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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.

Impacts and costs of embodied and nutritional energy of food waste in the US food system: distribution and consumption (Part B)

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1 Impacts and costs of embodied and nutritional energy of food 2 waste in the US food system: distribution and consumption (Part 3 B) 4

5 Matteo Vittuari, Marco Pagani, Thomas G. Johnson, and Fabio De Menna
6

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

17 Appropriate food waste reduction strategies such as improved demand forecasts, more efficient product handling,
18 discounted price on nearly expired foods, clearer product-life labeling, and more careful planning by consumers, could
19 achieve energy saving and reduce the United States fossil fuel dependence and greenhouse gas emissions.
20

21 1. Introduction

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

27 A staggering amount of natural resources, such as water and land, is embedded in FLW. Every year 170 km^3
28 of irrigation water, twice the discharge of the Nile River, and 200 million hectares of fertile land, more than
29 the cultivated land in India, are employed to produce food that is subsequently wasted (Lipinski et al.,
30 2013).

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

38 In this context, targeting downstream segments of the FSC should be an urgent priority since, especially in
39 industrialized countries, most food waste occurs at the consumer level (Parfitt et al., 2010; Gustavsson,
40 2011) and more energy is embodied in the food.

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

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

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

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

63

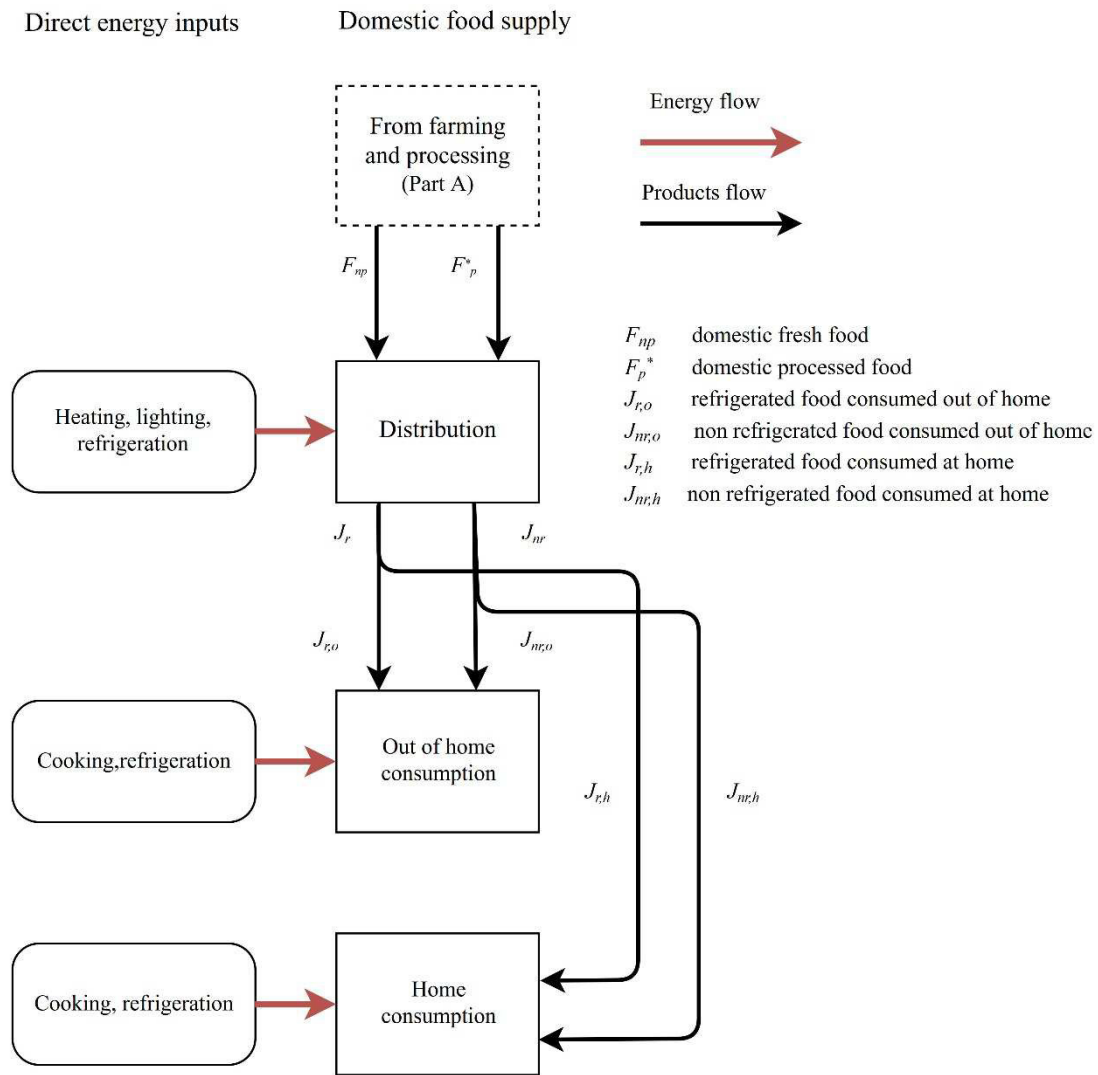
64 **2. Materials and methods**

65 **2.1 Food flows and waste at distribution and consumption levels**

66

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

71



72

73

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

75

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

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

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

86 Table 1 summarizes the average masses of all food retailed in the US in 2001-2015 subdivided in 13
 87 categories reflecting the Food and Agriculture Organization (FAO) taxonomy. Products were split into
 88 refrigerated (R) and non-refrigerated (NR), due to the significantly different energy intensity both at the
 89 distribution and consumption level. No differentiation was made between chilled and frozen food, due to

90 the lack of detailed data from the Energy Information Administration. See Supplementary material, Annex
 91 A, for more detailed information.

92
 93

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

94
 95

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

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

103

$$J_o = J_{r,o} + J_{nr,o} = \sum a_k J_r(k) + \sum a_k J_{nr}(k)$$

104 (1)

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

105

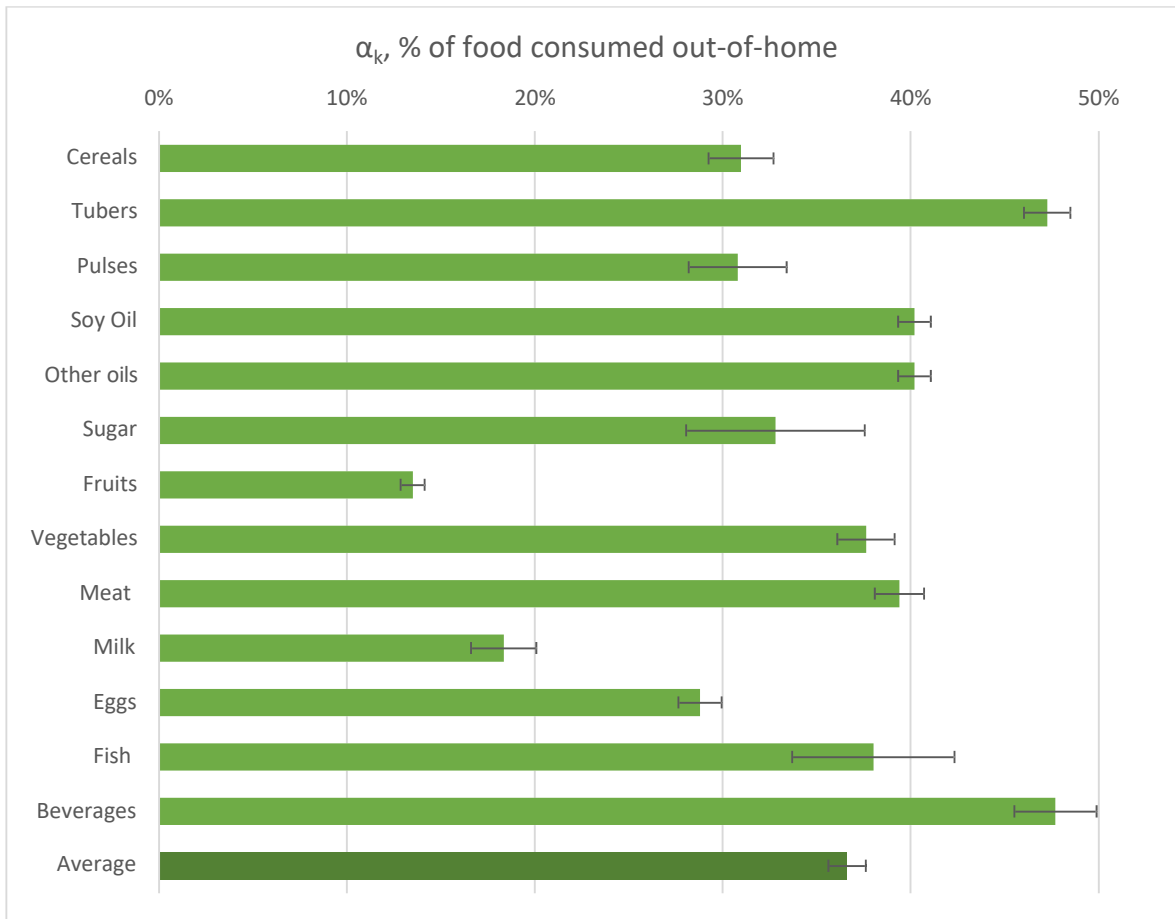


Fig. 2 Average quote α_k of food consumed out-of-home with respect to total food consumption for all product categories k . Error bars denote standard deviations due to year-to-year variations (period 1998-2008).

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

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

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

126 Beverage waste at the consumer level (overserving, accident, not used in time) was assumed to be 3.6% for
 127 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

128 lack of US data, these figures were estimated applying the absolute avoidable beverages waste in the UK
 129 (Wrap 2013) on the corresponding beverage consumption in the US (BSDA 2015; Wilson, 2016).

130 Table 2 shows consumption waste figures for fresh and processed food. Each percentage is a mass-
 131 weighted average of all foods of the same category. In the case of vegetables, 31 fresh, 9 canned, and 10
 132 frozen product categories were considered (for more details see Annex A). Figures in table 2 agree with
 133 previous waste estimates at the consumer level for 2008 and 2010 (Buzby and Hyman, 2012; Buzby et al.,
 134 2014) although these studies covered only a few food categories. Waste data reported in Table 2 represent
 135 only the edible waste and do not include non-edible components, such as cores, peels, seeds, shells or
 136 bones.

137
 138 Table 2. Food waste percentages in the distribution (w_4) and consumption (w_5) sectors (food waste w_1 , w_2 , and w_3
 139 refer to pre-harvest, post-harvest and manufacturing steps of the FSC as detailed in Part A, Pagani et al., 2019)

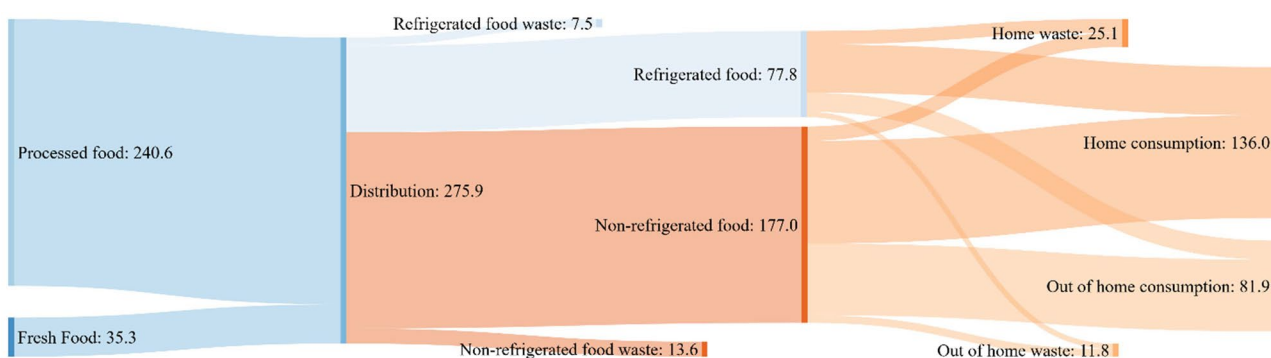
Food category	Refrigerated products			Non-refrigerated		
	Number of products	$w_{4,r}$ (%)	$w_{5,r}$ (%)	Number of products	$w_{4,nr}$ (%)	$w_{5,nr}$ (%)
1 Cereals	-	-	-	8	12±0.2	21.2 ± 4.3
2 Tubers	1	6.0	16	4	7.6±1.5	15.3 ± 2.8
3 Pulses	2	6.0±0.2	24.5±1.11	8	6.0	10
4 Soybean oil	-	-	-	1	21.0±0.7	15
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

140140 Sources: see text and Annex A

141141

142142 Figure 3 shows the mass-flow diagram of the downstream FSC, with all the related waste.

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144144

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

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147 2.2 Energy use and cost in upstream stages of the FSC

148148

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

151 1.099 and 1.48 ± 0.03 per joule of final energy was assumed for oil and natural gas respectively, while the
152 gross energy equivalent of 1 J of electricity decreased from 3.27 to less than 3.04 from 2001 to 2015.

153

154

155 *Food farming and manufacturing*

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

160

161 *Packaging*

162 The Environmental Protection Agency (EPA 2016a) reports information on packaging materials used in the
163 United States from municipal waste streams and the related recovery rate $r(t)$ at year t . The energy
164 intensity $E(t)$ of packaging materials depends on $r(t)$, according to the expression: $E(t) = E_o[1 - r(t)] +$
165 $E_o^*r(t)$, where ϵ_o and ϵ_o^* are the embodied energy intensity of virgin and recycled material, respectively
166 (EPA, 2016b). Energy intensity is always lower for recycled material, so $\epsilon(t)$ decreases for increasing
167 packaging recovery rates. For each material, energy embodied in the packaging (E_{pack}) is computed
168 multiplying the energy intensity by the mass of packaging used.

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

173 Historical prices for both virgin and recycled materials were used as a proxy of packaging cost. Prices of
174 virgin and recycled aluminum and steel were retrieved from the US Geological Survey (USGS 2019a and
175 2019b). Prices of wood pulp from the Global Economic Monitor Commodities (World Bank, 2019) were
176 used as proxy for virgin paperboard and paper. Unit price of recycled paper was determined from the US
177 import value of waste and scrap of paper and paperboard, available in the UN Comtrade Database (UN
178 Comtrade, 2019). The same method was used to calculate the value of glass containers and cullet,
179 respectively for virgin and recycled glass (UN Comtrade 2019). Finally, historical prices for virgin and
180 recycled plastic were retrieved on Plastics News (2019). Average prices were then calculated for a selection
181 of widely used polymers (details in Annex B).

182182

183 2.3 Energy use and cost in food transportation, retail and consumption

184184

185 *Transportation*

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

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

196 Energy use for transport from retail to home was estimated assuming an average distance of 6.1 km (Ploeg
 197 et al., 2015), 71 visit to the supermarket per year (Minaker et al., 2016), and 32.3 kg of food mass per visit,
 198 considering 726 kg of per capita food consumption and an average household size of 2.58 people (Census,
 199 2012). Virtually all (94%) trips are done by car (Ploeg et al., 2015), resulting in 5.27 MJ/km of energy
 200 intensity, which is the weighted average of cars, SUVs, minivans, and pickups, as detailed in Annex B (EPA,
 201 2018).

202 Energy use for people transportation to restaurants was included and estimated assuming an average
 203 distance of 8.85 km (Kerr et al., 2012) and an average of 99 dining out events per year (Kant and Graubard,
 204 2018).

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

206

207 *Food retailing*

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

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

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

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

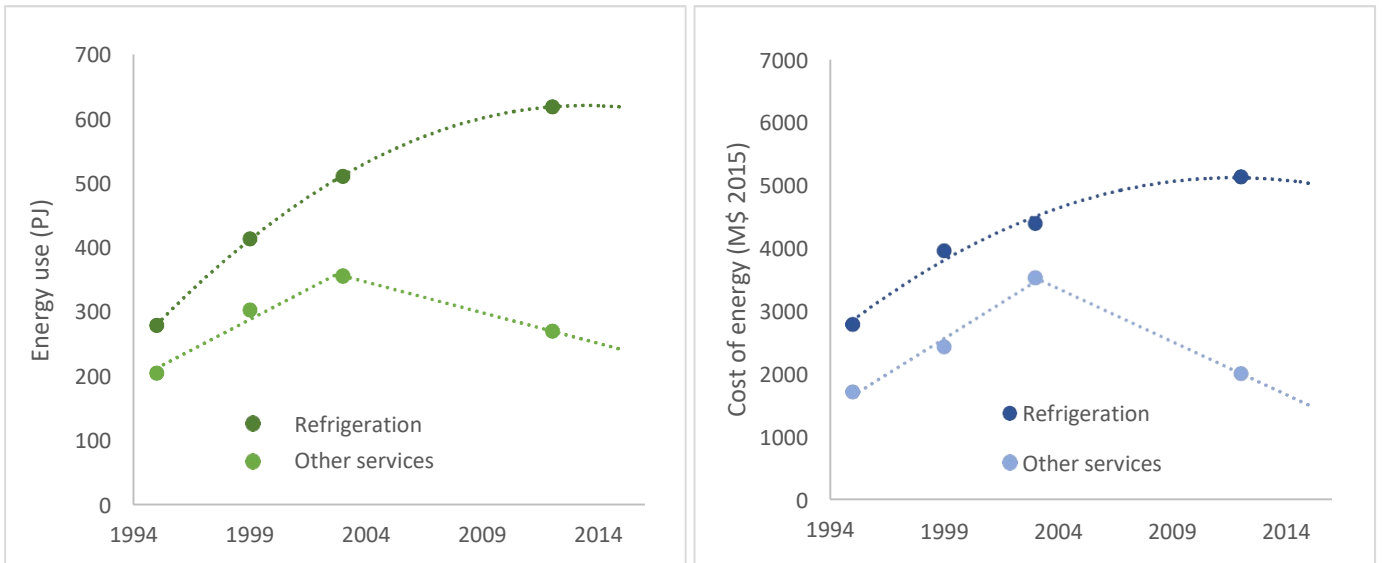
$$e_{4r}(k) = e_{up,r}(k) + \frac{E_{dist-R}(k)}{J_r(k)} + \frac{E_{dist-G}(k)}{J(k)}$$

2262 (2)

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

2
6

227 Where $e_{up-R}(k)$ and $e_{up-NR}(k)$ are the embodied energy intensities used in the upstream stages of the supply
 228 chain (1-pre-harvest, 2-harvest, 3-processing and packaging, as detailed in Pagani et al. 2019 and section
 229 2.2) for refrigerated and non-refrigerated products respectively. Detailed data are reported in Annex C.



230230 Fig. 4. Energy use (a) and cost of energy (b) in the food retail sector. Source CBECS (2012)

231231

232232

233 *Home and out-of-home food consumption*

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

239

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

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

2442 (3)

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

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.

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

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

2512 (4)

5

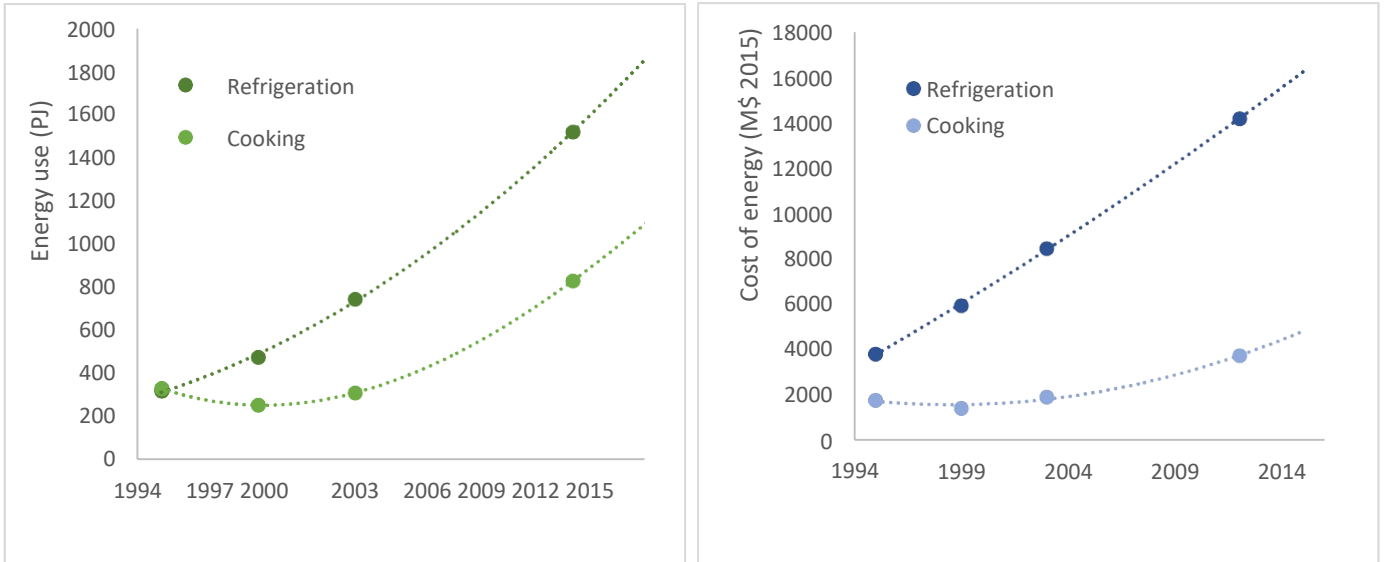
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$$e_{5nr,h}(k) = e_{4nr}(k) + \frac{E_{H-C}(k)}{J_h(k)}$$

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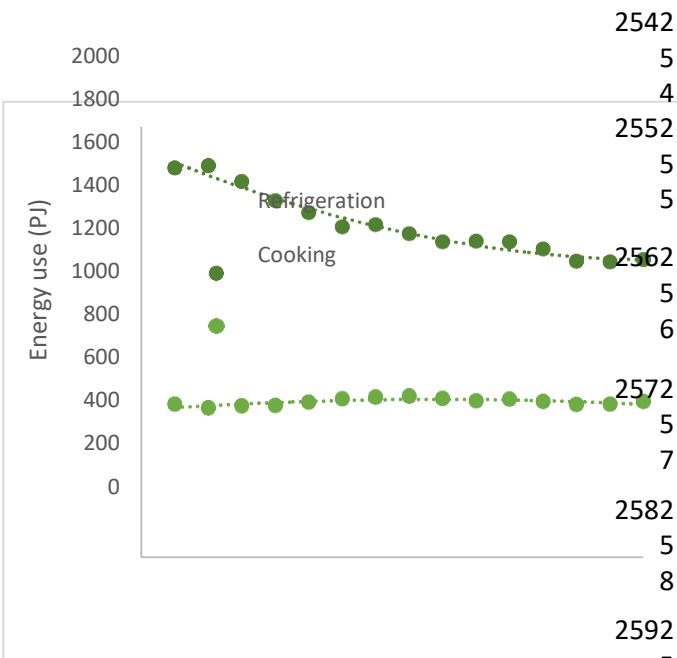


2

2532 Fig. 5. Energy use (a) and cost of energy (b) in away from home consumption sector. Source CBECS (2012)

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i g . 6 E n e r g y u s e (F a n d c o s t o f e n e r g y a n d f o r h o m e f o o d c o n s u m p t i o n) (2000 2002 2004 2006 2008 2010 2012 2014

016c)

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-

2652 refrigerated food mass wasted, obtained by
6 multiplying the waste percentages by the

2662
6
6

267 corresponding mass flows:

268 (5)

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

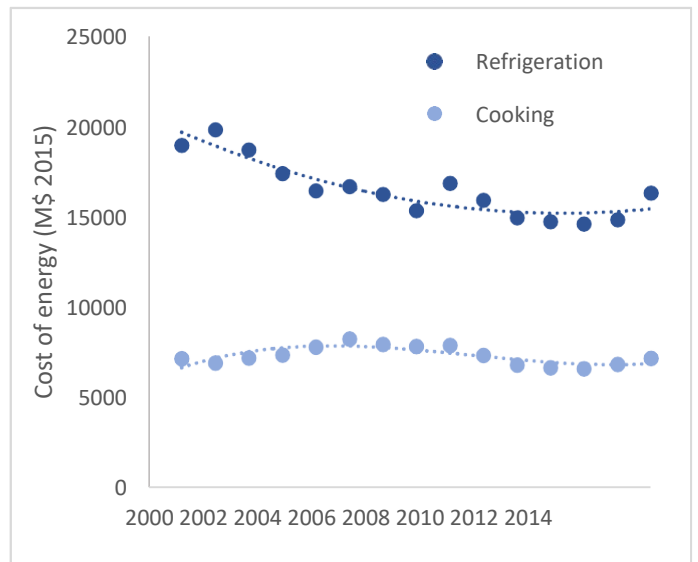
269 $W_{5,o} = W_{r,o} + W_{nr,o} = w_{5r}J_{r,o} + w_{5nr}J_{nr,o}$

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

270

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

10



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

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

$$\begin{aligned} EEW_4 &= e_{4r}w_{4r}J_r + e_{4nr}w_{4nr}J_{nr} \\ (6) \quad EEW_{5o} &= e_{5r,o}w_{5r,o}J_{r,o} + e_{5nr,o}w_{5nr,o}J_{nr,o}, \\ EEW_{5h} &= e_{5r,h}w_{5r,h}J_{r,i} + e_{5nr,h}w_{5nr,h}J_{nr,h} \end{aligned}$$

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

281

282 **3. Results and discussion**

283

284 **3.1 Energy inputs and costs of food transport, distribution and consumption and** 285 **allocation to food categories**

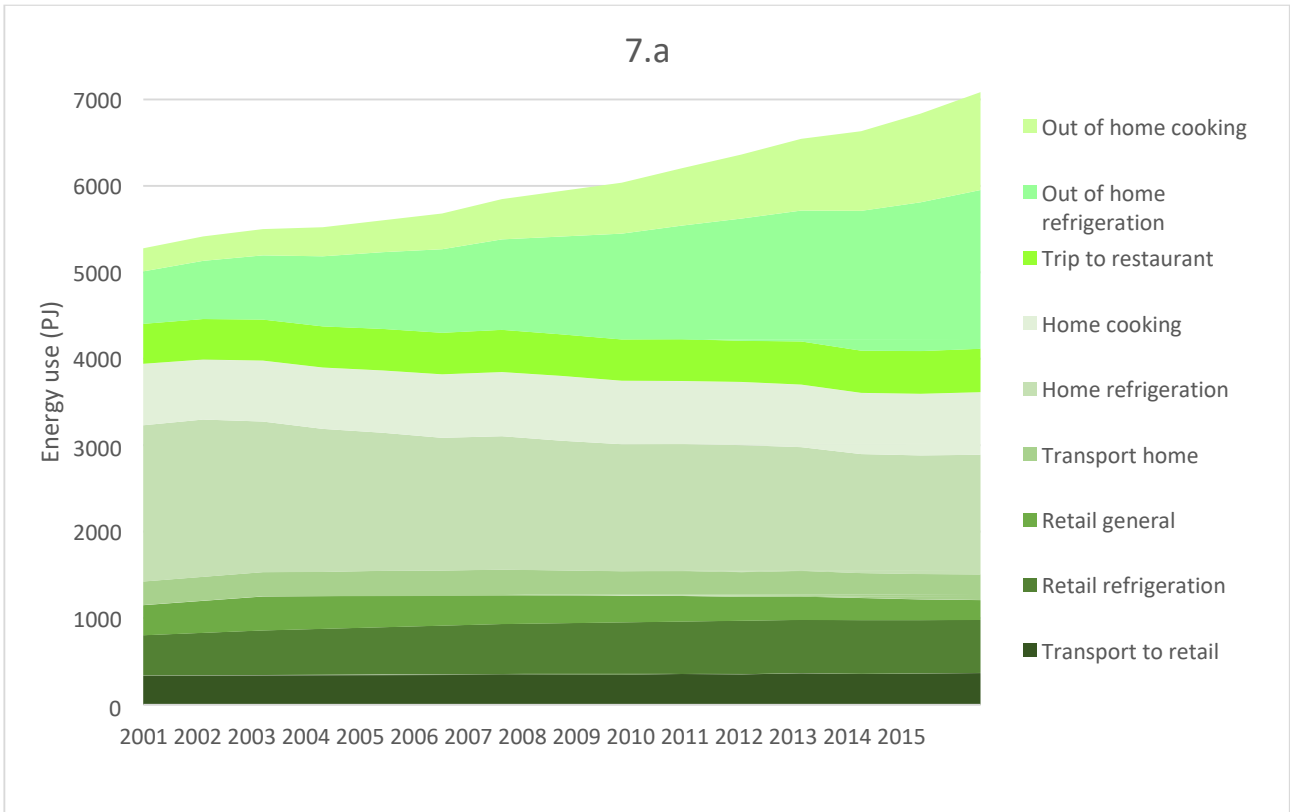
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287 During the period 2001-2015 the energy use for food transport, distribution, and consumption in the
288 United States was $6,070 \pm 560$ PJ (7.5% of total energy use), with a significant increase of more than one
289 third during the period from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

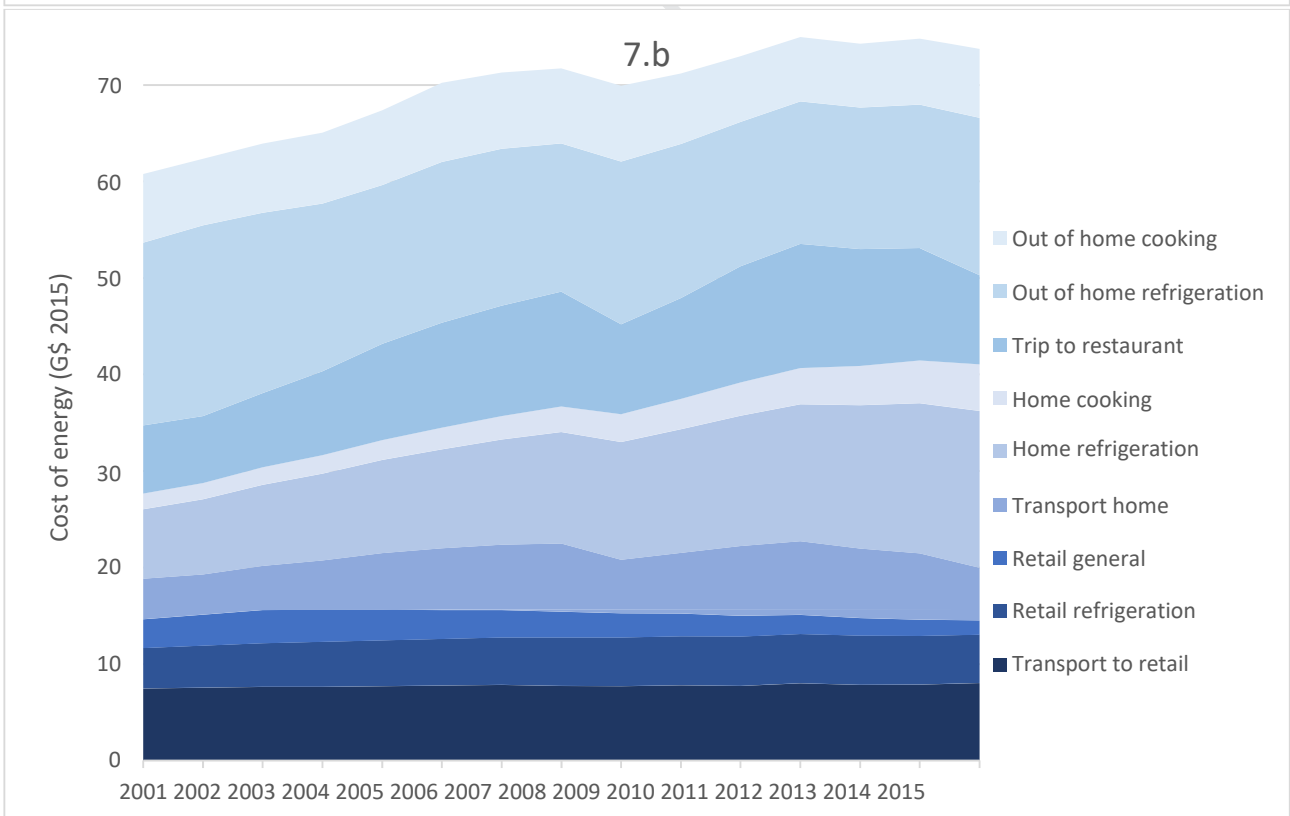
292 This growth was mainly due to out-of-home food consumption in restaurants and canteens, where primary
293 energy use for refrigeration tripled from 600 to 1,800 PJ and energy use for cooking more than quadrupled
294 from 270 to 1,130 PJ. The greatest increase in refrigeration energy occurred in food services within malls
295 and retail businesses (+450 PJ), followed by canteens (+220 PJ), and restaurants (+130 PJ). Energy used for
296 transportation was 1160 ± 25 PJ and remained almost constant over the period (+8%). Remarkably, more
297 than two thirds of this energy is attributable to moving food from retail to homes (23%) and moving people
298 from home to restaurants (47%). Both values were estimated according to average car fuel consumptions,
299 but pickup trucks would use about 50% more energy. Energy consumption in the distribution sector was
300 890 ± 30 PJ and remained almost constant over the period, but with consistent changes in the subdivision
301 between refrigeration and other services, since the former term increased by 33% while the latter
302 decreased by the same rate. Food-related home energy use was $2,260 \pm 140$ PJ, with gradual decrease (-
303 20%) due to improvements in refrigeration efficiency.

304 Fig. 7(b) shows the cost of energy for the same segments of the FSC. The general trends are similar to Fig.
305 6(a), as the total cost was $68 \pm \$4$ billion with an increase from 61 to 73 billion \$ in the 15-year period. For
306 comparison, energy use in the upstream part of the FSC was of the same order of magnitude, 80 ± 3 PJ
307 (including packaging), but without relevant trends (Pagani et al., 2019). Downstream FSC represents 51% of
308 the energy and 46% of the energy cost for the different weighting of electricity in terms of energy (primary
309 equivalents) and cost (final price).

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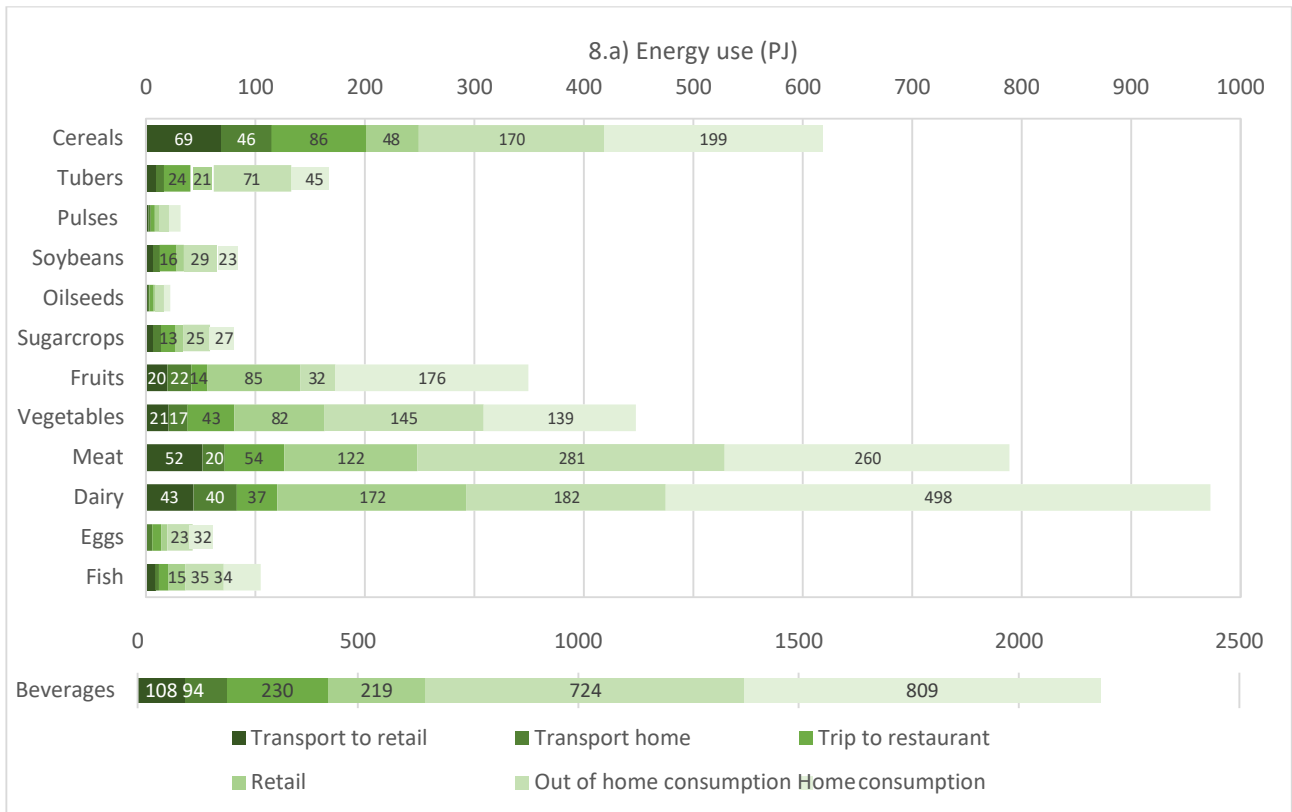


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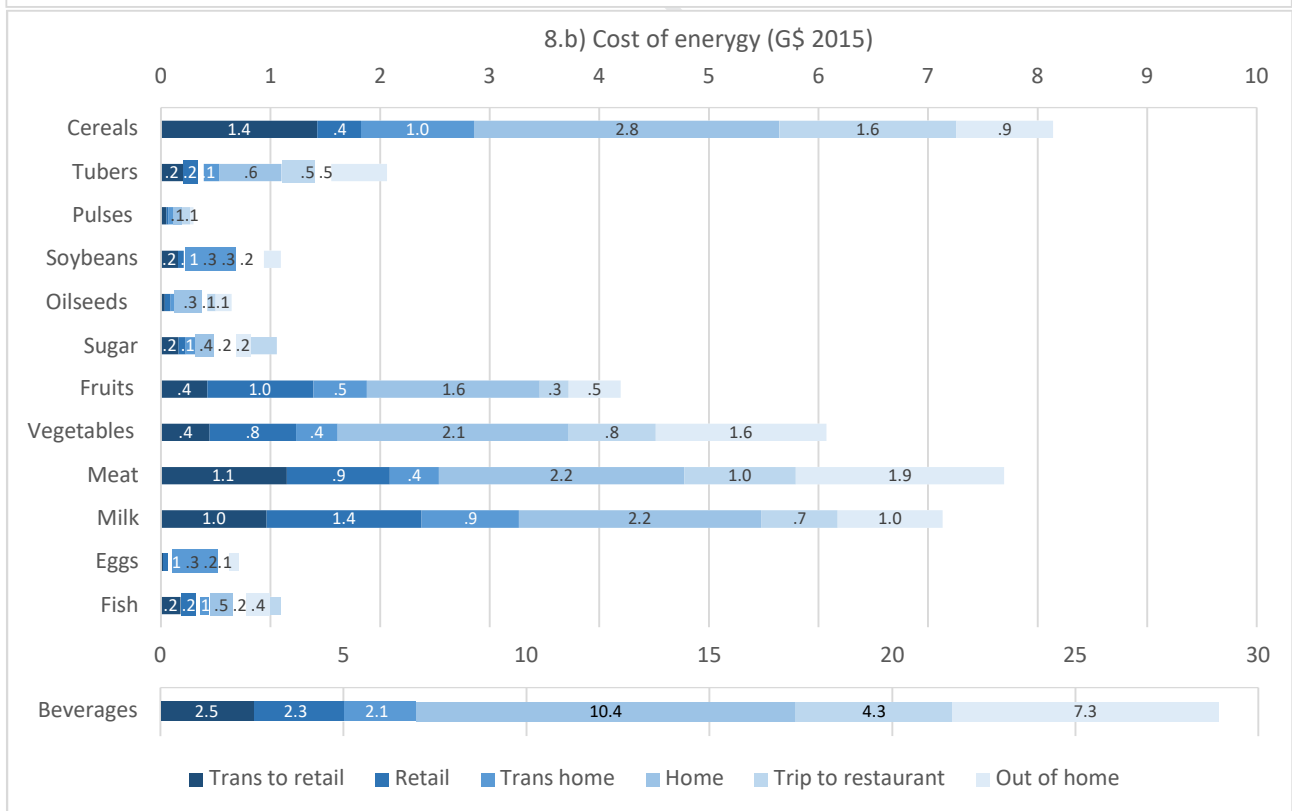
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Fig. 7 Energy consumption (7.a) and cost of energy (7.b) in downstream part of the FSC: transportation, distribution and consumption



315



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

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322
 323 Energy used in downstream processes was allocated to the 13 categories reported in Table 1 using the
 324 methodology outlined in paragraph 2. The results are shown in figure 8(a). Transportation, distribution, and
 325 consumption of vegetal products require 1,810 PJ (30% of the total) mainly allocated to cereals, vegetables,
 326 and fruit. Energy allocated to animal products is 1970 PJ (33% of the total), mostly used for dairy and meat.
 327 Beverages account for 2,270 PJ (37% of the total) mostly for refrigeration.
 328 Cost of energy by food category is reported in Fig 8(b) and has a similar distribution, with the exception of a
 329 larger energy use of cereals, due to the difference between primary and secondary electrical energy, which
 330 is required for the refrigeration of other products, but not for cereals.
 331

332 3.2 Energy intensity and cost embodied in food in downstream processes

333 Table 3 reports the cumulative embodied energy and cost intensity of food distributed and consumed in
 334 the United States, divided by food category and FSC segment of FLW origin. Being cumulative, all these
 335 values include intensities from upstream processes (farming, wholesale transportation, and processing)
 336 according to equations 2, 3, and 4.

337 Intensities for refrigerated products are usually higher than for their room temperature counterparts, with
 338 the exception of processed products, such as milk (condensed or powdered) and tubers (frozen, dried, or
 339 chips) that involve a significant mass shrinkage during processing. Results are consistent with other studies
 340 for most food categories and differences are likely due to methodological (Pelletier et al. 2011, Pimentel
 341 and Pimentel, 2008) and geographical (Carlsson-Kanyama et al. 2003) differences.
 342

343 Table 3. Cumulative embodied energy intensity (MJ/kg) and energy cost intensity (\$/kg) in US food wasted at different
 344 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

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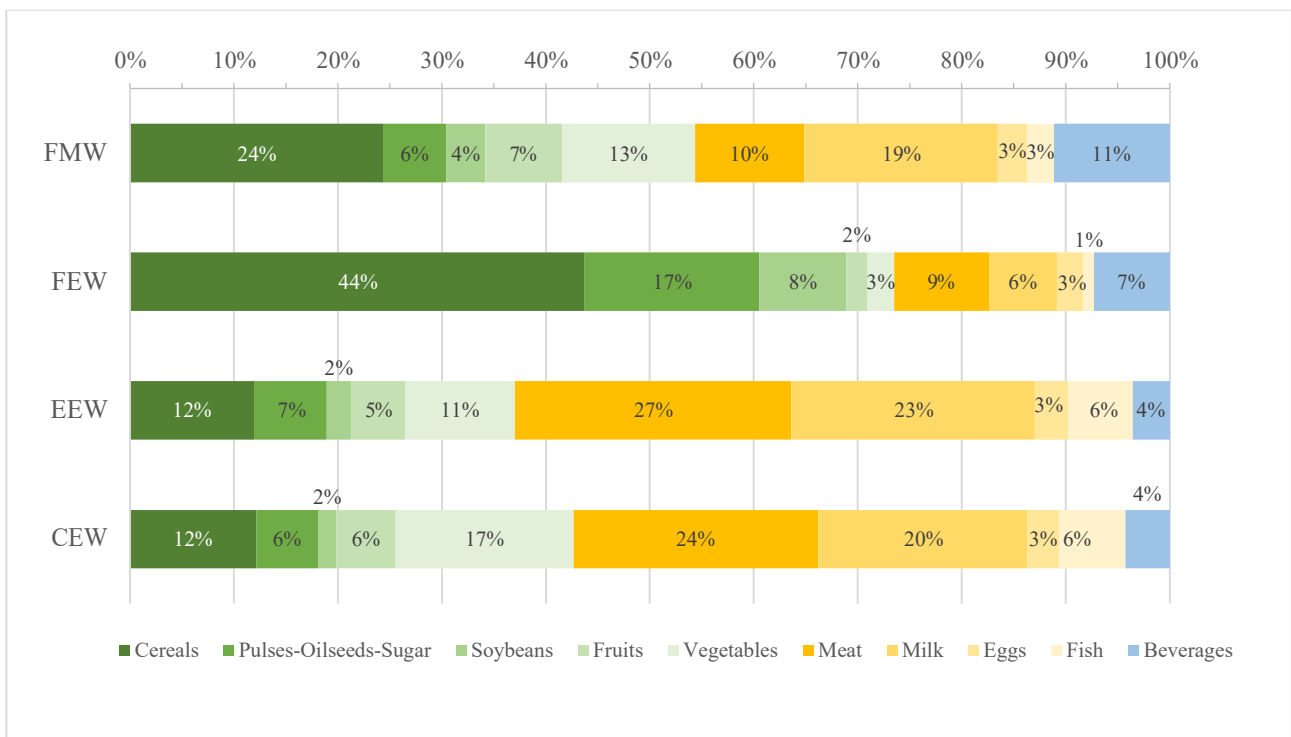
352 3.3 Waste of food energy, embodied energy and energy cost in downstream 353 processes

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

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

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

366 Food Energy Waste (FEW), which represents the loss of nutritional energy related to FLW, reaches 370 PJ,
367 equivalent to almost 23% of the total nutritional energy contained in US food produced for domestic use.
368



369 Fig. 9. Comparative composition of Food Mass Waste (FMW), Food Energy Waste (FEW), Embodied Energy Waste
370 (EEW) and Cost of Energy Waste (CEW) for various products considering waste at the distribution and consumption
371 levels.
372

373
374 This estimated waste is equivalent to about 800 kcal/p/day. Considering the upstream FEW of 310
375 kcal/p/day (Pagani et al., 2019), the total estimated waste is similar to the value reported by Kummu et al.
376 (2012) of 1,334 kcal/p/day. As shown in Figure 9, cereals, oilseeds, and sugar represent a large portion of
377 the FEW considering their high calorific value. For the opposite reason, the contribution of animal product

378 loss to FEW is relatively smaller. Because of this, it is important to stress that FEW is only one of several
 379 indicators of potential hotspots of FLW from a nutritional point of view.

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

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

390

391 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

392 Source: Authors' elaboration

393

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

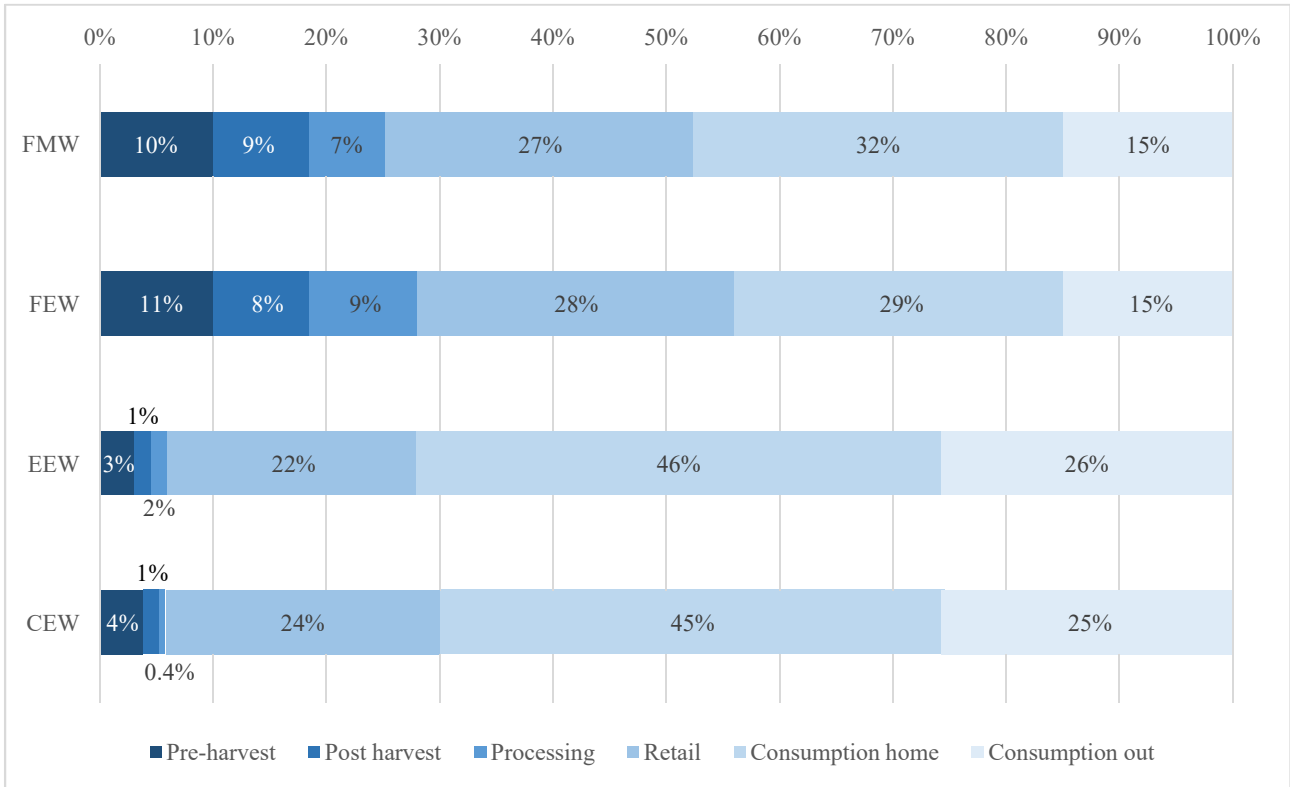
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399 3.4 Food Energy Waste and Embodied Energy Waste in the full supply chain

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

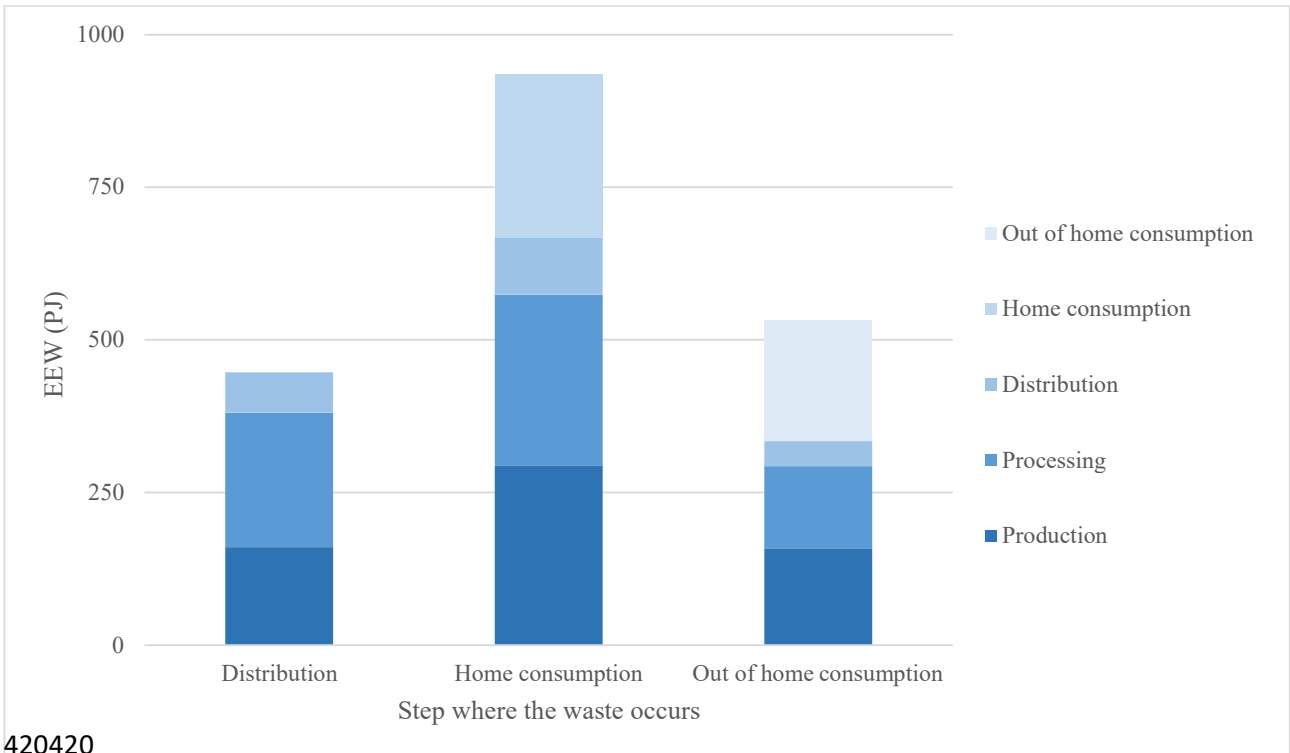
408 The overall picture could lead to the conclusion that the upstream part of the FSC is not relevant, at least
 409 numerically, when addressing the issue of food waste. However, this is not true from an energy
 410 perspective, because energy that was embodied upstream significantly contributes to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

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414414 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 415415 section (farming and manufacturing) are from Part A (Pagani et al., 2019).

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422 3.5 Strategies for reducing food and energy waste

423 The staggering amount of energy dissipated along with wasted food in the downstream part of FSC
424 suggests the need for urgent actions aimed at waste prevention. FSC stakeholders can implement some of
425 these measures while others might require larger policy interventions. Food waste at retail level could be
426 reduced by improving forecasting of market demand and better care in product handling (Canali et al.,
427 2017), as well as with discounted prices on nearly expired foods (Buisman et al., 2019). Several retailers
428 already employ these measures, but the introduction of incentives might accelerate the diffusion of these
429 practices. However, the existence of take-back agreements and the lack of sanctions on unfair trading
430 practices between retailers and producers does not discourage wastage. Actions are required to induce the
431 distribution sector to address its waste issues without shifting the burden upstream to the producers
432 (Eriksson et al., 2017; Piras et al. 2018). The payment of a deposit for the package may be an incentive for
433 the customer to eat/drink all the product and return it to the point of sale (Campbell et al. 2016). Some
434 measures are necessary to balance the tradeoff between increased inputs and efforts and reduced
435 wastage. For example, there is evidence of food waste reduction (20% for meat and 25 % for dairy) by
436 lowering the storage temperature from 8°C to 2°C (Eriksson et al., 2016), but the increase in energy
437 consumption would increase the embodied energy waste especially for dairy products.

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

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

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

456

457 3.6 Limitations

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

461 Unlike previous research, more recent available data, covering a longer period and national sectors, were
462 used, allowing a systemic approach and a long-term vision, identifying macro-trends and yearly variability.
463 However, while most data sources covered the 2001-2015 period, CBECS data on retailer and out-of-home

464 energy consumption were available only up to 2012. The extrapolation of energy use and costs for the
465 years 2013, 2014, and 2015 could eventually, but not necessarily, results in a slight overestimation.
466 Moreover, CBECS and EIA data does not differentiate between refrigeration and freezing, so it was not
467 possible to distinguish the embodied energy of chilled and frozen food. Allocation of different types of
468 packages to different food categories relied on a few assumptions and data from nonhomogeneous
469 sources, since there is no general assessment of food packaging material in the US. Data on retail-to-home
470 and restaurant-to-home travel distances and frequencies relied on data from statistical samples from
471 several American cities, but they might be difficult to generalize.
472 Data on food waste at retail and consumer level come from USDA (data are available for 203 food
473 products), the only exception is represented by beverage waste that is not covered by USDA; for this reason
474 UK data were used as a proxy. Considering the relatively small relevance of beverages on the overall
475 amount of FMW, the influence of this proxy on results can be deemed as limited.
476 Another source of uncertainty is related to the use of material prices as a proxy of packaging cost. This
477 assumption was needed to overcome the lack of available data on the price of packages. This
478 approximation likely results in an underestimation of the real cost of packaging, since some designs,
479 shapes, and sizes could require intensive processing and be more expensive than the original material.
480 Finally, being outside the systems boundaries, the model did not consider the current use or disposal of
481 food waste. Therefore, no analysis was done on the energy use for waste transport and disposal or on the
482 energy recovered from waste (incineration, biogas generation) and its valorization as fertilizer or animal
483 feed.

484

485 4. Conclusions

486

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

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

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

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

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

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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