Energy
Volume 167 Issue EN3
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ice | proceedings

Proceedings of the Institution of Civil Engineers
Energy 167 August 2014 Issue EN3
Pages 162–170 http://dx.doi.org/10.1680/ener.14.00014
Paper 1400014
Received 07/05/2014 Accepted 14/07/2014
Keywords: energy conservation/sustainability/waste management & disposal

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Energy demand and reduction opportunities in the UK food chain

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The food chain comprises agricultural production, manufacturing, distribution, retail and consumption. In the UK it involves approximately 300,000 enterprises, it employs 3·3 million people and accounts for £188 billion in consumer expenditure. The food chain is also responsible for 18% of total UK energy use, 176 $MtCO_2e$ emissions and 15 Mt of food waste. Estimates of energy consumption and emissions from the food chain vary between sources, primarily due to differences in the assumptions made, but the general consensus is that reduction in energy consumption and resource use in the food sector is not only vital for the profitability of the sector but also for food security and meeting the Government's greenhouse gas emissions reduction targets. This paper reviews the literature on energy consumption and emissions from each stage of the food sector and outlines approaches and technologies for demand reduction. It will provide the basis for further refinement of the estimates and development of methodologies and projects to effect significant reductions of energy and resource use as part of the End Use Energy Demand Initiative of Research Councils UK.

1. Introduction

It is predicted that, by 2030, the growth in global population and the impacts of climate change will increase food production needs by 50%, energy demand by 45% and water demand by 30% (Beddington, 2009). The UK forms part of the global food supply chain, which will be affected by climate change; consequently food security is high on the agenda of many governments, including that of the UK. In response to these challenges, the Food 2030 strategy sets out the UK government's vision for a sustainable and secure food system for 2030, and the steps that will be taken to achieve it (Defra, 2010). Among the main priorities of the strategy are to

(*a*) reduce the food system's resource use and greenhouse gas (GHG) emissions
(*b*) reduce, reuse and reprocess food waste
(*c*) ensure a resilient, profitable and competitive food system.

The food chain comprises agricultural production, manufacturing, distribution, retail and consumption. The main stages are illustrated schematically in Figure 1.

In the UK, the food chain involves approximately 300 000 enterprises and employs 3·3 million people. If agriculture, fishing, as well as self-employed farmers are included, employment in the food sector rises to 3·7 million people and constitutes 14% of national employment (Defra, 2013). The food and drink industry is also the largest manufacturing sector in the UK, employing 400 000 people and contributing to £27 billion value added (Defra, 2013). The industry uses two thirds of the UK's agricultural produce and plays a key role in rural prosperity. It also supports a number of ancillary industries, which support the production, processing, packaging, storage and distribution functions. Food and drink is also the biggest consumer spending category in the UK and, at over £188 billion (Defra, 2013), represents more than 20% of consumer expenditure in the UK.

It is estimated that the food chain is also responsible for 176 $MtCO_2e$ emissions (not including emissions from non-fertiliser pre-farm production, packaging, food waste and land use change), of which 115 $MtCO_2e$ are from the UK food chain activity and the remainder from food imports (Defra,

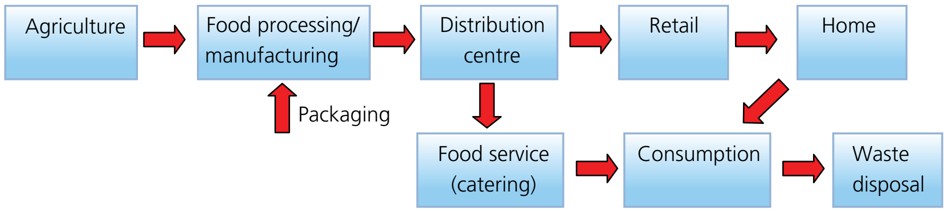

Figure 1. Schematic diagram of main stages in the food chain

2013). Emissions from the different activities in the food chain are illustrated in Figure 2.

In recent years, progress has been made in the reduction of energy consumption and emissions from the food chain in response to government initiatives and legislation, rising fuel prices and the desire of many companies to improve social and environmental performance (FPF, 2010). This has been achieved primarily through the application of well-proven energy conservation technologies, and projects and activities that could lead to quick return on investment. However, much more radical solutions will be needed to reduce further energy demand in the food sector and mitigate the related climate change impacts. The National Centre for Sustainable Energy Use in Food Chains (CSEF), one of six End Use Energy Demand Centres funded by the Research Councils UK (EPSRC, 2012) will make significant contributions in this field. CSEF brings together multidisciplinary research groups of substantial complementary experience and an internationally leading research track record from the universities of Brunel, Manchester and Birmingham, as well as key stakeholders, to investigate and develop innovative approaches and

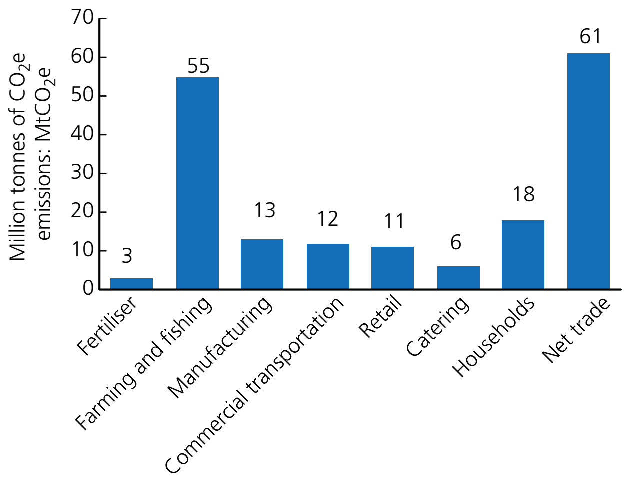

Figure 2. Greenhouse gas emissions from the UK agri-food sector (source: Defra, 2013)

technologies to effect substantial end-use energy demand reduction in food chains. The centre will engage both in cutting-edge research into approaches and technologies that will have significant impacts in the future, leading towards the target of 80% reduction in carbon dioxide emissions by 2050, but also into research that will have demonstrable impacts in the short term (CSEF, 2013). Key research themes of the centre include

(*a*) simulation of the food chain, farm gate to plate, to enable investigations of energy and resource flows and interactions between the stages of the chain and the external environment
(*b*) investigation of approaches and technologies for the reduction of energy use at all stages of the chain through reduction of the energy intensity of individual processes and optimisation of resource use
(*c*) study of corporate and consumer behaviour to identify drivers and barriers for reducing energy use.

To facilitate the simulation of energy and resource flows in the UK food chain, this paper reviews the latest literature on energy consumption and emissions and identifies opportunities for energy reduction.

2. Energy demand and reduction opportunities in agriculture

The UK agricultural sector employs about 440 000 people (Defra, 2013) and covers a land area of approximately 16·1 million ha used for arable, pasture and permanent crops (Eurostat, 2011). The aggregate primary energy consumption of this sector was reported to be 12·0 TWh by DECC (2013a), and 10·1 TWh by the International Energy Agency (IEA, 2014), corresponding to approximately 0·6% of the total UK consumption and associated with approximately 4·7 $MtCO_2e$ (0·8% of total UK GHG emissions) (NAEI, 2014). A study by Warwick HRI (2007) estimated the energy consumption of the agricultural sector based on 2005 data to be 20·0 TWh. The discrepancies in the published energy consumption data can generally be associated with the assumptions made. For example, the DECC (2013a) data include forestry and fisheries, and are based on returns made by energy suppliers, whereas the IEA (2014) data do not include fisheries. The Warwick HRI (2007) study employed a more detailed bottom-up approach, looking at the intricacies of the UK agricultural sector, but ignored forestry and fisheries. As a consequence, the different studies also report different GHG emissions for the sector, owing to a combination of the different energy consumption data and GHG emission conversion factors used.

The energy use in agriculture can be attributed to a number of processes, as shown in Figure 3. Heating processes, mainly fossil-fuel boilers for heating of greenhouse production, electrical heating for livestock conditioning, crop drying and storage excluding combined heat and power (CHP), account for approximately 36% of the total energy consumed. Heating by CHP represents 4% of the total energy consumed and is used to produce heat and carbon dioxide for nurseries and electricity for local use and export to the national grid. Field operations account for 36% of the energy consumed and include mainly oil and diesel for machinery, typically tractors. Ventilation accounts for 14% of the energy consumed, and is mainly used for temperature and humidity control in greenhouses, crop drying and storage, and intensive livestock housing. Refrigeration represents 6% of the energy and is mainly for the cooling of dairy products, potatoes and horticultural field crops to avoid spoilage. Lighting consumes 4% of the energy and is used in most areas of agriculture, specifically to provide appropriate environments for broiler production, egg laying, the raising of piglets and to improve crop productivity during low daylight periods. Motive power also represents 4% of the energy consumed and mainly refers to the processes of conveying and elevating crops and livestock, and pumping water or wet-feed around farms (Warwick HRI, 2007).

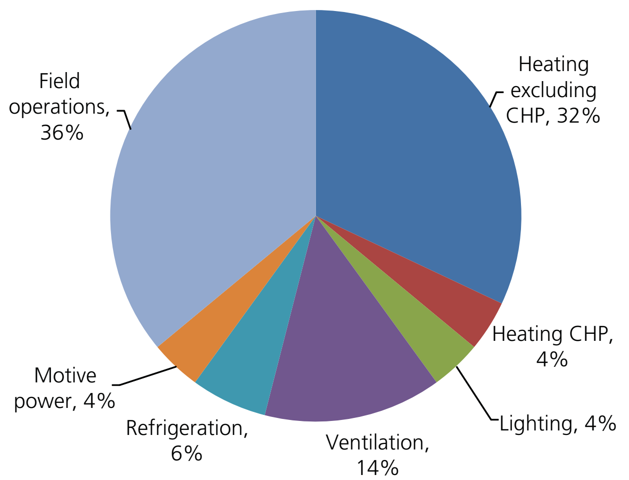

Figure 3. Relative direct primary energy consumption of the UK agricultural sector, excluding fisheries and forestry (source: Warwick HRI, 2007)

Although the energy consumption of the agricultural sector is not significantly high compared to the whole food chain, substantial energy improvements can be achieved in the sector, especially as the resources for renewable energy generation and space for their installation are readily available, and businesses are generally receptive to the application and integration of new technologies (Lillywhite *et al.*, 2013). Technological improvements can include decentralised boiler plants to reduce transmission energy losses, higher efficiency boilers and building insulation, use of heat pumps, intelligent temperature and humidity control systems, increased and enhanced use of natural ventilation strategies, increased use of CHP systems, the use of energy storage systems to level energy consumption and improve efficiency, use of more efficient lamps and lighting controls, and the use of higher efficiency motors (Warwick HRI, 2007). Furthermore, it has been estimated that 47% reduction in emissions can be achieved through reductions in electricity use; for example, by using heat instead of electricity for heating greenhouses and utilising wastes to recover energy. Overall, based on estimated energy-saving potential of 20% by AEA Energy and Environment (2007), this can lead to carbon dioxide savings of 757 000 t (Oakdene Hollins, 2009).

3. Energy demand and reduction opportunities in food processing

The UK Food and Drink manufacturing sector includes primary processing (such as milling, malting or slaughtering) as well as processing complex prepared foods. The sector in 2011 employed 10% of the UK food-chain labour workforce and accounted for 15% (60·5 TWh) of the total food-chain energy use, producing 13 $MtCO_2e$ emissions (Defra, 2013). The type of fuel used remained fairly constant in recent years, 61% natural gas, 31% electricity, 6% petroleum, with fuel oil and coal accounting for the rest (Defra, 2013). It has also been estimated that approximately 68% of the energy is used by fuel-fired boilers and direct heating systems for process and space heating. From the remainder, 16% is electrical energy used by electric motors, 8% by electric heating, 6% by refrigeration equipment and the remainder by air compressors (AEA Energy and Environment, 2007). Technological improvements have been implemented in the food manufacturing sector, resulting in a general trend of reduction in carbon dioxide emissions since 1990 (Defra, 2013), but efficiency enhancements have to continue in order to lead to a competitive and sustainable food sector (Campden BRI, 2011).

Energy consumption figures also indicate that a small number of products are responsible for 80% of the carbon emissions (FPF, 2010). The most prominent of these are manufacture of bread and fresh pastry goods, production of cheese and other dairy products, production of meat and poultry products, and manufacture of beer and alcoholic beverages. This therefore points to the need for improvements in technologies used by these sectors, such as processing equipment, refrigeration, boilers, ovens, pumps, space heating and lighting. Food manufacturing is also responsible for 3·2 Mt of food waste (Defra, 2013), which is mainly landfilled. This presents opportunities for more efficient resource use through the minimisation of waste, the manufacture of co-products or by-products (Campden BRI, 2011) and the improved use of waste to recover energy through efficient incineration, gasification, pyrolysis or anaerobic digestion technologies.

Energy can be saved at the processing plant level by optimising and integrating processes and systems to reduce energy intensity. Approaches that can be considered include (Campden BRI, 2011)

(*a*) design, optimisation and validation of new and modified processes including identification and rigorous assessment, and development of more efficient and effective technological approaches for food and drink processing and packing operations
(*b*) better understanding of how processes work and use of knowledge for better process control, better application of automation, and improved process efficiency and flexibility through better scheduling and logistics
(*c*) advanced sensors and equipment for on-line measurement and intelligent adaptive control of key parameters
(*d*) reduction of processing requirements to improve quality without compromising safety
(*e*) minimisation of waste through energy recovery and better use of by-products.

4. Carbon dioxide emissions and reduction opportunities in food transportation

It is estimated that commercial food transport, excluding food shopping, is responsible for emissions of the order of 12·0 $MtCO_2e$ per year (Defra, 2013). Of this, nearly 6·0 $MtCO_2e$ is for food freight in the UK, more than 80% of which is performed by heavy goods vehicles (HGVs). It is also estimated that approximately a third of food freight is temperature controlled. On-board refrigeration can account for between 25% and 40% of total vehicle fuel consumption. Various approaches can be employed to reduce transport emissions; these include: food chain optimisation and reduction in food transport intensity; modal shift; improved vehicle fuel efficiency; alternative refrigeration technologies (Tassou *et al.*, 2009) and electrification of transport with zero or low-carbon electricity (McKinnon, 2009).

5. Energy demand and reduction opportunities in food retail

Retail food stores are large consumers of energy, which in developed countries amounts to between 3% and 5% of total electricity consumption. Food retailing in the UK is responsible for around 12·0 TWh and approximately 3% of total electrical energy consumption (Tassou *et al.*, 2011). Estimates for GHG emissions from retail operations vary between 6 and 9·5 $MtCO_2e$ (FPF, 2010). A sizeable portion of this, up to 20%, is direct emissions from refrigerant leakage.

The energy consumption of supermarkets will depend on business practices, store format, product mix, shopping activity, the equipment used for in-store food preparation, preservation and display. Energy use varies but current benchmarks do not reflect this. The electrical energy consumption can vary widely from around 700 kWh/m^2 sales area per year in hypermarkets to over 2000 kWh/m^2 sales area per year in convenience stores (Tassou *et al.*, 2011). Research has been carried out for individual categories and Figure 4 shows diagrammatically the energy use by various processes and activities in a hypermarket. In general, the refrigeration systems account for between 30% and 60% of the electricity used (taking into consideration smaller stores), whereas lighting accounts for between 15% and 25% with the heating, ventilation and air-conditioning (HVAC) equipment and other utilities such as bakery, for the remainder. Gas is normally used for space heating, domestic hot water and in some cases for cooking, and consumption can be as high as 250 kWh/m^2 per year in hypermarkets.

There is evidence that supermarkets in the UK have significantly improved their operational efficiency in recent years (Sullivan and Gouldson, 2013). A recent report (British Retail Consortium, 2014) suggests that progress since the mid-2000s are due to improvements in

(*a*) retail operations by improving energy monitoring and control systems; developing investment models to support corporate energy demand reduction strategies; and improving the operational efficiency through placing doors on fridges and chillers and implementing auto-defrost processes to tackle waste energy consumption

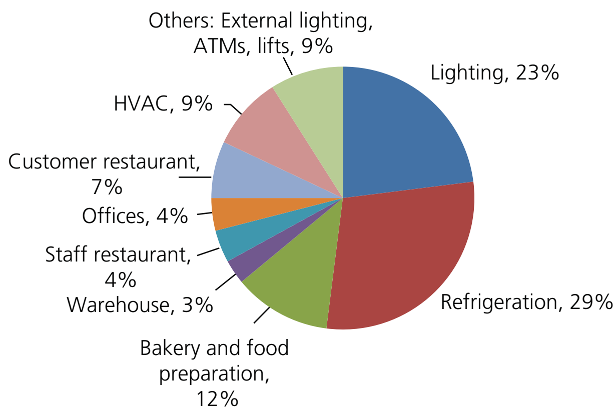

Figure 4. Percentage contribution of electrical energy use processes in a hypermarket (source: Tassou *et al.*, 2011)

(*b*) energy use in buildings by deployment of energy-efficient technologies such as light-emitting diode (LED) lighting, trialling new and innovative technologies in refrigeration, heating and ventilation equipment and increasing the use of renewable energy on site such as biomass boilers, solar power and wind turbines
(*c*) transport by increasing the use of alternative fuels in fleets, such as bio-diesel and fuels from waste, developing better route optimisation models and increasing delivery efficiency and driving techniques
(*d*) staff training and behavioural changes in energy use.

Supermarkets have also supported research that will be useful for improving energy efficiency in their stores and statistical models have been developed to assist in this. For example, Mavromatidis *et al.* (2013) describe a model based on artificial neural networks (ANNs) that can be used as a diagnostic tool in a specific store, and Spyrou *et al.* (2014) present a regression model for the prediction of energy use in a number of supermarkets based on a few measureable parameters such as floor sales area, food–non-food ratio, volume of sales, year of construction, ceiling height, number of floors, the existence or not of CHP and so on. Such models are by nature restrictive and static in their applicability, and depend on the original data which informed their development.

There are examples of low-carbon supermarkets and guidelines on how to achieve such buildings. Two reports sponsored by leading supermarket chains in the UK have been published in recent years (Hill *et al.*, 2010; Target Zero, 2011). In both reports, a base case supermarket was created based on the operational details of an existing store and energy efficiency measures were investigated, including renewables.

Hill *et al.* (2010) summarise low-energy design initiatives as

- enhanced utilisation of daylight
- a combination of natural and mechanical ventilation, with heat exchange
- improved refrigeration cabinets, with doors on frozen food cabinets
- improved control of lighting and ventilation, and acceptance of a wider range of internal temperatures
- LED display lighting
- renewable energy sources, such as biomass or wind power.

The overall effect of these measures is typically to reduce energy consumption to around 400 kWh/m^2, with the proportional reduction in energy use for lighting and refrigeration being slightly higher than for heating and cooling. This sets a baseline for considering future reductions in energy use and emissions.

As noted earlier, refrigeration systems are a large consumer of energy in food retailing. Carbon dioxide refrigeration systems have been used in recent years because of the environmental benefits they offer in terms of energy use reduction and avoidance of harmful refrigerant leakage to the atmosphere. At Brunel University, novel carbon dioxide refrigeration systems have been developed for supermarkets, notably with the integration of carbon dioxide refrigeration and trigeneration systems where the refrigeration generated by the trigeneration system is used to condense the carbon dioxide refrigerant in a cascade arrangement (Ge *et al.*, 2013; Suamir *et al.*, 2012). The trigeneration system consists of a natural gas engine based CHP system and a sorption refrigeration system. The heat rejected by the CHP system is used to drive the sorption chiller, with the cooling energy produced employed to condense the carbon dioxide refrigerant of the subcritical carbon dioxide refrigeration system.

The above highlights that significant energy savings can be achieved by improving the efficiency of refrigeration systems, refrigeration and HVAC system integration, heat recovery and amplification using heat pumps, demand side management, system diagnostics and local combined heat and power generation and trigeneration. Energy saving opportunities also exist from the use of low-energy lighting systems, improvements in the building fabric, integration of renewable energy sources and thermal energy storage (Carbon Trust, 2010; Kolokotroni *et al.*, 2014; Tassou *et al.*, 2011). Another area that provides significant opportunities for energy savings is the design of more efficient refrigerated display fixtures. Infiltration in low, open-fronted, chilled food display cabinets can account for more than 75% of the cooling load, which has led to proposed and implemented solutions on the reduction of this load, including the use of doors (Tassou *et al.*, 2011).

6. Energy demand and reduction opportunities in food consumption

6.1 Catering

Recent statistics of energy use in the UK (DECC, 2013b), indicate that 24 TWh/year (almost 13% of total energy use by non-domestic buildings) is used by hotel and catering buildings and is responsible for approximately 6·0 MtCO_2e emissions. Of this energy, 26% (6·24 TWh) is used by catering processes, primarily cooking and refrigeration.

Carbon Trust (2012) estimates that over 30% of the energy in the catering sector is used in purely commercial catering establishments and hotel restaurants, and more than 40% in non-commercial catering such as schools, hospitals and Ministry of Defence (MoD) organisations.

A recent report sponsored by Defra, Carbon Trust and AEA focuses on contract catering, which covers ‘the provision of food services to people at work in business and industry, catering in schools, colleges and universities, in hospitals and healthcare as well as welfare and local authority catering and other non-profit making outlets' (AEA, 2012). It highlights that approximately 40% of the energy used in kitchens is used for cooking, 28% for refrigeration, 17% for air extraction and 5% for dishwashing, with estimated carbon emissions at approximately 1·3 million t carbon dioxide per year; the energy use and carbon dioxide emissions calculated by monitoring four categories of sites (business and industry; hospital; school; and MoD) are shown in Figure 5.

Energy efficiency in commercial kitchens has been addressed by many publications in the UK and internationally, for example Cibse (2009), which have identified many opportunities for energy savings, including those of lighting, ventilation and more efficient cooking/refrigeration equipment. However, behavioural changes with respect to type of food consumed, food preparation practices, environmental conditions in the catering premises and their interaction with refrigeration and HVAC equipment provide additional energy-saving opportunities.

6.2 Home

It is estimated that food consumption in the home accounts for 18 $MtCO_2e$ emissions (Defra, 2013). Major contributors to this include refrigeration, cooking and food shopping. The IEA (2008) reported that cooking for a group of 19 IEA countries (IEA19) accounted for 5% of energy use in the home, a percentage similar to energy use by lighting. Even though the diffusion of energy-efficient large appliances such as refrigerators and freezers is improving, energy use of appliances is increasing owing to an increase in the amount of small, electrically powered household equipment.

Savings can be achieved from the use of more efficient appliances and food preparation methods such as microwave rather than oven cooking, the use of more temperature-stable foods, and changes in consumer diets and behaviour such as internet shopping.

Food consumption, however, is affected by a wide variety of factors including food availability, food accessibility and food choice, which in turn may be influenced by social and human factors such as disposable income, urbanisation, marketing, religion, culture and consumer attitudes (Kearney, 2010).

7. Waste reduction and opportunities for utilisation of energy in food waste

The Waste and Resources Action Programme (Wrap) estimates that the post-farm-gate food chain is responsible for around 15 Mt of food waste, which accounts for more than 20 $MtCO_2e$ emissions (Wrap, 2013). Household waste is responsible for 7·0 Mt of this, manufacturing, retail and wholesale account for 4·3 Mt, and the hospitality and food service sectors 0·92 Mt. The remainder is attributed to the service and other sectors of the chain, in addition to 2·2 Mt by-products from the manufacturing sector used for animal feed. Alongside food waste, non-recycled packaging waste accounts for an additional 3·6 Mt of waste, amounting to approximately another 6 $MtCO_2e$ emissions (Wrap, 2013).

Part of the food waste (≈6 Mt) is avoidable, and is mainly due to food/drinks that are thrown away untouched, excess production, personal preference or accidents (Wrap, 2013). These are mainly obtained at the food consumption stage of the food chain, with the relative distribution shown in Figure 6, whereby a majority of the waste goes to landfill (Defra, 2013).

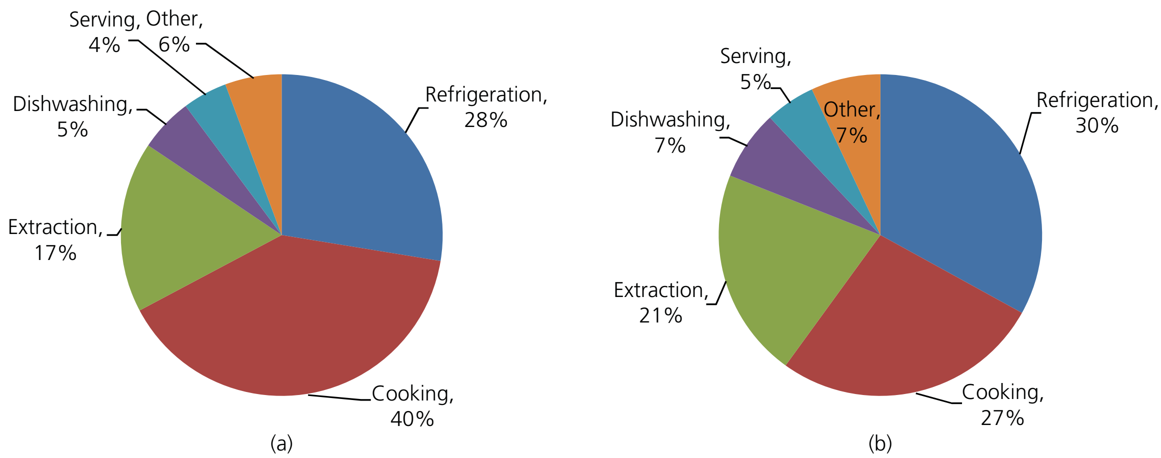

Figure 5. (a) Energy use and (b) carbon dioxide emissions by end use in four catering sites (source: AEA, 2012)

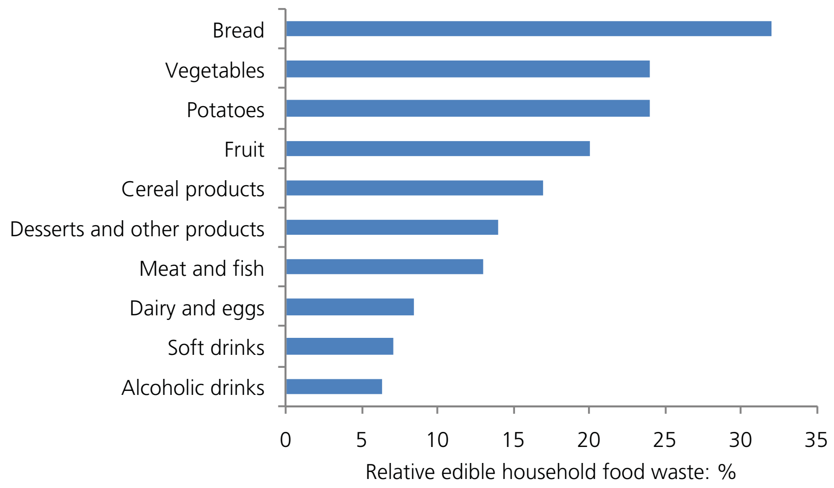

Figure 6. Relative edible household waste for each food category (source: Defra, 2013)

The waste in Figure 6 can be avoided through changes in food labelling and consumer behaviour, and a relaxation of quality standards, but also through technological changes (Bond *et al.*, 2013). Figure 6 also shows that those products such as fruits and vegetables, meat and bakery, which are perishable, delicate and possess short shelf-life, are most likely to be wasted. This suggests that further waste can be reduced through improved manufacturing processes and logistics, better temperature control across all sectors of the food chain, hence making significant savings in energy use and GHG emissions.

Unavoidable waste from the food chain arises from both food (9 Mt) and packaging (10 Mt) (Wrap, 2013). Packaging waste can be mainly reduced through increased recycling, re-use of packaging and avoiding packaging (Defra, 2011a). Unavoidable food waste can be effectively used as an energy resource in different stages of the food chain through anaerobic digestion or gasification. Such technologies can also provide additional benefits of producing valuable bio-fertilisers. With respect to the agricultural sector, waste consists mainly of weather-related losses, and retail-driven losses. Food production is highly dependent on demand, such that high demand and stringent regulations on quality can result in up to 40% waste (Bond *et al.*, 2013). Under such circumstances, GHG mitigation measures may include an adjustment of the regulations to reduce waste, but also anaerobic digestion technologies to convert the yearly 90 million t of slurry and manures from animal breeding to useful energy (Defra, 2011b). Hence, energy use and emissions from waste in the food chain can essentially be reduced through a combination of improved technological, legal and consumption efficiencies, as well as through an increase in re-use, recycling and use of energy conversion technologies at all stages of the chain.

8. Summary and conclusion

Energy is an important input in growing, processing, packaging, distributing, storing, preparing and disposing of food. It is estimated that the energy consumption of the food chain is responsible for approximately 18% of total UK primary energy use. Domestic operations, cooking and refrigeration make the highest contribution, followed by manufacturing, commercial transport, agriculture, retail and catering. The food chain is also responsible for 176 $MtCO_2e$ emissions and 15 Mt of food waste.

In agriculture, even though the energy consumption is not very high compared to the whole food chain, energy savings of up to 20% can be achieved through renewable energy generation and the use of more efficient technologies and smart control systems. The government is promoting energy generation from waste through anaerobic digestion, and the number of plants and generation capacity is expected to increase significantly in the next few years. In food processing, energy can be saved at the processing plant level by optimising and integrating processes and systems to reduce energy intensity. Approaches that can be considered include better process control, advanced sensors and equipment for on-line measurement and intelligent adaptive control of key parameters, including minimisation of waste through energy recovery and better use of by-products, among others.

In the food retail sector, significant progress in energy efficiency has been made in recent years but potential still exists through improvements in the efficiency of refrigeration systems, refrigeration and HVAC system integration, heat recovery and amplification using heat pumps, demand side management, system diagnostics and local CHP generation and trigeneration. Energy-saving opportunities also exist from the use of low-energy lighting systems, improvements in the building fabric, integration of renewable energy sources, and thermal energy storage.

Energy consumption in catering facilities is primarily from cooking and baking, refrigeration and HVAC systems. Energy efficiency can be achieved from the use of more efficient equipment and behavioural changes with respect to type of food consumed, food preparation practices, environmental conditions in the premises and their interaction with refrigeration and HVAC equipment. In the home, energy savings can be achieved from the use of more efficient appliances and food preparation methods such as microwave rather than oven cooking, the use of more temperature-stable foods, and changes in consumer diets and behaviour.

Food consumption is affected by many factors, including food availability, disposable income, urbanisation, marketing, religion, culture and consumer attitudes. All these factors should be taken into consideration in devising approaches and technologies to effect significant reduction in energy consumption and resource use in food chains.

Acknowledgements
The authors would like to acknowledge the funding received from RCUK for the establishment of the National Centre for Sustainable Energy Use in Food Chains (grant no. EP/K011820/1), as well as contributions made by industry partners and other stakeholders.

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