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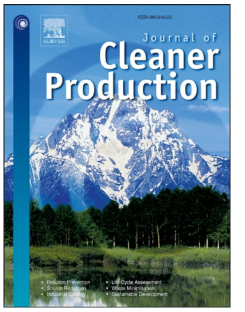

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All authors contributed equally to the conception and design of the study, in its framework and general assumptions. All authors contributed equally to the writing and review processes. Pagani and De Menna collected the data related to mass flows, energy use, and cost. Vittuari, De Menna, and Pagani contributed to the modelling and performed the analysis. Vittuari and Johnson provided supervision and coordination.

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Matteo Vittuari, Marco Pagani, Thomas G. Johnson, and Fabio De Menna

An efficient energy use in the food supply chain (FSC) is a major policy priority, considering the dual challenge of decreasing non-renewable resource availability and increasing world population. This article is one of two that analyzes the concept of the "dual energy waste" caused by food losses and waste (FLW): *(i)* nutritional energy and *(ii)* embodied energy used to produce food. Part A focused on the upstream segments (production, transport, and processing) of the United States FSC. In Part B the downstream segments (distribution, transport, home and out-of-home consumption) are analyzed. All direct and indirect energy inputs involved in food produced for domestic use in the USA were considered. From 2001 to 2015 the average energy use in the downstream part of FSC was 6,000 ± 550 PJ (about 5.8% of total energy use), while FLW were estimated at 57.8 Mt. This caused 370 PJ of nutritional energy waste, 2,250 PJ of embodied energy waste, and a wasted energy cost of almost $28 billion. Animal products represented only 34% of the FLW mass but generated 60% of the embodied energy waste.

Appropriate food waste reduction strategies such as improved demand forecasts, more efficient product handling, discounted price on nearly expired foods, clearer product-life labeling, and more careful planning by consumers, could achieve energy saving and reduce the United States fossil fuel dependence and greenhouse gas emissions.

1. Introduction

Food loss and waste (FLW) represents a global problem for humanity, generating a misuse of resources and increasing food insecurity in the world's poorest countries. Each year 1.3 billion tons of food, about one third of the total production, are lost or wasted globally (Gustavsson et al., 2011). For these reasons, several international organizations and national governments (UN, 2015; EC, 2015; USDA/FDA/EPA 2018) have introduced measures targeting FLW prevention and reduction.

A staggering amount of natural resources, such as water and land, is embedded in FLW. Every year 170 km³ of irrigation water, twice the discharge of the Nile River, and 200 million hectares of fertile land, more than the cultivated land in India, are employed to produce food that is subsequently wasted (Lipinski et al., 2013).

Similarly, FLW is also related to a significant waste of energy (Cuellar and Weber, 2010. While energy use in food production has increased due to agricultural mechanization, use of chemicals, and intensive processing, later segments of the supply chain have increased energy use due to longer distance transport, refrigeration, and out-of-home food consumption (Pimentel and Pimentel, 2008). Therefore, from a system perspective, food systems are responsible for up to 30% of final energy use (Cuellar and Weber, 2010), higher than the relatively limited share of energy use attributed to the agriculture and forestry sectors in official statistics (IEA, 2013).

In this context, targeting downstream segments of the FSC should be an urgent priority since, especially in industrialized countries, most food waste occurs at the consumer level (Parfitt et al., 2010; Gustavsson, 2011) and more energy is embodied in the food.

Despite this and the relative maturity of the embodied energy concept, few authors have addressed the "food waste - resource" nexus (FAO, 2013; Kummu et al., 2012; Usubiaga et al., 2018), with only three known studies focusing on energy use by food systems. Cuellar and Weber (2010) analyzed the United

States FSC to evaluate the amount of embodied energy losses, using 2001-2003 food mass data and product-specific energy intensities from a single source on energy consumption in food production. Therefore, their findings cannot be easily extrapolated to a longer period or other contexts, considering the changes likely occurring in both energy efficiency and food production. Vittuari et al. (2016) focused on the Italian FSC using national sectorial statistics and including nutritional energy loss. However, the consumption stage was excluded from the study due to lack of data. Similarly, Sheppard et al. (2019) focused on the embodied energy in preventable food manufacturing waste in the United Kingdom, excluding later stages in the supply chain. None of these studies evaluated the related economic impact of energy use and waste, through a cost assessment.

This two-part study builds on the “dual energy waste” concept: wasting food causes a waste of nutritional energy and “embodied energy”, that is energy used to produce, process, transport, sell, preserve, and cook food. Interestingly the latter type of energy waste is usually much larger than the former.

While food production and processing were the focus of Part A (Pagani et al., 2019), part B aimes at carrying out a complete assessment of the nutritional and embodied energy waste and related economic costs of the FLW in the downstream section of FSC of the United States (US), including retail, home and out-of-home consumption, and related transport. This research advances the related literature in terms of comprehensiveness and robustness of the data, avoidance of yearly variability by analyzing a multiple-year period, by using national sectoral statistics, and by including more analytic detail on farming machinery, fisheries, food manufacturing, packaging, transport, retail, and consumption.

2. Materials and methods

2.1 Food flows and waste at distribution and consumption levels

Fig. 1 shows the distribution and consumption segments (hereafter referred to as downstream) of the United States FSC, with the mass flows of products and the related energy flows analyzed in this paper. Upstream steps (farming and processing) are discussed in Part A (Pagani et al., 2019). Transport has been associated with mass flow in each case.

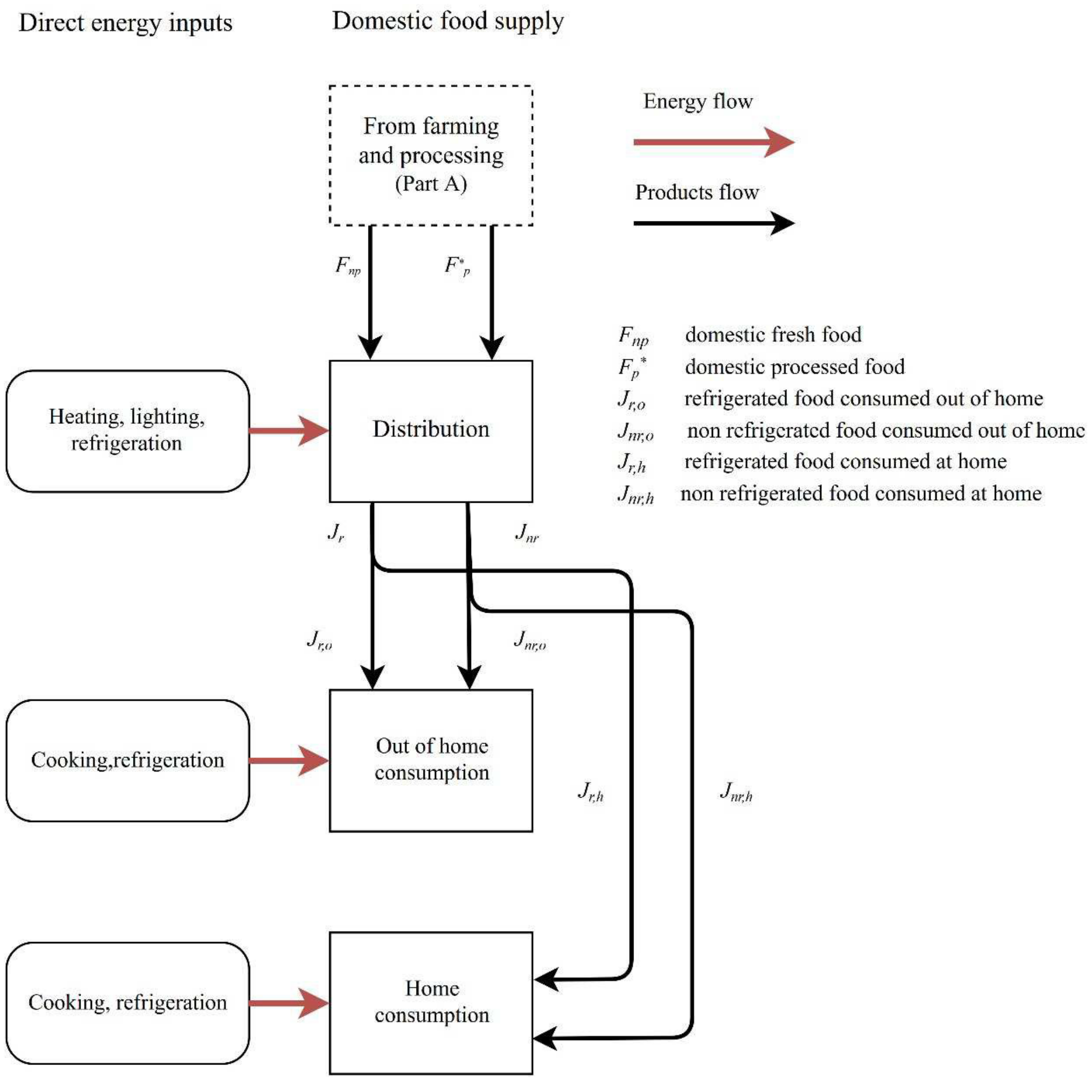


Fig. 1 Structure of the downstream steps of the U.S. FSC. For farming and processing see Part A (Pagani et al., 2019)

Processed (F_p) and non-processed (F_{np}) food products from upstream processes merge at the distribution level and then are split again between refrigerated (J_r) and non-refrigerated (J_{nr}) products. This distinction is essential given the significant and increasing energy use for refrigeration. These flows are further split downstream into home (subscript "h") and out-of-home consumption (subscript "o").

consistent with the upstream analysis in Pagani et al. (2019), no energy was attributed to the product losses and waste associated with: *(i)* fresh or processed exported food, not retailed in US; *(ii)* imported food, both fresh for domestic processing and retail and already processed, due to the lack of reliable information on the energy embodied in its production in the exporting country and international transport.

The boundary of the system is set at food consumption. Therefore, neither the valorization or disposal of food and package waste, nor the operations of dish cleaning were considered.

Table 1 summarizes the average masses of all food retailed in the US in 2001-2015 subdivided in 13 categories reflecting the Food and Agriculture Organization (FAO) taxonomy. Products were split into refrigerated (R) and non-refrigerated (NR), due to the significantly different energy intensity both at the distribution and consumption level. No differentiation was made between chilled and frozen food, due to the lack of detailed data from the Energy Information Administration. See Supplementary material, Annex A, for more detailed information.

Table 1. Average food domestic use in the US for the period 2001-2015

k	Food category	Food available *J (k)* (Mt)	Refrigerated J_R *(k),* Mt	Non-refrigerated J_{NR} *(k),* Mt
1	Cereals	46.8 ± 1.5	-	46.8 ± 1.5
2	Tubers	8.4 ± 0.4	2.5 ± 0.1	5.8 ± 0.9
3	Pulses	1.4 ± 0.07	0.2 ± 0.02	1.4 ± 0.1
4	Soybean oil	6.6 ± 0.7	-	6.6 ± 0.7
5	Oilseeds and oils	1.7 ± 0.6	-	1.7 ± 0.6
6	Sugar	6.6 ± 0.4	-	6.6 ± 0.4
7	Fruits	17.6 ± 0.7	7.76 ± 2.2	9.9 ± 0.1
8	Vegetables	18.7 ± 0.7	8.6 ± 0.6	10.1 ± 0.2
9	Meat	24.3 ± 0.57	24.3 ± 0.5	-
10	Milk	35.3 ± 0.7	33.5 ± 0.6	1.8 ± 0.1
11	Eggs	5.0 ± 0.2	5.0 ± 0.2	-
12	Fish	3.9 ± 0.2	2.6 ± 0.4	1.4 ± 0.2
13	Beverages	99.7 ± 0.2	-	99.7 ± 0.2

Sources: see Annex A

The allocation of food consumption between home and out-of-home (restaurants and canteens) was done according to Biing-Hwan et al (2016), according to United States Department of Agriculture (USDA, 2018) for alcoholic beverages and to Kit et al. (2013) for non-alcoholic beverages. The same percentage was applied to refrigerated and non-refrigerated foods. Fig. 2 reports the share α_k of out-of-home consumption for all product categories.

The total mass of out-of-home (*o*) and home (*h*) food consumption was defined as the sum of refrigerated and non-refrigerated components, for 13 food categories in Table 1.

(1)
$$J_o = J_{r,o} + J_{nr,o} = \sum a_k J_r(k) + \sum a_k J_{nr}(k)$$
$$J_h = J_{r,h} + J_{nr,h} = \sum (1 - a_k) J_r(k) + \sum (1 - a_k) J_{nr}(k) \quad ,$$

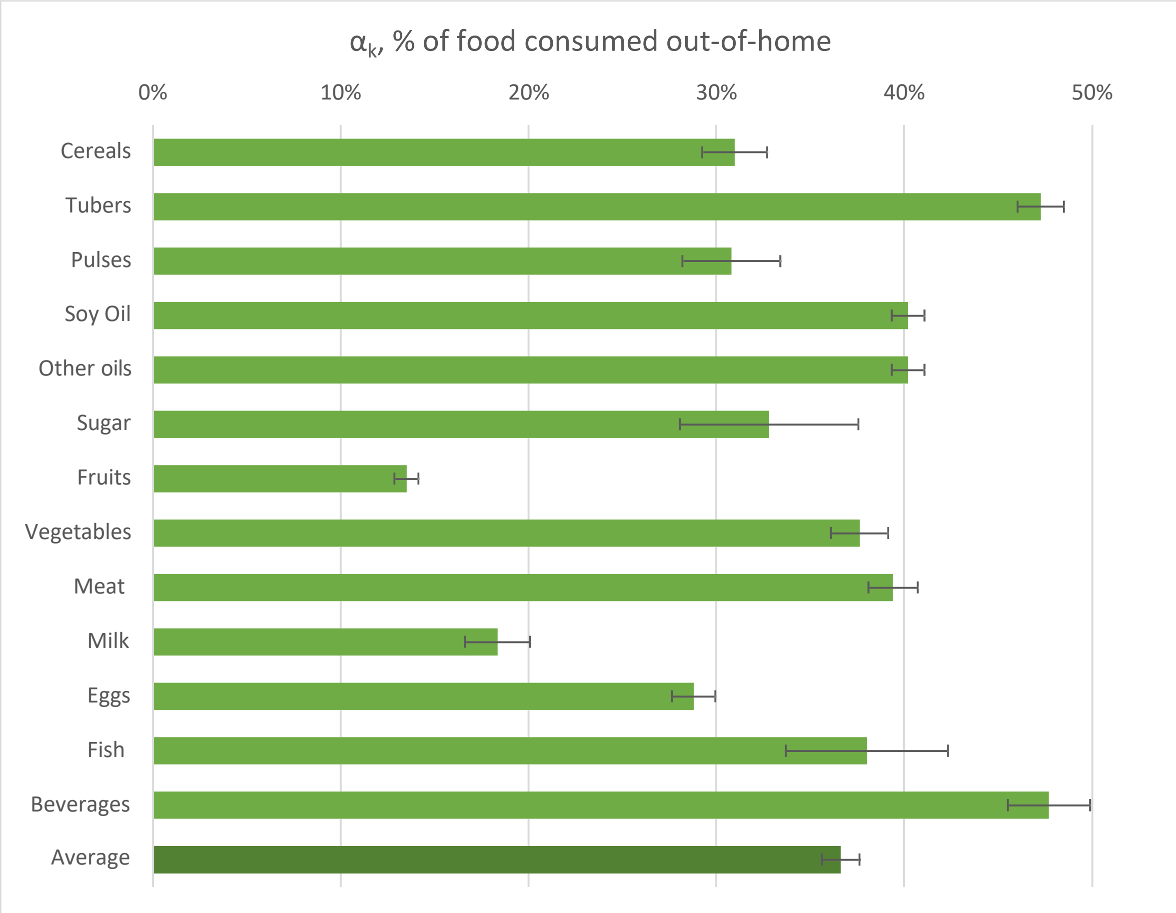


Fig. 2 Average quote α_k of food consumed out-of-home with respect to total food consumption for all product categories *k*. Error bars denote standard deviations due to year-to-year variations (period 1998-2008).

The FLW definition by Parfitt et al. (2010), identifying it as “wholesome edible material intended for human consumption, arising at any point in the FSC that is instead discarded, lost, degraded or consumed by pests”, was adopted. In addition, consistent with the FAO distinction between losses and waste, this article focused on the waste - and the related cost – of energy embedded in FW, while Pagani et al. (2019) focused on losses.

Food waste in the distribution sector is mainly caused by damaged packaging, unsold food near the expiration date, spillage, inadequate storage, overstocking or over-preparing. Waste were monitored by the United States Department of Agriculture in the period between 2005 and 2012 (see Annex A for details). Waste of foods with shorter shelf-life, like vegetables, fruits, meat and fish, was monitored more frequently than for less perishable goods, but there are at least two different estimates for each category during this period. Averages and standard deviations of waste percentages are reported in the first three columns of Table 2. No data are available for beverage waste.

Food waste at the consumption level, both at home and out-of-home, can be caused by spillage, inadequate storage, sprouting and aging, or uneaten food. Data on waste percentages for all categories are available from the United States Department of Agriculture loss-adjusted food availability documentation (Muth et al., 2011; USDA 2016a), which covers more than two hundred food products.

Beverage waste at the consumer level (overserving, accident, not used in time) was assumed to be 3.6% for soft drinks, 2.5% for bottled water, 4.3% for beer, and 4.8% for wine, with an average value of 3.6%. Due to lack of US data, these figures were estimated applying the absolute avoidable beverages waste in the UK (Wrap 2013) on the corresponding beverage consumption in the US (BSDA 2015; Wilson, 2016).

Table 2 shows consumption waste figures for fresh and processed food. Each percentage is a mass-weighted average of all foods of the same category. In the case of vegetables, 31 fresh, 9 canned, and 10 frozen product categories were considered (for more details see Annex A). Figures in table 2 agree with previous waste estimates at the consumer level for 2008 and 2010 (Buzby and Hyman, 2012; Buzby et al., 2014) although these studies covered only a few food categories. Waste data reported in Table 2 represent only the edible waste and do not include non-edible components, such as cores, peels, seeds, shells or bones.

Table 2. Food waste percentages in the distribution (w_4) and consumption (w_5) sectors (food waste w_1, w_2, and w_3 refer to pre-harvest, post-harvest and manufacturing steps of the FSC as detailed in Part A, Pagani et al., 2019)

		Refrigerated products			Non-refrigerated		
	Food category	Number of products	$w_{4,r}$ (%)	$w_{5,\,r}$ (%)	Number of products	$w_{4,\,nr}$ (%)	$w_{5,\,nr}$ (%)
1	Cereals	-	-	-	8	12±0.2	21.2 ± 4.3
2	Tubers	1	6.0	16	4	7.6±1.5	15.3 ± 2.8
3	Pulses	2	6.0±0.2	24.5±1.11	8	6.0	10
4	Soybean oil	-	-	-	1	21.0±0.7	15
5	Oilseeds	-	-	-	1	21.0±0.7	15
6	Sugar crops	-	-	-	2	11.0±0.3	34.0
7	Fruits	29	9.5±3.1	17.7±5.3	31	9.1±2.3	15.8 ± 4.3
8	Vegetables	36	9.8±4.4	21.7±8.1	27	8.8±1.5	23.4 ± 9.5
9	Meat	5	4.2±1.0	21.7±6.6	-	-	-
10	Milk	1	12.2	22.1	11	12	1.0
11	Eggs	1	9±0.1	26.1	-	-	-
12	Fish	2	9.0±0.3	40.0	2	6.0	18.1 ± 4.5
13	Beverages	5	3.0	3.6 ± 0.7	5	3.0	3.6 ± 0.7

Sources: see text and Annex A

Figure 3 shows the mass-flow diagram of the downstream FSC, with all the related waste.

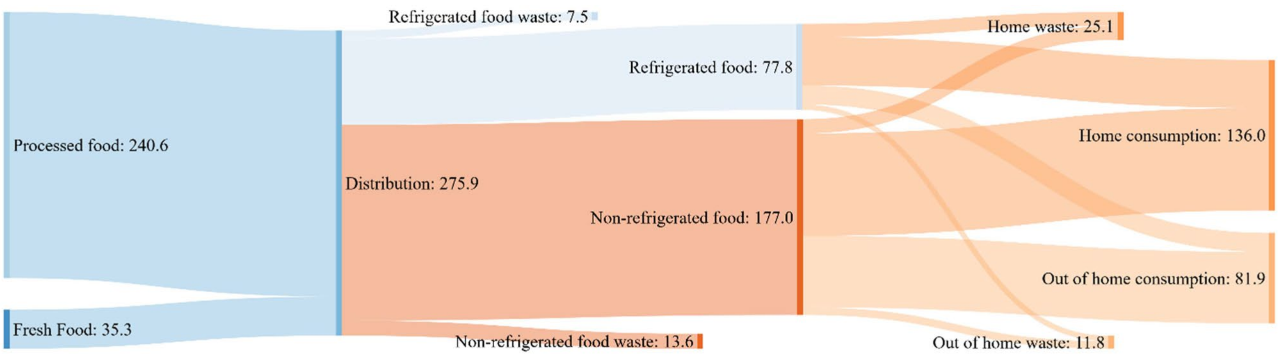


Fig.3 Mass flow and waste diagram of downstream US FSC

2.2 Energy use and cost in upstream stages of the FSC

Energy consumption data were converted into primary gross equivalents, to assure consistency with the energy use in a life cycle approach. As reported in Pagani et al. (2019), a primary gross equivalent factor of

1.099 and 1.48±0.03 per joule of final energy was assumed for oil and natural gas respectively, while the gross energy equivalent of 1 J of electricity decreased from 3.27 to less than 3.04 from 2001 to 2015.

Food farming and manufacturing

Energy use in food farming and manufacturing has been analyzed in Part A (Pagani et al., 2019). While in that case, embodied energy intensity was determined per unit of fresh food mass, in this paper, the intensity has been recomputed per unit of processed food mass whenever necessary. Conversion factors between fresh and processed masses were obtained from USDA (USDA 2016a).

Packaging

The Environmental Protection Agency (EPA 2016a) reports information on packaging materials used in the United States from municipal waste streams and the related recovery rate *r(t)* at year *t*. The energy intensity $\mathrm{E(t)}$ of packaging materials depends on *r(t)*, according to the expression: $\mathrm{E(t)} = \mathrm{E_o}[1 - \mathrm{r(t)}] + \mathrm{E_o^*}\mathrm{r(t)}$, where ε_o and ε_o^* are the embodied energy intensity of virgin and recycled material, respectively (EPA, 2016b). Energy intensity is always lower for recycled material, so ε*(t)* decreases for increasing packaging recovery rates. For each material, energy embodied in the packaging (E_{pack}) is computed multiplying the energy intensity by the mass of packaging used.

This energy has been allocated as precisely as possible to the different food categories according to assumptions based on literature or anecdotal evidence (see Annex B for details). The energy values obtained for food manufacturing and packaging are comparable with energy input-output Life Cycle Assessment, considering all indirect energy uses not primarily related to the FSC (Egilmez et al. 2014).

Historical prices for both virgin and recycled materials were used as a proxy of packaging cost. Prices of virgin and recycled aluminum and steel were retrieved from the US Geological Survey (USGS 2019a and 2019b). Prices of wood pulp from the Global Economic Monitor Commodities (World Bank, 2019) were used as proxy for virgin paperboard and paper. Unit price of recycled paper was determined from the US import value of waste and scrap of paper and paperboard, available in the UN Comtrade Database (UN Comtrade, 2019). The same method was used to calculate the value of glass containers and cullet, respectively for virgin and recycled glass (UN Comtrade 2019). Finally, historical prices for virgin and recycled plastic were retrieved on Plastics News (2019). Average prices were then calculated for a selection of widely used polymers (details in Annex B).

2.3 Energy use and cost in food transportation, retail and consumption

Transportation

Transportation data for raw and processed food from production and processing to retail and food services were recovered from the Commodity Flow Survey (BTS, 2019). Masses and mass-distance products (t-km) by mode of transportation (road, rail, and water) for the years 1997-2017 were obtained for the six food groups considered in the survey: agricultural products; animal feed and products of animal origin; grain products; other foodstuff, fats and oils; alcoholic beverages. Detailed values are reported in annex B.

Energy used in transportation (E_{trans}) was determined for each food category by multiplying mass-distance products by the energy intensity values (MJ/t-km) for each transport mode according to Kamakaté and Schipper (2009): road, 2.44 MJ/t km; rail, 0.24 MJ/t km; water, 0.37 MJ/t km. Refrigerated transport needs on average an additional 20% energy (Tassou et al., 2009). Intensities (MJ/kg) were obtained for each food category by dividing E_{trans} by the transported masses reported by BTS.

Energy use for transport from retail to home was estimated assuming an average distance of 6.1 km (Ploeg et al., 2015), 71 visit to the supermarket per year (Minaker et al., 2016), and 32.3 kg of food mass per visit, considering 726 kg of per capita food consumption and an average household size of 2.58 people (Census, 2012). Virtually all (94%) trips are done by car (Ploeg et al., 2015), resulting in 5.27 MJ/km of energy intensity, which is the weighted average of cars, SUVs, minivans, and pickups, as detailed in Annex B (EPA, 2018).

Energy use for people transportation to restaurants was included and estimated assuming an average distance of 8.85 km (Kerr et al., 2012) and an average of 99 dining out events per year (Kant and Graubard, 2018).

Cost for transport energy was calculated using unit prices of fuels, gas, and electricity from EIA (2019).

Food retailing

Energy consumption and expense data in the retail sector E_{dist} were obtained from the Commercial Buildings Energy Consumption Survey (CBECS 2012); data were obtained from the 1995-2012 surveys. Food sales energy data were integrated also with energy consumed for warehouse and storage refrigeration, which was considered part of the food distribution chain. Detailed data are presented in Annex C.

Fig. 4(a) shows the subdivision of E_{dist} in the two main contributions for refrigeration (E_{dist-R}) and for general services (E_{dist-G}). The significant growth in refrigeration energy is due to the large increase in warehouse refrigeration capacity (+37% between 2011 and 2015, USDA, 2016b) and in retail refrigerated areas (+75% for walk-in areas, + 73% open cases, + 51% closed cases, CBECS 2012). By contrast, energy for all other uses peaked in 2003 and then decreased, mainly due to energy savings achieved by the introduction of LED in lighting (Goulding et al., 2011). The large share of refrigeration is caused by the use of electrical energy, which has a gross energy equivalent three times larger than final use.

Energy consumption in years between surveys was estimated with a quadratic function for E_{dist-R} and with two linear functions for E_{dist-O} (to avoid excessively low estimation for years 2014 and 2015). The same approach was used for the cost of energy, which shows similar trends (Fig 4(b)). Coefficients are reported in Annex C.

Energy for refrigeration was allocated to chilled and frozen food masses (see Table 2), while other services (lighting, heating, cooling, cooking) were allocated to all foods. For each food category, specific embodied energy for refrigerated and non-refrigerated food at the retail stage is defined as

$$e_{4r}(k) = e_{up,r}(k) + \frac{E_{dist-R}(k)}{J_r(k)} + \frac{E_{dist-G}(k)}{J(k)} \quad (2)$$

$$e_{4nr}(k) = e_{up,nr}(k) + \frac{E_{dist-G}(k)}{J(k)} .$$

Where $e_{up\text{-}R}(k)$ and $e_{up\text{-}NR}(k)$ are the embodied energy intensities used in the upstream stages of the supply chain (1-pre-harvest, 2-harvest, 3-processing and packaging, as detailed in Pagani et al. 2019 and section 2.2) for refrigerated and non-refrigerated products respectively. Detailed data are reported in Annex C.

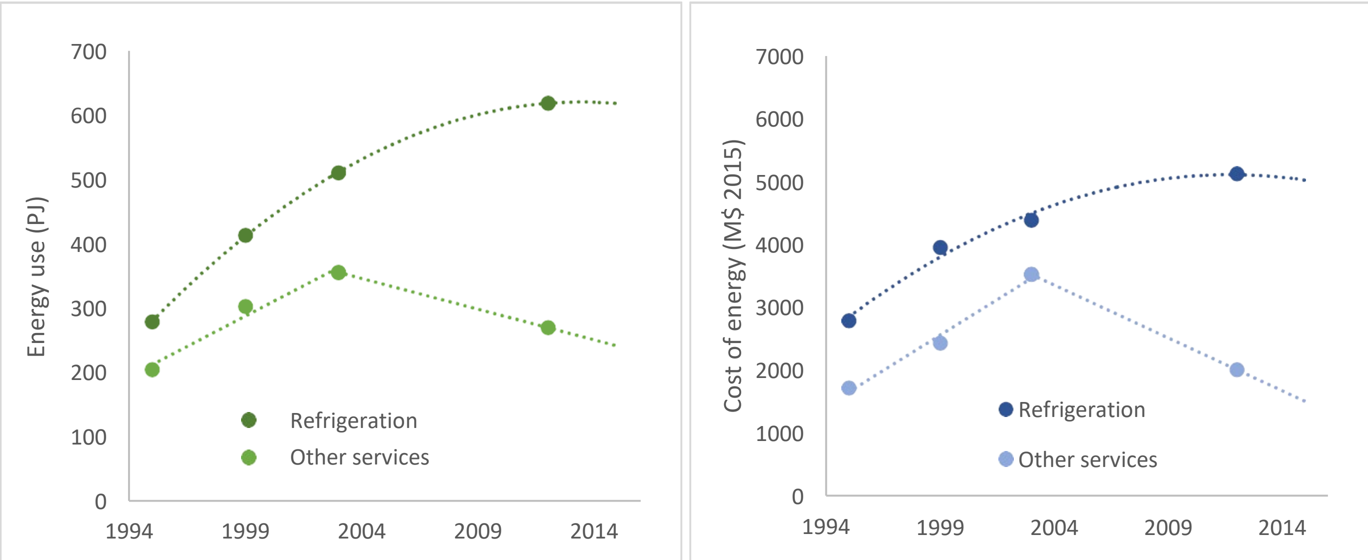


Fig. 4. Energy use (a) and cost of energy (b) in the food retail sector. Source CBECS (2012)

Home and out-of-home food consumption

Energy use and expenses for out-of-home consumption in various food services, E_o, was recovered from CBECS (2012) for the years 1995-2012. Energy consumption in years between surveys was estimated with polynomial fits. Detailed data are reported in Annex C. Only energy for cooking and refrigeration was considered, because other energy uses (heating, cooling, ventilation, lighting, office) are independent of the amount of food wasted.

Fig. 5(a) shows the subdivision of E_o in the two main contributions of refrigeration ($E_{O\text{-}R}$) and cooking ($E_{O\text{-}C}$). Refrigeration energy was allocated to chilled and frozen food masses, while cooking was allocated to all foods. For each food category, specific embodied energy for refrigerated and non-refrigerated food is defined as

$$e_{5r,o}(k) = e_{4r}(k) + \frac{E_{O-R}(k)}{J_{r,o}(k)} + \frac{E_{O-G}(k)}{J_o(k)} \quad (3)$$

,

$$e_{5nr\,o}(k) = e_{4nr}(k) + \frac{E_{O-G}(k)}{J_o(k)}$$

Energy data for food home consumption of food, E_h, were obtained from the Energy Information Administration Annual Energy Outlook (EIA 2016c) for all the years covered by the analysis. Only energy use for refrigeration (electricity) and cooking (natural gas, propane, and electricity) were considered, while dishwashing energy was not considered as it is largely unrelated to food waste levels.

Total energy related to food consumption at home is reported in Fig. 6, split into refrigeration ($E_{H\text{-}R}$) and cooking ($E_{H\text{-}C}$), so the specific embodied energies for refrigerated and non-refrigerated food are defined as

$$e_{5r,h}(k) = e_{4r}(k) + \frac{E_{H-R}(k)}{J_{r,h}(k)} + \frac{E_{H-C}(k)}{J_h(k)} \quad (4)$$

$$e_{5nr,h}(k) = e_{4nr}(k) + \frac{E_{H-C}(k)}{J_h(k)}$$

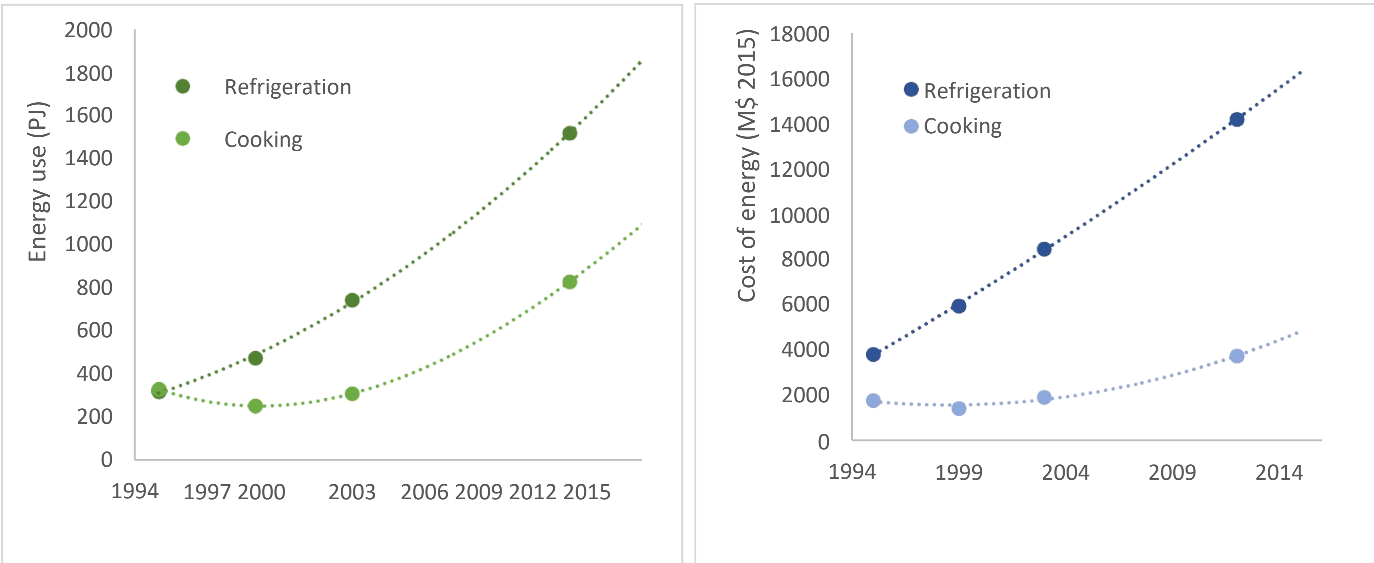
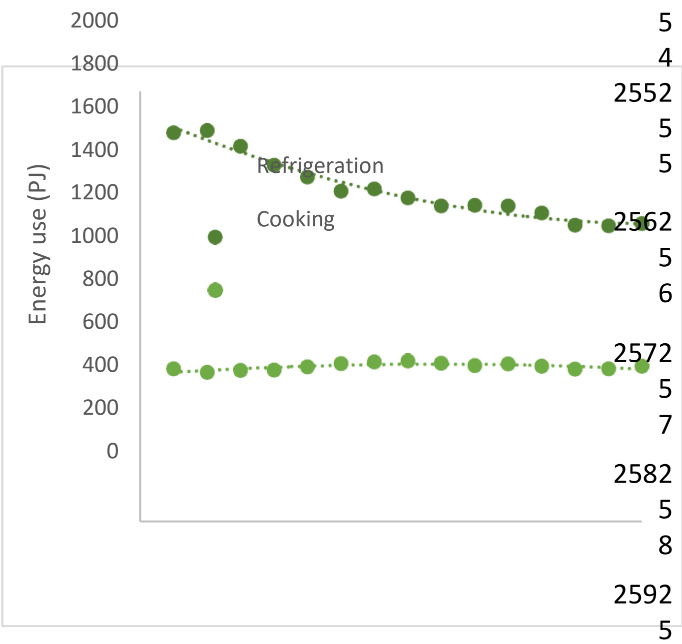


Fig. 5. Energy use (a) and cost of energy (b) in away from home consumption sector. Source CBECS (2012)



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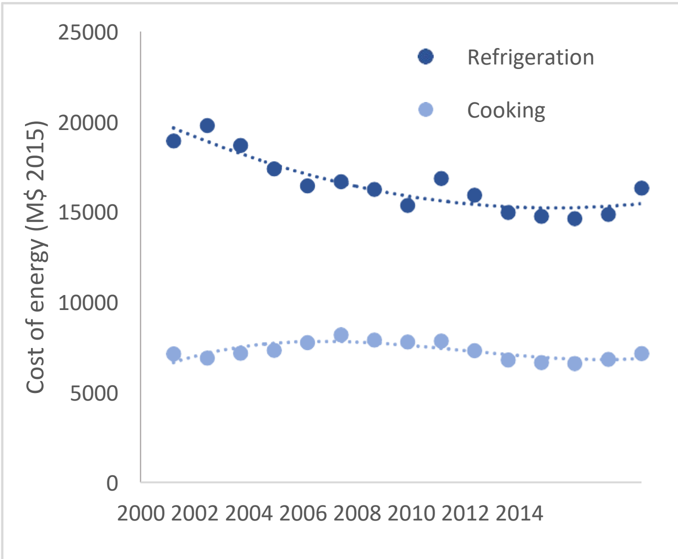

Fig. 6 Energy use (a) and cost of energy (b) for home food consumption. Source EIA (2016c)

2.4 Embodied energy and cost assessment in food and food waste

For every food category and every food supply chain step (4- distribution, 5,o- out-of-home consumption and 5,h- home consumption), the absolute amount of *Food Mass Waste* (FMW) is defined as the sum of refrigerated and non-refrigerated food mass wasted, obtained by multiplying the waste percentages by the corresponding mass flows:

(5)

$$W_4 = W_{4r} + W_{4nr} = w_4(J_r + J_{nr})$$

$$W_{5,o} = W_{r,o} + W_{nr,o} = w_{5r}J_{r,o} + w_{5nr}J_{nr,o}$$

$$W_{5,h} = W_{r,h} + W_{nr,h} = w_{5r}J_{r,h} + w_{5nr}J_{nr,h}$$

Nutritional *Food Energy Waste* (FEW) is defined as the nutritional energy in wasted food and was computed by multiplying FMW data for each food category and

FSC step that were obtained from the previous equations, by the nutritional energy intensity of each food category (FAO, 2017c).

Embodied Energy Waste (EEW) is defined as the energy consumed and embodied within food waste. It was computed by multiplying FMW data for each food category and FSC step by the embodied energy intensities defined in eq. (2), (3) and (4):

$$\begin{gathered} \mathrm{EEW}_4 = \mathrm{e}_{4\mathrm{r}}\mathrm{w}_{4\mathrm{r}}\mathrm{J}_{\mathrm{r}} + \mathrm{e}_{4\mathrm{nr}}\mathrm{w}_{4\mathrm{nr}}\mathrm{J}_{\mathrm{nr}} \\ \mathrm{EEW}_{5\mathrm{o}} = \mathrm{e}_{5\mathrm{r,o}}\mathrm{w}_{5\mathrm{r,o}}\mathrm{J}_{\mathrm{r,o}} + \mathrm{e}_{5\mathrm{nr,o}}\mathrm{w}_{5\mathrm{nr}}\mathrm{J}_{\mathrm{nr,o}}, \\ \mathrm{EEW}_{5\mathrm{h}} = \mathrm{e}_{5\mathrm{r,h}}\mathrm{w}_{5\mathrm{r}}\mathrm{J}_{\mathrm{r,i}} + \mathrm{e}_{5\mathrm{nr,h}}\mathrm{w}_{5\mathrm{nr}}\mathrm{J}_{\mathrm{nr,h}} \end{gathered} \tag{6}$$

A comparable method was used to calculate the total cost of embodied energy waste (CEW).

3. Results and discussion

3.1 Energy inputs and costs of food transport, distribution and consumption and allocation to food categories

During the period 2001-2015 the energy use for food transport, distribution, and consumption in the United States was 6,070 ± 560 PJ (7.5% of total energy use), with a significant increase of more than one third during the period from 5,320 to 7,130 PJ (Fig. 7(a)). For comparison, energy use in the upstream part of the FSC was of the same order of magnitude, 5,810 ± 150 PJ (including packaging), but without a similar trend (Pagani et al., 2019).

This growth was mainly due to out-of-home food consumption in restaurants and canteens, where primary energy use for refrigeration tripled from 600 to 1,800 PJ and energy use for cooking more than quadrupled from 270 to 1,130 PJ. The greatest increase in refrigeration energy occurred in food services within malls and retail businesses (+450 PJ), followed by canteens (+220 PJ), and restaurants (+130 PJ). Energy used for transportation was 1160 ± 25 PJ and remained almost constant over the period (+8%). Remarkably, more than two thirds of this energy is attributable to moving food from retail to homes (23%) and moving people from home to restaurants (47%). Both values were estimated according to average car fuel consumptions, but pickup trucks would use about 50% more energy. Energy consumption in the distribution sector was 890 ± 30 PJ and remained almost constant over the period, but with consistent changes in the subdivision between refrigeration and other services, since the former term increased by 33% while the latter decreased by the same rate. Food-related home energy use was 2,260 ± 140 PJ, with gradual decrease (-20%) due to improvements in refrigeration efficiency.

Fig. 7(b) shows the cost of energy for the same segments of the FSC. The general trends are similar to Fig. 6(a), as the total cost was 68 ± $4 billion with an increase from 61 to 73 billion $ in the 15-year period. For comparison, energy use in the upstream part of the FSC was of the same order of magnitude, 80 ± 3 PJ (including packaging), but without relevant trends (Pagani et al., 2019). Downstream FSC represents 51% of the energy and 46% of the energy cost for the different weighting of electricity in terms of energy (primary equivalents) and cost (final price).

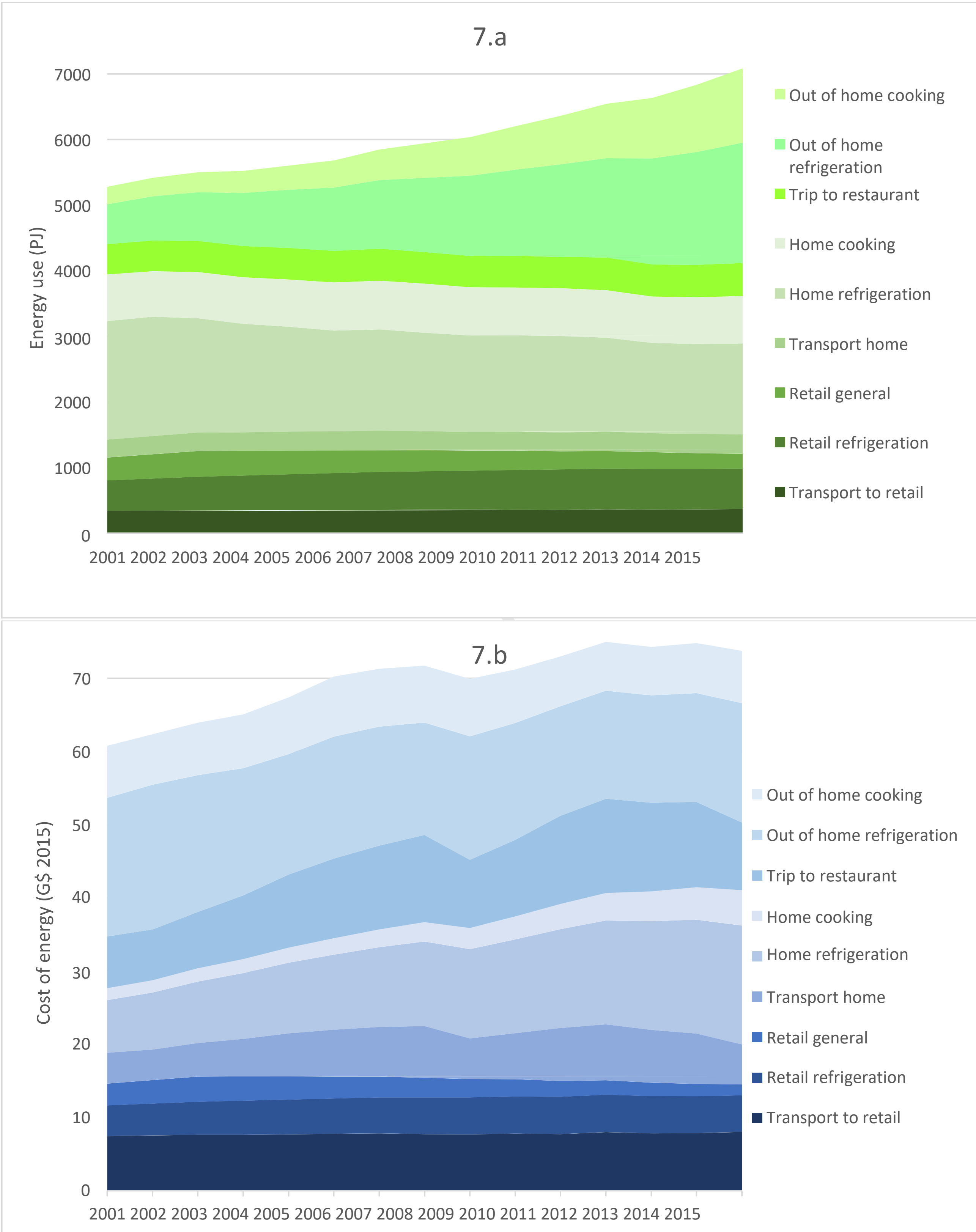

Fig. 7 Energy consumption (7.a) and cost of energy (7.b) in downstream part of the FSC: transportation, distribution and consumption

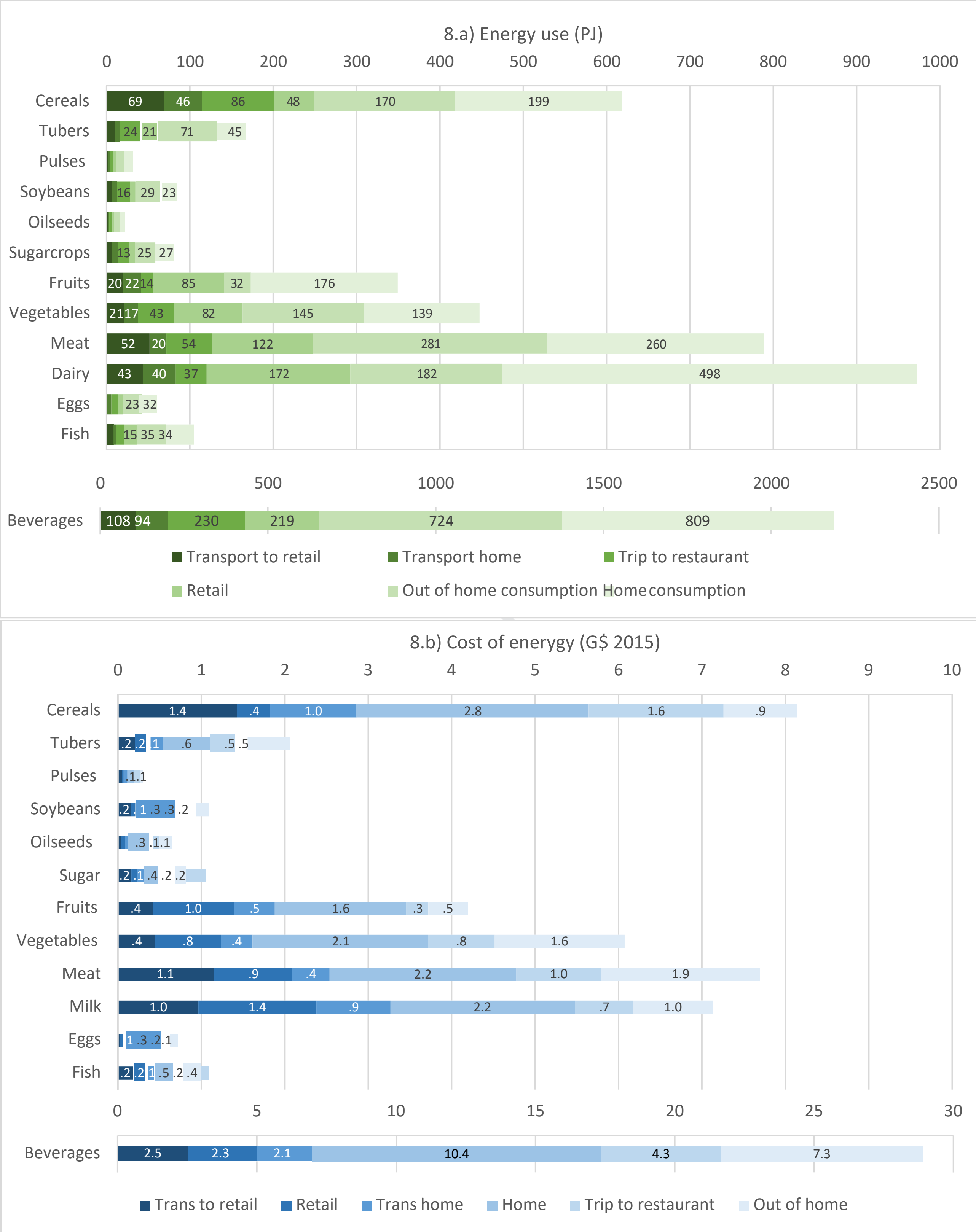

Fig. 8 Allocation of energy (8.a) and cost of energy (8.b) for transportation, distribution and consumption to the different food categories. A different scale was used for beverages because energy use is much higher. All figures are averages 2001-2015.

Energy used in downstream processes was allocated to the 13 categories reported in Table 1 using the methodology outlined in paragraph 2. The results are shown in figure 8(a). Transportation, distribution, and consumption of vegetal products require 1,810 PJ (30% of the total) mainly allocated to cereals, vegetables, and fruit. Energy allocated to animal products is 1970 PJ (33% of the total), mostly used for dairy and meat. Beverages account for 2,270 PJ (37% of the total) mostly for refrigeration.
Cost of energy by food category is reported in Fig 8(b) and has a similar distribution, with the exception of a larger energy use of cereals, due to the difference between primary and secondary electrical energy, which is required for the refrigeration of other products, but not for cereals.

3.2 Energy intensity and cost embodied in food in downstream processes

Table 3 reports the cumulative embodied energy and cost intensity of food distributed and consumed in the United States, divided by food category and FSC segment of FLW origin. Being cumulative, all these values include intensities from upstream processes (farming, wholesale transportation, and processing) according to equations 2, 3, and 4.
Intensities for refrigerated products are usually higher than for their room temperature counterparts, with the exception of processed products, such as milk (condensed or powdered) and tubers (frozen, dried, or chips) that involve a significant mass shrinkage during processing. Results are consistent with other studies for most food categories and differences are likely due to methodological (Pelletier et al. 2011, Pimentel and Pimentel, 2008) and geographical (Carlsson-Kanyama et al. 2003) differences.

Table 3. Cumulative embodied energy intensity (MJ/kg) and energy cost intensity ($/kg) in US food wasted at different steps of the FSC

k	**Food category**	**Distribution**				**Home**				**Out-of-home**			
		Chilled or frozen		Non-refrigerated		Chilled or frozen		Non-refrigerated		Chilled or frozen		Non-refrigerated	
		MJ/kg	*$/kg*	MJ/kg	*$/kg*	MJ/kg	*$/kg*	MJ/kg	*$/kg*	MJ/kg	*$/kg*	MJ/kg	*$/kg*
1	Cereals	28.2	0.28	16.7	0.22	47.2	0.39	23.7	0.32	63.2	0.45	33.1	0.39
2	Tubers	35.8	0.58	72.5	1.15	54.8	0.75	79.5	1.26	70.7	0.91	88.9	1.32
3	Pulses	24.4	0.38	21.2	0.33	43.5	0.55	28.2	0.43	59.4	0.72	37.6	0.50
4	Soybeans	-	-	12.4	0.23	-	-	19.3	0.34	-	-	28.8	0.40
5	Oilseeds	-	-	20.8	0.54	-	-	27.8	0.64	-	-	37.2	0.71
6	Sugar crops	-	-	39.7	0.51	-	-	46.7	0.61	-	-	56.1	0.68
7	Fruits	28.2	0.43	26.7	0.48	47.3	0.52	33.7	0.51	63.2	0.71	32.4	0.60
8	Vegetables	42.5	0.78	37.1	0.78	61.5	0.95	44.1	0.88	77.4	1.12	53.5	0.95
9	Meat	77.4	1.58	-	-	96.4	1.75	-	-	112.3	1.92	-	-
10	Milk	33.2	0.68	85.1	2.13	52.3	0.78	92.0	2.16	68.2	0.97	90.7	2.25
11	Eggs	24.8	0.52	22.7	0.27	43.9	0.69	29.7	0.38	59.8	0.86	39.1	0.45
12	Fish	77.1	1.03	71.3	1.92	96.2	1.20	78.3	2.02	112.1	1.36	87.7	2.09
13	Beverages	14.7	0.20	10.6	0.17	28.1	0.30	12.0	0.20	38.9	0.49	16.3	0.29

3.3 Waste of food energy, embodied energy and energy cost in downstream processes

Using food losses and waste estimates from Tables 2 it was possible to estimate the Food Mass Waste (FMW) related to the downstream U.S. food supply chain for the 2001-2015 period. The total value of FMW was 57.8 Mt, which is about 20% of all food distributed in the U.S. market. Waste is proportionally higher for animal products (29% compared to 17% for vegetal products) likely due to their shorter shelf life.

Per capita FMW in 2015 ius estimated to be 180 kg/year. Including the 360 kg of food loss occurring upstream (Pagani et al., 2019), the total FMW sums to nearly 540 kg per capita, which is significantly higher than the amount reported by Gustavsson et al. (2011) for North America. This is probably because of the inclusion of a more precise estimate of pre-harvest losses and the inclusion of feed losses as indirect energy loss in the current study.

As the most important food category, cereals represent about one quarter of the total FMW, followed by milk (19%), vegetables (13%), and beverages (11%). About two thirds of the waste occurs at the consumption level, which is consistent with findings in other studies.

Food Energy Waste (FEW), which represents the loss of nutritional energy related to FLW, reaches 370 PJ, equivalent to almost 23% of the total nutritional energy contained in US food producted for domestic use.

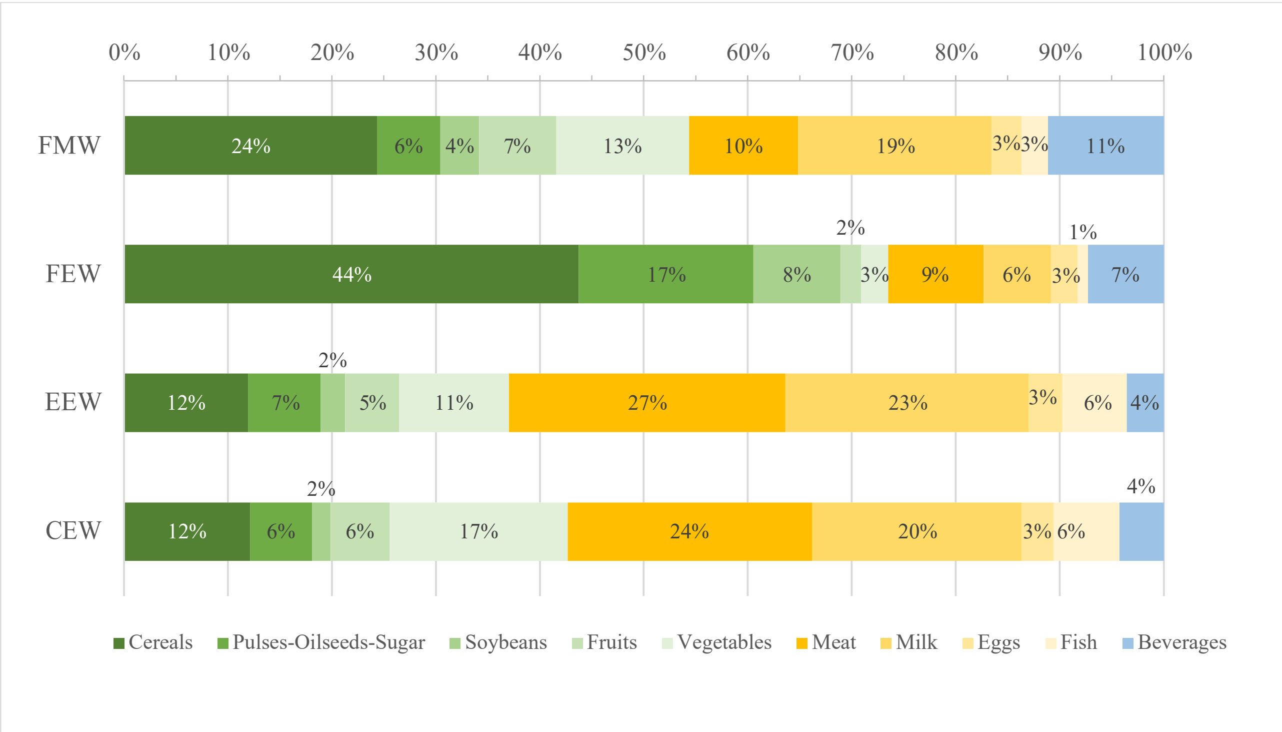

Fig. 9. Comparative composition of Food Mass Waste (FMW), Food Energy Waste (FEW), Embodied Energy Waste (EEW) and Cost of Energy Waste (CEW) for various products considering waste at the distribution and consumption levels.

This estimated waste is equivalent to about 800 kcal/p/day. Considering the upstream FEW of 310 kcal/p/day (Pagani et al., 2019), the total estimated waste is similar to the value reported by Kummu et al. (2012) of 1,334 kcal/p/day. As shown in Figure 9, cereals, oilseeds, and sugar represent a large portion of the FEW considering their high calorific value. For the opposite reason, the contribution of animal product loss to FEW is relatively smaller. Because of this, it is important to stress that FEW is only one of several indicators of potential hotspots of FLW from a nutritional point of view.

Embodied Energy Waste (EEW) is equal to 2,250 PJ, which represents 37.3% of the energy used for food distribution and consumption. The difference between this value and the previously reported percentage for FMW is due to the high impact of refrigeration energy. The largest amount of energy waste occurs in waste of from animal products: these foods represent only 35% of FMW but are responsible for 60% of EEW. Meat products alone constitute 11% of FMW but are 27% of EEW. Similarly, fish accounts for 6% of wasted energy but only 3% of the wasted mass.

In the US almost $28 billion is wasted annually along with the energy inputs needed for food distribution and consumption. This represents 40% of the total cost of embodied energy. The incidence of animal products on CEW is slightly less than for EEW, because the cost of electricity is related to final consumption and not to primary energy use.

Table 4. FMW, FEW and EEW for the different steps of the FSC, 2001-2015. R. refrigerated, NR, non-refrigerated

Waste type	Distribution		Home consumption		Out-of-home consumption		Total
	R	NR	R	NR	R	NR	
Food Mass Waste (Mt)	7.5	13.6	12.2	12.9	4.9	6.9	57.8
Food Energy Waste (PJ)	20.4	123.2	39.1	111.8	18.2	57.0	370.4
Embodied Energy Waste (PJ)	282.3	242.1	784.1	316.6	407.7	214.6	2,247.5
Cost of Energy Waste (M$)	3,749	3,388	8,561	4,596	4,618	2,876	27,786

Source: Authors' elaboration

These estimates are quite sensitive to variations in input parameters. In particular, variations in food loss rates (Table 2) would result in a maximum deviation of ± 9.3 Mt (16%), ± 50 PJ (13%), and ± 500 PJ (23%) for FMW, FEW, and EEW respectively. A larger effect on EEW (± 780 PJ or 34.7%) would derive from variations in the embodied energy estimates of Table 3. CEW shows a similar sensitivity to the same parameters.

3.4 Food Energy Waste and Embodied Energy Waste in the full supply chain

Fig. 10 compares the four categories of waste of all products for the combined upstream and downstream sections of the FSC. While upstream FMW is about 25% of the total, it accounts for only 6% of the EEW and CEW. Therefore, the downstream segments are responsible for the overwhelming majority of the wasted energy, due to both the larger amount of wasted food and the larger embedded energy. Consumption waste (47% of total FMW) is then even more relevant from a dual energy perspective. Interestingly, 46% of the total EEW occurs at home and 26% in restaurants and canteens, but in this latter case 53 MJ are wasted for every kg of food wasted compared to 44 MJ wasted in the first case. In general, refrigerated food accounts for only 42% of the wasted mass but is responsible of 66% of the wasted energy.

The overall picture could lead to the conclusion that the upstream part of the FSC is not relevant, at least numerically, when addressing the issue of food waste. However, this is not true from an energy perspective, because energy that was embodied upstream significantly contributes to the overall downstream EEW. As can be seen in Fig. 11, upstream segments contribute to 55%, 61%, and 85% of out-of-home consumption, home consumption, and retail total EEW respectively.

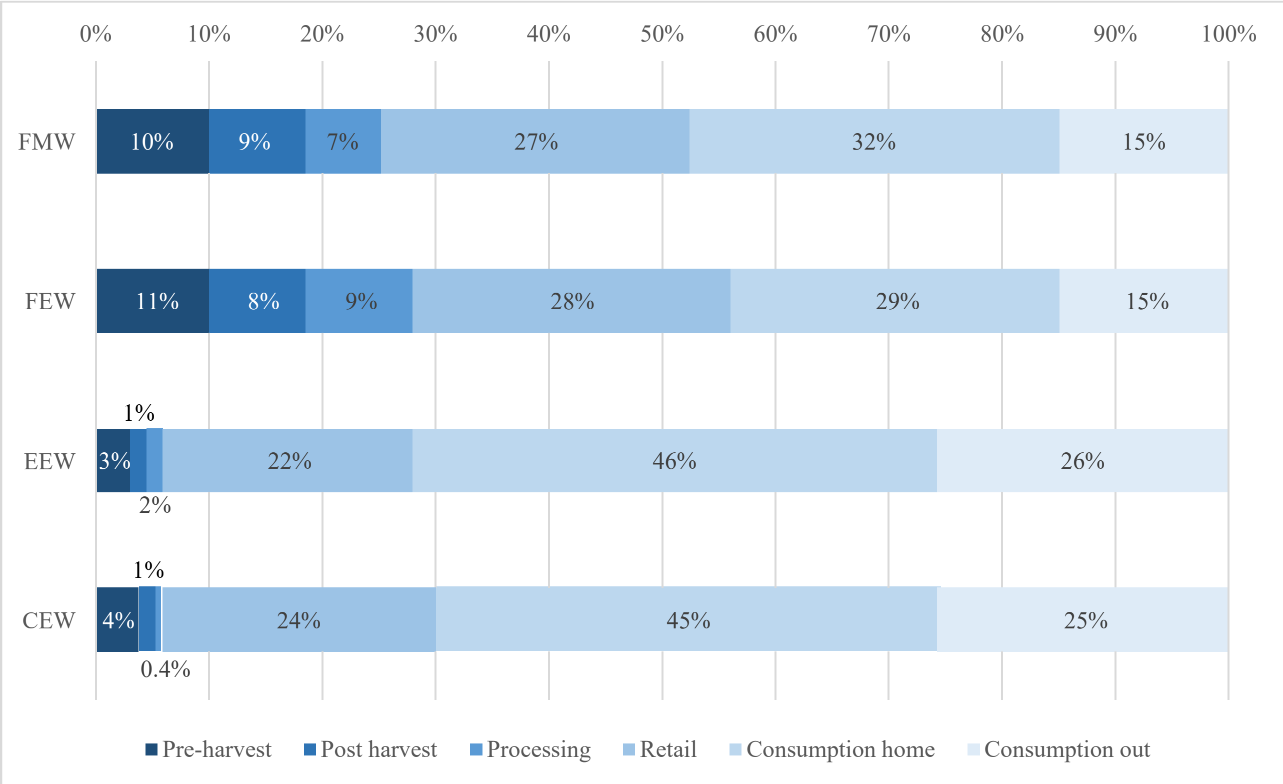

Fig. 10. Comparative composition of Food Mass Waste (FMW), Food Energy Waste (FEW), Embodied Energy Waste (EEW) and Cost of Energy Waste (CEW) for all products for different stages of the whole FSC. Data for the upstream section (farming and manufacturing) are from Part A (Pagani et al., 2019).

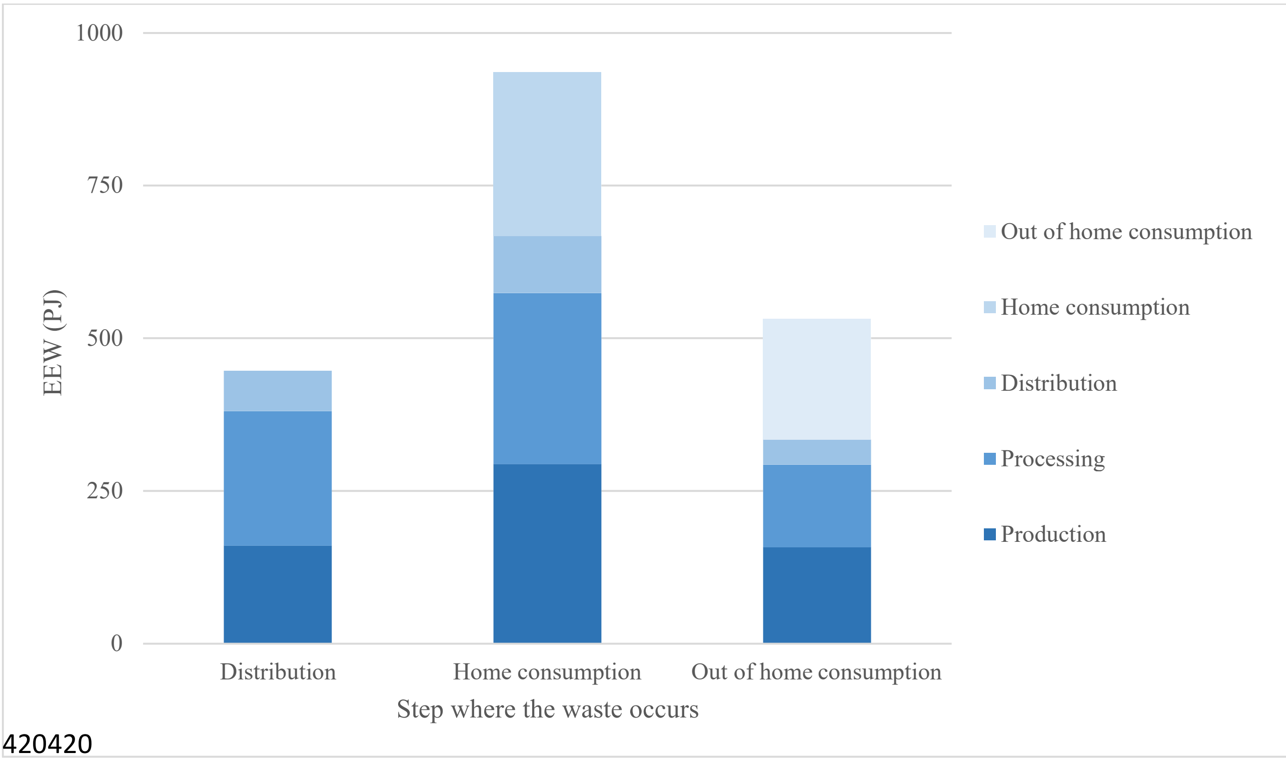

Fig. 11 Contribution to downstream EEW from upstream and downstream steps of the PSC

3.5 Strategies for reducing food and energy waste

The staggering amount of energy dissipated along with wasted food in the downstream part of FSC suggests the need for urgent actions aimed at waste prevention. FSC stakeholders can implement some of these measures while others might require larger policy interventions. Food waste at retail level could be reduced by improving forecasting of market demand and better care in product handling (Canali et al., 2017), as well as with discounted prices on nearly expired foods (Buisman et al., 2019). Several retailers already employ these measures, but the introduction of incentives might accelerate the diffusion of these practices. However, the existence of take-back agreements and the lack of sanctions on unfair trading practices between retailers and producers does not discourage wastage. Actions are required to induce the distribution sector to address its waste issues without shifting the burden upstream to the producers (Eriksson et al., 2017; Piras et al. 2018). The payment of a deposit for the package may be an incentive for the customer to eat/drink all the product and return it to the point of sale (Campbell et al. 2016). Some measures are necessary to balance the tradeoff between increased inputs and efforts and reduced wastage. For example, there is evidence of food waste reduction (20% for meat and 25 % for dairy) by lowering the storage temperature from 8°C to 2°C (Eriksson et al., 2016), but the increase in energy consumption would increase the embodied energy waste especially for dairy products.

Findings from this paper provide further grounds for the prioritization of consumers' food waste reduction. Household food waste could be reduced by improving consumer information on expiration dates (Collart and Interis, 2018) and by requiring labels that distinguish between "best before" and the expiry date. Education and raised awareness regarding the embedded energy impacts of food waste are crucial for steering behaviors towards practices such as more careful planning of purchases to prevent overbuying. There is evidence that a simple tool like a shopping list could lower food waste by about 20% (Jörissen et al., 2015; Schanes et al., 2018). In addition, fridges and freezers enable people to purchase larger amounts of food than needed for weekly needs, leading to more waste when food is forgotten or neglected (Hebrol and Heidenstrøm, 2019). Products life could be significantly improved by introducing multiple compartments in refrigerators, with different temperatures and moistures (Holsteijn and Kemna, 2018), and smart fridges signaling approaching expiration dates of products.

Food waste at restaurants and diners could be decreased by better management of provisioning and by reducing portions size, in order to reduce uneaten food that cannot be reused in any way for safety regulations (Hennchen, 2019).

Focusing on the reduction of related EEW, as shown in Fig. 11, the additional role of later FSC stages is rather limited, especially in the retail stage. Efficiency gains and a general shift towards renewables could reduce the added impacts at later stages but might be frustrated by the increasing diffusion of refrigeration.

3.6 Limitations

Limitations of this work derive mainly from data quality and availability. In similar analyses with a broad focus, there are unfortunately no single source for all the data needed, so it is inevitable that analysts use multiple sources and sometimes proxies for missing data.

Unlike previous research, more recent available data, covering a longer period and national sectors, were used, allowing a systemic approach and a long-term vision, identifying macro-trends and yearly variability. However, while most data sources covered the 2001-2015 period, CBECS data on retailer and out-of-home energy consumption were available only up to 2012. The extrapolation of energy use and costs for the years 2013, 2014, and 2015 could eventually, but not necessarily, results in a slight overestimation. Moreover, CBECS and EIA data does not differentiate between refrigeration and freezing, so it was not possible to distinguish the embodied energy of chilled and frozen food. Allocation of different types of packages to different food categories relied on a few assumptions and data from nonhomogeneous sources, since there is no general assessment of food packaging material in the US. Data on retail-to-home and restaurant-to-home travel distances and frequencies relied on data from statistical samples from several American cities, but they might be difficult to generalize.

Data on food waste at retail and consumer level come from USDA (data are available for 203 food products), the only exception is represented by beverage waste that is not covered by USDA; for this reason UK data were used as a proxy. Considering the relatively small relevance of beverages on the overall amount of FMW, the influence of this proxy on results can be deemed as limited.

Another source of uncertainty is related to the use of material prices as a proxy of packaging cost. This assumption was needed to overcome the lack of available data on the price of packages. This approximation likely results in an underestimation of the real cost of packaging, since some designs, shapes, and sizes could require intensive processing and be more expensive than the original material.

Finally, being outside the systems boundaries, the model did not consider the current use or disposal of food waste. Therefore, no analysis was done on the energy use for waste transport and disposal or on the energy recovered from waste (incineration, biogas generation) and its valorization as fertilizer or animal feed.

4. Conclusions

The present study analyzes the issue of food losses and waste in a systemic perspective, providing the key concept of “dual energy waste”: nutritional energy *and* embodied energy used in production and cooking. Further, embodied energy builds up along the food chain, so more energy is discarded if the waste occurs later in the supply chain. This concept has been explored with a comprehensive analytical model for the quantification of embodied energy waste and cost for a country with high energy intensity and significant amounts of FLW such as the United States. The main innovation in such models is the possibility to understand from a system perspective the crucial points in the food supply chain where embodied energy and/or nutritional energy are lost and with what economic cost, and establish a prioritization of potential FW reduction to achieve a sustainable and secure food system.

In terms of nutritional energy, the amount of food lost and wasted in the downstream part of the FSC could feed more than 120 million people on a 2,000 kcal daily basis. In terms of embodied energy, every kg of food wasted carries a burden of 20-60 MJ for vegetal products and 30-110 MJ for animal products in the downstream part of the FSC. This burden is equivalent to a range from 0.5 to 2.6 kg of oil equivalent. On average, every megajoule of energy in food wasted carries a burden of other 6 megajoule of energy wasted in the upstream FSC; the ratio is lower for vegetal products (3 MJ of embodied energy per MJ of nutritional energy) but it can be as high as 19 for animal products.

Reducing embodied energy waste could be achieved by decreasing waste at the retail level through better management and at the consumption through better consumer information and education; this could result in a significant energy saving of up to 2,200 PJ, equivalent to more than 50 Mt, roughly the annual oil consumption of countries like Australia or Taiwan.

Another key aspect is that the methodology presented in this paper could be replicated for other countries, provided that a consistent account of energy use in the FSC is available, as in the case of Canada or Great Britain. For other countries, more assumptions and proxies would be needed, which could weaken the robustness of the approach.

In addition to the need for more detailed energy and food statistics, further research in this issue could include an analysis of food waste disposal and recovery scenarios and the assessment of the maximum recoverable waste for each sector of the FSC. Achieving one hundred percent waste prevention is not only unrealistic, but would certainly require more energy use than te energy saved through waste prevention.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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