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Embodied energy in preventable food manufacturing waste in the United Kingdom

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ABSTRACT

The food processing and manufacturing industry is the UK's largest manufacturing sector and consequently a large consumer of natural resources and source of environmental impacts. Considerable research effort has been made to quantify and characterise food waste and energy consumption from the industry, enabling the sector to set targets for reductions which contribute to national targets and the UN Sustainable Development Goal 12.3, and to identify improvement measures to meet the targets. A gap in this research is a detailed estimation of the energy consumption which could automatically be avoided through preventing food waste in food manufacturing. This paper reports research which estimates the energy embodied in preventable manufacturing food waste in the UK using available data for 2014. Whilst the estimate of 106 GW h per year is a tiny proportion of the industry's annual energy consumption, it is 1.75 percentage points of the main 20% energy efficiency improvement target and over half the contribution expected from energy management measures to improve energy efficiency. Preventing food waste in the factory could therefore also contribute significantly to energy efficiency and climate change targets with no extra effort.

1. Introduction

The UK has had ambitious climate change targets since it signed the United Nations Framework Convention on Climate Change following the Earth Summit in 1992 (United Nations, 1992), and the Climate Change Act 2008 imposed a legal requirement on the Government to achieve greenhouse gas emissions levels by a series of target dates. The manufacturing sector has been allocated an important contribution to these targets, as it emits 16.5% of the UK's CO₂ total (Office for National Statistics, 2018). Food is the fourth largest emitting manufacturing sub-sector with 8.2% of manufacturing CO₂ emissions (calculated from Office for National Statistics, 2018), and accounts for 16%¹ of UK energy consumption in manufacturing (Department for Business, Energy and Industrial Strategy, 2018).

Energy efficiency actions are well programmed in the UK food manufacturing sector, driven by Climate Change Agreements on emissions reductions with many food sub-sectors under the Climate Change Levy (CCL),² and by the 'Courtauld Commitment' to meet resource use and CO₂-equivalent (CO₂e) targets between 2015 and 2025 (WRAP,

2019). The measures by which the CCL target reductions will be achieved have been identified by the main industry body, the Food and Drink Federation (FDF) (Reeson, 2015). The measures are mainly technological, with a small proportion due to energy management measures. On top of this, the Government and several food industry bodies have published a detailed joint roadmap and action plan for decarbonisation and energy efficiency (Department for Business, Energy and Industrial Strategy et al., 2017).

Specific energy consumption in food manufacturing (MJ/kg of product output, also called specific embodied energy or SEE) has also been estimated for many foodstuffs, mainly through lifecycle inventories (LCIs) which contribute to lifecycle assessments (LCAs). The Waste and Resources Action Programme (WRAP) researched and published SEE values for the UK's top 50 grocery food products (WRAP, 2013a), broken down in many cases by stage of the supply chain; others have also collated such data (Ramírez et al., 2006; Wang, 2008, Dallemard et al., 2015). (All the references for SEEs used in this study are in Supplementary Information 1.)

At the same time, there is also pressure on all actors in the food

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¹ The UK National Environmental Accounts produced by the Office for National Statistics would put this proportion slightly higher due to a difference in methodology.

² Accessible at <https://www.gov.uk/government/collections/climate-change-agreements-umbrella-agreements>

chain, including consumers, to reduce food waste, which post-farm gate has been estimated at around 10 m tonnes per year in the UK (WRAP, 2018a) - approximately 25% of the UK's food consumption - and 1.7 m tonnes from manufacturing (WRAP, 2016). The study by WRAP was a definitive work, intended to correct and refine the methodologies of previous work (WRAP, 2013b) and produce the most authoritative estimates of UK food waste. It was carried out under a contract rather than a research grant.

As well as CO₂e targets, the Courtauld Commitment also includes targets for food waste reduction by manufacturers and other parts of the supply chain and consumers (WRAP March 2017, personal communication), supporting Sustainable Development Goal (SDG) 12.3. Many studies have conceived and analysed ways to reduce food waste (e.g. Garrone et al., 2016; Göbel et al., 2015; Parry et al., 2015).

Food intended for human consumption but not actually consumed embodies the resources used to produce it, and energy is one of those resources. This simple fact has been observed by a number of authors (Zisopoulos et al., 2015; Dorward, 2012), but our review of the literature has identified only four studies of the relationship, in the UK, USA and Italy. It is important because it means that reductions in food waste automatically deliver reductions in embodied energy, with no additional effort. Reductions in embodied energy are the focus of this paper.

2. Previous work

The Waste Resources Action Programme (WRAP), a UK government-supported not-for-profit company, calculated the CO₂e emissions arising from the energy embodied in food waste in two stages (WRAP, 2014). First, the energy used in food & drink manufacturing for the year 2012 from each energy source was multiplied by the CO₂e emissions factors for each source (electricity, gas etc) to produce a total CO₂e emissions figure; second, emissions per tonne of output were calculated by dividing the CO₂e total by the total industry output, and this average was applied to food waste so that a gross figure for the potential emissions which could be avoided by reducing manufacturing food waste was produced.

Whilst useful for some purposes, this calculation does not take account of the different SEEs associated with different categories of food, nor of the relative quantities of each category produced.

Cuéllar and Webber (2010) used data on food production, food waste and embodied energy by type of foodstuff (which is not always the final food product) from different years to produce a preliminary estimate of embodied energy in food waste in the USA for 2007. Their source data for waste quantities did not break down into stage of the food supply chain, so a figure for processing/manufacturing cannot be reported. SEE values for each type of foodstuff were calculated by multiplying:

- US Department of Agriculture (USDA) estimates of total food waste mass arising throughout the supply chain
- SEE figures derived from the mass ratio of the type of foodstuff to total food produced and the total energy used for the food processing stage.

The authors point out that the methodology used by the USDA as well as the age of the data it used “implies a large margin of error”. The SEE data used implies a one-to-one relationship between every kilogram of mass output and energy input, which is not the case because energy input varies by type of foodstuff.

Vittuari et al. (2016) used secondary data for food waste and energy

inputs into the Italian food supply chain to produce estimates of embodied energy in food waste for the year 2011. For the processing (manufacturing) stage of the supply chain, their estimate was 28.43 PJ (7.9 TW h) of energy embodied in 2.47 m tonnes of food waste (average 3198 kW h/tonne). This was 12.2% of the energy consumed through the food supply chain excluding households and 1.3% of total energy consumption in Italy. They analysed foodstuffs (rather than food products) of 13 types or categories (e.g. cereals, vegetables, meat, milk). For food waste mass quantities for these foodstuffs, they used estimates for the Europe region from the UN Food and Agriculture Organization (FAO) (Gustavsson et al., 2011). These estimates do not appear to account for quantities in mixed, processed food products, such as sauces, ready meals, snacks, and deem all edible waste as preventable. For embodied energy figures, they used official government data on energy consumption of the ‘agri-food’ industry in Italy split by fuel type. It appears that the total figure for energy use by the agri-food industry was not granulated by type of foodstuff processed, so that the final results do not reflect the different amounts of energy required to produce each type.

Tonini et al. (2018) carried out a lifecycle assessment of avoidable food waste in the UK. This was focused on identifying the environmental impacts associated with different stages of the food lifecycle, so had a much broader remit than the present paper. There were several other features which makes this study of limited value for our purposes. The energy data they used combined farming and processing, and it covered only the processing stage of manufacturing for a minority of product categories (e.g. cutting of meat), and no manufacturing for the remainder. For half this minority the data was relatively old, from a study published in 2007. The study reported CO₂-equivalent emissions for each stage of the food lifecycle and not embodied energy for each food category.

The four previous studies in this field therefore have some drawbacks, which is to be expected with complex calculations using incomplete data from different sources representing different food production systems. Two of them do not cover the UK situation, and these were not able to make use of recent research updating estimates of UK food waste. None focused more closely on the preventable portion of manufacturing food waste.

This paper seeks to add to the body of knowledge in the field, describing a method for estimating the energy embodied in preventable waste from food factories in the UK and discussing the significance of the resulting numbers.

Section 3 (Methodology) explains how secondary data was used to define preventable manufacturing food waste, quantify it and calculate SEE values for 196 sub-categories. Section 4 reports the results. Section 5 (Discussion) interprets the results to understand whether a useful quantity of energy could be saved in preventing food waste in manufacturing, and therefore whether such action should have a higher priority in corporate and public policy. This section also discusses the assumptions and caveats associated with the source data and the calculations. The paper finishes with section 6 (Conclusions).

3. Methodology

3.1. Overview

Fig. 1 summarises the steps taken in this study, for which we first present a brief overview to introduce the key concepts and paradigm.

The calculation of annual embodied energy (EE) in preventable manufacturing waste (PMW) from food and beverage (F&B) factories is

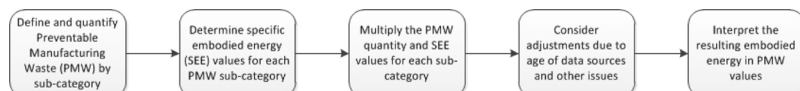


Fig. 1. Summary of Methodology.

at the top level very simple, as was done by WRAP (WRAP, 2014): multiply the quantity of food waste arising with a figure representative of the energy used to produce the waste (Eqs. 1 and 2).

$$\begin{aligned} & \text{Average specific embodied energy (kWh/kg)} \\ & = \frac{\text{Total process energy consumed by UK F\&B manufacturing (MWh)}}{\text{UK food manufacturing output (tonnes)}} \end{aligned} \quad (1)$$

$$\begin{aligned} & \text{Total embodied energy in PMW (GWh)} \\ & = \text{Average specific embodied energy (kWh/t)} \times \text{UK food PMW (tonnes)} \end{aligned} \quad (2)$$

However, these calculations hide significant variability or weighting in both quantities of waste arising and in specific embodied energy (SEE) values between food types.

3.1.1. Food waste

Food becomes waste when it is no longer part of the supply chain for placing on the market for human consumption (Östergen et al., 2014). Not all food waste can be prevented, as explained in section 2.2, so it is only the manufacturing food waste which can realistically be prevented on which we focus.

3.1.2. Embodied energy

The energy required to produce food products varies widely (Ramírez et al., 2006; Wang, 2008; WRAP, 2013a) so using the average figure for SEE of food products manufactured in the UK (510 kWh/tonne, 2014) in Eq. 2³ will give an incorrect estimate of total embodied energy unless the quantities arising compensate very closely for the SEE differences between food products down to sub-category level. Empirical data for SEEs of all food products by sub-category are therefore needed.

3.1.3. Target calculation

Eqs. 1 and 2 must therefore become more nuanced calculations (Eq. 3):

$$\text{Total EE in PMW} = \sum_n^1 (\text{SEE}^{\text{FSC}} \times \text{PMW}^{\text{FSC}}) \quad (3)$$

where: $\text{SEE}^{\text{FSC}} = \text{SEE}$ (food sub-category); $\text{PMW}^{\text{FSC}} = \text{PMW}$ (food sub-category).

Recognising the mass and energy differences between food sub-categories and isolating values for each of these sub-categories means that this study is using the principle of an input-output approach, although it does not need to take account of flows between them as such an approach does. The data used is mainly process-based, or bottom-up, as described below.

3.2. Manufacturing food waste definitions

The first requirement was to identify data on the quantities of food waste arising from UK food factories. The most recent definitive work on this was published by the Waste and Resources Action Programme (WRAP, 2016), updating and correcting WRAP's previous estimations (WRAP, 2013b). They estimated a total of 1.7 m tonnes of waste arising annually from UK food factories, which from their report could be classified as follows:

3.2.1. Manufacturing surplus

Products & material intended for sale for human consumption but

³ Sources: 'Total process energy consumed by UK F&B manufacturing' [calculated from various sources, set out in the data available for this paper, divided by 'UK food manufacturing output' [WRAP, 2016, p10]].

not actually sold, and diverted to secondary use (redistribution or animal feed) – e.g. overruns, products not sold within date.

3.2.2. By-Products

Material not suitable for the manufactured product but which can be diverted to secondary use or conversions – e.g. peelings, bone, sludges from cleaning (which are a significant component).

3.2.3. Preventable Manufacturing Waste (PMW)

Products and material not sent for sale, or surplus material which need not have been manufactured – e.g. spilt products, below-quality rejects, over-ordered ingredients, mislabelled product.

Manufacturing Surplus is difficult to prevent because the reasons for its occurrence are largely out of the manufacturer's control. Variations in demand over short periods are difficult to predict, and market expectations demand that any potential excess of demand over supply can be met by the manufacturer. Events such as the daily weather can affect demand for some products. Whilst there is scope for reducing the manufacture of Surplus, it is limited, and accordingly the scope for reduction in energy use by the manufacturer is also limited.

By-Products are impossible or difficult to avoid or reduce so again there is limited potential for reducing the energy used in producing them.

The WRAP researchers developed a scenario in which the allocation of food waste to redistribution to charity and to animal feed was maximised, depending on its nature. These options technically involve food material before it becomes waste, and are higher in the 'waste' hierarchy than anaerobic digestion, composting, landspreading, thermal conversion and landfill.

In the WRAP 'maximised' scenario, PMW remained, with prevention being the best action available. PMW can be reduced or eliminated by the manufacturer, and this is therefore the category which can provide a useful number for preventable energy consumption in the factory.

3.3. Quantity of preventable manufacturing waste

3.3.1. PMW total and by category

The WRAP (2016) report estimated the total quantity of PMW for their reference year of 2014 at 150,100 tonnes which could be prevented by 2025, arising from the 11 categories shown in Fig. 2:

The authors used several data sources to produce their estimates, mainly Environment Agency permitting data (in which food wastes are categorised into many waste streams and quantified), records, observations and interviews gained from 34 visits to manufacturing sites in the 11 categories, although the number of these in each sector visited varied from one to six. The information from site visits was also supplemented with expert judgement found in published reports by WRAP, industry and other stakeholder bodies.

The data were then scaled up to UK-wide level using appropriate reference sources. Due to the heterogeneity of data sources in terms of definitions, time periods and quality, this exercise was necessarily imprecise and the report sets out the uncertainties associated with the estimates of waste arisings. A subsequent report (WRAP, 2018b) has estimated arisings for 2015 using the same methodology as the WRAP, 2016 report, putting total food manufacturing waste at 1.85 m tonnes compared to 1.7 m for 2014. However, PMW was not separately estimated.

Note that the estimated 150,100 tonnes of PMW is 8.8% of the 1.7 m tonnes of food manufacturing waste for 2014 (WRAP, 2016) and 1.5% of total UK post-farm gate food waste of 10.2 m tonnes (WRAP, 2018b⁴). Reductions in PMW can therefore make a worthwhile

⁴ The 22 May 2018 press notice accompanying this report (at www.wrap.org.uk/content/wrap-restates-uk-food-waste-figures-support-united-global-action) says that this total, a calculation for the year 2015, "remains unchanged", so

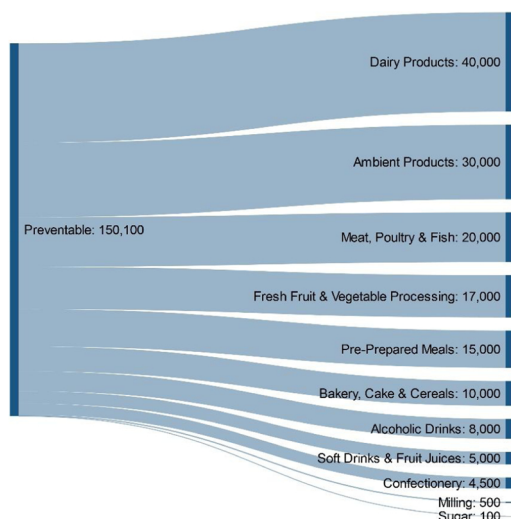


Fig. 2. Preventable Manufacturing Waste by Sector (tonnes). Data from WRAP (2016).

contribution to SDG 12.3 for UK food manufacturing, but the focus of this paper is the free energy efficiency gains which can be made by reducing PMW.

3.3.2. PMW by sub-category

3.3.2.1. *Defining the sub-categories of production.* As explained in section 3.1 (Overview), in order to calculate Eq. 3 it was necessary to determine PMW arising by sub-category.

The sub-categories used by the WRAP researchers were those used in the PRODCOM database of industrial production published by the Office for National Statistics.⁵ Each category in PRODCOM comprises sub-categories down to 8 digits, as exemplified in Fig. 3 (Office for National Statistics, 2015a):

The PRODCOM sub-categories were mapped by WRAP onto categories which were not exactly the same as the PRODCOM categories; some of the WRAP categories (shown in Fig. 1) were unique to the WRAP study.

For our study, WRAP’s mapping from one to the other was not available, so our mapping is original. Table 1 shows our mapping of the PRODCOM categories onto the WRAP categories:

An assessment of how close our category classifications seem likely to be to that of the WRAP researchers is at Appendix A.

3.3.2.2. *Quantifying PMW by sub-category.* The WRAP study did not estimate arisings of PMW to sub-category level, so, without the data being available, it was necessary to assume that the quantity of PMW in each sub-category was related to the level of production.

This was done by calculating the percentage of a category’s output which was accounted for by each of its sub-categories, as shown in Fig. 4. In this example, the output of the sub-category ‘Cakes & Pastry Products’ was 14% of the output of the PRODCOM category ‘Bakery, Cake & Cereals’ in 2014, so this percentage was used to derive the quantity of PMW ice cream from the WRAP estimation of 10,000 tonnes

(footnote continued) also applies to 2014.

⁵ Available from: <https://www.ons.gov.uk/businessindustryandtrade/manufacturingandproductionindustry/bulletins/ukmanufacturerssalesbyproductprodcom/intermediateestimates2015> PRODCOM is compiled from responses to a paper questionnaire from a sample of around 21,500 UK manufacturers circulated each January (Office for National Statistics, 2015a). Completion and return is a legal requirement (Office for National Statistics, 2015b).

- Division: 10 - Manufacture of food products
 - Industry code: 10.83 - Processing of tea and coffee
 - Product aggregate code: 10.83.11 - Coffee, decaffeinated or roasted
 - Product code: 10.83.11.30 - Decaffeinated coffee, not roasted
 - Product code: 10.83.11.50 - Roasted coffee not decaffeinated
 - Product code: 10.83.11.70 - Roasted decaffeinated coffee

Fig. 3. Example of PRODCOM 8-digit hierarchy.

of Bakery, Cake & Cereals PMW in 2014. Multiplying 10,000 by 14% gives 1384 t of ‘Cakes & Pastry Products’ waste which could have been prevented in UK factories.

Our analysis of the extent to which it is reasonable to assume that PMW arises in the same proportions as product outputs, reproduced as Appendix A, concluded that it was reasonable and not distorting overall and for each of the WRAP categories except for Ambient Products and Bakery, Cake & Cereals. For these, there is a possibility that the embodied energy is overstated in the present study.

3.4. Embodied energy

To calculate Eq. 3, the SEEs of food products down to the level of 196 sub-categories were also needed.

SEE values (reported as MJ/kg and converted in this analysis to kWh/kg) have been obtained for many food products by measuring the consumption of all energy-using equipment in a factory used to produce the target products, usually as part of a life cycle inventory (LCI) or assessment (LCA) study. These have then been published in academic papers and other reports. The following sources provided the data used in this study, from a total of 112 papers:

Source	Comments
(WRAP, 2013a)	A study which gathered published LCI and LCA data to produce SEE values at different stages of the supply chain for the UK’s 50 most purchased food products. Many products had values for the manufacturing stage. For most products there was more than one study, so the median value was reported.
Other published LCIs and LCAs	Additional research for the present study identified further peer-reviewed studies giving SEE values for specific food products. These were either published after 2013 (the year of the WRAP publication) or not referenced by the WRAP authors.

For a minority of sub-categories there was no published data. In these cases, sub-categories were identified which were probably similar in terms of processing requirements and for which there was data, and the SEE value for the most similar was used.

Although not used directly for SEE values, a review by the European Commission’s Joint Research Centre on current energy use in the food sector and opportunities for improvement (European Commission Joint Research Centre, 2015) was used for comparison purposes when compiling the SEE values. This report contains manufacturing SEE values for some of a basket of the most purchased food products in the EU.

The full list of SEE values and their sources for the 196 sub-categories is in Supplementary Information 1.

4. Results

4.1. Uncorrected values

Using the above values in Eq. 3, Table 2 shows the values for PMW quantities and total embodied energy (EE) for each of the categories in the WRAP report of 2016.

Sugar was excluded due to the absence of data in PRODCOM, but

Table 1
Category relationships between WRAP (2016) study and PRODCOM (2014, provisional).

WRAP Categories	PRODCOM Categories
Dairy products	SIC(07) 1051 – Operation of dairies & cheesemaking
Ambient products	SIC(07) 1052 – Manufacture of ice cream
Meat, poultry and fish	SIC(07) 1039 – Other processing and preserving of fruit and vegetables
	SIC(07) 1084 – Manufacture of condiments and seasonings
Fresh fruit and vegetable processing	SIC(07) 1089 – Manufacture of other food products n.e.c.
	SIC(07) 1011 – Processing and preserving of meat
Pre-prepared meals	SIC(07) 1012 – Processing and preserving of poultry meat
Bakery, cake and cereals	SIC(07) 1013 – Production of meat and poultry meat products
	SIC(07) 1020 – Processing and preserving of fish, crustaceans and molluscs (Note 1) (Note 2)
Alcoholic drinks	SIC(07) 1085 – Manufacture of prepared meals and dishes
	SIC(07) 1071 – Manufacture of bread; manufacture of fresh pastry goods and cakes
Soft drinks and fruit juices	SIC(07) 1072 – Manufacture of rusks and biscuits; manufacture of preserved pastry goods and cakes
	SIC(07) 1061 – Manufacture of grain mill products
Confectionery	SIC(07) 1102 – Manufacture of wine from grapes
	SIC(07) 1103 – Manufacture of cider and other fruit wines
Milling	SIC(07) 1105 – Manufacture of beer (note 3)
	SIC(07) 1107 – Manufacture of soft drinks; production of mineral waters and other bottled waters
Sugar	SIC(07) 1032 – Manufacture of fruit and vegetable juice
	SIC(07) 1082 – Manufacture of cocoa, chocolate & sugar confectionery
	SIC(07) 1061 – Manufacture of grain mill products (note 4)
	Not assessed.

- 1.For canned tuna output, used Sea Fish Industry Authority (2015) - Factsheet Tuna Industry 2014.
- 2.Output values are from WRAP (2016) which in turn are from Defra (2015) Horticultural Statistics.
- 3.Also obtained split of lager and ale from the British Beer and Pub Association (personal communication) and data for non-sparkling wines from the Food Standards Agency.
- 4.The sub-categories used here were different to those used for ‘Bakery, Cake and Cereals’.

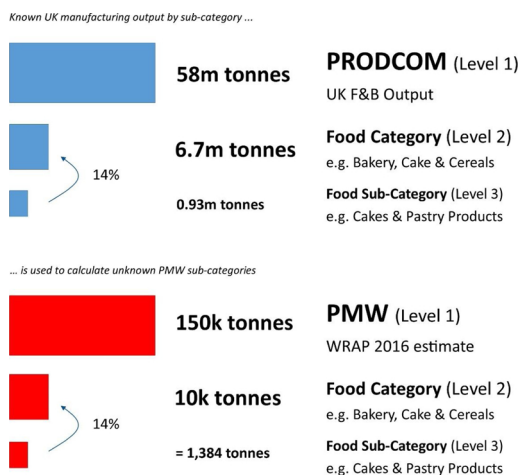


Fig. 4. Method for quantifying PMW by sub-category.

since its estimated PMW was only 100 t per year it can be considered an insignificant category with respect to the energy saving potential associated with PMW.

4.2. Corrected values

It was necessary to reduce the above total EE values to take account of:

- Reductions in SEE due to energy efficiency improvements since the LCI/LCA data contained in the sources used for SEE values were gathered
- The inclusion in those reductions of non-process energy (buildings systems) and tobacco manufacturing (which makes up around 1% of the F&B total (personal communication, March 2017).

The main approach is illustrated in the steps shown in Appendix B using example data entries and values.

Table 2
Total embodied energy by WRAP, 2016 category (uncorrected).

Category	PMW (Tonnes/yr)	Total Embodied Energy (MWh)
Dairy products	40,000	17,508
Ambient Products	30,000	24,285
Meat, poultry and fish	20,000	21,879
Fresh fruit and vegetable processing	17,000	2,624
Pre-prepared meals	15,000	15,900
Bakery, cake and cereals	10,000	14,292
Alcoholic drinks	8,000	8,808
Soft drinks and fruit juices	5,000	1,436
Confectionery	4,500	14,414
Milling	500	163
Total	150,000	121,310

This process was complicated by the fact that the WRAP (2013a) report only listed its sources separately and did not identify the specific sources used for each SEE value it reported. A separate procedure was carried out to weight the sources from WRAP (2013a), which accounted for 66.3% of the total embodied energy value in PMW. This procedure is set out in Appendix C.

These corrections reduce the estimate of total embodied energy in 2014 PMW from the gross figure of 121.31 GW h (Table 2) to 105.98 GW h.

4.3. Counter considerations

Against the corrections reported above, other considerations need to be noted:

- PRODCOM did not provide data for every sub-category of food product used in the WRAP (2016) study. Data for some sub-categories is “suppressed” for commercial confidentiality or security reasons, whilst for others it is not gathered. The number of sub-categories with suppressed or missing data is 51, compared to the number with data of 196. We have not attempted to estimate quantities for these products, but their absence means that the PMW

quantities by category and in total calculated in this study are understated.

- For some PRODCOM sub-categories, data for 2014 was not available, so an earlier year's output was used, mainly from the range 2011–2013 inclusive. This may also have introduced understated values.
- Where there was uncertainty about the correct SEE value to use, or where there was a choice of SEE values for a sub-category but no evidence to support any option, the most conservative (smallest) value was used. For this reason also the total EE in PMW may be understated.
- There is the possibility that some SEEs are overstated because not all PMW arises as a finished product, at the end of the manufacturing line, and therefore the full energy input will not have occurred in all cases.

We analysed this by listing all the causes of PMW identified by the WRAP researchers and allocating each to the beginning, middle or end of the production process. A score of 1, 2 or 3 was allocated to each stage respectively. Totalling the scores within each category located the point during production at which the PMW most likely arose within each category. This point was then weighted within all 11 food categories by relating it to the proportion of total PMW accounted for by a category. The weighted scores were then summed and calculated as a proportion of the score for 100% occurrence of the PMW at the end of production. The result was that 89% of PMW arose at the end of production. We did not analyse the PMW contributing to the balance of 11% for whether any energy was saved through the PMW arising before the end of the production line, but believe it can be considered sufficiently small a proportion as to not significantly affect the overall result, and in any case is counter-balanced by our disregard of the energy used to manage PMW arising. This energy is used to clear up or collect the waste, transport it to storage and then off the site, as well as clean the production equipment if necessary.

Our analysis is available in Supplementary Information 2.

- There are also caveats associated with the secondary sources of the data. The WRAP study highlighted the understandable limitations encountered with respect to the work it reported. Examples relating to their field work are:

“... recruitment to the project was challenging and it was difficult to book fieldwork within a constrained time period, as many sites had other commitments, such as site audits and peak production periods. “In total 37 sites participated [out of a target total quota of 42], with quotas fulfilled in five of the 10 sub-sectors.”

“... there was considerable variation in terms of the granularity and completeness of the data captured by different organisations ranging from aggregated waste management company data (by month / by lift across a limited number of waste streams) to detailed, line-specific data (by day / by shift recording weight / product / reason code) at key points in the manufacturing process.”

WRAP also listed limitations of their Environmental Permitting and other data sources together with the researchers' mitigating actions. These are detailed in the report (pages 60–65).

- Quantity and quality of embodied energy data

The WRAP 2013 study highlighted the fact that LCI and LCA studies can report a range of embodied energy values for the same food product, reflecting real world diversity of process and energy efficiencies; bread is a good example. They used the median values of ranges from their sources.

This points to the need ultimately for at least several data sources for each food sub-category manufactured in a country or geographical region in order to be more precise about the levels of EE in PMW.

These assumptions and caveats associated with the source data and the calculations need to be weighed in any further elaboration of this exercise.

5. Discussion

5.1. Value of the calculation for public policy and corporate action

5.1.1. Total EE in PMW

This study aimed to reach a valid estimation of the energy embodied in Preventable Manufacturing Waste, and in this we believe it has succeeded. Whilst hedged with a number of assumptions and caveats, discussed below, we have arrived at a total figure which has sufficient reliability to provide a signpost for public policy and corporate action in food manufacturing economies such as the UK.

When seen as a proportion of the food and drink manufacturing sector's total energy consumption, total EE in PMW is tiny and of little value. When seen as a proportion of sector energy efficiency targets, it carries more weight. The sector currently has two energy-related targets: the Climate Change Agreements (CCAs) under the Climate Change Levy aggregate to an 18% reduction in energy consumption between 2008 and 2020 (Reeson, 2015); under the current Courtauld Commitment, the sector's signatories are committed to a 20% reduction in greenhouse gas emissions between 2015 and 2025.⁶ In Europe, the EU's next overall target across all sectors is to reduce energy consumption by 20% by 2020 (when compared to the use of energy in 2020 projected in 2005) (Council, E.P., 2012). A revision to the Energy Efficiency Directive to increase the 2030 target to a 32.5% reduction (compared to 2005 (European Commission, 2016)) has been agreed (European Commission, 2018a, 2018b) If we smooth these targets into a notional but typical 20% reduction in energy use over any period from 2015 inclusive, we find that the total EE in PMW comprises 1.79 percentage points of such a target. Whilst relatively small, a portion of this from one percentage point upwards would be a useful contribution to the target, particularly as it would also contribute to waste reduction targets, which are included in the Courtauld Commitment.

Going further, the FDF has estimated that, to meet the current CCA target, about 18 percentage points of the target will be contributed by technical changes and innovation, and 4.7 percentage points by improved energy management (Reeson, 2015). Since the target period started in 2013 and covered eight complete years, on a linear basis 'energy management' should have had 3.5 percentage points left to contribute after the year of our data (2014). The total EE in PMW we have calculated is 51% of this amount of energy. The conclusion is therefore that focusing on substantial reductions in PMW would, strategically and financially, be a very effective way to meet both public and industry energy and waste reduction targets simultaneously. This should be incorporated into policymaking with respect to the achievement of SDG 12.3.

These observations do not quantify the associated saving of energy expended on the PMW material higher up the supply chain, on the farm, transport and any pre-processing operations. This study could be extended in this way.

Another way to assess the value of PMW reduction as an energy efficiency measure is to consider the costs relative to alternative actions. The average cost of purchased electricity to F&D manufacturers was ~£80 per MWh in 2013 (Reeson, 2015). (Data on the levelised cost of on-site generating systems is not collected by government (BEIS, personal communication, May 2017).) The costs of PMW reductions may need to be estimated in a further study, but are likely in most cases to be small, involving mainly management/organisational actions, and they generate both savings in costs and income through sales of the product. The business case is therefore overwhelming.

At a system level, most of the treatment options below waste prevention in the material management hierarchy shown in Fig. 5 mitigate the saving of EE in PMW through conversion into power and heat and/

⁶ WRAP website at www.wrap.org.uk/content/courtauld-commitment-2025. No published documents are available.

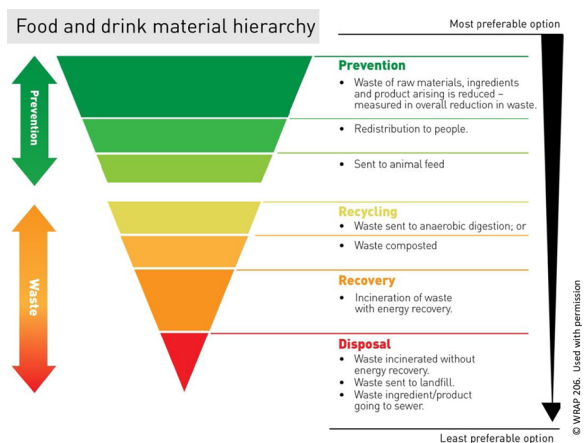


Fig. 5. Food and Drink Material Hierarchy (WRAP, 2016).

or substitution of energy to a greater or lesser extent. From a policy perspective therefore, EE in PMW could be seen as of less value, since much of the energy is 'recovered' downstream through substitution or conversion. However, using the energy embodied in foodstuffs for other functions is not the most efficient or economic allocation of energy resources because it involves higher energy losses than other sources would incur, and uses other resources such as land which could be used more efficiently for the total food value rather than just the energy value. Lifecycle analysis would be needed to flesh out this argument.

5.1.2. EE in PMW by category

It is useful to note that the total EE calculated by taking into account the differences in SEE between food products (106 GW h) is 38% higher than the total EE from Eq. 2, calculated using just the industry average for embodied energy (77 GW h). This relationship is also shown when the our total EE figure is broken down by sector, as shown in Table 3 and Figs. 6 and 7.

Fig. 6 orders the PMW categories by how much they account for EE, whilst Fig. 7 presents the categories in the same order but by their quantity of PMW, showing that the two measures are not the same. 'Fresh fruit and vegetables' is in the top five categories by mass (Fig. 7) but not by EE (Fig. 6), and 'Confectionery' comes into the top five by EE. Perhaps more interesting is the distribution of values between the two metrics: for PMW quantities, the top five categories make up 81% of the total value, whilst for EE the top five are 68%; energy is more distributed across the categories than mass, with the smaller categories of PMW requiring proportionately more energy input than their share of total mass.

For public food waste policy and corporate strategies, the analysis at category level points to a reordering of priority categories for action if reduction of EE is the main objective, and to the energy benefits of addressing the top six or seven categories rather than just the top five. The policy priority is that of Fig. 6, rather than of Fig. 7 ordered by mass as shown in Fig. 8.

Table 3
WRAP (2016) categories ranked by proportion of total EE.

Preventable production waste	EE (MWh)	% of total EE
Ambient products	21,215	17.5
Meat, poultry and fish	19,114	15.8
Dairy products	15,295	12.6
Pre-prepared meals	13,891	11.5
Confectionery	12,593	10.4
Bakery, cake and cereals	12,486	10.3
Alcoholic drinks	7,695	6.3
Fresh fruit & vegetable processing	2,293	1.9
Soft drinks & fruit juices	1,255	1.0
Milling	142	0.1

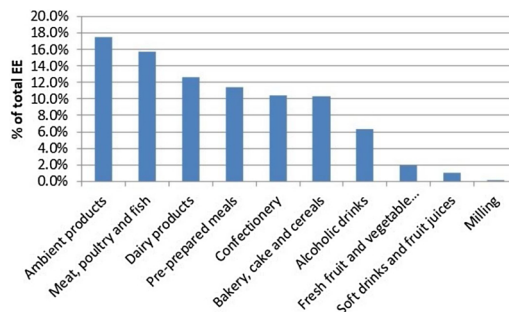


Fig. 6. WRAP (2016) categories ranked by proportion of total EE.

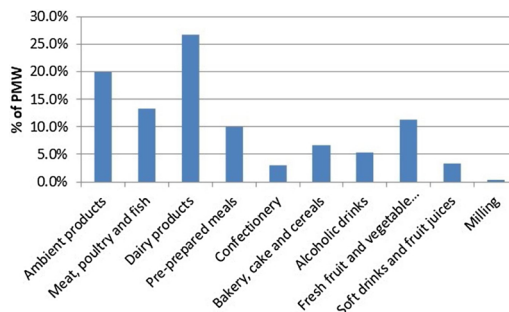


Fig. 7. WRAP (2016) categories in the same order as Fig. 6 but measured as proportion of PMW.

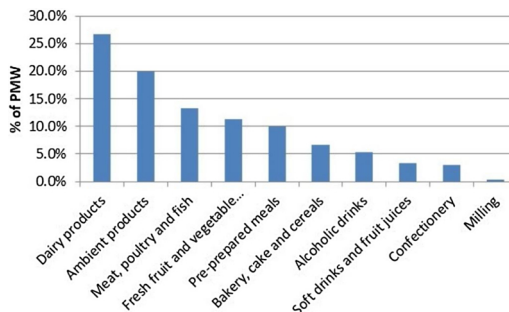


Fig. 8. WRAP (2016) categories ranked by proportion of PMW.

Another possible criterion for prioritising food waste prevention actions is the energy and nutritional content or value of the PMW (Vittuari et al., 2016). This would require a separate study, but a comprehensive approach to the classification and characterisation of food waste has been proposed and described (Garcia-Garcia et al., 2016), and this could be used to provide such information.

6. Conclusion

In this study we have assembled secondary data on the estimated quantity of waste arising in UK food and drink factories which could be prevented by 2025 and on the energy used in those factories to produce an estimate of the total energy embodied in the preventable food waste.

Despite the need to make assumptions and introduce caveats associated with the secondary nature of the data and the inherent difficulty of corraling so much disparate information from uncontrolled activities, the methodology is coherent and sufficiently reliable to enable useful interpretation. We find that:

- Preventing food factory waste would also provide a significant contribution to meeting energy efficiency targets with no extra effort on top of preventing such waste; energy efficiency gains are an automatic by-product.

- When the probable small cost of preventing food manufacturing waste is compared to the cost of energy paid by food manufacturers, the business case for prioritising prevention is overwhelming.
- Embodied energy is spread across more food categories than quantities of waste arising. Public policy and corporate strategies aimed at energy efficiency should therefore address the top six or seven categories rather than the top five where food waste by quantity is concentrated.

Whilst there are counter-balancing energy gains in downstream waste treatment operations, these would be a sub-optimal policy choice in the allocation of resources for energy supply or conservation.

The WRAP authors recommended that their study provided an opportunity for WRAP to:

“Refine the estimates for how much food waste might be prevented from arising based on a) the evaluation of innovations in processing, equipment, packaging management etc., as these are implemented, b) from monitoring the levels of food surplus and waste arising over time and c) from feedback on the barriers to implementing relevant innovations.”

An alternative view is that the benefits of refining this exercise to eliminate some of the assumptions and caveats do not appear to be of sufficient magnitude beyond the present study to warrant an attempt. It may be better to use public and corporate funding to optimise and

Appendix A. Comparison of Category Classifications

Since WRAP’s mapping from PRODCOM sub-categories onto their categories was not available, it was necessary to use our own judgement to allocate PRODCOM sub-categories to the WRAP categories. Table A1 shows the production output values for each category respectively reported by the WRAP researchers and ourselves, and the differences.

The total output figure is virtually the same between WRAP and ourselves, showing that the analysis for the overall embodied energy is based on a consistent translation from the WRAP study. Four categories are the same or similar, but there are significant differences for five of the categories. For three of these (Ambient Products, Bakery, Cake & Cereals and Alcoholic Drinks) WRAP was lower and for two (Pre-Prepared Meals and Soft Drinks & Fruit Juices) we were lower.

For Alcoholic Drinks, we used data from the Food Standards Agency (FSA) for non-sparkling wines, which could explain the difference. For Pre-Prepared Meals, the difference by value is small so is less important in terms of the central question, which is whether our study, by virtue of deriving quantities of waste arising linearly from quantities of food produced in each sub-category, has attributed waste arising to PRODCOM sub-categories for which WRAP did not attribute waste arising.

If we can dismiss the differences for Alcoholic Drinks and Pre-Prepared Meals, then three categories remain: Ambient Products, Bakery, Cake & Cereals and Soft Drinks & Fruit Juices. For the last of these, our production output figure was significantly lower both by value and percentage, so there is no risk of overstating embodied energy for this category. For the other two, there is a possibility that the embodied energy is overstated in the present study.

Table A1

Discrepancies between production outputs data by category (in WRAP, 2016 Appendices) and the PRODCOM outputs data used in the present study.

All million tonnes	WRAP, 2016	Sheppard & Rahimifard	Difference	% difference (against lowest)	
			WRAP lower	S&R lower	
Dairy Products	No significant difference				
Ambient Products	1.6	2.3	0.7		44%
Meat, Poultry & Fish	5.3	4.9		0.4	8%
Fresh Fruit & Vegetable Processing	Only sales values differ because same source was used for quantities				
Pre-Prepared Meals	1.3	0.9		0.4	44%
Bakery, Cake & Cereals	5.6	6.7	1.1		20%
Alcoholic Drinks	8	10.9	2.9		36%
Soft Drinks & Fruit Juices	15	10.6		4.4	42%
Confectionery	No significant difference				
Milling	6.1	6.5	0.4		7%
Total			5.1	5.2	

Appendix B. Process for correcting total Embodied Energy values

The process shown in Figure B1 takes account of energy efficiency improvements since source data for specific embodied energy values (SEEs) were gathered and the inclusion of buildings energy use in those improvements.

implement methods of reducing PMW.

Further research could usefully look at other embodiments of manufacturing energy. One of these is the energy and nutritional content or value of the PMW (Vittuari et al., 2016). Going beyond PMW but taking the concepts of embodied energy in waste further, Alexander et al. (2017) calculated that, worldwide, over-eating on each of the four measures of dry and wet matter, energy and protein content was found to be at least as large a contributor to global food system losses as consumer food waste. Protein over-consumption was over three times the level of protein losses in consumer waste. A study of the embodied manufacturing energy associated with both energy and nutritional content of PMW and with over-eating would also provide useful support for prioritisation of action in health policy and practice.

Declarations of interest

None.

Acknowledgements

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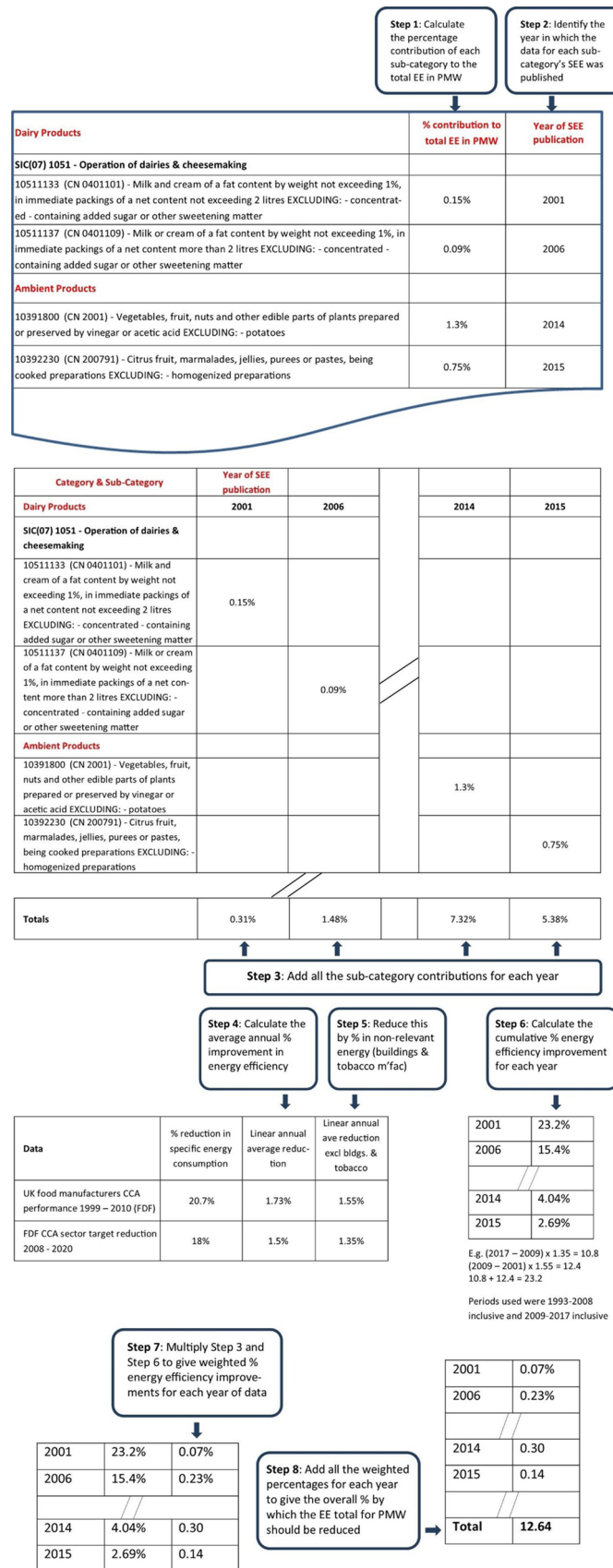


Fig. B1. Process for correcting total embodied energy values.

Appendix C. Corrections to account for energy efficiency improvements since source data was published

This appendix shows the results from Steps 2, 4 and 5–8 in [Appendix B](#).
[Tables C1](#) [Table C2](#)

Table C1
 Corrections relating to (WRAP, 2013a) sources.

Year	# W13 sources	Year's W13 sources as % of all W13 sources	Reduction to % of all sources	% reduction on total due to age of study ^a	% reduction reflecting contribution of study to total EE
1993	1	1.03%	0.68%	35.51%	0.24%
1996	1	1.03%	0.68%	30.87%	0.21%
1998	4	4.12%	2.73%	27.77%	0.76%
1999	1	1.03%	0.68%	26.23%	0.18%
2000	4	4.12%	2.73%	24.68%	0.67%
2001	2	2.06%	1.37%	23.13%	0.32%
2002	2	2.06%	1.37%	21.59%	0.30%
2003	12	12.37%	8.20%	20.04%	1.64%
2004	5	5.15%	3.42%	18.49%	0.63%
2005	6	6.19%	4.10%	16.95%	0.70%
2006	11	11.34%	7.52%	15.40%	1.16%
2007	3	3.09%	2.05%	13.85%	0.28%
2008	9	9.28%	6.15%	12.31%	0.76%
2009	16	16.49%	10.94%	10.76%	1.18%
2010	6	6.19%	4.10%	9.42%	0.39%
2011	6	6.19%	4.10%	8.07%	0.33%
2012	8	8.25%	5.47%	6.73%	0.37%
Total	97	100	150.8	321.80	10.11

^a This column also includes a reduction for the inclusion of buildings energy and tobacco manufacturing in the original data (Step 5 in [Fig. B1](#)).

Table C2
 Corrections relating to non-W13 sources.

	Year	% contribution from non-W13 years to EE total	% reduction on total due to age of study	% reduction reflecting contribution of study to total EE
1 source	2001	0.0031%	23.13%	0.07%
2 sources	2006	0.0148%	15.40%	0.23%
2 sources	2009	0.1461%	10.76%	1.57%
3 sources	2013	0.0400%	5.38%	0.22%
3 sources	2014	0.0732%	4.04%	0.30%
4 sources	2015	0.0538%	2.69%	0.14%
15 sources	Total	0.3311		2.53

Total % reduction due to age of studies: 12.64% (W13 + non-W13 source totals).

Appendix D. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.resconrec.2019.03.002>.

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