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Towards a Sustainable Agri-Food System by an Energetic and Environmental Efficiency Assessment

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Feeding the world's population sustainably is a major challenge of our society and has been stated as one of the key priorities for development cooperation by the EU policy framework on food security. However, the current pattern of natural resources exploitation to meet humanity's demand for food threatens long-term food security. Food systems represent around 30 % of final energy use, generating up to 30 % of greenhouse gas (GHG) emissions. Given the expected increase of global population (9 billion people by 2050) and the amount of food losses and waste generated (a third of global food production), improving the efficiency of food systems along the supply chain is essential to ensure food security. This work combines life cycle assessment (LCA) and data envelopment analysis (DEA) to assess the efficiency of Spanish agri-food system and propose improvement actions in order to reduce energy usage and GHG emissions. Results suggest that sweets and vegetable fats categories provide the largest nutritional energy to consumer per unit of embedded energy in its production. Around a 70 % average reduction target is estimated for the Spanish agri-food system to be efficient, with a similar reduction in related greenhouse gas emissions.

1. Introduction

Food industry is the major manufacturing sector, representing 15 % of the sales in the European Union and more than 1,200,000 million euros. However, despite food industry contributes significantly to a nation's economy, it is also responsible for a large consumption of natural resources and significant emissions to air, water and land. A considerable use of energy can be attributed to agri-food systems, estimated at 30 % of final energy consumption (Pimentel, 2008). Given the strong dependency on fossil fuels of our current energetic system, such energy consumption is responsible for 20 – 30 % of total anthropogenic greenhouse gases (GHG). Energy is required at every stage in food production including cultivation and harvesting of crops, animal husbandry, transportation and distribution and food processing for consumption. This causes a low efficiency for food systems, around 10 kcal of fossil fuel energy to produce 1 kcal of food (Pimentel, 2008). Some foods are very efficient in their use of resources to produce a nutritious meal, such as fruits and vegetables, while others are very inefficient, such as animal based products. In general, animal foods require 8 times more energy than plant based commodities (Pelletier et al., 2011). In particular, livestock production shares around 18 % of GHG, equivalent to industry and larger than the transport sector (Vittuari et al., 2016). The inefficiency problem is wider when food losses and waste are taken into account. Around a third of all food produced for human consumption is lost or wasted, c.a. 88 million tonnes of food in Europe. Since the embodied amount of energy builds up along the chain, the latter the waste occurs, the higher the energy waste and the related GHG. On the other hand, there is an expected trend of global population increase, for which a 60 % rise in food production is

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forecasted for the year 2050, entailing a 50 % rise in global energy consumption (Vora et al., 2017). Therefore, improving the food supply chain (FSC) efficiency has been identified as an essential means to ensure food security, while reducing pressure on natural resources.

2. Methodology

The methodology described in this work attempts to assess the energetic and environmental efficiency of Spanish agri-food system using a life cycle approach. First, a life cycle assessment (LCA) is conducted to estimate the primary energy demand (PED) and related global warming potential (GWP). Second, the energy return on investment (EROI) is estimated to describe the energy efficiency of food categories under study. Finally, data envelopment analysis (DEA) is synergistically combined to LCA results to explore the operational inefficiencies and the improvement actions.

2.1 Life cycle assessment (LCA)

LCA is a tool to assess the potential environmental impacts and resources used throughout a product´s life-cycle (Margallo et al., 2016). In this regard, LCA has become one of the most relevant methodologies to help organizations to perform their activities in the most environmental friendly way along the whole value chain.
In this work, LCA is conducted following the recommendations of ISO 14040 and ISO 14044 international standards (ISO, 2006a; ISO, 2006b). The study is performed from cradle to consumer considering the phases of agricultural production, processing & packaging, wholesale & retail and consumption (Figure 1). The functional unit is described as the food basket with the representative food products consumed by a Spanish citizen in a year, covering the daily energy requirement of 2,000 kcal of an adult.
Daily average consumption data for 48 representative commodities were sourced from the consumption database of the Spanish Department of Agriculture and Fishery, Food and Environment (MAPAMA, 2017) for the 2006-2016 period. Items were grouped into 11 food categories (eggs, meat, fish & seafood, dairy, cereals, sweets, pulses, vegetable oils, vegetables, fruits and roots). Food losses and wastes (FLW), referring to a decrease in food quantity along the food supply chain (FSC) were taken into account using the weight percentages of Gustavsson et al. (2013). An extensive life cycle inventory (LCI) was built up using data from the literature and GaBi software. Imported food products were taken into account based on trade statistics compiled by the Spanish Tax Agency (Datacomex, 2018). For transportation, 400 km and 100 km distances to wholesale and retailers were assumed. Electricity consumption for retail storage was considered, assuming 2 days storage for products requiring cooling conditions, and 15 days under freezing conditions. Transport to home was estimated based on Milà i Fontanals et al. (2007). Regarding home storage, data from the LCA Food Database was used (Nielsen et al., 2003). For cooking, energy factors of Foster et al. (2006) were taken. The impact assessment method selected follows the ILCD/PEF recommendations v1.09 for determining the global warming potential (GWP). The consumption of Primary energy resources (net calorific value, PED) is determined according to PE International (2014) life cycle inventory. Once the PED and GWP embodied along the agri-food supply chain are determined, the embodied energy and CO_2 in FLW and can be determined using FLW rates from Gustvasson et al. (2013) as indicated in Figure 1.

2.2 Energy return on investment (EROI)

EROI is the estimation of the quantity of energy delivered by a production technology relative to the quantity of energy invested (Pelletier, 2010). Although this concept was initially devised to the assessment of energy systems, the concept has been adapted to quantify ratios of food energy output relative to industrial energy inputs. Pelletier et al. (2011) propose the application of three distinct EROI measures for studying energy efficiency in food systems, although the most widely used is human-edible food energy return on industrially energy investment, as indicated in Eq. (1). This provides an anthropocentric perspective on the nonrenewable resource efficiencies of competing food production technologies. Nutritional data for the EROI estimation were obtained from the food composition tables of the Institute for Education in Nutrition and Dietetics from Spain (Farran et al., 2003). Such tables are registered in the FAO’s International Network of Food Data Systems (FAO-INFOODS, 2018).

$$EROI = \frac{Nutritional\ energy\ provided\ to\ consumer}{Primary\ energy\ invested} \tag{1}$$

2.3 Data envelopment analysis (DEA)

DEA is a nonparametric tool that quantifies empirically the relative efficiency of multiple similar entities named decision making units (DMUs) (Cooper et al. 2007). This linear programming method uses input and output data from the different DMUs to formulate an optimization model, whose solution identifies the inefficient DMUs and the target performance improvement values. Although DEA has been individually used for environmental and eco-efficiency assessments, it can be synergistically nourished from life cycle inventory (LCI) data in order to more effectively detect and remedy the technical inefficiencies that are sources of unnecessary environmental impact (Vazquez-Rowe et al., 2010). The approach calculates the efficient frontiers for the DMUs under study: the result for each DMU is an efficiency score and, for those DMU identified as inefficient, a target operating point. The number of DMUs under study must satisfy the following equation:

$$n \geq max\,\{m \cdot s, 3 \cdot (m + s)\} \tag{2}$$

where *m* is the number of inputs used in the DEA study and s is the number of outputs involved.
In this work, the primary energy invested in food production and the global warming potential were considered as inputs for the DMUs, while the nutritional energy supply was taken as outputs. Since there are 11 food categories under study and each category corresponds to one DMU, the rule is satisfied. The DEA optimization mode seeks to minimize inputs to produce the same output.

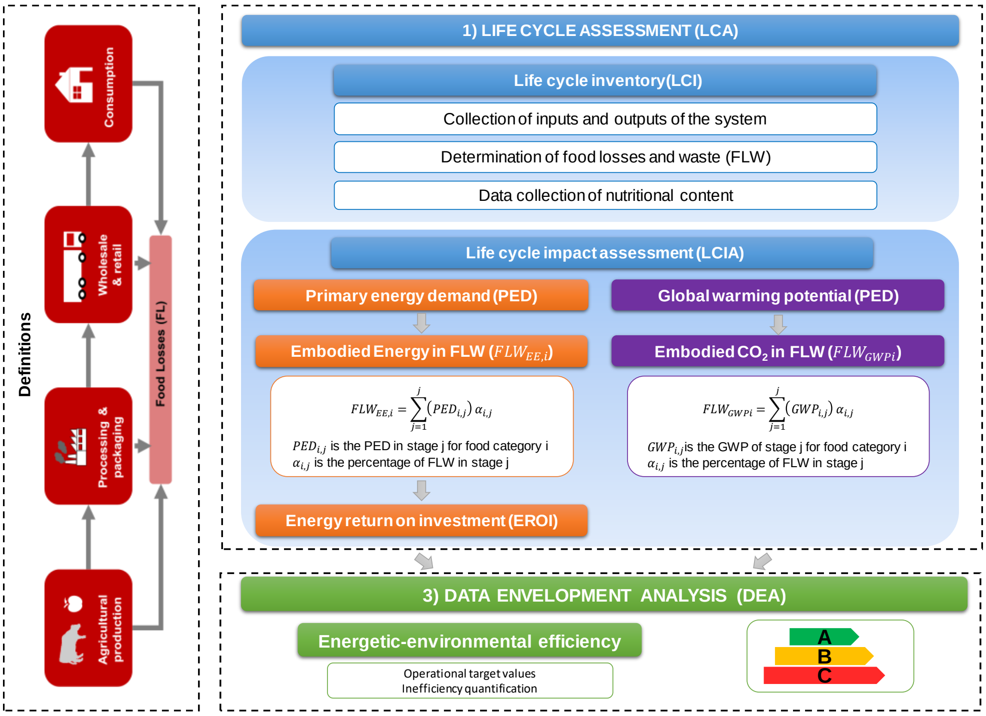

Figure 1: System boundaries of this work

3. Results

As shown in Table 1, the total energy invested in food production amounts daily to 19500 kcal for an average Spanish citizen. This involves close to 4 kg of CO2 per day, being meat production the main responsible of such emissions (42 %). Dairy and fish & seafood are the second main categories contributing to GWP, each sharing a 12 % of the total emissions. Results suggest a high correlation between the investment of energy along the FSC and the generation of greenhouse gas emissions, owing to the high dependency of the energetic model on fossil fuels. Conversely, this is not directly related to the nutritional energy provided to consumer. As displayed in Table 1, the major contributors to Spanish average diet are vegetable oils and cereals, being responsible of nearly half of the energy supply. In fact, the contribution of meat to nutritional energy supply is relegated to less than 12 %.
When considering FLW, it is observed that embodied energy waste duplicates the daily energy supplied to consumer. The largest contributor to this fact is cereal category, accounting for 38%. This is directly related to the unnecessary emission of CO2-eq., which also contributes 38% to the total GWP. It is followed by pulses and fish & seafood categories, for which a 27 % embodied energy waste is estimated. The second largest embodied CO2 waste is observed in pulses and fruits categories, estimated at 32 %.

Table 1: Energy invested from cradle to plate for the food categories under study and related CO2 emissions. Nutritional energy provided to consumer is also displayed.

	PED (kcal/cap/d)	Energy provided to consumer (kcal)	GWP (g CO_2/ cap/d)	Embodied energy in FLW (kcal/cap/d)	Embodied GWP in FLW (g/cap/d)
Eggs	1059	41	221	163	35
Meat	5465	216	1673	1162	378
Fish & seafood	3170	99	468	852	128
Dairy	1411	289	496	137	55
Cereals	2717	456	372	1042	143
Sweets	156	103	28	35	8
Pulses	490	58	85	142	27
Vegetable Oils	717	461	158	150	39
Vegetables	3297	72	261	745	70
Fruits	690	159	159	171	52
Roots	330	53	51	88	16
Total	19501	2000	3971	4685	951

These findings suggest the need of estimating the efficiency of the Spanish agri-food system. As a first approach, the EROI indicator is used to estimate the energetic efficiency. As displayed in Table 2, the maximum EROI is observed for sweets and vegetable oils, which means that such food categories are the most efficient under the energetic point of view. These results also suggest the need of studying more in-depth nutrients to encourage and to limit in order to provide a nutritional efficiency perspective. Results also show that animal based products such as eggs, meat and fish present the lowest EROI (3.1 - 4.0 %), which agree with the study of Pelletier et al. (2011), where a 8 times higher energy is reported for the production of animal products in comparison to plant based products. An exception is observed in our results for vegetables. This is mainly due to the inclusion of processed commodities in this category, in particular tomato sauce product, which exhibits a 1.2 % value for EROI.

Table 2: Energy return on investment (EROI).

Eggs	Meat	Fish & seafood	Dairy	Cereals	Sweets	Pulses	Vegetable Oils	Vegetables	Fruits	Roots
3.90	3.96	3.14	20.52	16.79	66.00	11.75	64.27	2.18	23.05	16.10

However, these efficiency results do not consider the environmental impacts of food production along the supply chain. For this reason, DEA has been combined to LCA results, so that a wider scope of the efficiency of the Spanish agri-food system can be provided.

Results provided by the DEA model for efficient and inefficient food categories are gathered in Figure 2. A food category is deemed inefficient when efficiency score is lower than the unity, whereas relative efficiency equal to the unity represents an efficient category. According to this, sweets are the sole efficient category, while a 97 % efficiency is observed for vegetable oils. The less efficient DMU results again vegetables category, which is mainly due to the consideration of tomato sauce, as above described. Results suggest that the planification of citizen’s diet could affect to the quantity of embodied energy waste and related environmental impacts. For this reason, specific strategies should be addressed to the categories revealing larger inefficiency scores, such as meat, eggs, fish and vegetables, which agree to have better nutritional reputation than sweets or processed cereals.

The previous findings agree with the pattern observed for EROI assessment, just based on energetic analysis. While this can be taken as a verification of both approaches, DEA also provides a further exploration of the operational inefficiencies and the improvement actions of the system under study. Hence, the DEA model was also used to formulate new virtual and efficient values for the inputs of the inefficient DMUs, by projecting the inefficient scores on the efficient targets established by the previously assessed as efficient food categories. Both primary energy demand and global warming potential were subjected to minimisation while maintaining the same nutritional supply.

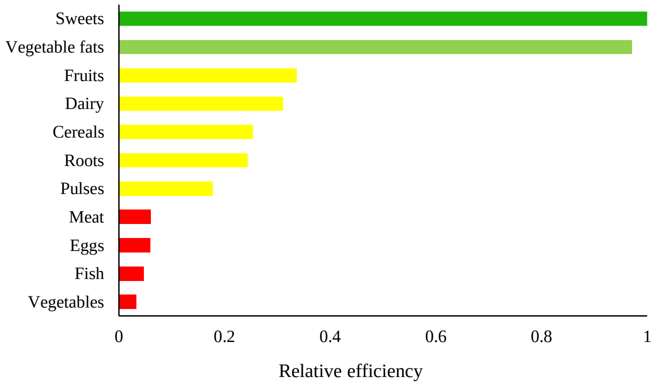

Figure 2: Relative efficiency of the different food categories under study.

As suggested by Figure 3a, significant reduction targets are needed for primary energy demand of inefficient food categories, ranging from 96.7 to 2.8 %. This would reduce significant the environmental impact of such categories, ranging from 96.4 % for meat to 19 % of vegetable fats (Figure 3b). Note that no improvement values are suggested for sweets category, since it was designated as efficient DMU. In general, the methodological approach suggests an average reduction target of 68 % for the primary energy demand, involving a similar reduction in CO2-eq emissions. As previously suggested, reducing FLW has been identified as an essential means of increasing efficiency along the supply chain, while reducing pressure on natural resources and related environmental impacts. Currently the waste hierarchy, introduced by the Waste Framework Directive, has been the rule followed to prioritize food waste prevention and management measures and to set reduction targets according to the environmental criteria (Cristobal et al., 2018). The study of the correlation between food waste generation and related embodied resources and environmental impacts enables the proposal of integrated reduction targets. The competitiveness of the food sector can be improved in the various parts of the production chain according to the circular economy concept. Currently, the environmental and sustainability vision of this sector sets about ensuring more sustainable sourcing, resource efficiency, and sustainable consumption and production towards the year 2030. A food eco-innovation strategic policy is necessary to support green innovation whilst also improving the competitiveness, specifically for Small and Medium Enterprises (EASME).

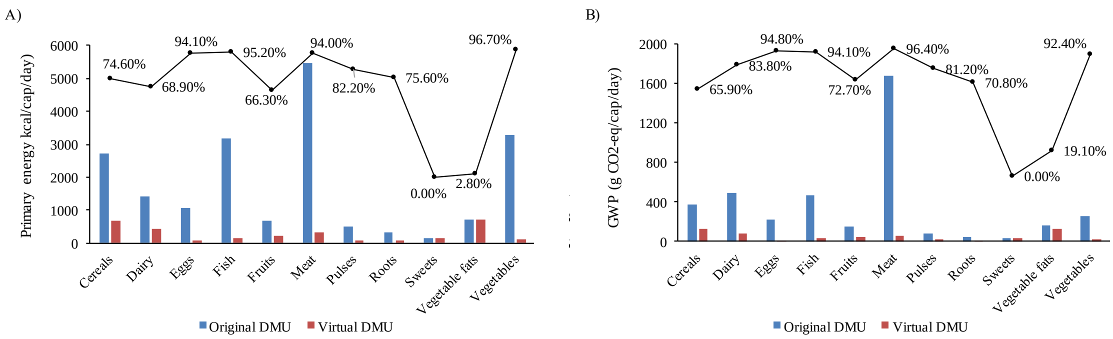

Figure 3: a) Reduction targets for primary energy demand; b) Reduction targets for global warming potential.

4. Conclusions

Food systems are heavily reliant on energy resources, especially non-renewable resources. This causes significant amounts of greenhouse gas emissions. In this study, the efficiency of the Spanish agri-food systems is addressed from an energetic and environmental point of view. First, energy return on investment (EROI) is used to perform an energetic efficiency assessment. Then, data envelopment analysis (DEA) is conducted to include the environmental issue in the efficiency assessment. Both approaches provide similar results, suggesting the high correlation between primary energy demand and CO2 emissions. Best results are obtained for sweets and vegetable oils categories, while vegetables, fish, eggs and meat exhibit the lowest efficiency. As expected, animal based products required more energy resources in their production. The unexpected results for vegetables categories are due to the inclusion of processed products in this category. Around a 70 % average reduction target is estimated for the Spanish agri-food system to be efficient, with a similar reduction in related greenhouse gas emissions. These results suggest the need of improving the efficiency of the supply chain by introducing strategies of circular economy, such as stablishing appropriate food waste management measures and the consequent reduction of food losses and waste. The introduction of nutritional and energetic criteria besides the environmental one, provides an integrated framework to propose integrated reduction targets.

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