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The Hidden Burden of Food Waste: The Double Energy Waste in Italy

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Abstract: The energy intensity of modern food systems represents a major issue in a scenario of decreasing oil resources and increasing population. Beside the use of renewable energy, an increased efficiency in food systems could contribute to reduce fossil fuels dependence. In this sense, food losses and waste (FLW) have crucial consequences on the energy balance. Based on the concept of "embodied energy", food wastage can be framed as a double waste of energy, both in terms of non-consumed food energy and the inputs used for production. Secondary data regarding direct and indirect energy inputs and FLW have been collected for the Italian food chain to estimate the embodied energy of food waste. Since in 2011 the production and distribution of food implied the use of 822 PJ and 18 Mt of food was discarded, 67 PJ of food energy and 100 PJ of embodied energy were wasted. These figures are equivalent to 12.2% of the total nutritional energy output and to 1.3% of the final energy use in Italy, respectively. The concept of double energy waste sheds new light on the intertwined relationship between energy and food security, suggesting that appropriate food waste reduction policies could result in a higher food production level and relevant energy savings.

Keywords: food waste; energy waste; sustainable food systems; Italy

1. Introduction

Since the world energy crisis during the 70s, the dependence on fossil fuels and other non-renewable resources has been acknowledged as a structural limit of the current socio-economic development model [1–3]. In a perspective of increasing world population, the current pattern of natural resource exploitation could endanger the sustainability of modern life styles. Therefore, the access to an adequate amount of resources should drive the transition towards a smart, equitable and sustainable use of energy, food, and water [4–8].

In this framework, there is a greater awareness of food production, not only as a basis for human life, but also as one of the most energy intensive economic activities. Historically, food production gradually increased its energy use in order to sustain a larger share of non-agricultural workers. This was obtained through the replacement of human and animal power with water and wind first, and the steam tractor later. The unmatched yields, granted by the "Green Revolution", led to the satisfaction of basic food needs in most of the industrialized countries. Nevertheless, the intensive use of machineries, fertilizers, electric irrigation, and plastic also caused relevant environmental and economic consequences [6,9–11].

Energy statistics do not usually expose the relevance of food production in terms of final energy use. The traditional division between economic sectors only reveals the residual share attributable to agriculture and forestry [12].

Nonetheless, when a system approach is adopted, food systems can represent up to the 30% of final energy use [11]. A considerable use of energy can be attributed to downstream segments such as processing, packaging, distribution and consumption of food. Therefore, the energy efficiency of food systems is rather low: for example, in the US, 10 kcal of fossil fuel energy are required in order to produce one kcal of food [11,13,14]. Likewise, a similar perspective allows estimating that the sole production of animal derived food implies an 18% share of global greenhouse gas (GHG) emissions, equivalent to industry and higher than transports [15–18]. Therefore, changes in food choices might have the same magnitude as modifications in mobility patterns [19].

The energy intensity of food systems also implies relevant socio-economic consequences. The recent food crisis revealed the profound interactions between food and energy markets [20,21]. In general, during the first decade of the XXIst century, global staple food prices followed almost immediately oil market trends [22]. This matching pattern posed a serious pressure on food security in developing countries and increased the vulnerability of production systems to energy costs, especially for small farmers [23].

Despite this energy burden, contemporary food systems entail a similarly excessive creation of residual biomass. A share of this inefficiency is intrinsically linked to production processes, as in the case of pruning, cultivation and processing by-products, inedible waste and potentially hazardous waste as used vegetable oil [24]. On the other hand, a relevant share (one-third of food produced for human consumption) is represented by losses and waste of edible food products, or parts, along the whole food supply chain (FSC) [25–28].

This often unexploited biomass should be perceived as a systemic inefficiency contributing to the depletion of limited resources, such as water, land, and fertilizers [29], as well as economic value [30]. In particular, food losses and waste (FLW) can be considered as a "double waste" of energy, because, on one hand the chemical energy contained in food, and, on the other hand the production energy inputs are wasted alongside with food [13,31].

Notwithstanding, while embodied energy is a quite established concept, its application to food waste remains limited. Few recent studies attempted to estimate resources embodied in food waste [29,32,33] and only one focused on energy [13]. Thus, this paper elaborates on the concept of "double waste" embedded in FLW through the application of an analytical model for the assessment of embodied energy in food waste in the Italian FSC, which is characterized by a relevant use of energy [34] and by considerable amounts of edible FLW along the whole chain [27].

2. Materials and Methods

The assessment of the embodied energy wasted in FLW of the Italian FSC was structured in four main stages:

- Assessment of the total direct and indirect energy inputs in the different segments of the FSC;
- Calculation of the embodied energy per unit of mass in Italian food;
- Quantification of the extra energy input for animal-derived food;
- Final estimation of the energy embodied in FLW in FSC segments.

The following segments of the FSC were analyzed: farming, processing (including packaging), logistics, and distribution. Household consumption was not considered, since no reliable data were available in Italy on home energy inputs for food conservation and cooking. Consequently, also the end-of-life of products was not considered, since it occurs after household consumption.

All data utilized and elaborated in this work are referred to Italy, with the exception of:

- energy intensity of chemicals and plastics since these products are similar across countries, therefore differences are negligible;
- energy intensity of transport, since differences are not relevant across countries.

Percentages of wasted mass that were applied to Italian production data since European averages represent the more reliable estimates of food waste available at July 2016.

2.1. Assessment of Energy Inputs of the FSC

Energy inputs of the Italian FSC were analyzed according to the framework presented in Figure 1. Inputs (red arrows) are split into *direct* (energy use in process operations) and *indirect* inputs (energy embodied in materials or machinery used in the chain). Figure 1 shows also biomass flows of raw (green arrows) and processed products (black arrows). Logistics is divided into two segments only for conceptual and graphical clarity, because it has been analyzed as a whole, according to available data (see Section 2.1.3).

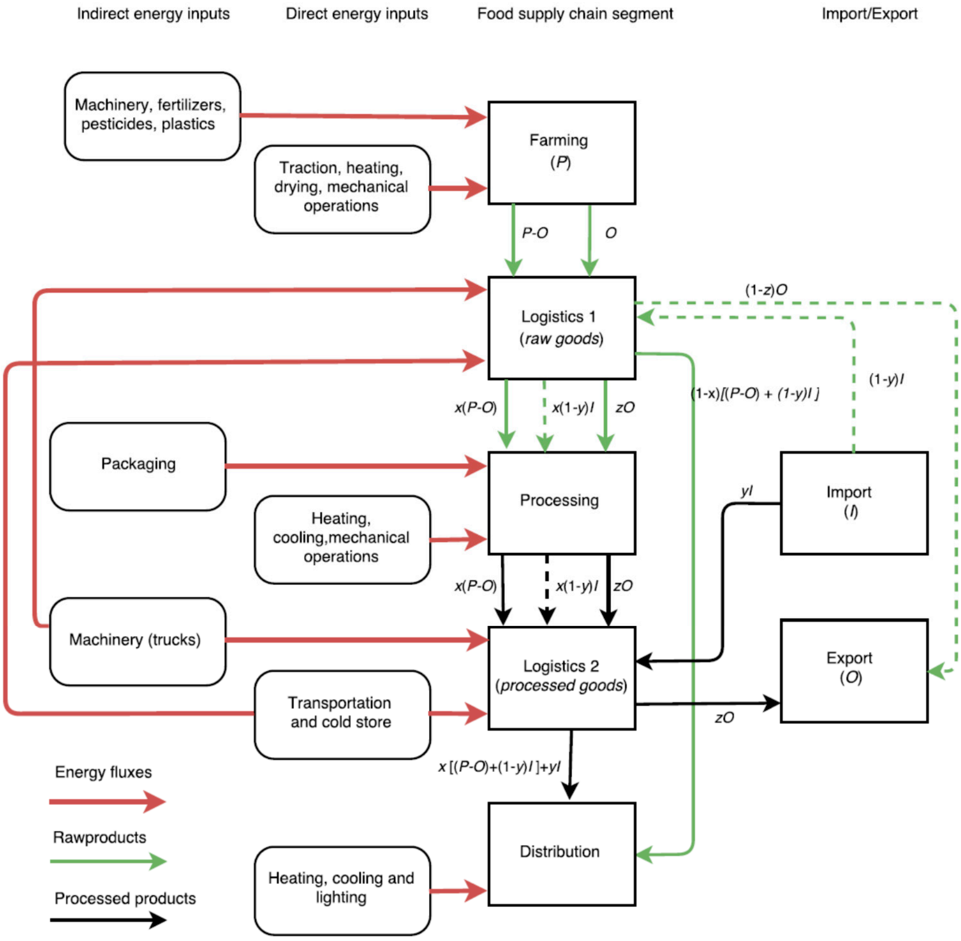

Figure 1. Flow chart of Italian FSC with direct and indirect energy inputs and raw and processed biomass fluxes; x, y and z are the fractions of processed food in national production, import and export, respectively (see Section 2.2). Products for animal feed are not indicated.

All energy inputs associated with food produced on Italian territory, both for internal consumption and for export, were considered in the present study. Thus, the analysis focuses only on energy consumed in Italy, including energy used for exported food, while the energy burden of the imported food was not accounted for, since in this approach, it is symmetrically attributed to the country of origin. For the same reason, international transportation energy for imported food was not considered.

For each fuel, lower heating values and refinery efficiencies η were considered, so that 1 MJ of net energy is equivalent to $1/\eta$ MJ of gross primary energy (see Table A1 of Appendix). In the period 2000–2014 the primary energy equivalent of one joule of electrical energy decreased from 2.25 J to 1.55 J owing to the great development of renewable energies, wind, photovoltaic and, to lesser extent, hydroelectric. For instance, in 2014 every J of final use, 0.366 J came from renewable sources; the remainder 0.633 J of final energy came from 1.19 J of primary fossil fuels (coal gas and oil); see details in Figure A1 of the Appendix.

2.1.1. Farming

Energy utilized at the farm level (E_{farm}) is composed of four different main contributions: (i) direct inputs for the production of food and animal feed; indirect inputs from (ii) machinery; (iii) fertilizers and pesticides and (iv) plastic materials.

(i) Direct energy use data for farming operations (fuel for traction, irrigation, heating, drying, electrical energy for mechanical operations and lighting) were obtained from the Italian national energy balance [35] split by fuel type. Direct use of fuel for fisheries was also considered.

(ii) The energy equivalent of machinery was estimated in approximately 140 MJ for every kg of equipment [36,37]. This value is quite high, as it accounts not only for production (around 80 MJ/kg), but also for maintenance and repair. This figure has been substantially confirmed by a more recent analysis on tractors and relative equipment [38]. The number of new tractors entered in use in Italy for the years 2000–2014 was retrieved from the professional association [39]. A mass/power ratio of 60 kg/kW was considered [40], while the average power is roughly 90 kW (average over 26,000 tractors on sale in June 2014 on the site www.agriaffaires.it (accessed on 21 January 2016); the average tractor mass was therefore assumed to be 5.4 t, and the average energy input per tractor is 745.8 GJ.

(iii) Data for nitrogen (N), phosphate (P) and potash (K) fertilizers use in Italian agriculture were sourced from national and international databases [41,42]. Average specific energy inputs for fertilizers are assumed to be 49 MJ/kg for urea, 42 for ammonium sulfate, 13 for simple perphosphate and 19 for triple perphosphate [43], 40.6 MJ/kg for ammonium nitrate [44], 5 MJ/kg for potassium sulfate and chloride, 18 and 31 MJ/kg for NP and PK fertilizers, respectively [45], 6 and 7 MJ/kg for NK and NPK fertilizers, respectively [46,47]. Data for pesticides use were obtained from FAO [48], while average specific energy inputs are assumed to be 310 MJ/kg for herbicides and insecticides and 220 MJ/kg for fungicides [49–53].

(iv) The use of plastic material in agriculture (tunnels, mulching, nets, piping and containers) was documented by Scarascia-Mugnozza et al. [54]. Input energy for plastics production at farm level was assumed to be 79 MJ/kg, as an average of the most used polymers in agriculture: polyethylene [55] and polypropylene [56].

2.1.2. Food Processing and Packaging

Energy use in the food transformation industry (E_{proc}) is the sum of direct energy use and energy use for packaging. Direct energy utilized in mechanical processes, cooking, freezing, and space heating/cooling related to the food industry was retrieved from the national energy balance [35] split by fuel type. The small quote of energy related to the processing of feed Fe_B that is not part of the human FSC (see Section 2.2) was subtracted from the MSE data.

Energy use for packaging was computed by multiplying specific embodied energy (see Table A2 in Appendix) by total masses of food packages. For each material, data and percentage of usage in the food sector were estimated from Iascone et al. [57] and the Italian Packaging Institute [58], with the exception of wood pallets [59].

2.1.3. Transport Logistics

Energy use for food transport (E_{tran}) was computed by multiplying masses-distance products (t-km) by energy intensity values (GJ/t-km) for each transport mode; this value has been detailed for national ($E_{tran\text{-}n}$) and international ($E_{tran\text{-}i}$) transport. Since only energy associated with export was accounted for in the present study and no separate statistics were available for import/export masses-distances products, energy associated to food exports ($E_{tran\text{-}ex}$) was obtained as the quote of energy for international transport corresponding to the quote of exportations with respect to international trade:

$$E_{tran-ex} = E_{tran-i}\frac{O}{O+I} \tag{1}$$

where O and I are the masses of food exported and imported, respectively (see Table 1).

Masses-distances products for road and rail transport were reported by Eurostat [60,61], both for national and international traffic. According to different analysis relative to Europe or Italy, an energy intensity of 3.0 ± 0.2 MJ/t-km and 0.3 ± 0.02 MJ/t-km was used, for road and rail transport, respectively [62–65]. The energy intensity value for road freight, which is higher than the typical consuming of heavy goods vehicles [66], takes into account the fact that in approximately 30% of the voyages the trucks are empty [67].

Mass-distances products for sea transport were not directly available, therefore they were computed for national and international routes. For internal transport the routes among the 17 Italian ports that cover roughly 70% of the traffic between regions (while 10% of the traffic is within regions) were considered. Distances were computed using a Geographic Information System software and averaged using as weights the volumes of traffic along the routes, leading to a weighted average sea distance of 565 km. This value was multiplied by the masses of food loaded or unloaded at the ports [68].

For international sea transport, 85% of sea traffic to and from Italy corresponds to just 27 countries. The 87% of this traffic is directed to/from 13 Italian ports. The distances between those countries and these ports were estimated using a GIS software. A weighed average distance for each country was computed, using as weight the volume of traffic in each Italian port. These values were multiplied by the masses of food loaded or unloaded at the ports [68].

The energy intensity of bulk carrier ships was determined by the expression e_{ship} = 0.024 + 0.827/DWT (MJ/t-km), where DWT is the ship deadweight [69]. Typical values range from 0.1 MJ/t-km for smaller ships (10,000 t), to 0.029 MJ/t-km for the largest ships (150,000 t). The average energy intensity was computed taking into account the distribution of ships among the five commercial classes, Handysize, Handymax, Supramax, Panamax and Capesize [70], leading to an average value of 0.035 MJ/t-km.

2.1.4. Distribution

Energy utilization in the distribution sector (E_{dist}) was calculated by multiplying retail areas by energy intensity per unit area. Global areas of retail stores attributable to food were obtained from Magelli [71], and split for hypermarkets, superstores, supermarkets and small dealers. In ten years (2004–2014), retail areas increased from 11 to 17 million square meters.

According to an analysis of a sample of 46 superstores and hypermarkets, the intensity is 1275 ± 110 MJ/m^2 year for electrical energy and 150 ± 23 MJ/m^2 year for thermal energy [72]. These values were converted in primary energy equivalents according to the conversion factors of Table A1 (gas) and Figure A1 (electrical energy).

Table 1. Mass balance of the Italian food supply chain (FSC) (in Mt).

j	Product Type	Production (P)	Import (I)	Export (O)	Supply (S)	Food (Fo)	Feed (Fe)	Other
1	Cereals	19.03	12.03	5.04	25.33	9.45	14.08	0.98
2	Tubers	1.56	1.54	0.17	2.89	2.35	0.06	0.48
3	Pulses	0.14	0.29	0.02	0.41	0.29	0.09	0.03
4	Soybeans	0.57	4.20	0.28	4.48	-	4.28	0.21
5	Oilseeds	3.56	0.59	0.15	4.01	1.88	0.05	0.04
6	Sugar crops	3.55	-	-	3.55	1.65	-	0.05
7	Vegetables	14.29	1.99	5.76	10.52	8.78	0.55	1.20
8	Fruits	17.65	2.77	4.72	15.71	8.55	-	0.67

Table 1. *Cont.*

j	Product Type	Production (P)	Import (I)	Export (O)	Supply (S)	Food (Fo)	Feed (Fe)	Other
9	Wine, beer	6.34	1.22	3.08	4.87	3.65	-	0.39
10	Meat	5.07	2.18	0.95	6.3	6.13	-	-
11	Milk	11.22	8.02	2.37	17.09	15.95	0.58	0.32
12	Eggs	0.76	0.04	0.04	0.75	0.71	-	0.04
13	Fish	0.39	1.62	0,23	1.79	1.54	0.24	-
	Total	84.57	84.11	36.49	22.80	97.70	60.93	19.95

Source: [73,74] Soybeans expressed as soybean cake.

2.2. Energy Embodied in Food

Mass balance of the Italian FSC for the year 2011 for the 13 most important vegetal and animal product types is reported in Table 1 [73,74]. Soybeans were considered as a separate category, since FAO includes them among oil crops, despite the fact that they are pulses and their main byproduct is soy cake for animal feed. Meat included also animal fats and offal, while milk included also butter and cheese. Domestic supply (S) was obtained as the result of Production (P) plus Imports (I) $-$ Exports (O); slight differences between S and $P + I - O$ may derive from stock variations.

Supply is split in three different destinations: food (Fo), feed (Fe) and other uses, which include employment as seeds, biofuels, industry feedstock and waste. Food is intended as the fraction of agricultural and livestock production dedicated to human consumption, both as raw or processed products. In order to limit the number of product types, in the case of oilseeds and sugar crops this voice includes also transformed food: 1.88 Mt of "oilseeds food" is constituted by 0.18 Mt of oilseeds and 1.70 Mt of oils, while 1.77 Mt of "sugar crops food" is just refined sugar.

Feed is the sum of two different contributions: Fe_A is the feed for the meat, milk, egg and fish (aquaculture) human FSC, while Fe_B is the feed for pets and horses for race and entertainment. Pet feed (dogs, cats, birds and aquarium fishes) amounts to 0.5 Mt per year, that is approximately 3% of total feed [75]. In the period 2009–2014, the average number of horses that were not part of human FSC was 273,000, approximately 2% of the total biomass of Italian livestock [76]. Assuming that feed consumption is proportional to the masses of different animals, horses should consume 2% of the total feed. Therefore, Fe_B is 5% of Fe, and Fe_A represents 95% of the feed column of Table 1. Fe and Fe_A are reported in Figure A2 of Appendix for the period considered.

For each of the items in Table 1, feed derived from national production was assumed to be proportional to the ratio of production to total supply; the remainder was imported feed:

$$Fe_{A-n} = \sum_{j=1}^{13} Fe_{A-n,j} = \sum_{j=1}^{13} Fe_{A,j} \frac{P_j}{S_j}, \; Fe_{A-i} = \sum_{j=1}^{13} Fe_{A-i,j} = \sum_{j=1}^{13} Fe_{A,j} \left(1 - \frac{P_j}{S_j}\right) \tag{2}$$

the national quota of feed was 56% ± 3% in the 2000–2013 period (see Figure A2 of the Appendix).

Industrially processed Feed Fe_{proc} is produced with both national and imported products; its amount in the period considered is also reported in Figure A2 [77].

Energy embodied per unit of mass of different food products was calculated according to the following procedure.

Average specific energy at farm level was defined as the ratio of energy use in agriculture and total vegetal and animal production P:

$$e_{farm} = \frac{E_{farm}}{P} \tag{3}$$

The specific amount of energy required for food processing was defined as:

$$e_{proc} = \frac{E_{proc}}{M_{proc}} \tag{4}$$

where M_{proc} is the actual mass of food products that underwent a transformation in the food industry; M_{proc} was determined according to the following formula:

$$M_{proc} = \sum_{j=1}^{13} M_{proc,j} = \sum_{j=1}^{13} [\underbrace{Fe_{proc,j}}_{\substack{\text{processed}\\ \text{feed}}} + \underbrace{z_j O_j}_{\substack{\text{processed}\\ \text{exports}}} + \underbrace{x_j(P_j - Fe_{A-n,j} - O_j)}_{\substack{\text{process of net}\\ \text{nonfeed production}}} + \underbrace{x_j(1-y_j)(I_j - Fe_{A-i,j})}_{\substack{\text{processed of raw}\\ \text{nonfeed imports}}}] \tag{5}$$

where for each commodity j reported in Table 1 (j = 1, 2, ... , 13), x_j, y_j and z_j are the percent of processed food in national production, imports and exports, respectively (see flowchart in Figure 1).

Values of x_j, y_j and z_j are reported in Table 2 for all product types. Sources for x_j are given in the table, while values of y_j and z_j were obtained from an elaboration of FAOSTAT trade data [78] and the FAO fishery dataset for fish [79]; in both cases the reported values shows averages and standard deviation for the 2000–2014 period. Equation (5) is the sum of four contributions:

- Processed feed, $Fe_{proc\text{-}j}$, that is approximately 70% of feed used in the human FSC FE_A (see Figure A2).
- Processed exports $z_j O_j$.
- Process quote x_j of the *net* production for direct human consumption (that is production minus exports and national feed).
- Process quote x_j of imported food for direct human consumption that was not already processed abroad $(1 - y_j)$ $(I_j - Fe_{A\text{-}I,j})$.

Table 2. Percent of processed food in Italy (x_j and z_j) or abroad (y_j) for different product types. In row 10 the processed percent of exported and imported meat is less than 100%, because the remaining part (unprocessed meat) is constituted by live animals.

j	Product Type	Processed Percent			Sources for x_j
		Internal (x_j)	Imported (y_j)	Exported (z_j)	
1	Cereals	92.7% ± 1.0%	6.1% ± 1.0%	87.3% ± 4.8%	All cereals except rice, dried at farms (3.3%)
2	Tubers	14.2% ± 2.3%	28.8% ± 2.8%	3.7% ± 1.1%	[80]
3	Pulses	87.6% ± 7.8%	81.2% ± 4.2%	58.4% ± 4.9%	[81,82]
4	Soybeans	100%	65.5% ± 5.5%	84.2% ± 9.8%	All soy is processed for oil and meals
5	Oilseeds	92.2% ± 2.1%	84.6% ± 1.9%	97.5% ± 1.2%	[76]
6	Sugar crops	100%	100.0%	100.0%	All sugar is processed from sugar beet
7	Vegetables	27.5% ± 2.7%	55.3% ± 3.6%	71.2% ± 1.7%	[81–83]
8	Fruits	12.2% ± 1.3%	20.8% ± 2.0%	21.5% ± 1.2%	[81–84]
9	Wine, Beer	100%	100.0%	100.0%	All beverages are processed
10	Meat	100%	74.0% ± 3.5%	91.6% ± 1.5%	All meat processed in slaughterhouses
11	Milk	100%	100%	100%	All milk is pasteurized or homogenized
12	Eggs	34%	17.6% ± 9.2%	44.2% ± 16%	[85]
13	Fish	92.08% ± 6.6%	76.6% ± 1.24%	48.2% ± 3.15%	[79]

Sources: x_j values, see last column; y_j and z_j values sourced from FAOSTAT [86] and FIGIS [79].

The specific input for transportation can be defined in relation to all food moved, that is total production, exports included:

$$e_{tran} = \frac{E_{tran-N} + E_{tran-E}}{P} \tag{6}$$

Specific input for distribution is related to the market quote q of modern retailers of the total food (Fo); in 2012 q was equal to 72% [87]:

$$e_{dist} = \frac{E_{dist}}{qFo} \tag{7}$$

2.3. Vegetal and Animal Products

The specific values defined in the previous section are representative for all products in the Italian FSC. Animal products require an additional specific energy input for feed farming, processing and transport, defined as

$$e_{feed} = \frac{Fe_{A-n}e_{farm} + Fe_{proc}\left(e_{proc} + e_{tran-N}\right)}{P_{anim}} \tag{8}$$

where P_{anim} is the production of animal products, meat, milk, eggs and fish:

$$P_{anim} = \sum_{j=10}^{13} P_j \tag{9}$$

The farming energy intensity is related only to the national products used for feed, while the processing intensity is related to industrial prepared feed. Transport was associated to Fe_{proc}, because this second quantity contains also the first. This value was added to e_{farm} to obtain the energy input for animal products. All equations from Equations (3) to (9) were used for all years from 2000 to 2013.

2.4. Nutritional and Embodied Energy in Food Waste

Available data for FLW at European level at different stages of the FSC (farming, post-harvest, processing, and distribution) are reported in Table 3 for the same 13 groups of vegetal and animal products listed in Tables 1 and 2.

Table 3. Percentage of food losses and waste at different steps of the FSC.

j	Product Type	FSC Step				
		w_{farm}-Farming		w_{proc}-Processing	w_{dist}-Distribution	Food Energy (MJ/kg)
		w_{farm1}-on the field	w_{farm2}-Post-Harvest			
1	Cereals	2.0%	4.0%	10.0%	2.0%	11.03
2	Tubers	20.0%	9.0%	15.0%	7.0%	2.64
3	Pulses	10.0%	1.0%	5.0%	1.0%	14.35
4	Soybeans					14.41
5	Oilseeds					6.82
6	Sugar crops	4.2% [a]	2.3% [b]	-	1.2% [c]	14.88
7	Vegetables	20.0%	5.0%	2.0%	10.0%	0.97
8	Fruits					1.76
9	Wine, Beer	-	-	0.89% [d]	-	2.62
10	Meat	3.2%	0.7%	5.0%	4.0%	6.71
11	Milk	3.5%	0.5%	1.2%	0.5%	1.68
12	Eggs	4%	-	0.5%	2.0%	6.20
13	Fish	9.4%	0.5%	6.0%	9.0%	5.89

Source: Gustavsson et al. [25,88], with the exception of [a] Smith et al. [89]; [b] Huijbregts et al. [90]; [c] [91]; [d] Castellucci et al. [92].

It is worth noting, that, according to the methodology developed by Gustavsson et al. [25,88], and as detailed below, all these percentages are related to different totals and cannot simply be summed to obtain a total food waste percentage.

The second column of Table 3 reports the "loss on the field" data that refers to crop left in the fields or to animals died before slaughtering. For each product group j (j = 1, 2, ..., 13) the percentages w_{farm1} were referred to the *gross* agricultural production P_0:

$$w_{farm1j} = \frac{P_{0j} - P_j}{P_{0j}} \tag{10}$$

Data for P_{0j} were not available but they were estimated from Equation (10) as:

$$P_{0j} = \frac{P_j}{1 - w_{farm1j}} \tag{11}$$

Therefore, absolute waste W_{1j} was defined as:

$$W_{farm1j} = w_{farm1j} P_{0j} \tag{12}$$

The second contribution is the post-harvest loss, due to inappropriate storing condition or quality controls. For each commodity, this fraction of post-harvest waste w_{farm2} (third column of Table 3) must be related to the total production P_J; consequently, the absolute amount of FLW at post-harvest was defined as:

$$W_{farm2j} = w_{farm2j} P_j \tag{13}$$

Gustavsson et al. [25,88] did not include feed values in the computation, considering strictly the *direct* waste of food. On the contrary, according to the specific approach used in the present work, animal feed was included in the computation of W_{farm2j} because it was an *indirect* waste of food and energy was *already* spent to produce it.

The FLW at farm level is the sum of the two contributions in Equations (12) and (13):

$$W_{farmj} = W_{farm1j} + W_{farm2j} \tag{14}$$

For each commodity, the fraction w_{procj} of FLW during processing (fourth column of Table 3) must be related to the corresponding j-term forming the total quantity of processed food M_{proc} (see Equation (5)), with the exception of processed feed, since it is assumed that the processing waste percentage of Table 3 applies only to food; the absolute amount of waste was defined as:

$$W_{procj} = w_{procj} \left(M_{proc-j} - Fe_{proc,j} \right) \tag{15}$$

For each group, the fraction w_{distj} of FLW at the distribution level (fifth column of Table 3) is related to all food Fo_j:

$$W_{distj} = w_{distj} Fo_j \tag{16}$$

The *Food Energy Waste* (FEW) was computed using FAO data on food energy values for all the above mentioned food categories [86]. The *Embodied Energy Waste* (EEW) was computed assuming that embodied energy builds up along the chain, so the latter the waste occurs, the greater the energy waste, as detailed in Table 4. Energy input at the farm level for animal products must also account for feed. At the distribution level, energy for processing is applied only to the fraction x of transformed products.

Table 4. Scheme for computing energy embodied in food waste. Source: Authors' elaboration.

Waste Occurs at:	Energy Wasted for Unit Mass of Food Waste
Farm	e_{farm} (+ e_{feed} for animal products)
Processing	$e_{farm} + e_{tran} + e_{proc}$ (+ e_{feed} for animal products)
Distribution	$e_{farm} + e_{tran} + x\, e_{proc} + e_{dist}$ (+ e_{feed} for animal products)

3. Results

3.1. Total Energy Use in the FSC

Total energy utilization of Italian FSC peaked in year 2002 to almost 1000 PJ (see Figure 2) and then steadily declined in the following decade to reach 758 PJ in 2014 (−23.3% with respect to 2002 maximum), with the greatest year-to-year variation between 2008 and 2009 (−7.2%) in conjunction with the oil price shock [93].

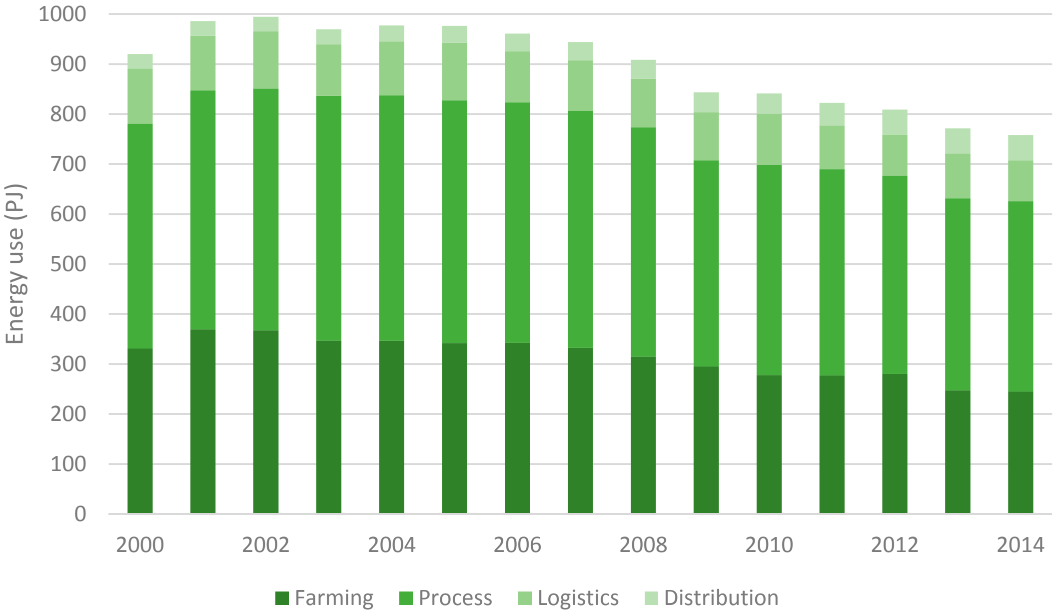

Figure 2. Total Energy use in the Italian food chain, 2000–2014.

The farming sector presented a 31% downturn between 2002 and 2014. Within farming, the strongest decrease occurred in new machinery (−55%), fertilizers (−40%) and pesticides (−43%) use.

During the same time period, the food process sector registered −21.6%, with the greatest decrease in direct energy use (−35%), while energy embodied in packaging changed only slightly (−11.2%). Logistics contracted by 22%, with the greatest reduction in exports (−55%). The distribution sector was in countertrend, because it presented an increase in energy use greater than 60% in the same period.

In the whole period under exam, energy utilized in the FSC decreased faster than total energy use (−14%), so the incidence of the FSC on the total energy budget declined from 12.5% to 11% of the national energy budget [35]. This range of variation (11%–13%) can be considered consistent with previous estimates provided by Campiotti et al. [34], and Sanfilippo and Ruggeri [94], that are slightly higher (16% and 15%–19%, respectively) as they include also the consumption segment. The reduction in energy employment is mainly linked to a decrease in the total production, which contracted from 100 to 78 Mt between 2000 and 2014, while energy intensity has remained almost constant (see Figure 3 below).

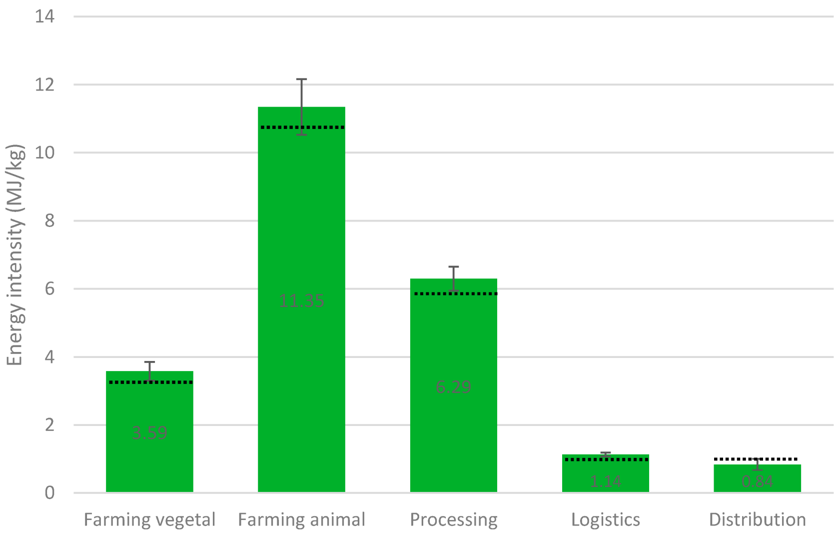

Figure 3. Average energy intensity for the different steps of the food chain, 2000–2011 (green bars), standard deviation (error bars) and energy intensity for the year 2011 (dotted lines).

In the year 2011, the most relevant contributions to energy use derived from the process sector (packaging included), with more than 410 PJ, or roughly half of the total, while packaging alone weighs 31%. Farming contributes with 277 PJ, that is more than one third of the total, with almost equal contributions from direct and indirect inputs, while transportation counted for 10.5% and retail for 5.5%.

These relative figures are hardly comparable to other studies [14,34,94], as agricultural indirect energy inputs were not always accounted for, and food consumption was usually included. Furthermore, the study did not include the recycling of packaging materials, which can provide significant energy savings with respect to disposal in landfill: 20% for glass, 60% for plastics and 80% and more for aluminum and steel [95]. Notably, more than half of the package impact derived from plastic polymers.

Since the total nutritional energy output of the FSC in 2011 was equivalent to 323 PJ [86], the average input/output ratio can be estimated in 2.54, that is 2.54 MJ of primary energy were required to obtain 1 MJ of food before consumption. This figure seems lower than data from other countries, such as UK [96], probably because of the diversity in terms of intensity of production systems, energy use, role or renewable sources, share of imported commodities, and average national diets.

Figure 3 shows the average energy intensity for the different segments of the Italian FSC in the 2000–2013 period; the small values of standard deviations (indicated by error bars in Figure 3) denote little change in energy intensity during the period. Dotted lines show the energy intensity levels of 2011, used in Section 3.2 for the determination of the energy embodied in food waste.

At the farming level 3.6 ± 0.3 MJ were required per kg of vegetal product, while every kg of animal products requires an additional 7.8 ± 0.6 MJ of feed energy (Equation (8)), for a total footprint of 11.4 ± 0.8 MJ (for year 2011, the intensities of vegetal and animal farming were 3.28 and 10.79 MJ/kg, respectively).

Processing contributed for 6.3 ± 0.4 MJ/kg (5.89 in 2011), while the impact of logistics and distribution is significantly smaller, 1.14 ± 0.05 MJ/kg (1.03 in 2011) and 0.84 ± 0.2 MJ/kg (1.04 in 2011), respectively.

On average, fresh vegetal products have an intensity of 5.7 ± 0.5 MJ/kg, while processed vegetal are double, 12.0 ± 0.8 MJ/kg. Almost all animal products are processed and require an energy intensity of 19.1 ± 1.2 MJ/kg.

As can be seen from Table 5, these values are comparable with energy inputs determined for single raw or processed vegetal products, and with a weighted average of animal products [97,98], for animal products the average is weighted according to the Italian production). The distribution segment was not included, since it is not considered by the environmental product declarations.

Processed products reported in Table 5 are packed in paper, plastics or steel and reflect the average process energy intensity outlined in this study. By contrast, products contained in glass have an overall significant higher energy intensity (14–20 MJ), owing to the greater mass of glass [99].

Table 5. Comparison between results on FSC energy intensity from the present work (without the distribution segment) and selected data from Italian Environmental Product Declarations.

Products		Energy Intensity (MJ/kg)
Raw vegetal products	Apples	4.7
	Potato	3.57
	This work	*5.1 ± 0.3*
Processed vegetal products	Industrial bread	10.08
	Pasta	9.84
	Canned beans	12.91
	Canned tomato	12.13
	Packed salad	16.7
	This work	*11.4 ± 0.7*
Processed animal products	Average of meat (bovine-swine), milk, eggs	16.3
	This work	*18.5 ± 1.1*

Source: Authors' elaboration on data from Carlsson-Kanyama [97], Environdec [98] and Pagani et al. [100,101].

3.2. The Double Energy Waste

Using FAO estimates for Europe [25,88], it was possible to estimate FLW related to Italian FSC (Table 6). In fact, no reliable data with the same level of specification in food categories were available for the Italian territory. Thus it was deemed more conservative to rely on European averages. The determination was performed for the year 2011, since no more recent data are available from FAO. Food mass waste (FMW) amounted to 17.9 Mt, so 17.3% of the total food supply $S = P + I - O$ of 103 Mt [86] did not reach consumption. Taking into account that Italy has slightly more than sixty million inhabitants, per capita FLW were therefore equal to roughly 301 kg/year, which is consistently higher than the figure provided by Gustavsson et al. [25] for EU Countries, due the inclusion of feed waste and despite the exclusion of consumption waste. The greatest waste occurred for fruit and vegetables (two thirds of the total), followed by cereals and tubers. Most waste occurred at agricultural level.

From an energy point of view, this value represents a double waste, since both the nutritional energy contained in food (FEW) and the embodied energy (EEW) used at the different steps of the FSC are discarded. Absolute results of this analysis are reported in Table 6 for the different steps of the FSC, while Figure 4 shows the percent incidence of the different product types on FMW, FEW, and EEW. Detailed results, both for product type and FSC steps are reported in the Tables A3 and A4 of the Appendix.

Table 6. Food Mass Waste (FMW), Food Energy Waste (FEW) and Embodied Energy Waste (EEW) for the different steps of the FSC, year 2011.

Waste Type	Farming	Processing	Distribution	Total
Food Mass Waste (Mt)	12.75	2.47	2.64	17.87
Food Energy Waste (PJ)	37.04	21.35	8.49	66.89
Embodied Energy Waste (PJ)	47.42	28.43	24.21	100.07

Source: Adapted by the authors based on Gustavsson [25,88].

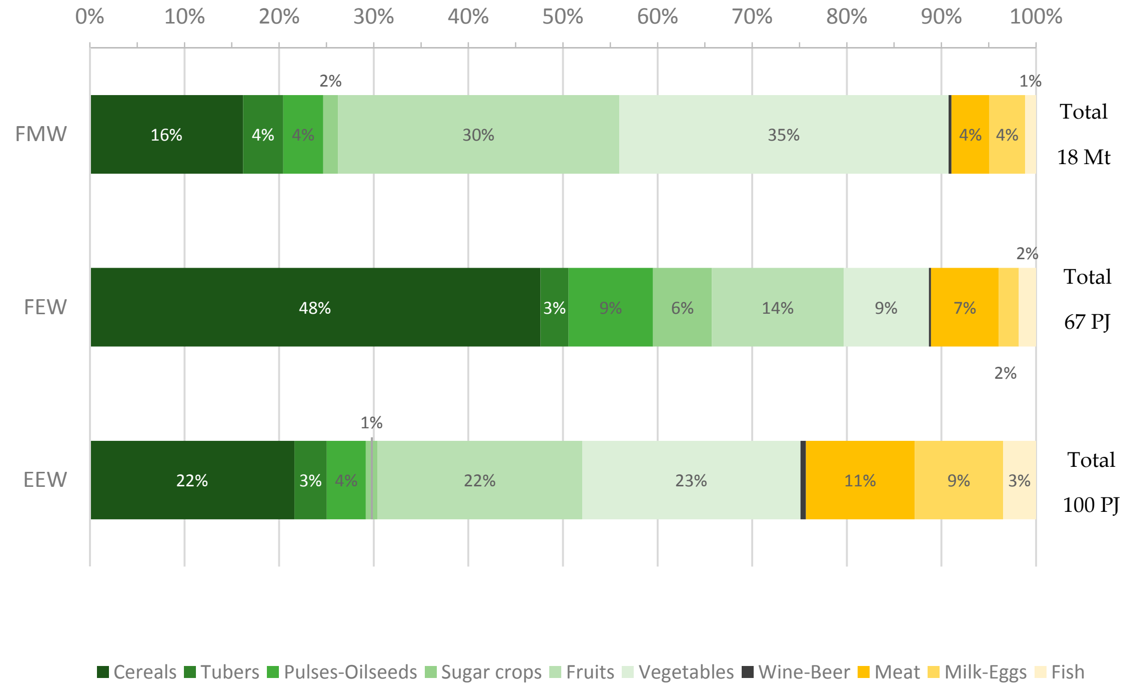

Figure 4. Comparative composition of Food Mass Waste (FMW), Food Energy Waste (FEW) and Embodied Energy Waste (EEW), year 2011.

In 2011, Italian FEW reached 66.89 PJ, equivalent to 15% of the total potential energy output of production P_0 (444 PJ) and 21.9% of the energy output of all food. Preventing this waste would have significant consequences on FSC efficiency with a 13.6% decrease in the average input/output ratio, due to a higher output.

Despite the large difference in terms of FMW, cereals have a higher relevance than fruits and vegetables, when nutritional energy content is taken into account. Similarly, the impact of oilseed, pulses and meat on FEW is much larger. The inclusion of food nutritional properties in the characterization of food waste could represent a way to prioritize the prevention or recovery of some product categories. However, optimal strategies cannot rely solely on the calorific content, as several other nutritional aspects should be taken into account.

EEW was equal to 100 PJ, which was the 12.2% of the energy spent in the FSC, and 1.3% of the total final use. It is important to emphasize how this estimate is significantly lower than the average value calculated for the US [13] most probably due to the exclusion of the energy embodied in the consumption segment. Notwithstanding, the energy wasted through discarded food is roughly 15% greater than the energy demand by food transport and equivalent to 2.5 times the energy required by the distribution segment. Compared to other energy policy measures, EEW savings correspond to the 26.6% of total Italian production from all the renewable energy sources [102]. However, it must be noted that further food waste data specifically related to Italy are needed to draft definitive conclusions.

Different level of EEW savings would be achievable basing on the different product categories. In fact, owing to a higher energy footprint, animal derived food waste (meat, milk, and fish) is responsible for a much more than proportional energy loss, weighing only 9% in terms of mass, but 21% in terms of wasted energy.

3.3. Sensitivity Analysis

Variations in data reported in the previous section were related to year-to-year changes in energy use or food production. All direct energy use data may be considered reliable, as they were sourced from official statistics, while indirect inputs rely on energy intensities. Each of the values used for the parameters was considered by the authors as the best choice at the moment of publication, but nevertheless each of them is characterized by a degree of uncertainty. It is therefore important to define the sensitivity of the results to a change in energy intensity parameters. Results are referred to data of year 2011.

3.3.1. Farming

Taking into account energy intensity values reported by several authors, a ±17% variation was considered with respect to the average fertilizer energy intensity assumed in Section 2.1.1.

For pesticides, differences among various data can be estimated as ±100 MJ/kg for insecticides, ±70 MJ/kg for herbicides and ±110 for fungicides.

Machinery energy intensity presents the largest variance, due to the limited availability of data. Estimation may vary from 90 MJ/kg, in the case of perfect operations with no maintenance, to 180 MJ/kg [38]. However, the impact of machinery energy on the overall agriculture input is so small that its indetermination does not lead to any significant difference.

Energy for farming can thus vary of ±25 PJ (see Figure 5).

3.3.2. Processing

Energy intensities were defined more precisely for packages and variations are smaller, as detailed below:

- Paper: from 7.7 to 8.9 MJ/kg [103].
- Glass: from 12.5 to 20 M/kg [104,105].
- Aluminum: from 145 to 165 MJ/kg [105,106].
- Steel: from 17.5 to 27.5 [105,107].
- Plastics: from 75.3 to 79.6 [55,56,108–112].
- Wood: no significant variation [105].

As a consequence, energy for process may vary of ±21 PJ.

3.3.3. Logistics

The analysis was performed on road freight that represents more than 97% of the total energy for logistics. According to International Energy Agency [65], energy intensity for road transport can vary form 1.9 MJ/t·km to as much as 6.5 MJ/t·km. This upper value was taken into account to define the worst possible scenario for transportation. As a result, the energy for logistics may vary between 57 and 189 PJ, which is a great variation in relative terms, but not so relevant when compared to the entire FSC.

3.3.4. Distribution

Taking into account the values in energy use per square meter (900–1600 MJ/m^2 per year) reported by Santi and Elia [72], the overall variation in the distribution sector can change from 33 to 58 PJ.

The results of the analysis are shown in Figure 5 for the total energy use in the FSC. Changes can be significant, mainly for transport energy, due to the larger variation range in intensity. Nevertheless, main findings outlined in the previous section are not significantly altered by these variations. Process remains the most important factor, followed by farming, logistics and distribution. Only in the case of a highly efficient logistics and an inefficient retail, the two sectors have approximately the same relevance.

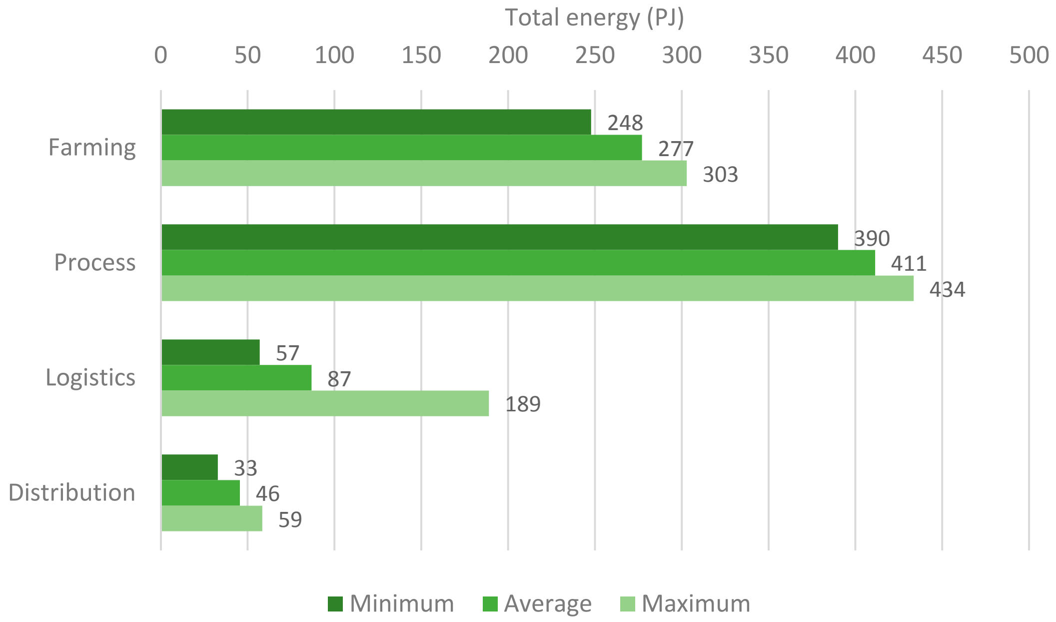

Figure 5. Variations in the total energy inputs of the Italian FSC of year 2011 as a consequence of a variation of the energy intensity parameters, as described in the text.

Figure 6 shows the percent variation of EEW for a change in the energy intensity at the various levels of the FSC. Changes are small for variations in the farming sector (±5%), process (±2%) and distribution (±1%), while are more significant for logistics, ranging from −2% to 7.6%; as before, this is due to the high upper limit of the road freight energy intensity (see Section 3.3.3).

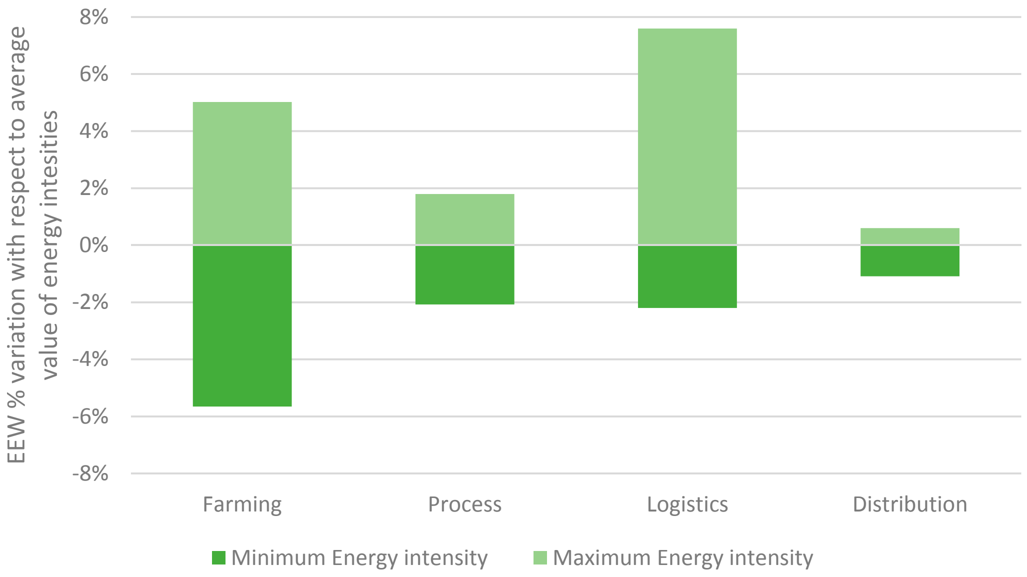

Figure 6. Percent variations in the total Embodied Energy Waste for year 2011 as a consequence of a variation in the Energy intensity parameters, as described from Section 3.3.1 to 3.3.4.

4. Policy Implications

The double energy waste concept can provide also relevant insights for policy design. Interventions could regard indirect inputs and their embodied energy, supporting both a quantitative reduction and a qualitative shift towards less energy intensive products and/or practices. For example, in the farming sector, potential measures could aim at a reduced use of machinery, promoting low tillage techniques, and a shift towards organic fertilizers and plant products, so to reach a higher energy efficiency without endangering food production levels.

The processing sector should be prioritized as well, so to reduce the use of packaging as much as it does not interfere with food safety, shift from disposable to recyclable/returnable packaging, and introduce as much as possible recycling for all material in local communities. A win-win measure that could augment the sustainability of the food systems would be the replacement of fossil power, heat, and fuels, with renewables counterparts, and in particular bioenergy deriving from byproducts (manure straw, husks). Most of this biomass is or could be easily converted into direct energy input for the food supply chain.

Last but not least, the typology of food consumption should be regarded as an important source of the overall energy bill of FSC, as the composition of the average national diet determines a higher or lower share of energy intensive products. The reduction in the consumption levels of meat is regarded as a crucial strategy not only for its positive public health externalities but also for the potential indirect effect on climate change emissions. A similar outcome could be achieved in terms of energy. However, such a shift toward a more sustainable diet will likely require long term and specific political choices and measures (i.e., investments in food education; changes in regulations and policies related to animal products etc.). Thus, short term policies should also focus on the intensiveness of animal farming and, in particular, on the production and composition of feed: less grain products and more hay and alfalfa would lower the energy footprint.

A strategy combining food waste prevention and recovery could represent another tool for reaching higher energy efficiency in the food system. Current levels of waste are a concrete and avoidable loss, both in nutritional and energy terms. The estimate related to the Italian case showed that meaningful gains could be achieved, with the possibility of a higher food availability level at the same cost, a lower energy bill with the same output, or a combination of both. This major insight suggests that food and energy security priorities could, and should be, coordinated within the same food waste policies, aiming at the sufficient amount of food produced and distributed using the lowest amount of energy. A combination of recovery and prevention of food waste could thus result in a mix of higher food availability with a lower energy I/O ratio, and avoided use of energy, to be consumed for other societal purposes.

Furthermore, policies aimed at food waste prevention should take in due account the "double energy" content of different product categories. For example, beside fruits and vegetables, the recovery of animal derived products should be prioritized basing on both their calorific content and embodied energy, while cereals wasting could be considered more relevant because of the related share of nutritional energy wasted. Similarly, also feed waste prevention should be regarded as a measure to lower embodied energy of feed and, thus, a more sustainable animal production.

5. Conclusions

The results of this study showed that the double energy waste concept provides an alternative perspective of the multiple interrelations between energy and food security. The analytical model elaborated provided a preliminary estimation of the intensiveness of food produced and distributed in the national territory. Moreover, it allowed investigating the consequences of the amount of food that did not reach final consumption on the nutritional output and energy use.

The reduction in the total energy use in the Italian food supply chain occurred during the 2000–2014 period is in mainly related to a decrease of the total volumes of production and only in a small proportion to a reduction of energy intensity due to increased efficiency.

The most relevant contributions to energy utilization in the food supply chain derives from processing (packaging included) that covers roughly 50% of the energy input while farming counts for approximately one third.

Moreover, in 2011, more than 20% of the energy output of all food was wasted. Reducing this waste would lead to a significant improvement in the efficiency of the food supply chain, which can be estimated in a 13.6% decrease in the average input/output ratio.

When nutritional energy content is taken into account, cereals have a higher relevance than fruits and vegetables. Similarly, the impact of oilseed, pulses and meat on Food Energy Waste is much larger than on Food Mass Wasted. The inclusion of food nutritional properties in the characterization of food waste could represent a way to prioritize the prevention or recovery of some product categories. However, optimal strategies cannot rely solely on the calorific content, as several other nutritional aspects should be taken into account.

Embodied Energy Waste represented more than 10% of the energy spent in the food supply chain, and 1.3% of the total final energy use. Due to a higher energy footprint, animal derived food waste (meat, milk, and fish) is responsible for a much more than proportional energy loss, weighing only 9% in terms of mass, but 21% in terms of wasted energy.

The double energy waste can provide also a relevant framework to design policy interventions aimed at improving the energy efficiency of the food systems stimulating a transition towards less energy intensive products and practices. Future research should address the estimation of energy potential of household food waste recovery and the assessment of the energy balance in the downstream segments of the food supply chain.

Author Contributions: Authors contributed equally to design the research and writing the paper. All authors proofread and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix

Table A1. Lower heating values and refinery efficiencies of fuel used in the food chain.

Energy Vector	LHV (MJ/kg)	Refinery Efficiency (η)	Equivalence Factor for Gross Energy (1/η)
Fuel oil Diesel fuel LPG	41.3 42.6 46.0	92.6%	1.08
Natural gas	34.3	98.5%	1.01
Coal	30.9	95.7%	1.04

Source: [35].

Table A2. Specific input energy for different packaging materials.

Material	Percentage Use for Food ^{A}	Energy Input (MJ/kg)
Paper	53.0%	8.08 ^{B}
Glass	89.8%	15.61 ^{C}
Aluminum	76.9%	155 ^{D}
Steel	25%	25.2 ^{E}
Wood	15%	44 ^{F}
Plastics (weighted average)	73.7%	77.44 ^{G}

Source: ^{A} [57]; ^{B} [103]; ^{C} [104]; ^{D} [106]; ^{E} [107]; ^{F} [105]; ^{G} [55,56,108–112].

Table A3. Masses of food losses and waste at different steps of the FSC.

j	Product Type	Food Mass Waste (Mt)			
		Farming	Processing	Distribution	Total
		W_{farm}	W_{proc}	W_{dist}	
1	Cereals	1.15	*1.55*	0.19	2.89
2	Tubers	0.53	*0.06*	0.16	0.76
3	Pulses	0.02	*0.01*	0.00	0.03
4	Soybeans	0.07	*0.01*	0.00	0.08
5	Oilseed	0.43	*0.17*	0.04	0.64
6	Sugar crops	0.24	*0.00*	0.04	0.28
7	Vegetables	5.29	*0.05*	0.86	6.20
8	Fruits	4.29	*0.13*	0.88	5.30
9	Wine. beer	0.00	*0.06*	0.00	0.06
10	Meat	0.20	*0.27*	0.25	0.71
11	Milk	0.46	*0.13*	0.08	0.67
12	Eggs	0.03	*0.00*	0.01	0.05
13	Fish	0.04	*0.03*	0.14	0.21
	Total	12.75	*2.47*	2.64	17.87

Source: [25,88].

Table A4. Food energy waste and embodied energy waste for the Italian food chain.

j	Product Type	Food Energy Waste (PJ)				Embodied Energy Waste (PJ)			
		Farming	Processing	Distribution	Total	Farming	Processing	Distribution	Total
1	Cereals	12.68	17.08	2.08	31.85	3.77	*15.82*	2.04	21.63
2	Tubers	1.40	0.17	0.43	2.00	1.74	*0.64*	1.05	3.43
3	Pulses	0.25	0.11	0.04	0.41	0.06	*0.08*	0.03	0.17
4	Soybeans	0.99	0.21	0.00	1.19	0.22	*0.15*	0.00	0.37
5	Oilseed	2.94	1.18	0.24	4.37	1.42	*1.77*	0.39	3.57
6	Sugar crops	3.53	0.00	0.63	4.16	0.78	*0.00*	0.48	1.26
7	Fruits	7.54	0.24	1.54	9.32	14.07	*1.37*	6.20	21.65
8	Vegetables	5.14	0.05	0.83	6.02	17.38	*0.55*	5.14	23.08
9	Wine, beer	0.00	0.15	0.00	0.15	0.00	*0.58*	0.00	0.58
10	Meat	1.36	1.78	1.65	4.79	2.19	*4.71*	4.60	11.50
11	Milk	0.78	0.22	0.13	1.13	4.99	*2.30*	1.48	8.78
12	Eggs	0.20	0.01	0.09	0.29	0.34	*0.02*	0.21	0.57
13	Fish	0.25	0.15	0.82	1.21	0.45	*0.45*	2.59	3.49
	Total	37.04	21.35	8.49	66.89	47.42	*28.43*	24.21	100.07

Source: Gustavsson [25] for food waste, [86] for food energy and authors elaboration.

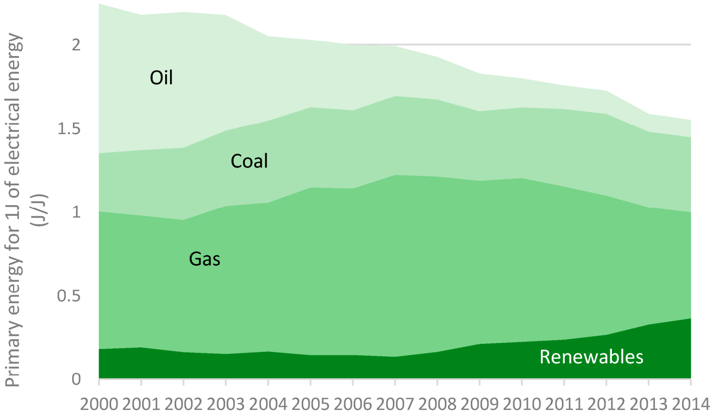

Figure A1. Primary energy equivalent of 1 J of electrical energy in Italy. Source [35].

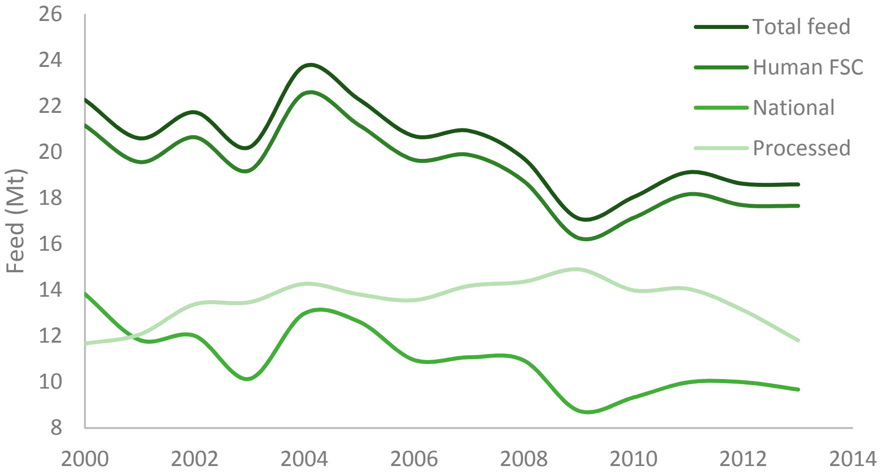

Figure A2. Total feed, feed for use in the human FSC, feed from national products and processed feed.

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