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Energy Embedded in Food Loss Management and in the Production of Uneaten Food: Seeking a Sustainable Pathway

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Abstract: Recently, important efforts have been made to define food loss management strategies. Most strategies have mainly been focused on mass and energy recovery through mixed food loss in centralised recovery models. This work aims to highlight the need to address a decentralised food loss management, in order to manage the different fractions and on each of the different stages of the food supply chain. For this purpose, an energy flow analysis is made, through the calculation of the primary energy demand of four stages and 11 food categories of the Spanish food supply chain in 2015. The energy efficiency assessment is conducted under a resource use perspective, using the energy return on investment (EROI) ratio, and a circular economy perspective, developing an Energy return on investment – Circular economy index ($EROI_{ce}$), based on a food waste-to-energy-to-food approach. Results suggest that the embodied energy loss consist of 17% of the total primary energy demand, and related to the food categories, the vegetarian diet appears to be the most efficient, followed by the pescetarian diet. Comparing food energy loss values with the estimated energy provided for one consumer, it is highlighted the fact that the food energy loss generated by two to three persons amounts to one person's total daily intake. Moreover, cereals is the category responsible for the highest percentage on the total food energy loss (44%); following by meat, fish and seafood and vegetables. When the results of food energy loss and embodied energy loss are related, it is observed that categories such as meat and fish and seafood have a very high primary energy demand to produce less food, besides that the parts of the food supply chain with more energy recovery potential are the beginning and the end. Finally, the $EROI_{ce}$ analysis shows that in the categories of meat, fish and seafood and cereals, anaerobic digestion and composting is the best option for energy recovery. From the results, it is discussed the possibility to developed local digesters at the beginning and end of the food supply chain, as well as to developed double digesters installations for hydrogen recovery from cereals loss, and methane recovery from mixed food loss.

Keywords: anaerobic digestion and composting; circular economy; energy return on investment; hydrogen bioenergy; food waste hierarchy

1. Introduction

The food supply chain is one of the most polluting daily activities when impacts along product life cycles are considered [1]. This is mainly due to several factors, such as the high degree of mechanization, the use of agrochemical products in agriculture, the long distances in distribution routes, the overpacking of products, and the growth of consumption of processed food, especially the so-called fourth and fifth range products (formed by products that are both ready to be consumed and sold refrigerated). These factors have entailed an increase in the energy consumption throughout the entire supply chain, transforming it from a net producer of energy, to a net consumer of energy [2]. However, this is not a new phenomenon; in fact, in the energy crisis of the 70s, Pimentel et al. [3] found that the energy efficiency of modern food production was declining. Over time, the energy inputs began to be higher than the energy outputs [4], and according to Cuellar and Webber [5], Lin et al. [6] and Vittuari et al. [7], nowadays the food supply chain requires 10–15 kJ of fossil fuel to produce 1 kJ of food. From the whole supply chain, the high-energy intensity of agriculture has meant an enormous increase in the consumption of fossil fuels; however, this is common in all phases of the food supply chain and it varies depending on the type of product and processing level. Therefore, the energy intensity of modern food systems represents a major issue in a current framework of decreasing limited resources, and growing population [8].

Due to the growing awareness regarding these problems, social pressure has been increasing in order to overcome these problems through the development of energy technologies that lead to sustainable development [9]. In this sense, although energy and food have a well-known connection from the perspective of chemical energy contained in food products, the energy resources embedded for food production is less explored, and the available related information is scarce. Moreover, estimations are often limited to the first stages of production, without taking into account the fact that the food supply chain consists of several successive steps, and each one of them needs energy for its specific processes. It is estimated that around 30% of the world´s total energy consumption is due to the food system [10]. According to the European Commission [11], industrial activities related to food systems require approximately 26% of the European Union´s final energy consumption. Thus, it is essential to focus on the reduction of energy used in food production systems by improving their efficiency, as it could be one of the most important drivers for development of sustainable food production systems. Searching for that efficiency, food losses (FLs) have central consequences on the energy balance on the food supply chain, additionally leading to a significant environmental impact in terms of inefficient use of natural resources, biodiversity and habitat loss, soil and water degradation, and greenhouse gas emissions [7]. According to the Organization for Economic Cooperation and Development [12], more than a third of the food produced is wasted, involving around 38% of the energy embedded in its production. Specifically, Spain has the seventh highest level of food wastage in the European Union, with 7.7 million tones. According to Garcia-Herrero et al. [13], each Spanish citizen is estimated to throw away in household consumption 88 kg of food per year, being this step the one that more FL generates. Besides, FL is directly related to food security and presents nutritional and ethical issues, as 795 million people suffer from undernourishment [14], and it is projected that by 2050 the world population will reach 9.8 billion persons [15]. Kummu et al. [16] estimated that the nutritional energy lost in the food supply chain would be enough to feed around 1.9 billion people, and approximately half of those losses could be prevented. Thus, FL supposes a missed opportunity to feed the world's growing population [17].

Related to this, it is necessary to consider the fact that with the FL, two types of energy are also lost: food energy loss (FEL), which is the nutritional energy of the FL, and embodied energy loss (EEL), which is the primary energy invested in producing FL. In addition, it is necessary to take into account the energy used in the management of FL after it has been disposed. Regarding to the latter, the efficiency in energy recovery through different management strategies, can vary considerably depending on the strategy and the FL composition. In summary, precise accountings of energy use for the production of consumed (and non-consumed) food are extremely challenging for developing strategies to mitigate energy losses [7].

In this overall framework, this paper aims to develop a novel model in the field of study, to analyse alternative FL management strategies under a circular economy concept based on a food waste-to-energy-to-food approach (Figure 1). While most studies in the literature are focused on the efficiency assessment of the food supply chain, either from a mass [18], an energy [19], or more than one point of view [20]; through the model proposed in this work, it is intended to go further and contribute to the development of integrated waste management strategies for energy-smart food systems. Thereby, the Food and Agricultural Organisation proposal [10] is followed, which focuses on the diversification of renewable energy sources through integrated food production systems, to ensure the access to energy and food security. Moreover, it is projected to follow two of the Sustainability Development Goals for 2030 established by the United Nations Member States [21]: (i) the seventh goal, whose objective is to reach at least a 27% share of renewable energy consumption by 2030; and (ii) the twelfth goal, which aims at halving FL at the retail and consumer level as well as reducing the FL along food production systems. On the other hand, the circular economy package adopted by the European Commission in 2015 is guided by the European Union waste hierarchy, which ranks waste management options according to their sustainability, and gives top priority to preventing and recycling of waste, placing the anaerobic digestion as an always-preferable option to incineration [22]. This ranking aims to identify the options most likely to deliver the best overall environmental outcome, and has been adopted worldwide as the principal waste management framework [23]. However, the waste hierarchy proposal considers FL as a set without taking into account the different specific fractions or at which points along the food supply chain are they produced. Thus, this paper aims also to develop the debate about the statement that the waste hierarchy is a too general proposal. This is in the same line as the thesis of Cristobal et al. [24], who highlighted the fact, that when more criteria are considered along with the environmental one, other tools are needed for making the decision of which FL management strategy is the most optimal.

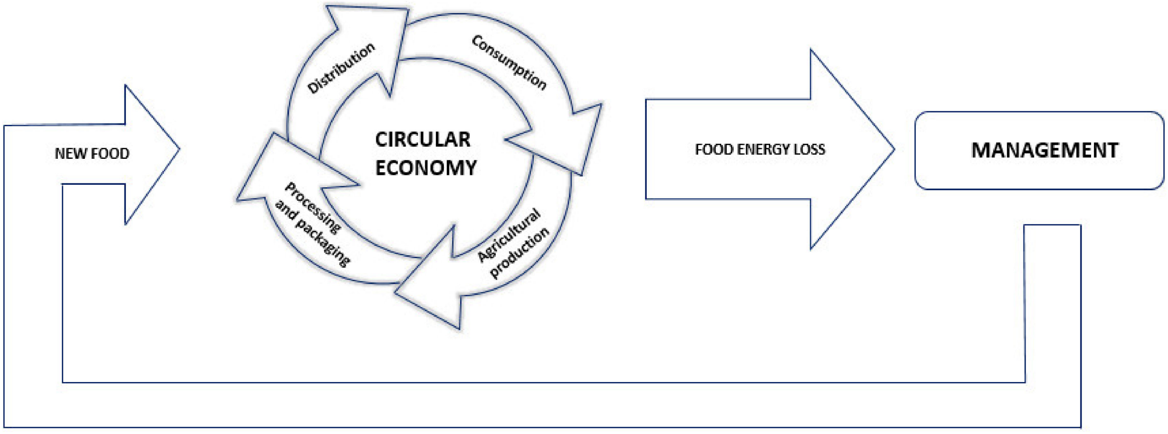

Figure 1. Conceptual diagram of the proposal of this work, recovering energy from food loss with a circular economy approach.

The paper is structured in two main parts. Firstly, Section 2 describes a detailed description of the methodology taking into account a Life Cycle Assessment approach, as well as the material flow analysis enabling to perform the energy flow analysis, conducting to the energy assessment along the food supply chain. Secondly, Sections 3 and 4 introduce the main results and discussion of the study. In particular, the first part includes a full discussion of the main parameters and the influence on the energy efficiency of the food supply chain. While last part reviews the FL management options and the expected improvement measures. The paper ends with a deployment of main conclusions and the future research.

2. Methodology

2.1. Goal and Scope

The main goal of the study is to develop a novel model to define alternative FL management strategies under a circular economy concept based on a food waste-to-energy-to-food approach.

For this objective, an empirical index so-called $EROI_{ce}$, is proposed, which quantifies the amount of nutritional energy that is recovered from the FL of each category of food under study, based on its treatment in three different scenarios: (i) landfill with biogas recovery (L), (ii) incineration with energy recovery (I) and (iii) anaerobic digestion and composting (AD&C). The results are expected to provide an interesting field for discussion about the best energy recovery strategy for the different fractions of FL, trying to develop the path to less generic energy recovery proposals. In view of the results, it is expected to open a debate around a new framework of decentralised FL collection strategies, instead, or as a complement to current centralised strategies.

2.2. Function, Functional Unit and System Boundaries

This work is conducted following the international standards 14,040 [25] and 14,044 [26] from the International Organisation for Standardization. The main function of the study is to determine what type of management strategy from the three different scenarios under study, is most appropriate for the FL management of the categories analysed, through the development of the $EROI_{ce}$ index. The functional unit is defined as the daily intake of an 11,493 kJ per capita and per day diet, by a Spanish citizen for 2015, which is obtained through an energy flow analysis (Table 1).

Table 1. Primary energy demand, nutritional energy provided to consumer and energy return on investment. Values expressed in kilojoules per capita per day and percentage.

Food Category	PED (kJ/cap/day)	Energy Provided to Consumer (kJ/cap/day)	EROI (%)
Eggs	5426	574	10.6
Meat	28,002	1901	6.8
Fish and seafood	16,243	209	1.3
Dairy	7230	938	13.0
Cereals	13,922	3827	27.5
Sweets	799	490	61.3
Pulses	2511	226	9.0
Vegetable oils	3674	2202	60.0
Vegetables	16,894	268	1.6
Fruits	3535	540	15.3
Roots	1691	318	18.8
Total	99,926	11,493	11.5

The system boundaries of this study includes the steps of agricultural production, processing and packaging, distribution and consumption, being therefore realised from "cradle to consumer" (Figure S1). As this study relies heavily on the loss percentages reported by the Food and Agriculture Organisation [27], the definition of FL is based on their latest definition provided in 2014 [28]: "food loss refers to any substance, whether processed, semi-processed or raw, which was initially intended for human consumption but was discarded or lost at any stage of the supply chain. It concerns to every non-food use, including discarded food that was originally produced for human consumption and then recycled into animal feed." Therefore, this work uses the terminology "food losses" to encompass both FL and food waste occurring at every stage, as done by Garcia-Herrero et al. [13].

2.3. Allocations

The scenarios under study are multi-outputs processes in which the management of FL is the main function of the system and the production of electricity and compost are additional functions. The environmental burdens must be allocated among the different functions. To handle this problem the International Organisation for Standardization [25] establishes a specific allocation procedure in which system expansion is the first option. Regarding the landfill scenario, since electricity generation depends on the methane concentration in the landfill biogas, electricity recovered from FL was allocated to the amount of total carbon available in the disposed organic residue.

The incineration process was modelled based on Margallo et al. [29], and in this sense, energy produced is calculated from the high heating value of each FL fraction and the amount that is incinerated.

In the anaerobic digestion scenario, methane is assumed to be combusted with a 25% efficiency of the low heating value of the biogas to generate electricity [30]. The delivering residue of the anaerobic digestion, i.e., digestate, is transferred to a composting plant for the production of biocompost. The compost is assumed to replace mineral fertilizer, with a substitution ratio of 20 kg N equivalent per ton of compost [31]. Energy intensity for fertilizer production as total N is obtained from Thinkstep's Database [32].

2.4. Life Cycle Inventory

For developing the energy flow analysis, data from different sources has been reviewed: the Department of Agriculture and Fishery, Food and Environment [33], the Spanish Institute for the Diversification and Saving of Energy [34], the Spanish Association of Plastics Industry [35], the Spanish Association of Pulp, Paper and Cardboard Manufacturers [36], a magazine specialised in informing about the life cycle of packaging [37], and the Foreign Trade Database [38]. Data for 48 representative commodities were sourced from the consumption database of the Spanish Department of Agriculture and Fishery, Food and Environment [33]. Items were grouped into 11 food categories (eggs, meat, fish and seafood, dairy, cereals, sweets, pulses, vegetable oils, vegetables, fruits and roots), which can be consulted in more detail in Table S1. It has been used several mass-to-energy conversion factors from different sources (Table S2). All the results of the PED, EEL and FEL by each food category under study, and on each food supply chain stage, can be consulted in Tables S3 and S4. Nutritional data for the EROI and the $EROI_{ce}$ estimation, were obtained from the Bedca Database [39] and can be consulted in Table S5. Food products or ingredients not available in that database were sourced from the National Nutrient Database for Standard Reference of the United States Department of Agriculture [40]. In practice, it has been assumed that the nutritional energy do not vary across the supply chain owing to the lack of data. The allocation, conversion and FL factors used (Tables S6 and S7), are based on Gustavsson et al. [27]. The exception were some products, such as apples and bananas, for which specific FL factors were available in Vinyes et al. [41] and Roibás et al. [42].

2.5. Assessment of Food Loss Management Scenarios

Based on Laso et al. [43], the electricity recovered in all the scenarios is assumed to be 100% sent to the grid, displacing electricity from the average electricity mix in Spain, and used for producing new food (Figure 2). This value could be lower if energy losses and its use for other purposes are considered. The analysis of these aspects would correspond to a consequential LCA, which could be analysed in future works.

Scenario 1: landfill with biogas recovery (L). This scenario describes landfilling of FL including biogas recovery. The landfill is composed of biogas and leachate treatment and deposition. The sealing materials (clay, mineral coating, and PE film) and diesel for the compactor is included. Leachate treatment includes active carbon and flocculation/precipitation processing. This scenario has been modelled based on the averages of municipal household FL on landfill process from Thinkstep's Database [32] for Spain, Portugal and Greece. According to the model, a 17% of the biogas naturally released from landfill is assumed to be collected, treated and burnt in order to produce electricity. The remaining biogas is flared (21%) and released to the atmosphere (62%). A rate of 50% transpiration/run off and a 100 years lifetime for the landfill are considered. Additionally, a net electricity generation of 0.0942 MJ per ton of municipal solid FL is assumed [32].

Scenario 2: incineration with energy recovery (I). The considered incineration plant, based on Margallo et al. [29], is composed of one incineration line with a capacity of 12.0 t/h. The combustion is conducted in a roller grate system reaching 1,025°C. Flue gases are treated by means of a selective non-catalytic reduction system (for NOx), bag filter (dust, dioxins, etc.) and semidry scrubbers (acid gases). The main solid residues are fly and bottom ashes. The latter is subjected to magnetic separation to recover the ferrous materials. The inert materials are assumed to be landfilled close to the incineration plant. Fly ashes, classified as hazardous material, are stabilised and sent to an inert landfill. Energy produced in combustion is transferred to flue gases for energy generation. Energy produced is calculated from the high heating value of each FL fraction and the incinerated amount. High heating values are obtained from the Thinkstep´s Database [32]. For example, average values of 4832, 14,758 and 4179 kJ/kg have been obtained for fish and seafood, cereals and vegetables.

Scenario 3: anaerobic digestion and composting (AD&C). This scenario considers the combination of AD&C of the solid fraction of digested matter, and is modelled using the life cycle inventory reported by Righi et al. [31]. The anaerobic digestion plant consists of a continuous two-steps process, where the first stage is a high-solid plug-flow reactor operating at thermophilic temperature and the second a completely stirred tank reactor at mesophilic temperature. The total retention time of substrates is about 100 days. The main product of anaerobic digestion is biogas, with an assumed 60% methane content. After it, methane is combusted in an engine to produce electricity. The delivering FL of the anaerobic digestion, i.e., digestate, is transferred to a composting plant for the production of biocompost. The potential production of methane for each food category is calculated using the procedure reported by Eriksson et al. [44], according to which the theoretical methane production is estimated as described in Equation (1):

$$Nm^3_{CH_{4,i}} = DS_i \cdot VS_i \cdot F_i \tag{1}$$

where $Nm^3_{CH_{4,i}}$ is the theoretical methane production of food category i; DS_i is the dry matter content; VS_i is the percentage of volatile solids in food category i expressed in dry matter terms; F_i is an specific production factor of methane expressed in $Nm^3_{CH_{4,i}}$ per ton of volatile solids. These values are sourced from Carlsson and Uldal [45].

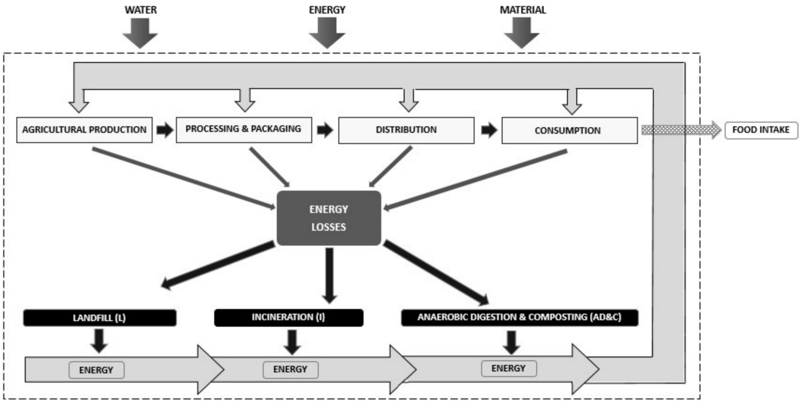

Figure 2. System boundaries, including the outline of the different considered scenarios.

2.6. Material and Energy Flow Analysis

A material flow analysis quantifies the mass/resources flow, loss in a system, and facilitates in data reconciliation in a well-defined space and time [46]. As seen in Equation (2), the material flow analysis consider the food losses occurring along the supply chain as follows:

$$FL_{i,j} = \frac{F_{i,1} \cdot \alpha_{i,j}}{\prod_{j=1}^{j} 1 - \alpha_{i,j}} \tag{2}$$

where $F_{i,j}$ is the food available for human consumption of category i leaving the supply chain sector j (j = 1 agricultural production, j = 2 processing and packaging, j = 3 distribution, j = 4 consumption). $\alpha_{i,j}$, is the percentage of food losses generated on each stage j for food category i. $F_{i,1}$ describes the daily intake of food category i for a 11,493 kJ per capita per day diet (Table 1). For this study, the material flow analysis made by Garcia-Herrero et al. [13], has been used as a reference. The energy flow analysis is developed through the combination of the material flow analysis and the calculated primary energy demand (PED) for each food category along the supply chain.

2.7. Energy Impact Assessment

In this work, it has been introduced as energy impact assessment the $EROI_{ce}$ index in order to quantify the amount of nutritional energy that is recovered from the FL of each category of food under study. The $EROI_{ce}$ index is based on a food waste-to-energy-to-food approach, assuming that the energy that is recovered from FL is reintroduced into the food supply chain in form of food (Figure 2). For its development, the proposed methodology (Figure 3) firstly develops an energy flow analysis through determining the PED of each of the four stages in which the food supply chain is divided (agricultural production, processing and packaging, distribution and consumption), as seen in Equation (3):

$$PED_{i,j} = W_{i,j} \cdot AP_{i,j} \tag{3}$$

where $W_{i,j}$ is the weighted average of energy intensity by mass of each category *i*, on each supply chain stage under study *j* (*j* = 1 agricultural production, *j* = 2 processing and packaging, *j* = 3 distribution, *j* = 4 consumption), in kJ/kg. $AP_{i,j}$ is the annual production of each category *i*, on each stage under study *j*, in kg.

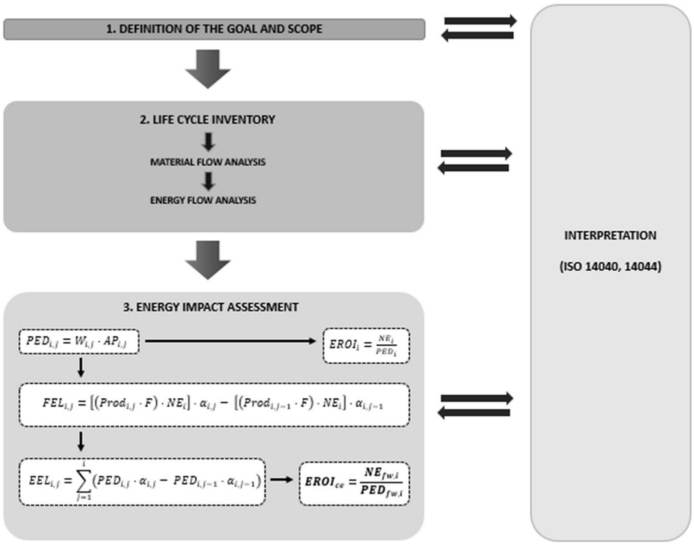

Figure 3. Methodology of the study.

Secondly, the EEL is computed, which means, the primary energy that was used to produce the food that is loss. EEL is calculated as stated in Equation (4):

$$EEL_{i,j} = \sum_{j=1}^{i} \left(PED_{i,j} \cdot \alpha_{i,j} - PED_{i,j-1} \cdot \alpha_{i,j-1} \right) \tag{4}$$

To calculate it, the sum of the $PED_{i,j}$ multiplied by their respective percentages of loss $\alpha_{i,j}$ is performed. From the second stage, these results are subtracted from the previous stage multiplied by their respective previous loss percentages $\alpha_{i,j-1}$.

Once these data have been obtained, the FEL of each food category *i* under study is calculated. Following the Food and Agriculture Organization concept for FL [28], FEL can be defined, as the amount of chemical energy contained in food and initially addressed to human consumption that, for any reason is not destined to its main purpose. It has been estimated according to Equation (5):

$$FEL_{i,j} = \left[\left[Prod_{i,j} \cdot F \right] \cdot NE_i \right] \cdot \alpha_{i,j} - \left[\left[Prod_{i,j-1} \cdot F \right] \cdot NE_i \right] \cdot \alpha_{i,j-1} \tag{5}$$

where $Prod_{i,j}$ is the production of each category of food, which is multiplied by F, which are the factors of allocation and conversion proposed by Gustavsson et al. [27] to represent the amount of food that is used for human consumption and that is considered edible. These values are firstly multiplied by the nutritional energy, and next by the percentages of losses considered in the literature $\alpha_{i,j}$. From the second stage, the previously lost amount is subtracted, multiplied by the conversion factor of the previous stage $\alpha_{i,j-1}$. Then, it has been calculated the EROI of each food category under study i, and each step j. EROI is the estimation of the quantity of energy delivered by a production technology relative to the quantity of energy invested [47]. Although it was initially devised to the assessment of energy systems, the concept has been adapted (Equation (6)) to quantify ratios of food energy output relative to food production energy inputs. This ratio can be estimated as follows:

$$EROI_i = \frac{NE_i}{PED_i} \tag{6}$$

where $NE_{i,}$ is the nutritional energy contained in each food category i, and PED_i is the primary energy demand for the production of each category i. Finally, the $EROI_{ce}$ is calculated. For it, the electricity recovered from the management of FL is transformed into its equivalent amount of primary energy, and assumed to be redirected to the production of food. As shown in Equation (7), this index consist in the division between the nutritional energy $NE_{fw,i}$, obtained from the transformation into nutritional energy of the primary energy that is recovered through each FL management strategy, and each FL fraction of a specific food category; between the primary energy demand $PED_{fw,i}$ that was used in the management of FL:

$$EROI_{ce} = \frac{NE_{fw,i}}{PED_{fw,i}} \tag{7}$$

3. Results

3.1. Energy Flow Analysis

Results from the energy flow analysis are shown in the Sankey diagram of Figure 4. The diagram represents the inputs and outputs of primary energy along the entire chain, using the reference unit (kJ/cap/day). By calculating the primary energy balance until the end of the chain (99,926 kJ) which is need to produce the 11,493 kJ/cap/day of nutritional energy provided to consumer on average by each Spanish citizen; it is suggest that in the Spanish food supply chain, 8.7 kJ of primary energy is needed to produce 1 kJ of nutritional energy. In the agricultural production stage, the allocated flow to FL is distinguished from the resulting flow assigned to non-food uses. The net domestic supply after considering agricultural production, imports, exports and stock variation is 24,476 kJ/cap/day. From this, 4970 kJ/cap/day (20%) are invested in producing animal feed, seed and other non-food uses such as oil and wheat for bio-energy. The other 19,506 kJ/cap/day of the primary energy (80%) are used for food for human consumption. In this diagram, it is highlighted the fact that the stages with a higher PED are distribution (which in addition to distribution places, also includes national and international import transportation, as well as consumer transport to go to the markets) and agricultural production, followed by the stage of processing and packaging. These results could reinforce the thesis that the more local, seasonal and unprocessed the consumption, the lower expenditure of energy in transport and distribution. It is, however, important to note that a lower energy expenditure in transport and distribution does not necessarily mean a lower total energy expenditure in food production. There are a number of other factors that should be analysed in future works in this field, as for example, the use of agrochemicals or tillage machinery.

When analysing the food categories studied, it is observed that the ones requiring the highest PED for their production are meat, vegetables, fish and seafood and cereals, respectively (Table 1). Of the four categories, meat is the one with the highest PED (28,002 kJ/cap/day), doubling the value of the other three, and representing alone the 28% of the PED for all categories. These results could reinforce the thesis of the need to reduce the consumption of meat due to the energy costs that its production requires, as stated by Popkin [48] and Laso et al. [43]. In addition, if the values for fish and seafood, eggs and dairy categories are added to meat, more than half of the total PED comes from the production of food of animal origin (56,901 kJ/cap/day). In contrast, some categories, especially sweets and roots, have very low values.

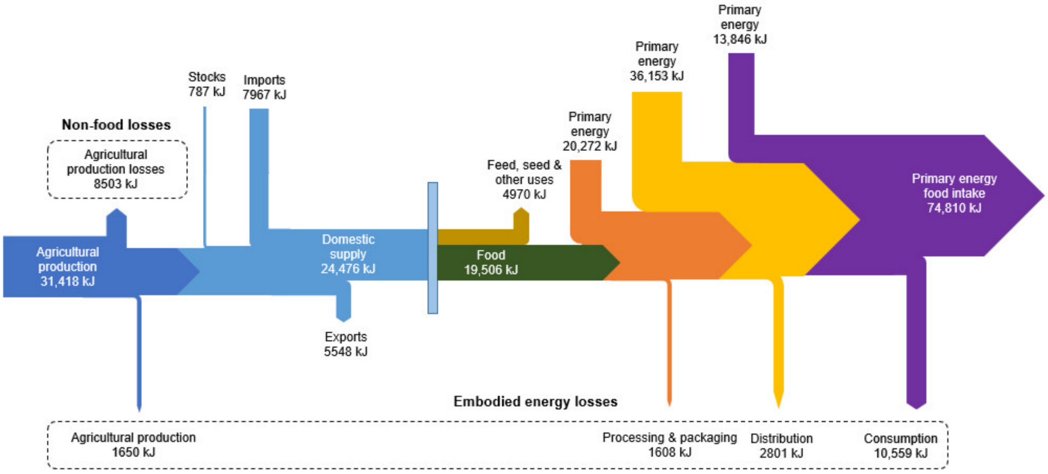

Figure 4. Sankey diagram for primary energy demand of the different food categories throughout the food supply chain. Values expressed in kilojoules per capita per day.

Regarding the values of EROI, sweets (61.3%) and vegetable oils (60.0%) are the food categories with the largest EROI, which indicates that these categories are the most efficient, although not necessarily the healthiest. It must be remarked that this work only assesses nutritional content in terms of energy; other nutritional features are not studied. They are followed by cereals and roots, with 27.5% and 18.8% EROI ratios, respectively. On the opposite side, fish and seafood, vegetables, meat and pulses have the lowest EROI, which indicates a very low energy efficiency in its production process. This agrees with results in the literature [3], which state that animal and animal derived food products consume large amounts of energy resources. Likewise, they reinforce the thesis of Popkin [48] and Laso et al. [43] on the environmental benefits of eating less meat and fish, since there is a huge potential for PED reduction.

3.2. Energy Food Losses Quantification

The energy flow analysis reveals that in terms of EEL, which means the primary energy invested in producing FL, meat, cereals, vegetables and fish and seafood are, respectively, the categories with the highest EEL values. Accordingly, they are the food categories most affected by the energetic inefficiencies in the food supply chain. Their EEL were estimated at 4027, 3259, 3143 and 2650 kJ/cap/day, respectively, which together accounts for almost 84% of the total Spanish EEL (Table 2).

In addition, once again, if the four categories of products of animal origin are added, it is highlighted the fact that around 50% of the total EEL is due to these products. In contrast, the categories with the lowest EEL values are sweets and vegetable oils, which represents values 20 times lower than the category with a higher value (meat). If the EEL is analysed in the different stages, it can be clearly perceived that the stage of consumption is the one in which the highest EEL is produced, representing more than 66% of the total in the whole food supply chain (Figure 5). The total sum of the EEL values obtained, were around 17% of the total PED in the entire food supply chain.

Table 2. Food energy loss and embodied energy loss.

Food Category	FEL (kJ/cap/day)	FEL (%)	EEL (kJ/cap/day)	EEL (%)
Eggs	113	2	521	3
Meat	553	11	4027	26
Fish and seafood	80	2	2650	17
Dairy	126	3	510	4
Cereals	2386	46	3259	21
Sweets	398	8	159	1
Pulses	96	2	421	3
Vegetable oils	687	13	233	2
Vegetables	176	3	3143	20
Fruits	381	7	661	4
Roots	155	3	331	2
Total	5151	100	15,915	100

In terms of the FEL, the categories of cereals, vegetable oils and meat, represent the highest values (Table 2). As this sequence coincides with the results of the energy provided to consumer (Table 1), these high values could be due to the high percentage of the European diet, which is based on cereals, vegetable oils and meat. On the other side, the categories with the lowest FEL are fish and seafood, pulses and eggs. This sequence agrees again with the results of the energy provided to consumer (Table 1), with the exception of eggs. Thus, the low values of FEL could be also related to the European diet, although other factors not analysed in this work could influence them. Regarding the different stages of the food supply chain, the results show that the stage of consumption is the one with the highest values (Figure 5). Moreover, agricultural production plus processing and packaging together would be the part of the food supply chain with the highest FEL. The distribution stage, despite being the one that requires the most PED, is at the same time the one that clearly generates less FEL (7.4%). When it comes to recover energy from FL, the qualitative and quantitative composition of FL is essential [13], and in this sense, from a quantitative point of view, these results suggest that the largest amount of FEL from which to recover energy occurs at the beginning and end of the food supply chain, being 1130 and 1290 kJ/cap/day the FEL in the stages of agricultural production and processing and packaging, and 2349 kJ/cap/day in the stage of consumption. The total results of the FEL highlighted that approximately 5154 kJ/cap/day are thrown away, which means that from a FEL point of view, for the consumption of two to three persons in Spain, one more person could eat.

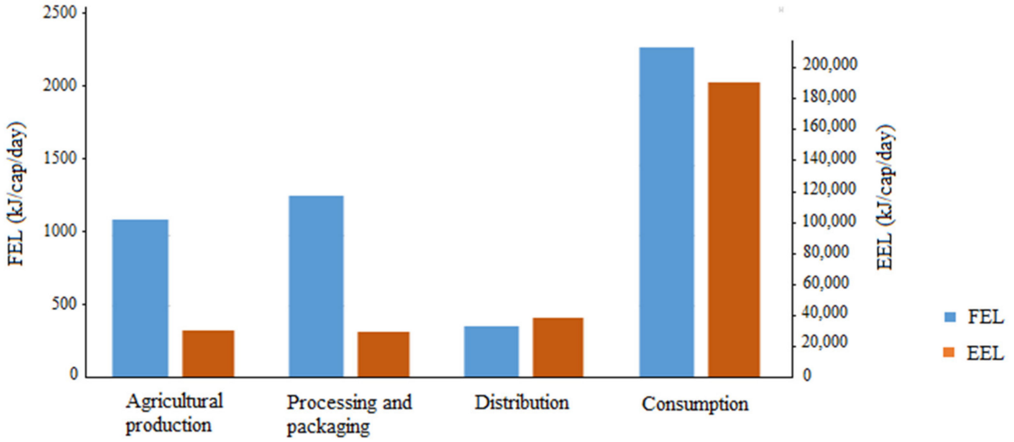

Figure 5. Food energy loss (FEL) and embodied energy loss (EEL) by stage of the food supply chain. Values expressed in kilojoules per capita per day (left and right ordinate axis).

3.3. Nutritional Assessment of the Energy Food Loss

The food categories under study have been classified according to four different diets: vegetarian, pescetarian, Mediterranean and omnivorous. A vegetarian diet includes cereals, roots and tubers, sweets, vegetable oils, vegetables, fruits, pulses, dairy and eggs. A pescetarian diet is a vegetarian diet that includes fish and seafood. A Mediterranean diet is similar to the pescetarian, but includes moderate amounts of meat. Omnivorous diets consider all food groups.

Figures 6 and 7 represent the values obtained from FEL (kJ/cap/day) and EEL (kJ/cap/day), respectively, for the different food categories (abscissa axis) and the different stages (different colors in each column), being the numerical values signified on the ordinate axis.

If the FEL values for each category and stage of the food supply chain are related, it is clear that the category of cereals is the most wasteful one. From a quantitative point of view, it suggests that cereals should be the main category for placing the focus when developing FL management strategies. Moreover, regarding the results, the change of the diet would not imply a significant change in terms of FEL, as can be seen in Figure 6:

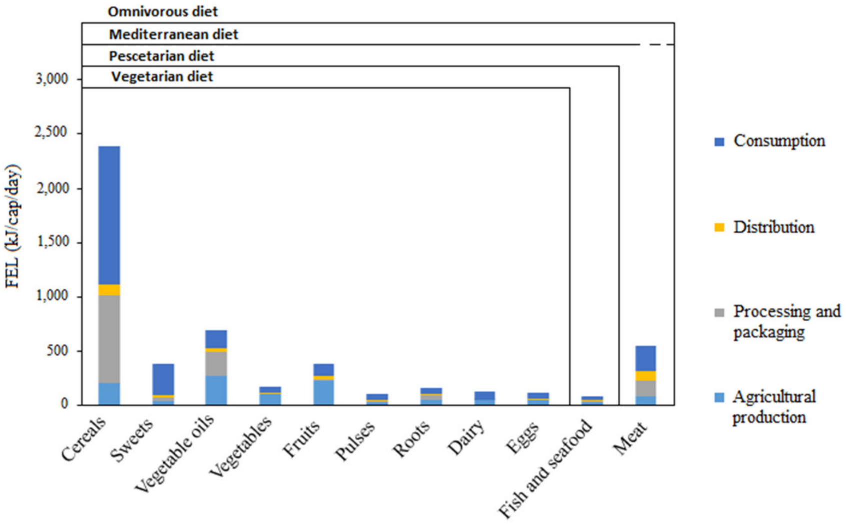

Figure 6. Food energy loss (FEL) of the different food categories throughout the supply chain. Values expressed in kilojoules per capita per day.

On the other hand, Figure 7 displays the EEL values for each category and stage of the food supply chain. From figure, it is observed that the type of diet does have a clear influence. The meat category presents the largest EEL values, followed closely by cereals, vegetables and fish and seafood, respectively. In terms of EEL, the vegetarian diet appears to be the one which the highest amount of primary energy saves, followed by the pescetarian diet. The consumption of meat in the Mediterranean and omnivorous diets supposes a significant increase of EEL.

Taking into account an overall results overview, it is suggested that due to the more mass losses of cereals, their value stands out against the others. However, in case of meat and fish and seafood, when analysing the energy used in its production, those categories have a very high PED to produce low levels of food.

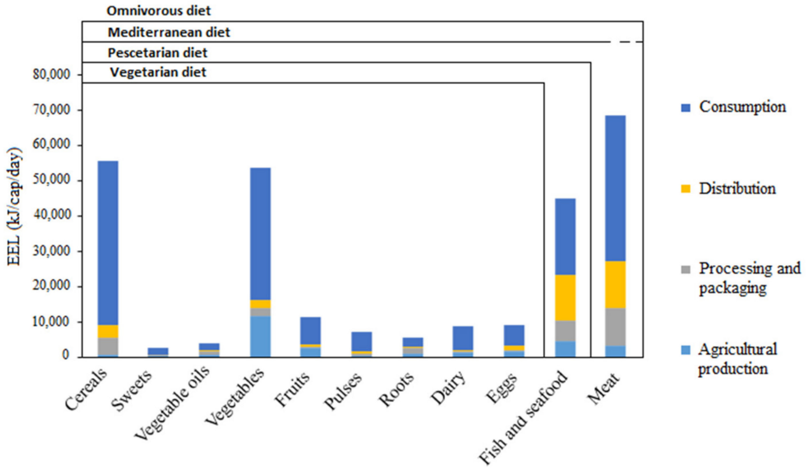

Figure 7. Embodied energy loss (EEL) of the different food categories throughout the supply chain. Values expressed in kilojoules per capita per day.

3.4. Energy Return on Investment–Circular Economy Index

Figure 8 shows a general trend for decreasing PED demand with higher priority levels in the food waste hierarchy. Negative values of $EROI_{ce}$ indicate that the energy recovered from the management of FL is larger than the energy requirements for its management. As shown, landfilling with biogas recovery (Scenario 1: L) do not recover enough energy to compensate the energy expenses of the treatment. Anaerobic digestions and composting (Scenario 3: AD&C) seems to be the best option for the food categories assessed. An exception is suggested for vegetables FL, for which a larger PED is observed for Scenario 2 (I), involving higher energy recovery from the incineration treatment. This may be due to the fact that the fermentation period is longer than the rest of the categories and therefore requires a higher energy consumption.

Afterwards, $EROI_{ce}$ scores have been assessed. Results from Figure 9 suggest that AD&C is the best FL management strategy. On the other hand, it is highlighted that cereals is the category with the highest potential for energy recovery, with values between 20 and 28 times higher than the rest of the categories, regardless of the scenario. This is undoubtedly influenced by the fact that it has the highest FEL value, representing 44% of the total. Finally, it is observed that vegetables appear again as the less energy efficient category, owing to the low energy recovered from its FL management, which could be due to a low carbon content. The numerical results can be consulted in Table S8.

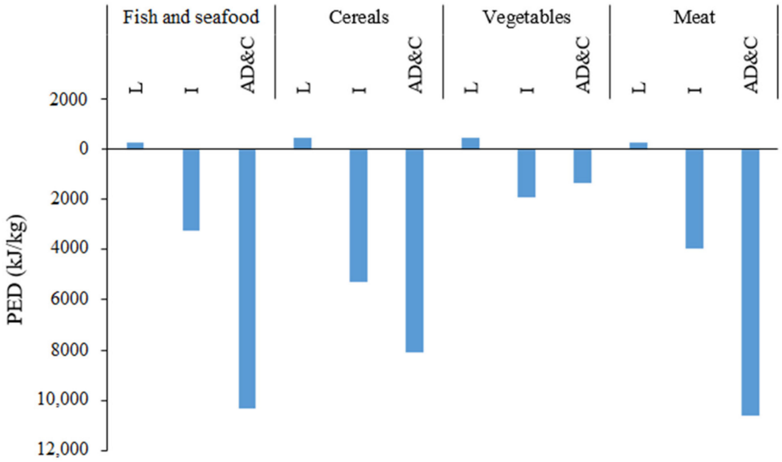

Figure 8. Primary energy demand values for the considered scenarios expressed in kilojoules per kilogram.

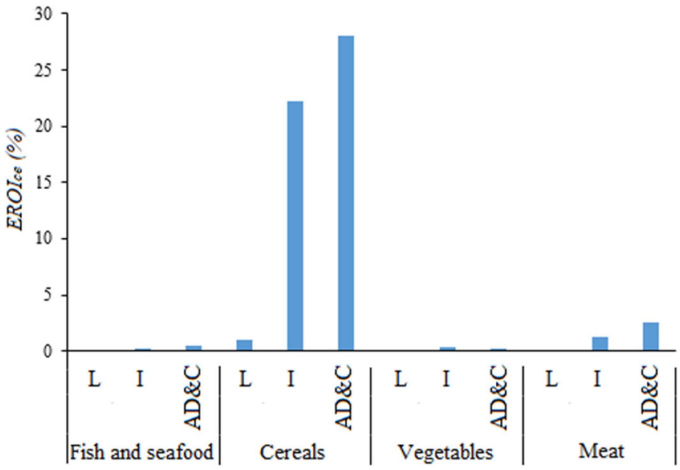

Figure 9. Energy return on investment–Circular economy index for the considered scenarios.

4. Discussion

The results of the energy flow analysis determined a total EEL value of 17% in relation to the total PED along the entire supply chain, showing the consumption stage as the most inefficient one. This is in accordance with Vittuari et al. [7], who assume that embodied energy builds up along the chain, so the latter the FL occurs, the greater the energy loss. The EEL results indicate that in the final part of the food supply chain, which means the sum of the distribution stage plus the consumption stage, the highest amount of EEL is concentrated. The FEL results point out that the stage of consumption is the one with the highest values. Moreover, if the FEL values for agricultural production and processing and packaging are added, it is suggested that the first part of the food supply chain accumulate the highest FEL. These results highlight the option of decentralise the energy recovery strategies, which could improve the efficiency in the FL management systems, by installing energy recovery plants at the beginning and at the end of the FSC.

Regarding the nutritional assessment in terms of EEL, vegetarian and pescetarian diets appear to be the most efficient ones. In this sense, several studies have supported similar thesis taking into account different approaches such as the greenhouse gas emissions [49] and the economic value of FL [13].

From FEL results, the high loss value generated by the cereals category (44%) is remarkable. After assessing the $EROI_{ce}$ scores, results also suggest that cereals is the category with higher potential for energy recovery. In addition, in three of the four categories analysed, results show a general trend for decreasing PED with higher priority levels in the food waste hierarchy [44], standing out the AD&C as the most appropriate for FL management. This reinforces the thesis that FL is an attractive substrate for AD&C because of its low total solids and high content of soluble organics, as stated by David et al. [50]. In this sense, the development of decentralised energy recovery strategies through AD&C could be proposed, as opposed to centralised strategies, which are large scale for the treatment of FL [51].

Following the previous context, new strategies for the different fractions of FL and its compositions could be introduced in order to meet the transition towards a more circular economy [52]. In this case, the cereal fraction stands out in terms of the amount of FEL and the amount of food that can be reintroduced into the food supply chain. In this sense, until now, AD&C has usually been focused on the recovery of biogas in form of methane mainly. In view of the high energy recovery potential of cereals and their high level of hydrocarbons in their chemical composition; it is proposed their separately management, based on the works of Kibbler et al. [53] and Bernstad and La Cour [54]. Due to its composition, it is considered that they have a high potential for the recovery of bioenergy in form of hydrogen. Therefore, this proposal of decentralisation would include the development of two types of AD&C digesters: one for the cereal fraction with hydrogen recovery, and another for the rest of FL, with methane recovery, as can be seen in Figure 10.

Decentralised AD&C plants of biogas production from organic waste and FL, could have clear advantages in concrete contexts like rural regions, and other local economies which are far away from power sources [55]. This has already been tested in many rural contexts around the world, existing good and diverse examples, as the works developed by Raha et al. [56] in India, and Kelebe and Olorunnisola [57] in Ethiopia. Another argument in favour of this decentralisation option is the fact that valorisation in form of biogas is, generally, more applicable when there is homogeneity of the waste [58], and homogeneous FL streams are most likely generated before being mixed with the rest of the FL [59]. In this sense, there are several technological challenges that require future research in order to deploy this technology for small and medium applications.

One of the main barrier for those strategies is the wide variation of feedstock and environmental conditions (e.g., temperature) over space and time, which are more difficult to control through small-decentralised digesters. Additionally, it is important to know that from an energetic point of view, small scale AD&C hardly can perform a strong separation between biodegradable and non-biodegradable fraction. If a stronger pre-treatment is demanded, local anaerobic digestion can become impracticable from both an energy and economic point of view [51].

On the other hand, the decentralised management option could also be applied to the consumption stage, as it is a very simple system [60]. It could be an especially interesting alternative in buildings where a large number of people are living, receiving a high and constant source of power to produce energy, for self-consumption in the first instance, and to sell to the electricity grid if consumption is less than production. As a practical example, a recent study in this field, carried out by Walker et al. [61], analysed systems of micro-scale anaerobic digesters in London, showing that this technology could provide a useful means of processing FL in urban areas.

The proposed change of strategies poses the debate of the 'sustainable de-growth' sustained by Amate [2] and Latouche [62], which emerged as a strategy that aims to generate new social values and new policies capable of satisfying human requirements whilst reducing the consumption of resources. It is also intended to support the European Union action plan for the transition to a more circular economy [63], and the Bioeconomy Strategy [64], contributing to meet the objectives of bioenergy and the sustainable use of renewable sources, through the replacement of fossil fuel by renewable raw materials and the replacement of chemical processes by biological ones.

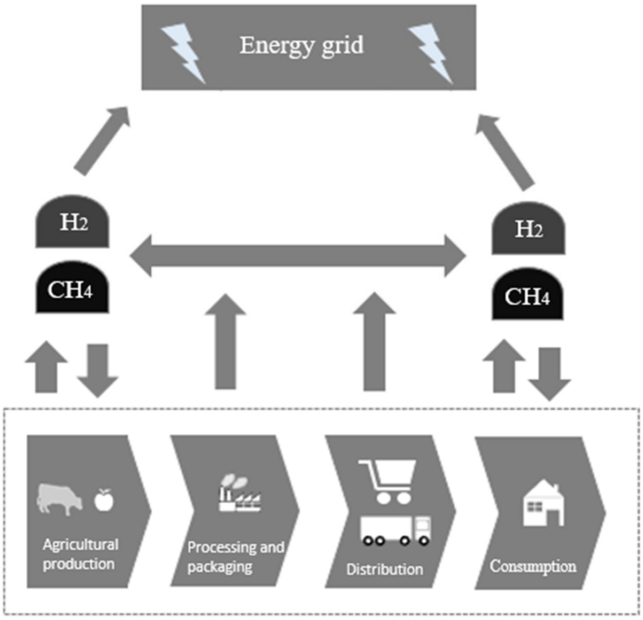

Figure 10. Outline of the proposed energy recovery strategies.

5. Conclusions

The energy flow analysis developed in this work suggest that to produce 1 kJ of nutritional energy, 8.7 kJ of primary energy is required, being the distribution and agricultural production stages the ones that require the most primary energy, respectively. From the 11 categories studied, the ones with the lowest EROI are fish and seafood, vegetables, meat and pulses. In terms of EEL, consumption is the stage with the highest values, representing more than 66% of the total in the whole food supply chain. The total sum of the obtained EEL results was 17% of the total PED. Meat, cereals, vegetables and fish and seafood have the highest values, which together accounts for almost 84% of the total Spanish EEL. If the four categories of products of animal origin are added, it is highlighted the fact that around 50% of the total EEL is due to these products. In terms of FEL, cereals, vegetable oils, meat and sweets, represent the highest values. The stage of consumption is clearly the one with the highest FEL value, although the beginning of the food supply chain would represent a higher FEL if agricultural production and processing and packaging values are added. The distribution stage, despite being the one that requires the most PED, is at the same time the one that clearly generates less FEL (7.4%).

The study suggests that the efficiency of energy of the agri-food supply depends heavily on the food category under study. Meat and fish and seafood have a very high PED to produce less food. Also, according to the $EROI_{ce}$ it is highlighted that cereals is the category with the highest potential for energy recovery from FL, with values between 20 and 28 times higher than the rest of the categories.

Related to the results, it is suggested that energy recovered from FL can contribute considerably to the national energy grid, as well as to energy self-consumption throughout the food supply chain. This could contribute to reduce the environmental costs, the demand of other types of non-clean energies such as coal- and nuclear- energy, and to produce new food from the recovered energy.

Although up to now the collection of FL is usually done in a centralised way, the use of AD&C for decentralised biogas production is, according to this work, one of the most potential technologies of bioenergy generation. It offers a good option of local FL management, which reduces the environmental impact due to transport, and encourages self-consumption, as well as benefiting the economy of local actors. Moreover, the recovery of energy in form of biogas can occur through the generation of different products. In this sense, a proposal of possible treatment strategies for residues of cereals with hydrogen recovery and mixed FL with methane recovery, is made. It is considered that the diversification and decentralisation in FL energy recovery strategies could facilitate the transition to a more circular economy. The efficiency of the proposed strategies could be further improved by intensifying research and optimisation studies. Thus, basic research is critical in order to advance the development of those technologies.

Results from the study allows to facilitate the decision-making process for the proper FL management, developing a general awareness on the need of energy-smart strategies or policies, which are decentralised and adapted to each stage of the food supply chain and the different fractions of food. This claim is in contrast to the waste hierarchy of the European Union, which is considered as a too generic proposal. Specifically, this work aims to highlight the need to address a decentralised and diverse FL management, in order to manage more efficiently the different fractions, and at each of the different stages of the food supply chain. Future works should: (i) simulate different scenarios of decentralised management, (ii) put into practice the cases of pilot studies already carried out, and (iii) optimize systems on a larger scale through the intervention of small-scale systems throughout the food supply chain, for which it is fundamental to establish regional strategies that support the already established global ones. Thus, the general objective of this research field is to follow strategies that act locally to achieve global development.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/12/4/767/s1, Figure S1: Outline of the assumed division in stages of the food supply chain, Table S1: Food commodities included in the study, based on Garcia-Herrero et al., Table S2: Mass-to-energy conversion factors and life cycle inventory sources, 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., 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, Table S5: Proteins, carbohydrates and energetic content for the food categories under study. Table S6: Allocation and conversion factors used for calculating the edible part of food production which is used for human consumption, 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. and Gustavsson et al. for Europe region, 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.

Author Contributions: Conceptualisation: R.A.; Investigation: D.H., I.G.H., and J.L.; Methodology and formal and technical analysis: P.F.P., A.B., A.I., and R.A.; Supervision: R.A. and M.M.; Writing and editing of manuscript: D.H., I.G.H. and J.L.

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Abbreviations

AD&C	Anaerobic Digestion and Composting
EEL	Embodied Energy Loss
EROI	Energy Return On Investment
EROIce	Energy Return On Investment—Circular Economy Index
FEL	Food Energy Loss
FL	Food Loss
I	Incineration with energy recovery
L	Landfill with biogas recovery
PED	Primary Energy Demand

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