWH and HPP technologies have the greatest commercialisation potential. On-going research focuses on reaching a complete understanding of process conditions and adapting HPP microbial safety protocols.

6.4. Decentralised food chains – distributed food manufacture

Energy is intensively used both for manufacture and product transport to the consumer. However, it might be possible to balance the intensity of the most energy demanding processes by decreasing the energy use at the transportation stage. For example, manufacturing of convenience food typically requires more energy, but it could reduce energy demand for storage and preparation in the retail and residential sector. Dried food products are also lighter to transport and their shelf life is extended, sometimes without the need of refrigeration (Ramirez et al., 2006b), e.g. transport of tea bags is more efficient than transport of bottled water. Distributed manufacture methods, in which only valuable ingredients are transported and other ingredients added later at the local level may lead to more energy efficient food chains (Roos et al., 2016). Such use of distributed manufacture will create entirely new decentralised food supply chains. In this decentralised food manufacture paradigm, techno-economic assessment tools are needed to decide which processes are the most efficient ones (Almena, Lopez-Quiroga, Theodoropoulos, Fryer, & Bakalis, 2017). LCA studies that evaluate the whole food chain will also be critical to understand how specific processes can impact other stages of the life cycle.

6.5. Future challenges

In addition to the environmental impact, the current global food system also creates socio-economic challenges such as market distortions and a dependence on food imports. However, the implications of creating a more decentralised/localised food supply system also need to be assessed (Almena et al., 2017). Findings that could improve the sustainability of the food system must reach a wider audience, including consumers and policy-makers, to allow concerned individuals to make more informed decisions. Recently, France has adopted a food labelling system, Nutri-Score (Santé Publique France, 2018) that allows consumers to compare nutritional characteristics in a standardised basis. A similar approach to energy efficiency labelling might be adopted in foods, aiding in the lifestyle changes needed to reduce energy use in the food industry. To make this possible, a greater collaborative effort is needed to report energy use data not only at processing stages but all across the food chain. Policies defining standard accounting basis must be developed to this purpose.

7. Conclusions

Energy demand quantification during food manufacturing and distribution is key to identify intensive activities, providing useful information for policy and industry decision makers. By targeting those processes that represent a hot spot (such as those involving phase changes) significant reductions on the sector energy consumption can be achieved.

Despite the variability on the energy demand figures for different products and processes available in the consulted sources, a database of energy consumption has been created from literature (Appendices available as Additional Material) and general trends on consumption due to manufacturing and transportation methods have been identified, paying special attention to the UK food system. The most energy intensive food products are powders (i.e. instant coffee and milk powder), fried goods (i.e. French fries and crisps) and bread, all involving thermal processes such freeze-drying or drying in their manufacture; in addition, hygienic and cleaning requirements are the main sources of water consumption and waste in the meat and dairy industries.

In terms of transportation, current trends point towards more decentralised/distributed supply systems and to local production. However, the environmental benefits of these changes are not always clear. Global environmental assessment tools (such LCA, carbon and water footprint) that take the whole food chain into consideration will be increasingly important.

Overall, it is necessary to standardise reported consumption data across the sector and policy efforts must be devoted to this task urgently. Only then will it be possible to develop efficient strategies to optimise the whole food system, allocate resources more effectively and reduce both waste and fossil fuel dependency.

Acknowledgments

Authors acknowledge financial support received from the RCUK Centre for Sustainable Energy Use in Food Chains (EPSRC grant no. EP/K011820/1).

Supplementary data

Supplementary data to this article (Appendices A–I) can be found online at https://doi.org/10.1016/j.tifs.2019.02.034.

References

AEA Energy and Environment (2007). *Resource efficiency in food chains. Report to Defra, ED05226. Oxford, UK.* http://sciencesearch.defra.gov.uk/Document.aspx?Document=WU0103_4830_FRA.pdf, Accessed date: 15 November 2018.

Aguilera, J., Simpson, R., Welti-Chanes, J., Aguirre, D., & Barbosa-Cánovas, G. (2011). *Food engineering interfaces.* New York, U.S.A: Springer.

Ahmed, J., & Rahman, M. (2012). *Handbook of food process design.* Chichester, UK: Wiley-Blackwell.

Almena, A., Lopez-Quiroga, E., Theodoropoulos, C., Fryer, P. J., & Bakalis, S. (2017). Modelling, simulation and economical evaluation of dry food manufacture at different production scales. *Computer Aided Chemical Engineering. 40*, 787–792. https://doi.org/10.1016/B978-0-444-63965-3.50133-1.

Andersson, K., Ohlsson, T., & Olsson, P. (1998). Screening life cycle assessment (LCA) of tomato ketchup: a case study. *Journal of Cleaner Production, 6*(3–4), 277–288. https://doi.org/10.1016/S0959-6526(98)00027-4.

Arendt, E., & Zannini, E. (2013). *Cereal grains for the food and beverage industries.* Oxford, UK: Woodhead Pub.
Atuonwu, J. C., Leadley, C., Bosman, A., Tassou, S. A., Lopez-Quiroga, E., & Fryer, P. J. (2018). Comparative assessment of innovative and conventional food preservation technologies: Process energy performance and greenhouse gas emissions. *Innovative Food Science & Emerging Technologies, 50*, 174–187. https://doi.org/10.1016/j.ifset.2018.09.008.
Augustin, M. A., Riley, M., Stockmann, R., Bennett, L., Kahl, A., Lockett, T., et al. (2016). Role of food processing in food and nutrition security. *Trends in Food Science & Technology, 56*, 115–125. https://doi.org/10.1016/j.tifs.2016.08.005.
Bagchi, D. (2010). *Global perspectives on childhood obesity: current status, consequences and prevention.* Amsterdam, The Netherlands: Academic Press.
Barba, F. J., Orlien, V., Mota, M. J., Lopes, R. P., Pereira, S. A., & Saraiva, J. A. (2016). Implementation of emerging technologies. *Innovation Strategies in the Food Industry: Tools for Implementation* (pp. 117–148). https://doi.org/10.1016/B978-0-12-803751-5.00007-6.
Beech, G. (1980). Energy use in bread baking. *Journal of the Science of Food and Agriculture, 31*(3), 289–298. https://dx.doi.org/10.1002/jsfa.2740310314.
Berry, R., & Makino, H. (1974). Energy thrift in packaging and marketing. *Technology Review, 76*(4), 32–43. http://berrygroup.uchicago.edu/papers/97.pdf, Accessed date: 15 November 2018.
Braschkat, J., Patyk, A., Quirin, M., & Reinhardt, G. (2003). Life cycle assessment of bread production – A comparison of eight different scenarios. *Proceedings of the Fourth International Conference on Life Cycle Assessment in the Agri-Food Sector. Bygholm, Denmark*Danish Institute of Agricultural Sciences. http://orgprints.org/id/file/59470, Accessed date: 15 November 2018.
Briam, R., Walker, M., & Masanet, E. (2015). A comparison of product-based energy intensity metrics for cheese and whey processing. *Journal of Food Engineering, 151*, 25–33. https://doi.org/10.1016/j.jfoodeng.2014.11.011.
British Sugar 2018. Available at: https://www.britishsugar.co.uk/about-us/what-we-do/. Accessed 15 November 2018.
Carlsson-Kanyama, A. (1998). Climate change and dietary choices — How can emissions of greenhouse gases from food consumption be reduced? *Food Policy, 23*(3–4), 277–293. https://doi.org/10.1016/S0306-9192(98)00037-2.
Carlsson-Kanyama, A., & Faist, M. (2000). *Energy use in the food sector: A data survey.* Stockholm, Sweden: Swedish Environmental Protection Agency. 15.11.208 http://citeseerx.ist.psu.edu/viewdoc/download?rep=rep1&type=pdf&doi=10.1.1.205.8375.
Chanakya, H., & De Alwis, A. (2004). Environmental issues and management in primary coffee processing. *Process Safety and Environmental Protection, 82*(4), 291–300. https://doi.org/10.1205/095758204323162319.
Cleland, A., Earle, M., & Boag, I. (1981). Application of multiple linear regression to analysis of data from factory energy surveys. *International Journal of Food Science and Technology, 16*(5), 481–492. https://doi.org/10.1111/j.1365-2621.1981.tb01841.x.
Coley, D., Howard, M., & Winter, M. (2009). Local food, food miles and carbon emissions: A comparison of farm shop and mass distribution approaches. *Food Policy, 34*(2), 150–155. https://doi.org/10.1016/j.foodpol.2008.11.001.
Compton, M., Willis, S., Rezaie, B., & Humes, K. (2018). Food processing industry energy and water consumption in the Pacific northwest. *Innovative Food Science & Emerging Technologies, 47*, 371–383. https://doi.org/10.1016/j.ifset.2018.04.001.
Cox, G., & Miller, E. (1986). Comparative energy efficiencies of the dairy manufacturing and processing industry: Australia and New Zealand. *Engineering Costs and Production Economics, 10*(4), 293–303. https://doi.org/10.1016/S0167-188X(86)80028-3.
Cunningham, J., & Harney, B. (2012). *Strategy & strategists.* Oxford, UK: Oxford University Press.
DEFRA (2005). *The Validity of food miles as an indicator of sustainable development.* Available at: http://webarchive.nationalarchives.gov.uk/20130131093910/http:/www.defra.gov.uk/statistics/files/defra-stats-foodfarm-food-transport-foodmiles-050715.pdf, Accessed date: 15 November 2018.
DEFRA (2015). *Family Food 2014 - report tables dataset*. Available at: https://www.gov.uk/government/statistics/family-food-2014, Accessed date: 15 November 2018.
DEFRA (2018a). *UK's carbon footprint 1997-2015. Annual carbon dioxide emissions relating to UK consumption.* London, UK: Department of Environment, Food and Rural Affairs. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/704425/UK-Carbon_Footprint_1997_2015.ods, Accessed date: 16 November 2018.
DEFRA (2018b). *Food statistics pocketbook 2018. Online resource.* London, UK: Department of Environment, Food and Rural Affairs. https://www.gov.uk/government/publications/food-statistics-pocketbook/food-statistics-in-your-pocket-chapter-1, Accessed date: 16 November 2018.
Del Borghi, A., Gallo, M., Strazza, C., & Del Borghi, M. (2014). An evaluation of environmental sustainability in the food industry through Life Cycle Assessment: The case study of tomato products supply chain. *Journal of Cleaner Production, 78*, 121–130. https://doi.org/10.1016/j.jclepro.2014.04.083.
Department for Business, Energy and Industrial Strategy (2018a). *Digest of United Kingdom Energy Statistics (DUKES) July 2018. London, UK.* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/736148/DUKES_2018.pdf, Accessed date: 15 November 2018.
Department for Business, Energy and Industrial Strategy (2018b). *Annual prices of fuels purchased by manufacturing industry (p/kWh). London, UK.* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/743784/table_314.xls, Accessed date: 15 November 2018.
Department for Transport (2018). *Domestic Road Freight Statistics, United Kingdom 2017. London, UK.* https://www.gov.uk/government/statistics/road-freight-statistics-2017, Accessed date: 22 November 2018.
Drewnowski, A., Rehm, C., Martin, A., Verger, E., Voinnesson, M., & Imbert, P. (2014). Energy and nutrient density of foods in relation to their carbon footprint. *American Journal of Clinical Nutrition, 101*(1), 184–191. https://doi.org/10.3945/ajcn.114.092486.
EEA (2015). *The European environment — State and outlook 2015: Synthesis report*Copenhagen, Denmark: European Environment Agency. https://www.eea.europa.eu/soer/#pdf-choice-synthesis, Accessed date: 15 November 2018.
Energy Information Administration, EIA (2017). *International Energy Outlook 2017.* https://www.eia.gov/outlooks/archive/ieo17/pdf/exec_summ.pdf last accessed November 2018.
European Commission (2012). *Energy roadmap 2050. Luxembourg, Belgium.* 978-92-79-21798-2. https://doi.org/10.2833/10759.
FAO (2011). *Energy-smart Food for People and Climate. Issue Paper. Food and Agriculture Organization of the United Nations. Rome, Italy.* www.fao.org/docrep/014/i2454e/i2454e00.pdf, Accessed date: 16 November 2018.
FAO (2017). *The future of food and agriculture – Trends and challenges.* Rome, Italy: Food and Agriculture Organization of the United Nations. http://www.fao.org/3/a-i6583e.pdf, Accessed date: 15 November 2018.
FDF (2016). *Ambition 2025 – Climate Change.* https://www.fdf.org.uk/sustainability-ambition2025-climate-change.aspx, Accessed date: 22 November 2018.
FDF (2018). *Facts and Stats. Stats at a glance.* London, UK: Food and Drink Federation. www.fdf.org.uk/statsataglance.aspx, Accessed date: 16 November 2018.
Fellows, P. (2009). *Food processing technology: Principles and practice* (3rd ed.). Boca Raton, USA: CRC Press.
FoodDrinkEurope (2015). *A time to act. Climate action and the Food and Drink industry. London UK.* http://www.fooddrinkeurope.eu/uploads/publications_documents/FoodDrink_Europe_Climate_Action_Brochure.pdf, Accessed date: 22 November 2018.
Foster, C., Green, K., Bleda, M., Dewick, P., Evans, B., Flynn, A., et al. (2006). *Environmental impacts of food production and consumption: A report to the Department for Environment*Manchester, UK: Food and Rural Affairs. Manchester Business School. http://randd.defra.gov.uk/Document.aspx?Document=EV02007_4601_FRP.pdf, Accessed date: 16 November 2018.
Fritzson, A., & Berntsson, T. (2006). Efficient energy use in a slaughter and meat processing plant-opportunities for process integration. *Journal of Food Engineering, 76*(4), 594–604.
Gazzard, N. (2014). *Improving the efficiency of freight movements: The contribution to UK economic growth, Interim Report*London, UK: Independent Transport Commission. http://www.theitc.org.uk/wp-content/uploads/2011/03/ITC-Freight-interim-report-July-14.pdf, Accessed date: 16 November 2018.
Gowreesunker, B., Mudie, S., & Tassou, S. A. (2017). The impact of the UK's emissions reduction initiative on the national food industry. *Energy Procedia, 123*, 30–35. https://doi.org/10.1016/j.egypro.2017.07.281.
Hendrickson, J. (1996). *Energy use in the U.S. food system: A summary of existing research and analysis.* Madison, USA: Center for Integrated Agriculture Systems, University of Wisconsin-Madison. https://www.cias.wisc.edu/wp-content/uploads/2008/07/energyuse.pdf.
Jermann, C., Koutchma, T., Margas, E., Leadley, C., & Ros-Polski, V. (2015). Mapping trends in novel and emerging food processing technologies around the world. *Innovative Food Science & Emerging Technologies, 31*, 14–27. https://doi.org/10.1016/j.ifset.2015.06.007.
Jindarat, W., Sungsoontorn, S., & Rattanadecho, P. (2014). Analysis of energy consumption in a combined microwave–hot air spouted bed drying of biomaterial: Coffee beans. *Experimental Heat Transfer, 28*, 107–124. https://doi.org/10.1080/08916152.2013.821544.
Jones, A. (2002). An environmental assessment of food supply chains: A case study on dessert apples. *Environmental Management, 30*(4), 560–576. https://doi.org/10.1007/s00267-002-2383-6.
Juliano, P., Bilbao-Sáinz, C., Koutchma, T., Balasubramaniam, V. M., Clark, S., Stewart, C. M., et al. (2012). Shelf-stable egg-based products processed by high pressure thermal sterilization. *Food Engineering Reviews, 4*(1), 55–67. https://doi.org/10.1007/s12393-011-9046-4.
Khatir, Z., Paton, J., Thompson, H., Kapur, N., & Toropov, V. (2013). Optimisation of the energy efficiency of bread-baking ovens using a combined experimental and computational approach. *Applied Energy, 112*, 918–927. https://doi.org/10.1016/j.apenergy.2013.02.034.
Klemes, J. (2013). *Handbook of process integration: Minimisation of energy and water use, waste and emissions.* Oxford, UK: Woodhead Publishing.
Klemes, J., Smith, R., & Kim, J. (2008). *Handbook of water and energy management in food processing.* Cambridge, UK: Woodhead Publishing Limited.
Konstantas, A., Jeswani, H. K., Stamford, L., & Azapagic, A. (2018). Environmental impacts of chocolate production and consumption in the UK. *Food Research International, 106*, 1012–1025. https://doi.org/10.1016/j.foodres.2018.02.042.
Konstantas, A., Stamford, L., & Azapagic, A. (2019). Environmental impacts of ice cream. *Journal of Cleaner Production, 209*, 259–272. https://doi.org/10.1016/j.jclepro.2018.10.237.
Koutchma, T., Popović, V., Ros-Polski, V., & Popielarz, A. (2016). Effects of ultraviolet light and high-pressure processing on quality and health-related constituents of fresh juice products. *Comprehensive Reviews in Food Science and Food Safety, 15*(5), 844–867. https://doi.org/10.1111/1541-4337.12214.
Lillywhite, R., Sarrouy, C., Davidson, J., May, D., & Plackett, C. (2013). *Energy dependency and food chain security* (1st ed.). Warwick: The University of Warwick. Warwick, UK. http://randd.defra.gov.uk/Document.aspx?Document=10557_FO0415_ENERGYDEPENDENCYANDFOODCHAINSECURITY_V.pdf, Accessed date: 16 November 2018.
Liu, Y., Zhao, Y., & Feng, X. (2008). Exergy analysis for a freeze-drying process. *Applied Thermal Engineering, 28*(7), 675–690. https://doi.org/10.1016/j.applthermaleng.2007.06.004.
Li, S., Ziara, R. M. M., Dvorak, B., & Subbiah, J. (2018). Assessment of water and energy

use at process level in the U.S. beef packing industry: Case study in a typical U.S. large-size plant. *Journal of Food Process Engineering, 41*(8), e12919. https://doi.org/10.1111/jfpe.12919.

Marquer, P., Rabade, T., & Forti, R., (2015). *Meat product statistics. Eurostat.* Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Meat_production_statistics#Poultry_meat, Accessed date: 16 November 2018.

Moejes, S. N., & van Boxtel, A. J. B. (2017). Energy saving potential of emerging technologies in milk powder production. *Trends in Food Science & Technology, 60*, 31–42. https://doi.org/10.1016/j.tifs.2016.10.023.

Morawicki, R. O., & Hager, T. (2014). Energy and greenhouse gases footprint of food processing. *Encyclopedia of Agriculture and Food Systems: Vol. 3*, (pp. 82–99). Oxford, UK: Academic Press.

Motevali, A., Minaei, S., & Khoshtagaza, M. (2011). Evaluation of energy consumption in different drying methods. *Energy Conversion and Management, 52*(2), 1192–1199. https://doi.org/10.1016/j.enconman.2010.09.014.

Mujumdar, A. (2014). *Handbook of industrial drying* (4th ed.). Boca Raton, USA: CRC Press Inc.

OECD (2012). *Energy and climate policy: Bending the technological trajectory, OECD Studies on Environmental Innovation.* Paris, France: OECD Publishing. https://doi.org/10.1787/9789264174573-en.

Okada, M., Rao, M., Lima, J., & Torloni, M. (1980). Energy consumption and the potential for conservation in a spray-dried coffee plant. *Journal of Food Science, 45*(3), 685–688 http:/dx.doi.org/10.1111/j.1365-2621.1980.tb04132.x.

Özilgen, M. (2016). Energy utilization and carbon dioxide emission during production of snacks. *Journal of Cleaner Production, 112*, 2601–2612. https://doi.org/10.1016/j.jclepro.2015.10.031.

Ozuna, C., Cárcel, J., García-Pérez, J., & Mulet, A. (2011). Improvement of water transport mechanisms during potato drying by applying ultrasound. *Journal of the Science of Food and Agriculture, 91*(14), 2511–2517. https://doi.org/10.1002/jsfa.4344.

Paloviita, A., & Järvelä, M. (2016). *Climate change adaptation and food supply chain management.* Abingdon, UK: Routledge.

Paoli, L., Lupton, R. C., & Cullen, J. M. (2018). Useful energy balance for the UK: An uncertainty analysis. *Applied Energy, 228*, 176–188. https://doi.org/10.1016/j.apenergy.2018.06.063.

Pardo, G., & Zufía, J. (2012). Life cycle assessment of food-preservation technologies. *Journal of Cleaner Production, 28*, 198–207. https://doi.org/10.1016/j.jclepro.2011.10.016.

Pathare, P., & Roskilly, A. (2016). Quality and energy evaluation in meat cooking. *Food Engineering Reviews, 8*(4), 435–447. https://doi.org/10.1007/s12393-016-9143-5.

Pimentel, D., & Hall, C. (1984). *Food and energy resources.* Oxford, UK: Elsevier.

Pretty, J. N., Ball, A. S., Lang, T., & Morison, J. I. L. (2005). Farm costs and food miles: An assessment of the full cost of the UK weekly food basket. *Food Policy, 30*(1), 1–19. https://doi.org/10.1016/j.foodpol.2005.02.001.

Prosapio, V., & Norton, I. (2017). Influence of osmotic dehydration pre-treatment on oven drying and freeze drying performance. *Lebensmittel-Wissenschaft und -Technologie-Food Science and Technology, 80*, 401–408. https://doi.org/10.1016/j.lwt.2017.03.012.

Ramirez, C., Patel, M., & Blok, K. (2006a). From fluid milk to milk powder: Energy use and energy efficiency in the European dairy industry. *Energy, 31*(12), 1984–2004. https://doi.org/10.1016/j.energy.2005.10.014.

Ramirez, C., Patel, M., & Blok, K. (2006b). How much energy to process one pound of meat? A comparison of energy use and specific energy consumption in the meat industry of four European countries. *Energy, 31*(12), 2047–2063. https://doi.org/10.1016/j.energy.2005.08.007.

Rivera, X. C. S., & Azapagic, A. (2016). Life cycle costs and environmental impacts of production and consumption of ready and home-made meals. *Journal of Cleaner Production, 112*, 214–228. https://doi.org/10.1016/j.jclepro.2015.07.111.

Roos, Y. H., Fryer, P. J., Knorr, D., Schuchmann, H. P., Schroën, K., Schutyser, M. A. I., et al. (2016). Food engineering at multiple scales: Case studies, challenges and the future—A European perspective. *Food Engineering Reviews, 8*(2), 91–115. https://doi.org/10.1007/s12393-015-9125-z.

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., et al. (2009). A review of life cycle assessment (LCA) on some food products. *Journal of Food Engineering, 90*(1), 1–10. https://doi.org/10.1016/j.jfoodeng.2008.06.016.

Santé Publique France (2018). *Nutri-Score.* https://www.santepubliquefrance.fr/Sante-publique-France/Nutri-Score Last accessed November 2018.

Sharma, G., & Prasad, S. (2006). Specific energy consumption in microwave drying of garlic cloves. *Energy, 31*(12), 1921–1926. https://doi.org/10.1016/j.energy.2005.08.006.

Sims, R., Flammini, A., Puri, M., & Bracco, S. (2015). *Opportunities for agri-food chains to become energy-smart.* Rome: FAO. http://www.fao.org/3/ai5125e.pdf last accessed November 2018.

Singh, B. (2013). *Biofuel crop sustainability.* Ames, USA: John Wiley & Sons9781118635643.

Slesser, M., & Wallace, F. (1982). *Energy consumption per tonne of competing agricultural products available to the EC.* Luxembourg, Luxembourg: Office for Official Publications of the European Communities. 16.112.08 http://bookshop.europa.eu/en/energy-consumption-per-tonne-of-competing-agricultural-products-available-to-the-ec-pbCBNA82085/.

Smith, D., Cash, J., Nip, W., & Hui, Y. (1997). *Processing vegetables: Science and technology.* Lancaster, UK: CRC Press.

Stanhill, G. (1984). *Energy and agriculture.* Heidelberg, Germany: Springer978-3-642-69784-5.

Swain, M. (2006). Energy use in food refrigeration - calculations, assumptions and data sources. *Fond Refrigeration and Process Engineering Research Centre*Bristol, UK: University of Bristol. Technical Report www.grimsby.ac.uk/documents/defra/usrs-top10users.pdf.

Tassou, S., De-Lille, G., & Ge, Y. (2009). Food transport refrigeration – Approaches to reduce energy consumption and environmental impacts of road transport. *Applied Thermal Energy, 29*(8–9), 1467–1477. https://doi.org/10.1016/j.applthermaleng.2008.06.027.

Tassou, S. A., Kolokotroni, M., Gowreesunker, B., Stojceska, V., Azapagic, A., Fryer, P., et al. (2014). Energy demand and reduction opportunities in the UK food chain. *Proceedings - Institution of Civil Engineers: Energy, 167*(3), 162–170. https://doi.org/10.1680/ener.14.00014.

The British Coffee Association (2018). *Coffee facts.* Available at: http://www.britishcoffeeassociation.org/about_coffee/coffee_facts/, Accessed date: 16 November 2018.

The Energy Conservation Centre (2016). *Food processing industry - output of a seminar on energy conservation in food processing industry.* United Nations Industrial Development Organisation (UNIDO).

Therdthai, N., Zhou, W., & Adamczak, T. (2002). Optimisation of the temperature profile in bread baking. *Journal of Food Engineering, 55*(1), 41–48. https://doi.org/10.1016/S0260-8774(01)00240-0.

Therkelsen, P., Masanet, E., & Worrell, E. (2014). Energy efficiency opportunities in the U.S. commercial baking industry. *Journal of Food Engineering, 130*, 14–22. https://doi.org/10.1016/j.jfoodeng.2014.01.004.

USDA (2016). *USDA Food Composition Database.* Available at:https://ndb.nal.usda.gov/ Accessed 16.11.208.

Van Alfen, N. (2014). *Encyclopedia of agriculture and food systems* (2nd ed.). Oxford, UK: Elsevier978-0-08-093139-5.

Van Hauwermeiren, A., Coene, H., Engelen, G., & Mathijs, E. (2007). Energy lifecycle inputs in food systems: A comparison of local versus mainstream cases. *Journal of Environmental Policy and Planning, 9*(1), 31–51. https://doi.org/10.1080/15239080701254958.

Walmsley, T. G., Atkins, M. J., Walmsley, M. R. W., Philipp, M., & Peesel, R.-H. (2018). Process and utility systems integration and optimisation for ultra-low energy milk powder production. *Energy, 146*, 67–81. https://doi.org/10.1016/j.energy.2017.04.142.

Wang, L. (2008). *Energy efficiency and management in food processing facilities.* Boca Raton, USA: CRC Press9781420063387.

Wang, L. (2014). Energy efficiency technologies for sustainable food processing. *Energy Efficiency, 7*(5), 791–810. https://doi.org/10.1007/s12053-014-9256-8.

Webb, G. (2012). *Nutrition - Maintaining and improving health* (4th ed.). Boca Raton, USA: Hodder Arnold -CRC Press9781444142464.

Wojdalski, J., Grochowicz, J., Dróżdż, B., Bartoszewska, K., Zdanowska, P., Kupczyk, A., et al. (2015). Energy efficiency of a confectionery plant – Case study. *Journal of Food Engineering, 146*, 182–191. https://doi.org/10.1016/j.jfoodeng.2014.08.019.

Wu, H., Tassou, S. A., Karayiannis, T. G., & Jouhara, H. (2013). Analysis and simulation of continuous food frying processes. *Applied Thermal Engineering, 53*(2), 332–339. https://doi.org/10.1016/j.applthermaleng.2012.04.023.

Xanthakis, E., Huen, J., Eliasson, L., Jha, P. K., Le-Bail, A., & Shrestha, M. (2018). *Evaluation of microwave assisted freezing (MAF) impact on meat and fish matrices.* Refrigeration Science and Technology. https://doi.org/10.18462/iir.iccc.2018.0024.

Xu, T., & Flapper, J. (2009). Energy use and implications for efficiency strategies in global fluid-milk processing industry. *Energy Policy, 37*(12), 5334–5341. https://doi.org/10.1016/j.enpol.2009.07.056.

Xu, T., & Flapper, J. (2011). Reduce energy use and greenhouse gas emissions from global dairy processing facilities. *Energy Policy, 39*(1), 234–247. https://doi.org/10.1016/j.enpol.2010.09.037.

Xu, T., Flapper, J., & Kramer, K. (2009). Characterization of energy use and performance of global cheese processing. *Energy, 34*(11), 1993–2000. https://doi.org/10.1016/j.energy.2009.08.014.