energies

Section S1-Food categories

Table S1. Food commodities included in the study, based on Garcia-Herrero et al. [1].

Food Category	Commodities Included
Cereals	Wheat, rice, maize, others
Roots and tubers	Potatoes
Sugar	Sugar
Vegetable oils	Sunflower seed oil, palm oil, olive oil, others
Vegetables	Tomatoes, onions, other
Fruits	Oranges and mandarins, grapes (excluding wine), apples, others
Pulses	Beans, peas, others
Meat	Bovine meat, mutton and goat meat, pig meat, poultry meat
Fish and seafood	Fish and seafood
Dairy	Milk, cheese, butter
Eggs	Eggs

Section S2-Primary energy demand calculations

The analytical part is done through the methodology of Life Cycle Assessment (LCA) following the recommendations of the international regulation ISO 14040 [2] and ISO 14044 [3], and based on the developed methodologies in several previous studies to perform the primary energy demand, mainly the works developed by Vittuari et al. [4], Infante-Amate et al. [5], and Cuellar and Webber [6]. To study the intensity and energy efficiency of the agro-food chain in Spain in 2015, The food supply chain is divided into four different stages: agricultural production, processing and packaging, distribution and consumption (Figure S1). The methodology of this work, starts by calculating the primary energy demand (PED) of the entire Spanish supply chain in 2015, followed by the calculation of the embodied energy loss (EEL) and the food energy loss (FEL), ending by the calculation of the novel index so-called $EROI_{ce}$. All data utilized and elaborated in this work are referred to Spain, with the exception of some mass-to-energy factors, which have been taken from the literature or Thinkstep's Database [7] and are assumed as internationals (Table S1). It has been tried to develop a consistent inventory, whit approaches to quantification and assumptions that would allow to make it comparable with other similar studies in the future. It has been intended to maintain a huge transparency related to the information obtained, the procedures and the assumptions.

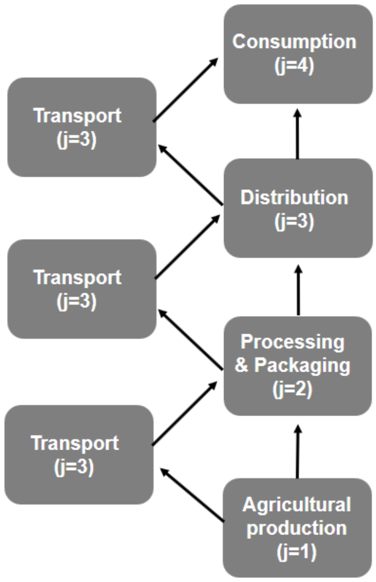

Figure S1. Outline of the assumed division in stages of the food supply chain.

PED values for each category and stage are firstly calculated in petajoules (PJ) per year in Spain and transformed to the functional unit (kJ/cap/day). It has been used a mass-to-energy conversion factor obtained from the division between the petajoules of each category of food in the agricultural stage between the tons of mass production values. To obtain the percentages corresponding to each food category, a proportion based on Laso et al. [8], is used. Those values are divided first by the Spanish population in 2015 (46.528.966 persons) and secondly by the 365 days of the year.

Section S2.1-Agricultural production

The PED calculated in this stage includes i) consumption of fuel for traction, irrigation, heating and drying, and ii) electrical energy for mechanical operations and lighting. Data were obtained from the Ministry of Agriculture and Fisheries, Food and Environment of Spain [9] and the Spanish Institute for the Diversification and saving of Energy [10]. On the other hand, it is considered the indirect energy use necessary for the production of i) machinery, ii) fertilizers, iii) pesticides and iv) plastic materials used in agriculture. The number of existing machineries for agricultural production in Spain during the reference period (2015) is retrieved for the statistical yearbook of the Ministry of agriculture of Spain [11]. To make a representative calculation of the weight of the machinery, it is used as a reference for each of the three categories of the yearbook (tractors, automotive machineries, trailers) the weight of one of the most sold models. To calculate the energy used in the construction and maintenance of the machinery, a mass-to-energy factor from Thinkstep's Database [7] is used (Table S2). For calculating the energy used in the production of fertilizers and treatments, the statistical data of the amount of fertilizers and pesticides consumed, extracted from the Department of Agriculture and Fishery, Food and Environment [9], were also considered. The different types of fertilizers used are added in three large groups: i) nitrogenous, ii) phosphate and iii) potassium. The different types of pesticides used are grouped into: i) fungicides, ii) herbicides, iii) insecticides and iv) molluscicides. For the group of molluscicides no specific factor was found, but it is assumed as acceptable to use the same as for insecticides. The use of plastic material in agriculture is deduced through the Department of Agriculture and Fishery, Food and Environment [9], considering the m^3 of i) quilting, ii) tunnels and iii) fixed installations. To move from m^3 to tons, the weight data of plastics in agriculture in Spain for the year 2015 has been used [12]. The mass-to-energy conversion factors for each group has been extracted from Thinkstep's Database [7] (Table S2). The energy used in the production of feed for livestock is calculated by multiplying the amount of average consumption obtained by the Spanish statistical yearbook [11] and multiplied by a mass-to-energy factor of Infante-Amate et al. [5], as represented in Table S1.

Section S2.2-Food processing and packaging

The PED for mechanical processes, cooking, freezing, and space heating/cooling during food processing, and the indirect energy use for packaging of products, has been taken into account. PED related to the food industry has been retrieved from the Spanish Institute for the Diversification and saving of Energy (IDAE) [10], transforming the ktep of each type of fuel to kJ, converting final to primary energy by using the updated transformation table for 2015. The energy use for packaging has been obtained by adding the energy use to produce i) plastics, ii) glass, iii) paper and cardboard and iv) light metal packaging. The energy used in wood and cork packaging is not considered as its proportional fraction is minimal. The production data of plastic packaging are extracted from the Spanish Association of Plastics Industry [12] and the Department of Agriculture and Fishery, Food and Environment [9]. The production data of glass packaging has also been taken from the Department of Agriculture and Fishery, Food and Environment [9]. The production data of paper and cardboard packaging has been taken from the Spanish Association of Pulp, Paper and Cardboard Manufacturers [13], and a proposed percentage of use for the food industry (42%), as well as the mass-to-energy conversion factor (Table S2) are extracted from Infante-Amate et al. [5]. The production data of light metal packaging have been found in Metal Packaging Europe [14]. A proposal for the percentage use of light metal packaging in the food industry in Spain (77%), as well as a proposal to perform the energy analysis based on the composition in aluminum (7%) and steel (93%), and its consequent mass-to-energy factors; are obtained from the magazine specialized in informing about the life cycle of packaging [15], as represented in Table S2.

Section S2.3-Distribution

In this stage it has been decided to include i) the transport of food products and ii) the distribution in food stores, accommodations and restaurants. According to Neira et al. [16], an important part of the discussion on sustainability in the food supply chain lies in the first part of this stage, related to the energetic cost of transporting food products throughout the chain. For developing the energy balance, firstly the national road transport associated with the food supply chain was first taken into account. For the estimation, the data of agriculture products, fish and other fishing products, and food products, beverages and tobacco; of the Ministry of Development of Spain [9], have been considered. The energy intensity value for road transport is taken from Monzon et al. [17] (Table S2). Besides, the energy of transporting imported products is calculated, by using Datacomex basis data [18], and 10 food categories are considered, excluding only the categories of beverages and tobacco. Transportation by boat, train, road and plane are analyzed. It has been used masses-distance products (t-km) coming from Simon-Fernandez et al. [19] and Monzon et al. [17], for i) international boat transportation, ii) international train transportation, iii) international road transportation and iv) airplane transportation (Table S2). Finally, the transport of consumers to go shopping has been also taken into account. It is assumed that all products are bought at the same time, and therefore the emissions of diesel consumption is divided by each product. This part needs to be highly assumed since little information is available about how Spanish people get and consume food products. For developing this information, the per capita consumption in Spain in one year in kg was extracted from the Department of Agriculture and Fishery, Food and Environment [9]. As it is estimated that 59% of the population goes shopping on foot, 35% by car and 4% using public transportation [9], it could be extracted the kg that have been bought by car and bus. According to the methodology of I Canals [20], to make the purchase by car, about 0.185 Km/Kg are transported, and when going by bus, about 0.00085 Km/Kg are transported. Through this assumption, the km traveled could be obtained related to the total purchases made by car and bus by the Spaniards. According to IDAE [10], a car consumes 8 liters of fuel every 100 kms traveled, and a bus consumes 40 l of fuel every 100 km traveled. Through these assumptions, it is extracted the data of fuel liters used to make the purchase. It has been searched the number of vehicles registered in Spain with diesel and gasoline consumption, as well as the energy factor of each of the two fuels in 2015. Finally, these two energy values were added in a single one. For the distribution part it has been taken into account, i) the energy that has been used in the distribution of food in wholesale and retail in Spain. For obtaining that information, it has been considered energy consumption data from the IDAE [10] which were taken into account for each reference year, and transformed from ktep to kJ. On the other hand, ii) the energy used in the production of food in restaurants and accommodation, which has been also taken from IDAE [10], is added to the data of this stage. Both kind of data were transformed from final energy to primary energy by using the updated transformation tables for each year.

Section S2.4-Consumption

As the energy associated with the distances and types of transportation to buy food for households consumption was already analysed, this stage considers only the energy used in the preparation and maintenance of food at homes. Energy consumption data from the IDAE [10] are considered, which have been transformed from ktep to kJ, and again from final energy to primary energy. From all the data in IDAE [10], only the categories of home appliances and electricity for cooking, are considered. From the first category, a factor extracted from Infante-Amate et al. [5] is used, which states that only 40% of the totality of home appliances are used for cooking food.

Section S2.5-Mass-to-energy conversion factors

Table S2. Mass-to-energy conversion factors and life cycle inventory sources.

	Energy-to-mass factor (MJ/Kg)	Source
Agricultural production		
Direct energy use		
Agriculture (fuel)		[10]
Agriculture (electricity)		[10]
Fisheries (fuel)		[10]
Indirect energy use		
Machinery	27.6	[7,9,10]
N Fertilizers	68.06	[7,9]
P Fertilizers	34.47	[7,9]
K Fertilizers	4.03	[7,9]
Fungicides	237.7	[7,9]
Insecticides	239.4	[7,9]
Molluscicides	351.2	[7,9]
Quilting	69.7	[7,12]
Tunnels	72.6	[7,12]
Fixed Installations	63.6	[7,12]
Food processing and packaging		
Direct energy use		
Fuel use		
Electricity		[10]
Indirect energy use		[10]
Glass		
Plastic	15.5	[5,9]
Paper and cardboard	77.7	[5,12]
Aluminum	18.4	[5,13]
Steel	46.3	[5,14]
Distribution	27.5	[5,14]

National road transportation		
International boat transportation	0.4	[9,17]
International train transportation	0.2	[9,17,19]
International road transportation	0.3	[9,17,19]
Airplane transportation	2.1	[17,18,19]
Transportation to purchase	21.0	[9,17,19]
Restaurants and accommodation		[9,10,20]
Storage		[10]
Consumption		[10]
Home appliances		[10]
Electricity cooking		[10]

Table S3. Results in petajoules per year in Spain of the primary energy demand by each food category under study, and on each food supply chain stage. The values are related to the percentages assumed, based on Laso et al. [8].

	%	Agric. Prod.	Proc. & Pack.	Distrib.	Consump.
Cereals	13.9	74.5	48.1	85.7	32.8
Roots	1.7	9.0	5.8	10.4	4.0
Sweets	0.1	4.3	2.8	4.9	1.9
Vegetable oils	3.6	19.7	12.7	22.6	8.7
Vegetables	16.9	90.4	58.3	104.0	39.8
Fruits	3.5	18.9	12.2	21.8	8.3
Pulses	2.5	13.4	8.7	15.5	5.9
Meat	28.0	149.8	96.7	172.4	66.0
Fish and seafood	16.3	86.9	56.1	100.0	38.3
Dairy	7.2	38.7	25.0	44.5	17.1
Eggs	5.4	29.0	18.7	33.4	12.8
TOTAL		534.7	345.0	615.2	235.7

Section S3-Embodied and nutritional energy losses assessment

Once the percentages of PED on each stage were distributed between each food category, the EEL and FEL were calculated. EEL was calculated through primary energy demand data. FEL was calculated throw the mass losses along the food supply chain, transforming the data in nutritional energy, through the factors of the Bedca Database [22], as shown in Table S3. For performing the material flow analysis and the energy flow analysis, it has been used the allocation and conversion factors of Gustavsson et al. [21] for each food category. It is considered only the part of the production that is considerate edible and used for human consumption.

EEL and FEL are in both cases calculated using mass-loss factors obtained from Garcia-Herrero et al. [1], and Gustavsson et al. [21]. The calculation of the energy losses of the stages of food processing and packaging, distribution and consumption, is based on the food mass and energy production values of the previous stage, to which the mass and energy loss of the previous stage of each category is subtracted. The values have been relativized in every stage according to the already mentioned mass-to-energy calculated factor. Results are shown in Table S4:

Table S4. Results in MJ/cap/day of the embodied energy loss and in kJ/cap/day of the food energy loss by each food category under study, on each stage.

	Agricultural production		Processing & packaging		Distribution		Consumption	
	EEL*	FEL**	EEL*	FEL**	EEL*	FEL**	EEL*	FEL**
Eggs	1.6	209.3	0.2	799.7	1.3	104.7	5.8	1285.3
Meat	3.3	92.1	10.6	598.7	13.4	71.2	41.2	83.7

Fish & Seafood	4.5	71.2	5.8	16.7	12.9	29.3	21.8	12.6
Dairy	1.4	184.2	0.1	4.2	0.4	16.7	6.8	104.7
Cereals	0.8	209.3	4.8	799.7	3.3	104.7	46.6	1272.8
Sweets	0.4	37.7	0.1	37.7	0.2	37.7	2.0	284.7
Pulses	0.4	29.3	0.7	8.4	0.5	16.7	5.6	46.1
Vegetable oils	0.5	276.3	1.1	213.5	0.4	41.9	2.0	159.1
Vegetables	11.8	100.5	1.9	4.2	2.4	16.7	37.4	54.4
Fruits	2.5	230.3	0.4	8.4	0.5	33.5	7.8	104.7
Roots	0.9	46.0	1.6	46.1	0.4	16.7	2.7	50.2

*Embodied energy loss is represented in MJ/cap/day. **Food energy loss is represented in kJ/cap/day.

Section S4-Nutritional content of the food categories

Table S5. Proteins, carbohydrates and energetic content for the food categories under study [22].

	Proteins (%)	Carbohydrates (%)	kJ (per 100 g)
Cereals	10	84	1516
Roots	12	85	306
Sweets	0	0	1708
Vegetable oils	0	0	3714
Vegetables	18	80	92
Fruits	4	95	214
Pulses	29	65	1269
Meat	50	0	687
Fish and seafood	89	0	348
Dairy	19	29	272
Eggs	34	0	628

Section S5-Allocation and conversion factors

Table S6. Allocation and conversion factor used for calculating the edible part of food production which is used for human consumption [21].

	Allocation factors	Conversion factors
Cereals (%)	0.2	0.77
Roots (%)	0.78	0.82
Sweets (%)	1	1
Vegetable oils (%)	0.2	1
Vegetables (%)	0.81	0.78
Fruits (%)	0.83	0.78
Pulses (%)	0.5	0.78
Meat (%)	1	0.66
Fish and seafood (%)	1	0.5
Dairy (%)	1	1
Eggs (%)	1	0.85

Section S6-Food losses factors

Table S7. Food losses percentages for each food category as a percentage of what enters on each supply chain stage. Unless stated otherwise, percentages are obtained from Garcia-Herrero et al. [1] and Gustavsson et al. [21] for Europe region.

	Agricultural production	Postharvest handling & storage	Processing & packaging		Distribution		Consumption	
		*	Milling	Proc.	Fresh	Proc.	Fresh	Proc.
Cereals (%)	6.6	0.5	1.8	12.1	2.0	2.0	25.0	25.0
Roots (%)	8.3	4.9		14.7	7.0	3.0	17.0	12.0
Sweets (%)	6.6	0.0		2.0	10.0	2.0	19.0	15.0
Vegetable oils (%)	5.9	0.0		5.0	1.0	1.0	4.0	4.0
Vegetables (%)	8.3	9.0		2.0	10.0	2.0	19.0	15.0
Fruits (%)	6.5	10.8		2.0	10.0	2.0	19.0	15.0
Pulses (%)	6.6	8.2		5.0	10.0	2.0	19.0	15.0
Meat (%)	3.2	0.0		6.3	4.0	4.0	11.0	11.0
Fish and seafood (%)	9.4	0.0		6.0	9.0	5.0	11.0	10.0
Dairy (%)	3.5	0.0		0.2	0.5	0.5	7.0	7.0
Eggs (%)	4.0	2.0		0.5	2.0	2.0	8.0	8.0

*Postharvest handling and storage losses percentages. This stage was not differentiated in the energy balance of this work. Therefore, these factors were applied in addition to agricultural production factors.

Section S7-Energy return on investment – Circular economy index calculation

This empirical index $EROI_{ce}$ is applied only to the four categories that stood out for high values of PED, FEL and EEL: fish and seafood, cereals, vegetables and meat. For its calculation, the kg of food loss of each category were found through the material flow analysis and multiplied by i) a specific factor for energy requirements for the management of each food category on each scenario and by ii) a specific factor of energy recovery for each food category (Tab. S7). The recovered primary energy will be multiplied first by the conversion factor applied in this study to obtain the kg produced, and finally this data would be multiplied by the Bedca Database factors [22] to obtain the kilojoules of nutritional energy reintroduced in the food supply chain. This data will be divided between the energy requirements, thus obtaining the dimensionless indicator that allows us to compare the scenarios of each category.

Table S8. Results of the Energy return on investment – Circular economy index ($EROI_{ce}$) on fish and seafood, cereals, vegetables and meat, on each of the considered scenarios.

	Fish & seafood			Cereals			Vegetables			Meat		
	L	I	AD	L	I	AD	L	I	AD	L	I	AD
Energy recovered (MJ/kg)	0.3	4.4	11.7	0.2	6.5	9.4	0.2	3.1	2.7	0.3	5.1	11.9
Energy requirements (MJ/kg)	0.6	1.2	1.3	0.6	1.2	1.3	0.6	1.2	1.3	0.6	1.2	1.3
Food loss (ktones)	381.2			2682.1			3257.8			1371.5		
$EROI_{ce}$	**0.03**	**0.2**	**0.4**	**1.0**	**22.2**	**28.1**	**0.03**	**0.3**	**0.3**	**0.2**	**1.2**	**2.5**

Section S8-Assumptions and data quality

All quantifications of this work are subjected to some degree of uncertainty, and many assumptions have been done due to the unavailability of data. In order to make consistent estimations, some estimations from other similar studies are used: Vittuari et al. [4], Infante-Amate et al. [5], and Cuellar and Webber [6]. For other estimations, indirect calculation methods have been developed. It has been noticed the fact, that some of the mass-to-energy factors vary between studies, which is mainly due to the differences in the concrete system boundaries of each study or the age of the study. In the agricultural stage, it is assumed that differences in climates and soils as well as cultivation methods influence the resource use, but it has not been considered due to lack of data. According to Carlsson-Kanyama [23], most fruits are produced from plants with a long lifetime (trees) and usually these crops have to be maintained and cared during several years before production on-set. Resource inputs during those unproductive years should, ideally, be allocated to the production period of the tree. However, data about resource inputs during establishment were not found. It is imperative that more data on resource use during crop production becomes available to better understand the magnitude of uncertainties by estimating the resource use. Food which is cultivated in greenhouses, sometimes requires the use of heaters for their production. In the Spanish context, due to the favorable climatic conditions, the use of heaters is very low and it was decided to reject it. Data about energy used in the extraction, desalination and purification of water, especially in areas of intensive agriculture such as the region of Almeria, should be collected in the future. It is assumed that the energy intensity of the agricultural production of each food category is the same in Spain and in the importing countries, although this may not be correct, especially for importation from countries without mechanized agriculture. Data about energy use for food processing show large variations in terms of energy used for different products. Assumptions about transportation distances were done. For the primary energy demand calculation, it has been only taken into account imported products and omitted exportation, to avoid duplication of data. It is assumed that operations in retailers is similar than in wholesalers, in terms of storage temperature and applied cooling technology. Moreover, I Canals [20] proposed to consider the traveled distance by workers (especially for seasonal works) to farms. This factor was not considered as no information has been found. Finally, another important source of uncertainty in this work is due to the loss percentages used for the calculations. Data used from Gustavsson et al. [21] are for Europe region and differences among countries are not considered. They are the best currently available data and have been assumed to be generalizable and extrapolated. Nonetheless, although they are considered a good reference for this work, they may lead to errors if they are assumed for a specific country. For this reason, they have been updated with Spanish data when possible based on García-Herrero [1].

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