Centralised electricity production from winter cereals biomass grown under central-northern Spain conditions: Global warming and energy yield assessments

Sastre C. M.[1]*, Maletta E.[2], González-Arechavala Y.[1], Ciria P.[2], Santos A. M.[1], del Val A.[2], Pérez P.[2], and Carrasco J.[2]

(1) Institute for Research in Technology - ICAI School of Engineering - Comillas Pontifical University. Alberto Aguilera 23, 28015 Madrid (Spain) Phone: +34 915422800, Fax: +34 915423176

(2) Research Centre for Energy, Environment and Technology, (CEDER-CIEMAT). Autovía de Navarra A15, S56 - 42290 Lubia, Soria (Spain), Phone:+34 975281013, Fax: +34 975281051

*Corresponding author: carlos.martin@iit.upcomillas.es

Abstract

The goal of this paper is to assess the sustainability of electricity production from winter cereals grown in one of the most important Spanish agricultural areas, Castilla y León Region, situated in central-northern Spain. This study analyses greenhouse gases (GHG) emissions and energy balances of electricity production in a 25 MWe power plant that was powered using straw biomass from three annual winter cereals (rye, triticale and oat) grown as dedicated energy crops. The results of these analyses were compared with those of electricity produced from natural gas in Spanish power plants. Assessments were performed using a wide range of scenarios, mainly based on the biomass yield variability obtained in demonstration plots of twelve different winter cereal genotypes. Demonstration plots were established in two different locations (provinces of Soria and León) of the Castilla y León Region during two crop seasons (2009/2010 and 2010/2011) using common management practices and input rates for rain-fed agriculture in these regions. Our results suggest that production of electricity from winter cereals biomass combustion yielded considerable reductions in terms of GHG emissions when compared to electricity from natural gas. Nevertheless, the results show that low biomass yields that are relatively frequent for Spanish farmers on low productivity lands may produce no significant reductions in GHG in comparison with electricity from natural gas. Consequently, the agronomic management of winter cereals should be re-examined in order to find potential improvements that achieve better energy balances and greater reductions in GHG emissions on land which is relatively uncompetitive in terms of crop yields and on existing low productivity scenarios.

Keywords: biomass; electricity; greenhouse gases; global warming potential; energy balance; winter cereals; annual crops; life cycle assessment.

1. Introduction

Climate change coupled with declining oil and gas reserves has led to the development of new energy sources to minimize greenhouse gases (GHG) emissions and expand energy supplies from solar, wind, hydraulic, geothermal and bioenergy sources [1]. The European Union (EU) Member States have committed themselves to increasing the share of renewable energy in the EU's energy mix to 20% and reducing GHG emissions by 20% by 2020 [2]. Furthermore, with the goal of keeping climate change below 2ºC, in February 2011 the European Council reaffirmed the EU objective of achieving by 2050 a reduction in GHG emissions of 80-95% with respect to the 1990 figures [3].

Solid and liquid biofuels are renewable energy sources that reduce GHG emissions [1,4-9], and may contribute to guarantee fuel security and play an important role in the accomplishment of those EU objectives. According to a study published by the European Environment Agency in the EU 27 [10], about 19 Mha of agricultural land could be available for introduction of energy crops for biofuels production under sustainable conditions, with a primary biomass potential of 295 Mtoe by 2030. Therefore energy crops would become the most important endogenous source for biofuels production. Lignocellulosic energy crops for heat and electricity production may perform better in GHG assessments when compared with crops used as feedstock for first generation liquid biofuels [11-14]. Algae liquid biofuels may also have good GHG assessments [15] due to high production yields [16,17], but they are not yet economically attractive [15].

In Spain, traditional extensive cereal area for food production has decreased by about 1.5 million hectares after 1991. Low profitability of winter cereals at the farm level in Spain is chiefly due to low crop productivity with a national average grain yield of 2.2 ton/ha [18]. This could be particularly relevant for large extensions of arable lands in continental Mediterranean countries like Spain, with relatively low rain-fed cereal competitiveness compared to other food suppliers like France, Germany or eastern European countries. Both current international market contexts and European Common Agricultural Policy (CAP) reforms have led to total dependency of famers on EU subsidies to guarantee minimum profits [19]. Past studies have suggested that Spanish agri-food system is inefficient and generates high environmental impacts [20,21].

In the described framework, winter cereals lands previously devoted to food production could be used to grow bioenergy crops lands and produce lignocellulosic biomass for electricity generation; that would help reducing current national energy dependence and accomplishing EU objectives of GHG reduction and increased share of renewable energies. Large scale experiences with triticale as feedstock for Spanish biomass power plants have already been reported in several projects [22] with good results. Nevertheless, environmental impacts of this alternative and, in particular, GHG emissions reduction, should be evaluated, as recommended by the European Commission as regards solid biomass production for electricity generation, heating and cooling [23].

Therefore, the aim of this study is to evaluate the energy balances and net reductions in GHG emissions that can be obtained in the production of electricity from the biomass of annual cereal crops in central-northern Spain, one of the most extensive agricultural areas in the country, and compare them with those obtained in Spanish power plants based on natural gas. Barriers and trends to improve the sustainability of this source of energy are also discussed. The environmental management technique selected to evaluate GHG savings and energy balances was Life Cycle Assessment (LCA).

2. Experimental plots design, biomass productivity and characterization.

In order to obtain experimental data for LCAs inventories (see **3**), winter cereals biomass was produced in demonstration plots utilizing traditional farming management techniques in two different locations of the cereal extensive production region in central-northern Spain (Region of Castilla y León). The plots were situated in the provinces of Soria and León.

Several varieties of Oat (*Avena sativa* L.), lopsided oat (*Avena strigosa* Schreb.), triticale (*X Triticosecale* Wittmack), and conventional and hybrid rye (*Secale cereale* L.) were selected for study due to their expected high biomass productivity, rusticity, as well as wide distribution, machinery availability and well known management practices in the region. The trials were carried out on large grass strips (0.2-0.4 ha/strip) in real farmers' plots. In order to establish the crops, commercial machinery was used to carry out typical farmers' management techniques. More detailed information about the experimental design, location and pedo-climatic conditions in the plot sites is shown in **Table 1.** Plots were established and monitored in agricultural years 2009-2010 and 2010-2011. Oat and lopsided oat plots were only established in 2009-2010 at the site of León (see also **Table 2**). In general, only one plot per tested specie, variety and location was implemented, but for some best suited varieties, according to indications of farmers, two plots were established.

Conventional and hybrid rye were grown separately due to the different sowing doses needed for the establishment; henceforth no other distinction was be made between conventional and hybrid rye types.

Table 1

Experimental plots design

	León		Soria	
1. Locations	León		Soria	
Coordinates	42º 24´N 5º31’W		41º 29´N 2º23´W	
Altitude	763 m		1079 m	
2. Soil type	Distric cambisol		Calcaric cambisol	
Texture	Sandy clay loam		Sandy loam	
Organic matter	1.82 %		0.90 %	
4. Plot type and size	Strips of 0.3-0.4 ha per variety		Strips of 0.2-0.3 ha per variety	
3. Experimental periods	2009-2010	2010-2011	2009-2010	2010-2011
4. Climate	Continental mediterranean	Continental mediterranean	Continental mediterranean	Continental mediterranean
Average temperature	8.7ºC	11.0ºC	9.0ºC	9.9ºC
Total rainfall	517 mm	482 mm	482 mm	386 mm
5.Winter Cereals (cultivar)	Oat (Aintre, Prevision) Lopsided Oat (Saia) Rye (Petkus) Hybrid rye (Gutino, Placido) Triticale (Amarillo, Sencozac, Trujillo)	Triticale (Trujillo)	Rye (Petkus) Hybrid rye (Askari) Triticale (Bienvenue, Colegial, Trimour, Trujillo)	Rye (Petkus) Hybrid rye (Askari) Triticale (Bienvenue, Colegial, Trimour, Trujillo)
6. Crop Management				
Seeding dose (kg ha^{-1})	Oat (130) Lopsided oat (90) Rye (165) Hybrid rye (60) Triticale (185)	Triticale (240)	Rye (120) Hybrid rye (60) Triticale (250)	Rye (120) Hybrid rye (60) Triticale (250)
Fertilization (kg ha^{-1})	NPK 8-15-15 (400) Calcium ammonium nitrate 27 % N (300)	NPK 8-15-15 (500) Calcium ammonium nitrate 27 % N (200)	NPK 8-24-8 (300) Calcium ammonium nitrate 27 % N (270)	NPK 8-24-8 (300) Calcium ammonium nitrate 27 % N (270)
Herbicides (Kg ha^{-1})	Clortoluron (0.720) Diflufenican (0.045)	Clortoluron (0.720) Diflufenican (0.045)	2,4-D (0,25) Tribenuron-methyl (0.016)	2,4-D (0,25) Tribenuron-methyl (0.016)

In order to assess the environmental and energy-generation performance of winter cereals’ biomass as solid fuel for electricity, the productivity and characterization (calorific value, ash content) of each separated genotype was measured in the experimental plots.

Table 2 shows the locations, species and varieties established, the period of development and the biomass production achieved in the study plots.

Table 2

Winter cereals biomass productivity

Place	Species	Genotype	Aerial Biomass Yield [odt/ha]	
			2009-2010	2010-2011
León	Oat	Aintre	3.06	
		Prevision	4.45	
	Lopsided Oat	Saia	5.66, 6.28[a]	
	Rye	Gutino	5.37	
		Petkus	7.42	
		Placido	6.59	
	Triticale	Amarillo	7.55, 7.84[a]	
		Seconzac	7.17, 7.57[a]	
		Trujillo	6.20, 6.63[a]	4.60
Soria	Rye	Askari	11.32	8.53
		Petkus	10.22	7.74
	Triticale	Bienvenue	9.36	9.62
		Colegial	9.53	6.20
		Trimour	7.69	10.25
		Trujillo	7.05	6.83

[a] Aerial Biomass Yield of genotypes tested in two plots are separated by comma.

Characterization results of the biomass obtained in the experimental plots are shown in **Table 3,** according data reported by Ruth et al. [24,25]. The net heating value at constant pressure is also given at 12% humidity content in the biomass (wet basis) since it is the humidity of the biomass at which efficiency and emission factors of the considered biomass power plant have been referenced (see later point **3.3.1.** (2)).

Table 3
Biomass composition and energy content

Species	C [%]	H [%]	N [%]	S [%]	Cl [%]	$NHV_{cp,0}$ [a] [MJ/kg, db[c]]	$NHV_{cp,12}$ [b] [MJ/kg, wb[d]]
Oat	44.60	6.10	1.22	0.11	0.72	16.78	14.48
Lopsided Oat	44.60	6.00	1.12	0.10	0.80	16.71	14.41
Rye	45.95	6.10	0.88	0.09	0.09	17.07	14.73
Triticale	44.65	6.08	0.79	0.08	0.07	16.61	14.32

[a] Net Heating Value at constant pressure and 0 % of water content.
[b] Net Heating Value at constant pressure and 12 % of water content
[c] Dry Basis
[d] Wet Basis

The energy equivalent in the biomass of each cereal variety tested per hectare is expressed as the result of multiplying the crop yield (see **Table 2**) at 12% humidity by the net calorific value at 12% humidity (see **Table 3**). Electricity production per hectare is the product of this value by the net efficiency of the process of biomass conversion into electricity in the considered biomass power plant (see **3.3.1.** (2)). This calculation suggests that under the conditions tested between 18 ha and 67 ha are needed to produce 1 TJ of electricity (values for the highest and the lowest yielding trials).

3 Energy and environmental assessment methodology

3.1. Goal, scope and evaluation of data sources and tools

LCA was the methodology selected to determine the energetic and environmental performance (GHG emissions) of winter cereals biomass for electricity generation in Spain and its comparison with the Spanish natural gas system as reference.

LCA involves a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle [26]. This environmental management tool is regulated by ISO 14040 [26] and ISO 14044 [27] standards, and according to them, LCAs should follow four steps: (1) goal and definition, (2) inventory analysis, (3) impact assessment and (4) interpretation.

As mentioned in section **2**, all information concerning biomass production has been obtained from the plots described in **Table 1**, whilst data on biomass conversion have been obtained from a 25MWe existing straw power plant.

Natural gas, one of the cleanest fossil energy sources for electricity generation, has been chosen as the reference system [28].

Simapro 7.2 [29] software tool and the Ecoinvent 2.2 [30,31] European database have been used to conduct the LCAs in this study.

3.2. Functional unit

The functional unit chosen has been 1 TJ of electrical energy generated from winter cereals biomass for the studied system and from natural gas as the reference system. This amount of electrical energy is a round number corresponding to about 12 hours of operation of the 25 MWe power plant taken as a reference for this study (see **3.3.1.** (2)).

3.3. Systems description

3.3.1. Bioenergy systems

The bioenergy systems analyzed included three subsystems: (1) cereal biomass production (agricultural phase), (2) power generation, and (3) transport. In the power generation subsystem natural gas is consumed as an auxiliary fuel in the biomass power plant. **Fig. 1** summarises the processes included in these bioenergy systems.

(1) Cereal biomass production subsystem (agricultural phase): The agricultural phase was defined by the crop management practices followed, the machinery used, and the agricultural raw materials (seeds, fertilizers, pesticides) utilised.

This information is shown in **Table 4** for the León case study and **Table 5** for Soria. For some field operations (e.g. biomass collection) fuel consumption depends on the productivity of the plot. Maximum, minimum, and (in parentheses) average fuel consumption are shown in **Table 4** and **Table 5**.

Table 4
Farming operations for León’s case study

Operation	Tractor / Mower		Implement			
	Weight [kg]	Power [kW]	Type	Weight [kg]	Operating rate [h/ha]	Fuel consumption [L/ha]
Primary tillage	7000	125	Plough	3000	1.34	30.9
Secondary tillage	7000	125	Harrow	2000	0.81	16.1
Base fertilization	7000	125	Spreader	400	0.54	4.3
Sowing	7000	125	Seeder	300	1.80	28.2
Herbicide treatment	7000	125	Boom sprayer	471	0.36	2.9
Top fertilization	7000	125	Spreader	400	0.54	4.3
Mowing[a]	13500	213	Self propelled mower	NA	0.97-0.65 (0.81)[b]	18.4-12.2 (15.3)[b]
Swathing	7000	125	Wheel rake	800	0.4	3.2
Baling[a]	4500	81	Baling packer	1700	0.97-0.65 (0.81)[b]	10.6-7.8 (9.7)[b]
Loading Bales[a]	7000	125	Loader	585	0.65-0.43 (0.54)[b]	3.8-2.6 (3.2)[b]

[a] Field work fuel consumption and operating rates depend on the harvest yield.
[b] Maximum-Minimum (Average) values.

Table 5

Farming operations for Soria's case study

Operation	Tractor		Implement			
	Weight [kg]	Power [kW]	Type	Weight [kg]	Operating rate [h/ha]	Fuel consumption [L/ha]
Primary tillage	7100	103	Chisel	700	0.44	20.0
Secondary tillage	7100	103	Cultivator	640	0.29	12.0
Base fertilization	5800	81	Spreader	450	0.13	4.0
Sowing	7100	103	Seeder	800	0.60	12.0
Herbicide treatment	5800	81	Boom sprayer	471	0.13	4.0
Top fertilization	5800	81	Spreader	450	0.13	4.0
Mowing[a]	5800	81	Mower	150	0.79-0.53 (0.69)[b]	18.6-11.6 (15.0)[b]
Swathing	5800	81	Wheel rake	800	0.2	4
Baling[a]	7185	136	Baling packer	1700	0.58-0.38 (0.50)[b]	14.9-9.2 (12.0)[b]
Loading Bales[a]	7185	136	Platform	9300	0.58-0.38 (0.50)[b]	5.9-4.1 (5.0)[b]

[a] Field work fuel consumption and operating rates depend on the harvest yield.
[b] Maximum-Minimum (Average) values.

(2) Power generation subsystem: As already mentioned, all the data used to model the biomass power plant system are real data from a 25 MWe straw power plant located in Sangüesa (Navarra - northern Spain) operated by the Spanish company Acciona Energía S.A. This plant consumes biomass at an average humidity of 12% and produces electricity with an average net conversion efficiency of 29.5%. The plant consumes natural gas as auxiliary fuel, particularly for start-up pre-heating, and produces ash and slag from biomass as solid residues. The average consumption of natural gas and the production of ash and slag per kilogram of straw biomass are shown in **Table 6**. Given the similar composition, it has been assumed that the studied biomasses will produce the same amounts of ash and slag as the straw used in the power plant, as well as the same emissions factors and conversion efficiency.

Table 6

Biomass power plant consumptions and residues

Items	Amount
Natural gas consumption [MJ/Kg Wet Biomass]	0.0342
Slag production [g/Kg Wet Biomass]	82.47
Ashes production [g/Kg Wet Biomass]	8.25

The power plant's air emissions are online submitted to the regional authorities and they are public. Emissions, as any other data about the power plant parameters utilised in this study, have directly been supplied to the authors by the power plant officers. **Table 7** shows an average of the power plant air emissions data. The emissions accounted for in the assessments are only those which affect the global warming potential (GWP). Carbon dioxide emitted from biomass combustion has not been considered because it was previously fixed from the air by the crop.

Table 7:
Biomass power plant aerial emissions

Substance	Combustion Origin	Amount [g/Kg Wet Biomass Burned]
Fossil carbon dioxide	Natural gas	1.94
Nitrogen oxides	Biomass	1.63
Carbon monoxide	Biomass	0.92
Sulphur dioxide	Biomass	0.32
Particulates	Biomass	0.24

(3) Transport subsystem: The transport system is summarized in **Table 8**. This table shows all modes of transport used, the distances between the origin and destination points and the energy consumption for every unit mass of material transported in the LCAs.

The means of transportation and distances for the transport of agricultural inputs to the regional storehouse are taken from the Ecoinvent database [32]. The distance from the regional storehouse to experimental plots was 10 km approximately, for both locations. Biomass, ash and slag means of transport and average distances were provided by the company in charge of the power plant operation.

Table 8
Transport system summary

Material	From	To	Distance [km]	Vehicle	Energy Consumption [MJ/ kg of Material]
Seed	Field	Processing center	30 km	Lorry 20-28t	0.098
	Processing center	Regional storehouse	100 km	Lorry 20-28t	0.327
	Regional storehouse	Demonstration plot	10 km	Lorry 16-32t	0.028
Fertilizers and herbicides	Manufacturer	Regional storehouse	600 km	Train	0.450
			100 km	Lorry >16t	0.226
	Regional storehouse	Demonstration plot	10 km	Lorry 16-32t	0.028
Biomass	Demonstration plot	Biomass plant	60 km	Lorry 16-32t	0.166
Ash and slag	Biomass power plant	Disposal site	37 km	Lorry 16-32t	0.102

3.3.2. Natural gas system

The natural gas system includes the gas field operations for extraction, the losses, the emissions, and the purification carried out by the main exporter countries of natural gas to Spain (Algeria 73% and Norway 27%). Furthermore, the energy consumption, losses and emissions resulting from the long distances involved and the local transportation of gas to a power plant in Spain are included in the inventory. Finally, the substances needed as well as the average efficiency of Spanish natural gas power plants are also taken into account [28].

3.4. Life cycle inventory structure

The inventories used to consider natural gas [28] consumption of the biomass power plant and the transportation [32] of agricultural inputs, biomass and power plant residues are taken from Ecoinvent.

The methods used for the inventory analysis of the agricultural system mainly follow those proposed in the life cycle inventories of agricultural production systems [32]. For the calculation of N_2O emissions we follow the guidelines of the RSB GHG Calculation Methodology v 2.0 [33].

3.4.1. Fertilizers production

Fertilizer inventories consider the various steps in the production process, such as the use of raw materials and semi-finished products, the energy used in the process, the transportation of raw materials and intermediate products, and the relevant emissions [34].

The inventories of calcium ammonium nitrate production are obtained from Ecoinvent database [35]. No inventories are given in Ecoivent for multi-nutrient fertilizers due to the number of different possible methods of mixing nitrogen, phosphorous and potassium compounds to produce NPK fertilizers [35]. The modelling of NPK fertilizer inventories has been approximated by combining inventories of single fertilizers - the quantity of which is determined by the multi-nutrient fertilizer specific contents of N, P_2O_5 and K_2O - as well as the form of the nitrogen provided (ammonium, nitrate or urea) [35].

3.4.2. Pesticides production

The inventory data related to emissions, energy and substance consumption in the production of the herbicides sprayed is taken from Ecoinvent [36]. The quantities of active substances (see **Table 1**) are taken from the formulations of the commercial herbicides used.

3.4.3. Seed production

Seed cultivation techniques and crop management for winter cereals have similar inputs compared to grain production. The only possible difference we found was the usage of gravity irrigation but we assumed that its contribution in terms of fossil energy and GWP was not significant since it does not use pumping and no fossil energy is needed for maintenance and operation. Irrigation takes place normally during late winter and early spring. Fertilization and machinery operations inputs for seed production of the selected genotypes was assumed to be similar compared to all cultivation techniques considered in the two study regions. Seed producers and suppliers often contract farmers in highly productive areas. Thus, yield outputs for seed production at the farm level were assumed to be 3.0 odt/ha for oat and lopsided oat, 5.5 odt/ha for triticale and non hybrid rye and 4.4 odt/ha for hybrid rye genotypes. The yield output for seed production of hybrid rye is lower than the yield for conventional rye as consequence of its specials conditions of seed production. These figures were all based on personal communication with seed producers and suppliers in Spain.

The energy consumption for cleaning, drying, seed dressing, and bag filling of the cereal seed in the processing plant has been estimated in 32.8 kWh/odt [37].

3.4.4. Diesel consumption and combustion emissions of agricultural machinery

The diesel consumption of agricultural machinery is obtained for each trial as can be seen in **Table 5** or **Table 6** depending on the plot location. The inventories for the extraction and transportation of crude oil, its transformation into diesel, and its distribution, are taken from Ecoinvent [38]. The diesel exhaust emissions from agricultural machinery engines are also taken into account [39].

3.4.5. Agricultural machinery manufacture

The inventories for agricultural machinery manufacture are specific to the various types of machinery (tractors, harvesters, tillage implements or other implements).

The amount of machinery (AM) consumed for carrying out a specific agricultural operation was calculated by multiplying the weight (W) of the machinery by the operation time (OT) and dividing the result by the lifetime of the machinery (LT) [34]:

$$AM\,[kg/FU] = W[kg]\cdot OT\cdot[h/FU]/LT[h];$$

where FU (See 3.2.) is the functional unit of the LCA. The lifetime of the machinery considered for these case studies was a Spanish average for each type of machinery [40].

3.4.6. Field and fertilizer derived emissions (Nitrous oxide emissions)

There is debate about the methodologies [33,41,42] and factors that should be taken into account in the estimation of N_2O emissions. This debate has been referred to in several bioenegy life cycle assessments [1,43,44] and reviews [13,45-47] given its critical importance when assessing GWP reductions [48]. To provide a good estimation of N_2O emissions we follow the RSB GHG Calculation Methodology v 2.0 [33], as it reflects the present state of research [49] and is based on methods which provide detail and consistency.

The calculation of N_2O emissions proposed by the RSB [33]is based on the formula in Nemecek et Kägi [32] and adopts the new IPCC guidelines [42]:

$$N_2O= 44/28\cdot(EF_1\cdot(N_{tot}+N_{cr})+EF_4\cdot 14/17\cdot NH_3+EF_5\cdot 14/62\cdot NO_{3-});$$

where:

N_2O = emissions of N_2O [kg N_2O/ha].

44/28 = conversion of N-N_2O in N_2O.

EF_1 = 0.01 (IPCC proposed factor [42]).

N_{tot} = total nitrogen input [kg N/ha].

Ncr = nitrogen contained in the crop residues [kg N/ha].

EF_4 = 0.01 (IPCC proposed factor [42]).
NH_3 = losses of nitrogen in the form of ammonia [kg NH_3/ha]. Calculated as proposed in the RSB [33] and Nemecek et Kägi [32] methodologies.
14/17= conversion of kg NH_3 in kg NH_3-N.
EF_5 = 0.0075 (IPCC proposed factor [42]).
14/62= conversion of kg NO_{3-} in kg NO_{3-}-N.
NO_{3-} = losses of nitrogen in the form of nitrate [kg NO_{3-}/ha]. They were estimated by using the RSB formula [33], which takes into account nitrogen supply and uptake, soil and crop characteristics, and local rainfall.

3.4.7. Carbon fixation into the soil

A rough estimation has been made of the CO_2 that is fixed by rhizo-deposits and remains in the soil. The estimation consists of calculating the total amount of carbon assimilated, knowing that 3% of this amount remains in the soil for the case study [50]. The carbon assimilated by the aerial part of the cereals in these trials is estimated by multiplying the crops' productivity (see **Table 2)** by their carbon content (see **Table 3**). By doubling this amount, the total amount of carbon assimilated is obtained, since the carbon content of the aerial part is considered to be half of the total carbon assimilated (Aerial part, roots, fixed carbon and respiration) [50]. Finally the estimated amount of fixed CO_2 is 3% of the previous quantity multiplied by the mass ratio CO_2/C. This calculation mode is applied for all the results that include estimations of CO_2 fixation.

3.4.8. Land use changes

Direct land used change (DLUC) is not relevant to this study because the plots selected for the study were previously winter cereal crop land. Indirect land use change (ILUC) is a complex process that is not fully understood by the scientific community [1].The factors used in its estimation are highly variable and frequently subject to changes in assumptions [51]. Historical analyses show that models may be overestimating ILUC emissions [51]. Furthermore, we assumed that in Spain most land available for winter cereal cultivation in order to produce electricity is actually marginal. Thus, it would not compete with food production. For these reasons ILUC have not been included in this study.

3.5. Life cycle impact assessment

Life Cycle Impact Assessment (LCIA) is the phase in a LCA where the inputs and outputs of elementary flows that have been collected and reported in the inventory are translated into impact indicator results [52].
LCIA includes mandatory and optional steps. The mandatory steps of classification and

characterization were carried out and the normalization and weighting optional steps were avoided in order to make results more comparable and free from the effects of value choices.

In the classification steps, elementary flows were assigned to the one or more impact categories to which they contribute. In the characterization steps, each quantitative characterization factor was assigned to all elementary flows of the inventory for the categories that have been included in the classification [52].

3.5.1. Environmental impact assessment method

The impact assessment method of IPCC 2007 [53] was chosen to assess the 100 years time horizon Global Warming Potential (GWP) with the Simapro 7.2 software tool [29]. This method calculates the cumulative radiative forcing caused by a unit mass emission of a GHG, integrated over a 100 year time horizon, as compared with the cumulative radiative forcing due to emission of a unit mass of carbon dioxide (CO_2) over the same time horizon.

3.5.2. Energy assessment method

In order to assess the energy consumed to generate electricity from winter cereal biomass and from natural gas, the Cumulative Energy Requirement Analysis (CERA) method [54] was chosen. This method aims to calculate the energy use throughout the life cycle of a good or service [54]. Primary fossil energy (FOSE) has been obtained by using this method.

4. Results

4.1. Global warming potential assessment

The results of global warming potential (GWP) of the are presented in **Fig. 2**, where the ratios of CO_2eq emission units per generated electricity energy unit [Mg CO_2eq/TJ electricity] are related to the aerial biomass yield obtained in each corresponding trial. The results are represented by hollow shapes when the CO_2 fixation by rhizo-deposits is considered, and by filled shapes when this parameter is not included. Biomass production at the farm level was the main stage contributing to the GWP generated by electricity production from biomass. Crop genotypes and biomass yields were the main drivers of GWP whereas sites and experimental periods appeared to have lesser influence.

As shown in the **Fig. 2**, the aerial biomass yield obtained in each trial was strongly (r^2 = 0.96) negatively correlated with the amount of total CO_2eq emissions per energy unit produced. Oat and lopsided oat produced lower yield and consequently had higher CO_2 emissions compared to rye and triticale. When CO_2 fixation in the soil was taken into account, it resulted in lower emissions of approximately 20 Mg CO_2eq per TJ of electricity for all the different biomass aerial yields obtained. Both tendency curves appear to have a lower horizontal asymptote since some phases of the assessment, such as biomass transportation and power plant operation and emissions, are independent from yields.

In **Fig. 3** the percentages of CO_2eq savings obtained when biomass emissions are compared to those of Spanish natural gas power plants are shown for each corresponding trial yield [odt]. As in **Fig. 2** the results with or without CO_2 fixation by rhizo-deposits are presented.

Aerial biomass productivity correlated positively with respect to CO_2eq savings, suggesting that genotype selection determined larger differences in CO_2eq emitted. For example, oat and lopsided oat trials obtained less than 25% and 45% in savings respectively (when CO_2 fixation was not considered). Higher yields corresponding to rye and triticale trials obtained greater CO_2eq savings. However, the range of variation of savings was wider for these crops than for the two oat species due to the higher number of trials and their variability regarding campaigns and locations. Triticale and rye productions which went from 4.5 odt/ha to 12 odt/ha produced GHG savings ranging from 30% to 75%.

There is a constant difference of about 15% higher savings obtained for every trial when rhizo-deposits fixation was included.

The European Commission recommends taking into account for solid and gaseous biofuels [23] the same binding sustainability criteria established by the RED [55] for liquid biofuels. Following this recommendation, we have assumed that sustainable electricity production from winter cereal biomass should require at least 60 % of savings compared to Spanish natural gas electricity, as this is the percentage required by the RED for liquid biofuels after 2017. Consequently we considered that electricity production from winter cereal biomass should produce savings of at least 60%. According data shown in **Fig. 3**, such savings require yields higher than 6.5 odt/ha if CO_2 fixation is taken into account and yields above 8 odt/ha if CO_2 fixation is not considered. We obtained CO_2eq savings over those thresholds for five out of eight rye trials and for five out of fifteen triticale trials when fixation was excluded. When fixation was considered, seven out of eight rye trials and thirteen out of fifteen triticale trials were within the limit. None of the oat or lopsided oat trials was close to achieving CO_2eq savings of 60% even considering CO_2 fixation. However, when aerial biomass yields tend to infinity, CO_2eq savings tendency curves reach a plateau at 88 % when fixation is included and at 73% when fixation is excluded.

In order to be able to make comparisons between sites, the average GWP per energy unit of electricity produced [Mg CO_2eq/TJ electricity] was calculated in **Fig. 4** for Soria and León provinces. The GWP of Spanish natural gas electricity production was also included to enable comparisons between biomass electricity production systems and the fossil reference for electricity production. Both bioenergy systems (Soria and León) produced less GWP than the Spanish natural gas system, with 63% and 41% less GWP, respectively, for Soria and León average scenarios (**Fig. 4**). Other works with Ethiopian mustard (*Brassica carinata* L.) as dedicated biomass energy crop grown in Spain for electricity production, considering for the conversion phase the same biomass power plant as in this assessment, obtained savings up to 33% [4].

While GWP from biomass power plant operation and biomass transport was very similar for both bioenergy systems, the consumption of raw materials and the agricultural emissions were respectively 55% and 60% higher for León. Also, the GWP derived of machinery use was considerably higher for León. This last circumstance can be explained due to the faster operating rate [h/ha] of Soria farming operations compared to León ones (**Table 4** and **Table** 5). Farming operations were carried out more rapidly in Soria because of the lighter texture of the soil and the larger working width of non-tillage implements.

The GWP share for the phases considered in the inventory is shown in **Fig. 5** for Soria and León average biomass systems. The agricultural phase was the factor which contributed most to GWP, and included the last seven phases listed in **Fig. 5** (from diesel combustion emissions to fertilizer production and transportation). It accounts for 94.2% and 96.3% of the GWP depending on the case study. In contrast, the rest of the phases corresponding to the transport of the biomass, power plant emissions, consumption and disposals accounted only for 6.8% and 4.7% of the GWP for both provinces' average scenarios.

With respect to the agricultural phase, fertilizer production and transportation, and the emissions derived from its application, accounted for 76.4% and 75.2% of total GWP respectively. These results are consistent with those found in previous research in Spain [4,56] and other countries in Europe [22]. Nitrous oxide (N_2O) fertilizer derived emissions accounted, approximately, for 30% of total GWP in both locations.

4.2. Energy yield assessment

The results shown in **Fig. 6** suggest that productivity, obtained from the different cereal genotypes studied, is positively correlated with electricity generation energy yields (output/input), which ranged from 1.1 to 3.7 for biomass productivities ranging from 3.6 odt/ha to 11.3 odt/ha. Energy yields from oat trials were considerably lower (1.1 and 1.3) compared to those of lopsided oat (1.6 and 1.8), rye (1.6 to 3.7) and triticale (1.8 to 3). All trials produced considerably more electric energy than primary fossil energy was consumed in the whole life-cycle, thus showing a positive energy balance in all cases.

Fig. 7 shows the fossil energy consumed per unit of electricity produced [TJ fossil / TJ electricity] for the two considered biomass average systems in central-northern Spain, as well as for the Spanish natural gas electricity production system. According to the data shown in the **Fig. 7**, consumption of fossil energy for electricity production is, respectively, 85.2% and 75.7% less for Soria and León biomass bioenergy systems than for the Spanish natural gas electricity system. Raw materials (fertilizers, pesticides and diesel) inputs share was 85% of the total fossil consumption in both sites. The amount of fossil energy consumed was 65.9% higher for León system than for Soria system, due to the larger quantity of raw materials consumed and the lower average yield obtained in biomass production stage. However, both sites produced more electrical energy than the quantity of fossil energy that was required for its generation.

Fig. 8 shows the fossil energy consumption shares for the stages considered in this LCA for the Soria and León biomass systems. Analogously to the case of GWP (**Fig. 5**), the agricultural phase (the last five stages listed in **Fig. 8**), was the phase which contributed most to fossil energy consumption: 86.6% and 91.7% of the total fossil energy for Soria and León bioenergy systems, respectively. The rest of the phases corresponding to biomass transportation, power plant consumption and disposal accounted for only 13.4% and 8.3% of the total fossil energy.

Regarding the components of the agricultural phase, fertilizers made the greatest contribution to fossil energy consumption, accounting for 51.5% and 49.8% of total. They were immediately followed in importance by diesel consumption, with 28.1% and 31.4% of the total fossil energy consumed. These results are consistent with other energy analysis studies that include winter cereals cultivated under rain-fed conditions in Spain [50]. The contribution of fertilizers was lower for fossil energy than for GWP since fertilizer-derived emissions, mainly consisting of N_2O emissions, have no effect on fossil energy balances.

5. Discussion

Results from the trials of annual energy crops suggest that the use of winter cereals might result in significant benefits with respect to GHG emission savings and fossil energy balances when compared to the production of electricity from natural gas in Spain. However, and despite the difference between species and varieties cultivated, only 37 % of the total trials satisfied the minimum limits of 60 % of GHG savings established by EU biomass sustainability recommendations [23]. This proportion is increased up to 74% when rhizo-deposits CO_2 fixation is considered. Being above the EU threshold in our case would imply obtaining biomass yields above 6.5 odt/ha if fixation is included in the calculations or above 8.0 odt/ha if it is excluded.

Based on our results from a wide productivity rank variation on real farms and over two campaigns, we found that there was a clear correlation between productivity at farm scale, fossil energy balances and GHG savings. This has considerable implications for sustainability criteria regarding adoption of energy crops in marginal lands where yields, as it is our case, are usually low and inputs consumed are often relatively high.

In the current discussion on energy policy and sustainability criteria [58-60], it is generally accepted that the energy crop species to be encouraged are those that are better adapted to marginal or abandoned arable land which is not competitive in terms of its capacity for food production [61-63]. Therefore, we suggest that annual grasses currently cultivated as feedstock in the studied area for power energy plants should be optimized to produce lower impacts and improved energy balances in these lands, particularly in those lands showing biomass yields below those indicated above. More trials and specific assessments should be carried out in order to select winter cereals varieties with higher biomass yields under semiarid Spanish rain-fed conditions. In this regard, a possible strategy could be to explore old rye and triticale genotypes with a lower harvest index (grain weight / whole plant weight), that would require less nitrogen fertilization per tonne of biomass produced given that grains usually have larger nitrogen contents.

With regard to the phases of the analysis, fertilizer production and application derived emissions were the most contributing phases in terms of GWP with more than 75 % of the total. This suggests that serious efforts should be made to optimise fertilizer utilization without compromising crop biomass yields, especially on low productivity rain-fed lands that are assumed to be more suitable for the cultivation of bioenergy crops. To provide an optimal quantity of fertilizer, the expected productivity of the crop on a specific plot as well as nutrient use efficiency must be considered. Nitrogen fertilization applications with low doses are also possible in combination with some soil nitrogen improvement management practices such as rotation with legumes, fallow management and conservative or no-tillage farming. For instance, rotation with legumes is a well documented technique for increasing soil nitrogen stocks (80 to 300 kg N fixed per hectare and year) [64]. The nitrogen balances of crop systems should be considered in order to optimise nitrogen use efficiency or to determine the use of reduced doses and/or specific techniques to improve nitrogen stocks.

Diesel consumption in our trials accounted for around 30 % of the total fossil energy consumed. The optimization of farming operations [65] and proper sizing of agricultural machinery [66] to increase energy efficiency could potentially reduce this consumption. In particular, non-tillage or conservative tillage farming operations have synergy effects, reducing diesel consumption significantly and improving soil nutrient stocks [67], thereby permitting a reduction in fertilizer doses.

Processing technology is another aspect that should be considered in the search for ways of improving LCA results. It also seems reasonable to assume that the negative effect of lower yields from dedicated energy plantations could be partially mitigated by higher efficiency transformations levels such as those described in other studies [68,69].

6. Conclusion

Based on our results from a wide productivity range variation on real farms and over two agricultural years, we conclude that there is a clear correlation between productivity at farm scale, fossil energy balances, and GHG savings. Therefore, considerable reductions of GHG emissions and more sustainable energy balances can be achieved by using winter cereal biomass compared to natural gas as fuel for electricity production if cereals biomass productivity is above 8 odt/ha. However, in low productivity scenarios an optimization on crop management and nitrogen fertilization practices should be carried out in order to satisfy EU sustainability recommendations of GHG savings for electricity production from biomass.

Acknowledgements

The authors thanks to Dr. Ruth Barro for her collaboration in performing biomass characterization tests and Mr. Pedro Lerga, of Acciona Energía S.A., for his relevant contributions and information regarding the biomass power energy plant considered in this study.

This work has been developed in the framework of the Spanish National and Strategic Project "On Cultivos" partly funded by the Spanish Ministry of Economy and Competitiveness (INNPACTO Programme) and the European Funds for Regional Development (ERDF), under the dossier PSE-120000-2009-15.

References

[1] García CA, Fuentes A, Hennecke A, Riegelhaupt E, Manzini F, Masera O. Life-cycle greenhouse gas emissions and energy balances of sugarcane ethanol production in Mexico. Appl Energy 2011;88:2088-97.

[2] European Commission. Europe 2020: A Strategy for Smart, Sustainable and Inclusive Growth: Communication from the Commission. : Publications Office, 2010.

[3] European Commission. A Roadmap for moving to a competitive low carbon economy in 2050. COM (2011) 2011;112. <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52011DC0112:EN:NOT> [accessed December 2012].

[4] Gasol CM, Gabarrell X, Anton A, Rigola M, Carrasco J, Ciria P et al. Life cycle assessment of a Brassica carinata bioenergy cropping system in southern Europe. Biomass Bioenergy 2007;31:543-55.

[5] Gasol CM, Gabarrell X, Anton A, Rigola M, Carrasco J, Ciria P et al. LCA of poplar bioenergy system compared with Brassica carinata energy crop and natural gas in regional scenario. Biomass Bioenergy 2009;33:119-29.

[6] Butnar I, Rodrigo J, Gasol CM, Castells F. Life-cycle assessment of electricity from biomass: Case studies of two biocrops in Spain. Biomass Bioenergy 2010;34:1780-8.

[7] Yee KF, Tan KT, Abdullah AZ, Lee KT. Life cycle assessment of palm biodiesel: Revealing facts and benefits for sustainability. Appl Energy 2009;86, Supplement 1:S189-96.

[8] Achten WMJ, Almeida J, Fobelets V, Bolle E, Mathijs E, Singh VP et al. Life cycle assessment of Jatropha biodiesel as transportation fuel in rural India. Appl Energy 2010;87:3652-60.

[9] Lubbe N, Sahlin U. Benefits of biofuels in Sweden: A probabilistic re-assessment of the index of new cars' climate impact. Applied Energy 2012;92:473-9.

[10] EEA. How much bioenergy can Europe produce without harming the environment? EEA (Environmental European Agency) Report No 7/2006. 2006. <http://www.eea.europa.eu/publications/eea_report_2006_7> [accessed December 2012].

[11] Elsayed MA, Matthews R, Mortinmed ND. Carbon and Energy Balances for a range of biofuels options. Project final report. Project number B/B6/00784/REP. Resource Research Unit, Sheffield Hallam University and Forest Research. 2003.

[12] Dworak T, Elbersen B, van Diepen K, Staritsky I, van Kraalingen D, Suppit I et al. Assessment of inter-linkages between bioenergy development and water availability. 2009. <http://ec.europa.eu/environment/water/quantity/pdf/2009Bioenergy.pdf> [accessed January 2013]

[13] Cherubini F, Bird ND, Cowie A, Jungmeier G, Schlamadinger B, Woess-Gallasch S. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resour Conserv Recycling 2009;53:434-47.

[14] Kalt G, Kranzl L. Assessing the economic efficiency of bioenergy technologies in climate mitigation and fossil fuel replacement in Austria using a techno-economic approach. Applied Energy 2011;88:3665-84.

[15] Singh A, Olsen SI. A critical review of biochemical conversion, sustainability and life cycle assessment of algal biofuels. Applied Energy 2011;88:3548-55.

[16] Daroch M, Geng S, Wang G. Recent advances in liquid biofuel production from algal feedstocks. Applied Energy 2013;102:1371-81.

[17] Odlare M, Nehrenheim E, Ribé V, Thorin E, Gavare M, Grube M. Cultivation of algae with indigenous species – Potentials for regional biofuel production. Applied Energy 2011;88:3280-5.

[18] European Commission. Eurostat: Your key to European statistics. 2012. *<http://*ec.europa.eu/eurostat> [accessed October 2012].

[19] Pardo Sanclemente G, Aibar Lete J, Ciria P, Lacasta C, Lezaún JA, Zaragoza Larios C. Organic versus conventional methods of fertilization and weed control in a long term rotation of cereals in semiarid Spain. 2011.

[20] Sánchez-Picón A, Aznar-Sánchez J, García-Latorre J. Economic cycles and environmental crisis in arid southeastern Spain. A historical perspective. J Arid Environ 2011;75:1360-7.

[21] Infante Amate J, González de Molina M. 'Sustainable de-growth'in agriculture and food: an agro-ecological perspective on Spain's agri-food system (year 2000). J Clean Prod 2013;38:27–35.

[22] Bioelectricity Crop. Project: “Big scale demonstration of energy crops utilization of bioelectricity generation". Programme for research, technological development and demonstration on "Energy, environment and sustainable development, 1998-2002". Contract NN5-2001-00605. European Union. 2003-2005.

[23] European Comision. Report on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling. 2010. <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52010DC0011:EN:HTML:NOT> [accessed January 2012].

[24] Barro R, Fernández MJ, Losada J, Rovira L, Salvadó A, Serra J et al. Differences on the quality of the biomass obtained from different species of winter cereals. 18th EU BC&E 2010;VP1.3.52:534,534-537.

[25] Barro R, Ciria P, Maletta E, Fernández MJ, Pérez J, Losada J et al. Variability on the Properties of Triticale and Rye Biomass Due to the Different Varieties and Growing Conditions. 19th EU BC&E 2011;VP1.3.13:569,569-578.

[26] ISO. 14040:2006. Environmental management-Life cycle assessment-Principles and framework. European Committee for Standardization. 2006.

[27] ISO. 14044:2006. Environmental Management–Life Cycle Assessment–Requirements and Guidelines. European Committee for Standardization. 2006.

[28] Emmenegger M. F., Heck T, Jungbluth N. Erdgas. In:*Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz*(ed. Dones R.). Final report ecoinvent data v2.0, No. 6-V. 2007.

[29] Goedkoop M, De Schryver A, Oele M, Sipke D, De Roest D. Introduction to LCA with SimaPro 7. PRé Consultants 2010.

[30] Frischknecht R, Jungbluth N. Overview and Methodology. Final report ecoinvent v2. 0: No. 1. Swiss Centre for Life Cycle Inventories 2007.

[31] Frischknecht R, Jungbluth N, Althaus H, Doka G, Dones R, Heck T et al. The ecoinvent Database: Overview and Methodological Framework (7 pp). The International Journal of Life Cycle Assessment 2005;10:3-9.

[32] Nemecek T, Kägi T. Life cycle inventories of agricultural production systems. Ecoinvent v2.0 Final report No. 15 2007.

[33] Faist M, Reinhard J, Zah R. RSB GHG Calculation Methodology v 2.0. 2011. <http://www.arb.ca.gov/fuels/lcfs/workgroups/lcfssustain/RSB_GHG_Calculation_Methodology.pdf> [accessed January 2012].

[34] Nemecek T, Heil A, Huguenin O, Meier S, Erzinger S, Blaser S et al. Life cycle inventories of agricultural production systems. Final report ecoinvent 2000;15:145–146.

[35] Davis J, Haglund C. Life cycle inventory (LCI) of fertilizer production. Fertilizer products used in Sweden and Western Europe (SIK Rep. No. 654). Swedish Institute for Food and Biotechnology, Gothenburg, Sweden 1999.

[36] Sutter J. Life Cycle Inventories of Pesticides. Final report ecoinvent v2.2. 2010.

[37] Narain M, Singh B. Energy profile of a seed-processing plant. Appl Energy 1988;30:227-34.

[38] Jungbluth N. Erdöl. In:*Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz*(ed. Dones R.). Final report ecoinvent data v2.0, No. 6-IV. 2007.

[39] SAEFL. Handbuch Offroad-Datenbank. Swiss Agency for the Environment, Forests and Landscape (SAEFL) 2000.

[40] Ortiz-Cañavate J. Las máquinas agrícolas y su aplicación. : Mundiprensa, 2003.

[41] Nemecek T, Kägi T, Blaser S. Life Cycle Inventories of Agricultural Production Systems. Final report ecoinvent data v2.0, No. 15. 2007.

[42] De Kleine C, Novoa RSA, Ogle S, Keith AS, Rochette P, Wirth TC. Chapter 11:N2O Emissions from Managed soils, and CO2 emissions from Lime and Urea Application. In: International Panel on Climate Change, editor. 2006 IPCC guidelines for national greenhouse gas inventories Volume 4: Agriculture, Forestry and Other Land Use: Intergovernmental Panel on Climate Change; 2006.

[43] Lechón Y, Cabal H, de la Rúa C, Caldés N, Santamaría M, Sáez R. Energy and greenhouse gas emission savings of biofuels in Spain's transport fuel. The adoption of the EU policy on biofuels. Biomass Bioenergy 2009;33:920-32.

[44] Koponen K, Soimakallio S, Tsupari E, Thun R, Antikainen R. GHG emission performance of various liquid transportation biofuels in Finland in accordance with the EU sustainability criteria. Applied Energy 2013;102:440-8.

[45] Börjesson P. Good or bad bioethanol from a greenhouse gas perspective – What determines this? Appl Energy 2009;86:589-94.

[46] Cherubini F, Strømman AH. Life cycle assessment of bioenergy systems: State of the art and future challenges. Bioresour Technol 2011;102:437-51.

[47] Malça J, Freire F. Life-cycle studies of biodiesel in Europe: A review addressing the variability of results and modeling issues. Renewable and Sustainable Energy Reviews 2011;15:338-51.

[48] Crutzen P, Mosier A, Smith K, Winiwarter W. N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmos Chem Phys Discuss 2007;7:11191-205.

[49] Hennecke AM, Faist M, Reinhardt J, Junquera V, Neeft J, Fehrenbach H. Biofuel greenhouse gas calculations under the European Renewable Energy Directive – A comparison of the BioGrace tool vs. the tool of the Roundtable on Sustainable Biofuels. Applied Energy 2013;102:55-62.

[50] Kuzyakov Y, Domanski G. Carbon input by plants into the soil. Review. Journal of Plant Nutrition and Soil Science/Zeitschrift für Pflanzenernährung und Bodenkunde 2000;163:421-31.

[51] Linares P, Pérez-Arriaga IJ. A sustainable framework for biofuels in Europe. Energy Policy 2013;52:166-9.

[52] EC-JRC-IES. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Provisions and Action Steps. Fisrt edition. 2010.

[53] Althaus H.J., EMPA. IPCC 2007 method in: Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent v2.2 No. 3. 2010.

[54] Jungbluth N, Esu-services, Frischknecht R, Ecoinvent-Centre, EMPA. Cumulative energy demand method in: Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent v2.2 No. 3. 2010.

[55] European Parliament. Directive 2009/28/EC of European Parliament of the council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union 2009.

[56] Sebastián F, Royo J, Gómez M. Cofiring versus biomass-fired power plants: GHG (Greenhouse Gases) emissions savings comparison by means of LCA (Life Cycle Assessment) methodology. Energy 2011;36:2029-37.

[57] Ciria P, Ciria CS, Pérez P, Carrasco JE. Energy Analysis of Agricultural Exploitations under Rain-Fed Continental Conditions in Central-Northern Spain. 19th EU BC&E - 2011 2011;VP1.3.15:585,585 -590.

[58] Koponen K, Soimakallio S, Tsupari E, Thun R, Antikainen R. GHG emission performance of various liquid transportation biofuels in Finland in accordance with the EU sustainability criteria. Appl Energy 2013;102:440-8.

[59] Srirangan K, Akawi L, Moo-Young M, Chou CP. Towards sustainable production of clean energy carriers from biomass resources. Appl Energy 2012.

[60] Yan J, Lin T. Biofuels in Asia. Applied Energy 2009;86, Supplement 1:S1-S10.

[61] Lewandowski I, Scurlock JM, Lindvall E, Christou M. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass Bioenergy 2003;25:335-61.

[62] Lewandowski I, Schmidt U. Nitrogen, energy and land use efficiencies of miscanthus, reed canary grass and triticale as determined by the boundary line approach. Agric , Ecosyst Environ 2006;112:335-46.

[63] Niblick B, Monnell JD, Zhao X, Landis AE. Using geographic information systems to assess potential biofuel crop production on urban marginal lands. Applied Energy 2013;103:234-42.

[64] Cuttle S, Shepherd M, Goodlass G. A review of leguminous fertility-building crops, with particular refence to nitrogen fixation and utilisation. Written as part of DEFRA project OF0316 “The development of improved guidance on the use of fertilitybuilding crops in organic farming”.Department for Environment, Food and Rural affairs.UK. 2003. <http://www.organicadvice.org.uk/soil_papers/leguminous_fert.pdf> [accessed January 2012].

[65] IDAE. Ahorro, eficiencia energética y sistemas de laboreo agrícola. Ahorro y eficiencia energética en la agricultura nº 4 2006:40. <http://idae.electura.es/publicacion/19/ahorro_eficiencia_energ%C3%A9tica_sistemas_laboreo_agr%C3%ADcola> [accessed March 2012].

[66] IDAE. Ahorro, eficiencia energética y estructura de la explotación agrícola. Ahorro y eficiencia energética en la agricultura nº 5 2006:44. <http://idae.electura.es/publicacion/18/ahorro_eficiencia_energ%C3%A9tica_estructura_explotaci%C3%B3n_agr%C3%ADcola> [accessed March 2012].

[67] Holland JM. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric , Ecosyst Environ 2004;103:1-25.

[68] Ahrenfeldt J, Thomsen TP, Henriksen U, Clausen LR. Biomass gasification cogeneration – A review of state of the art technology and near future perspectives. Appl Therm Eng 2013;50:1407-17.

[69] Chen M, Lund H, Rosendahl LA, Condra TJ. Energy efficiency analysis and impact evaluation of the application of thermoelectric power cycle to today's CHP systems. Appl Energy 2010;87:1231-8.

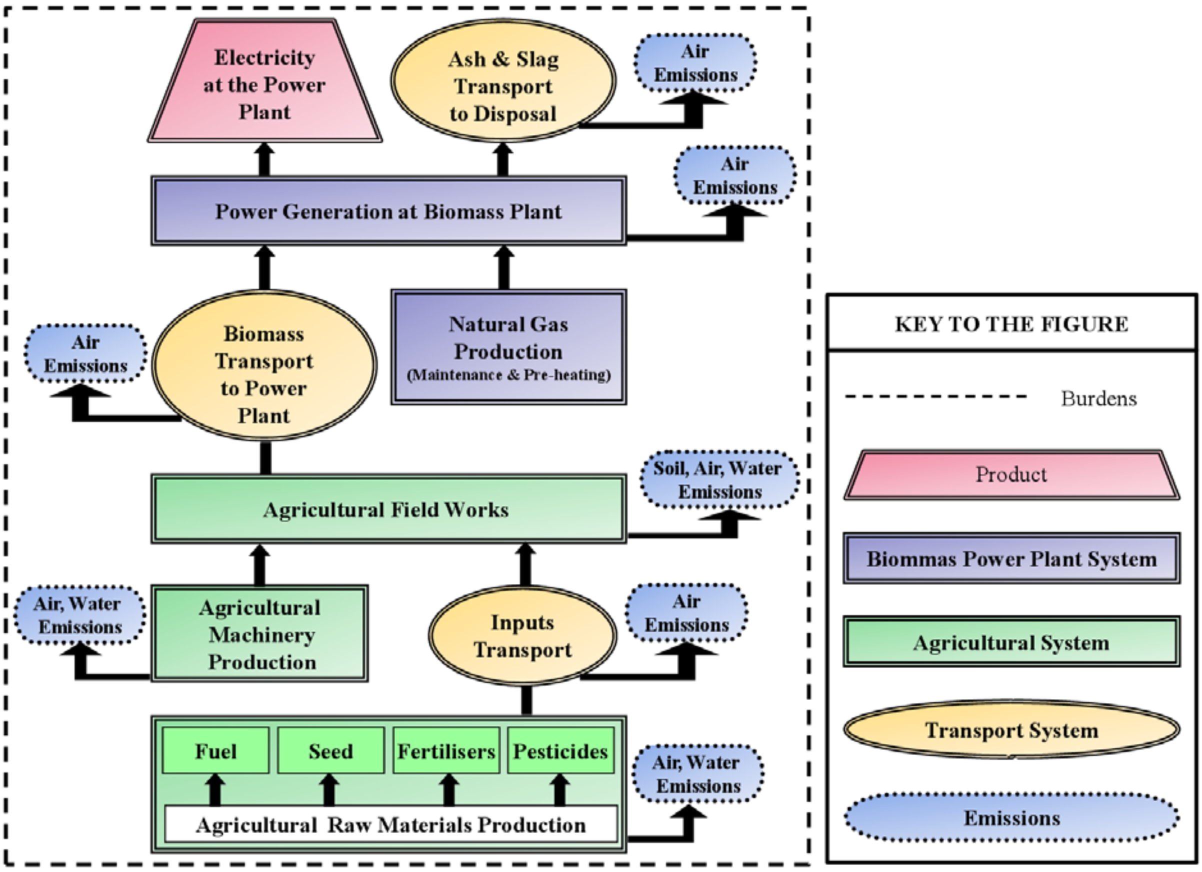

Fig. 1 Processes of the studied bioenergy systems.

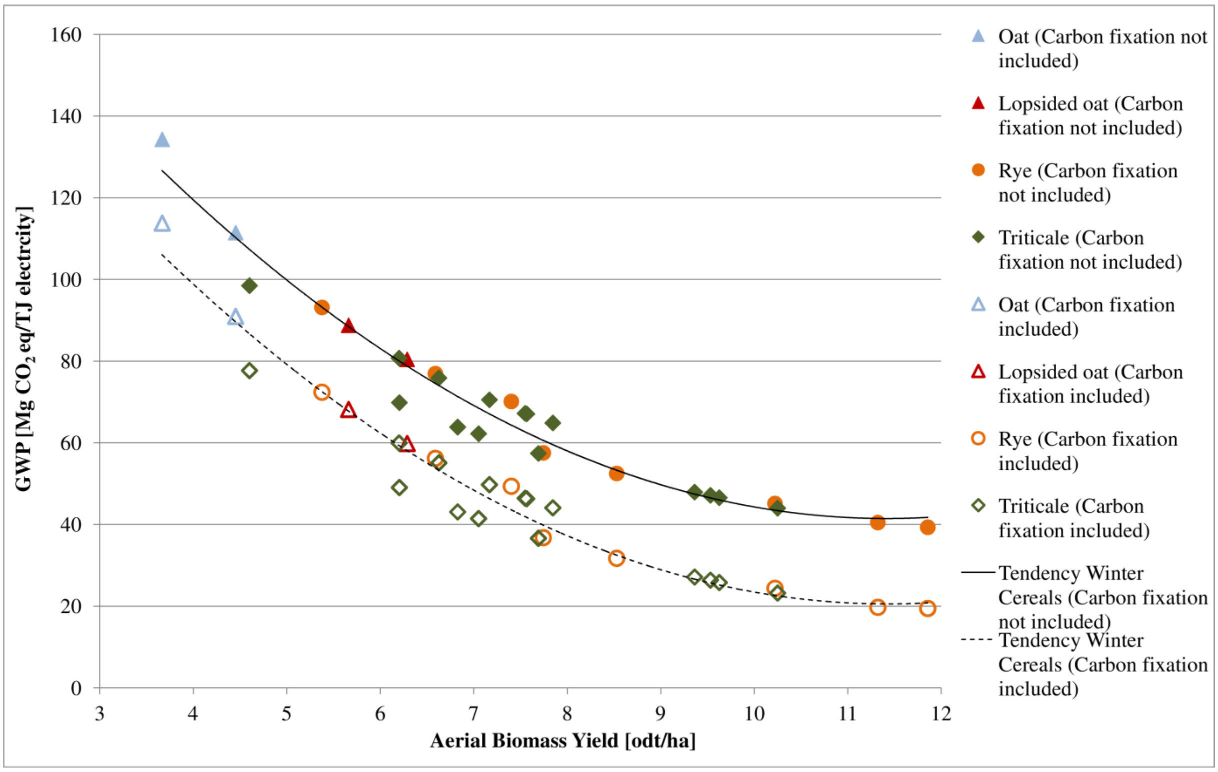

Fig. 2 Relationship between global warming potential (GWP) of winter cereals biomass electricity and whole plant yield.

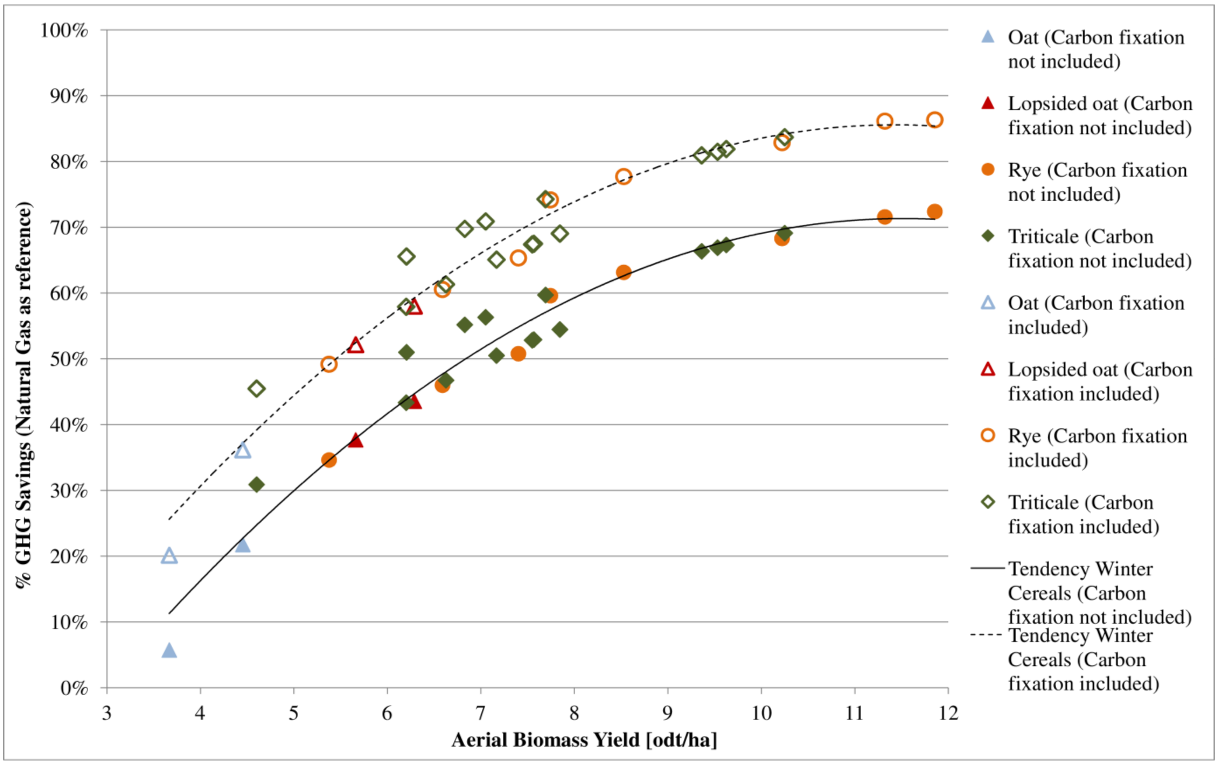

Fig. 3 Relationship between greenhouse gas emissions savings of winter cereals biomass electricity compared to natural gas and whole plant yield.

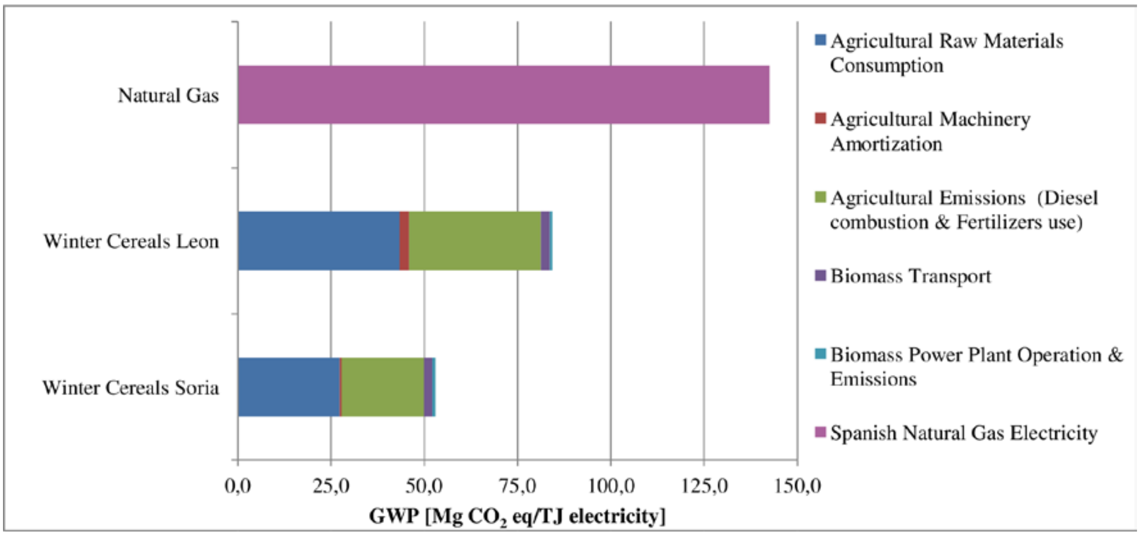

Fig. 4 Global Warming Potential generated in the production of electricity from winter cereals of the two studied sites compared to natural gas Spanish plants. (average scenarios).

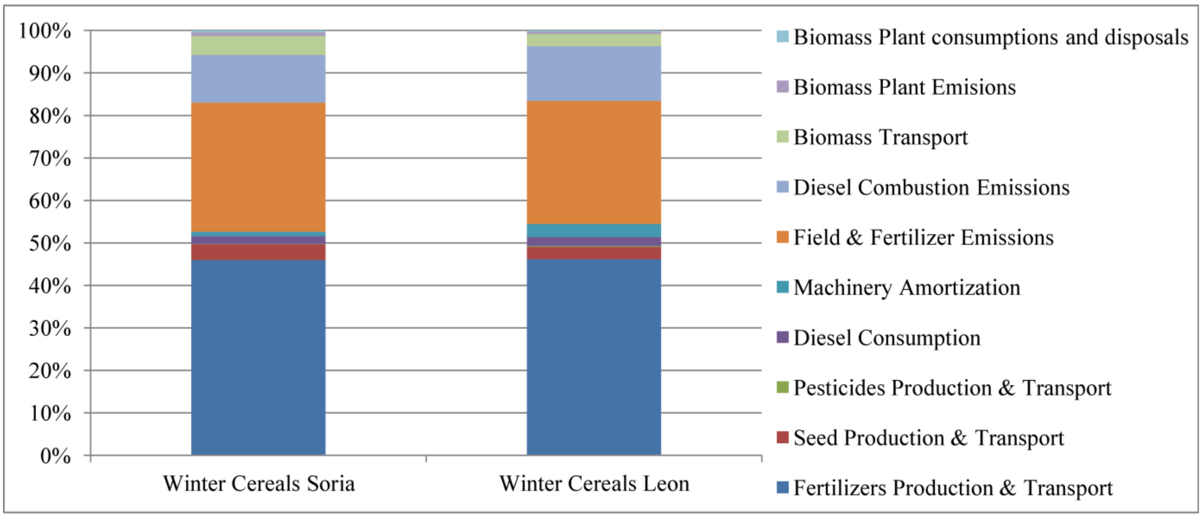

Fig. 5 Global Warming Potential (GWP) shares for biomass electricity production in average scenarios in Soria and León.

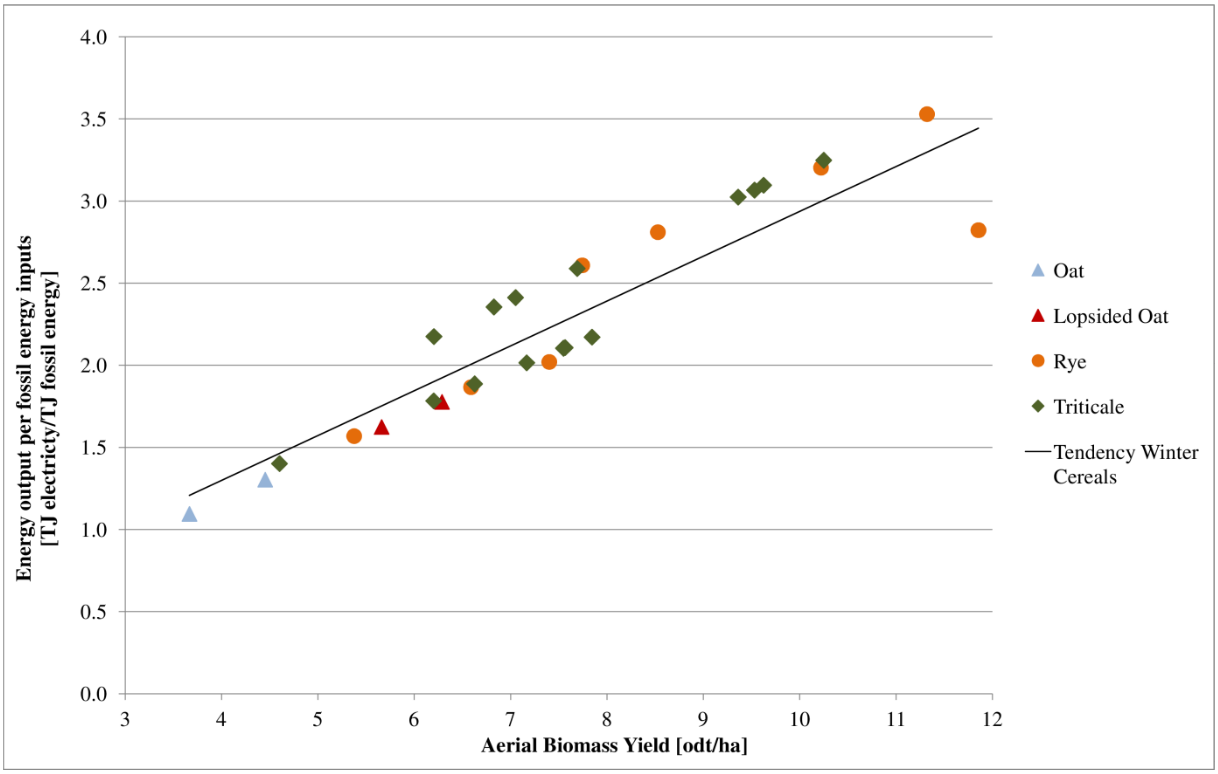

Fig. 6 Relationship between electrical energy output per fossil energy inputs of winter cereals biomass and whole plant yield.

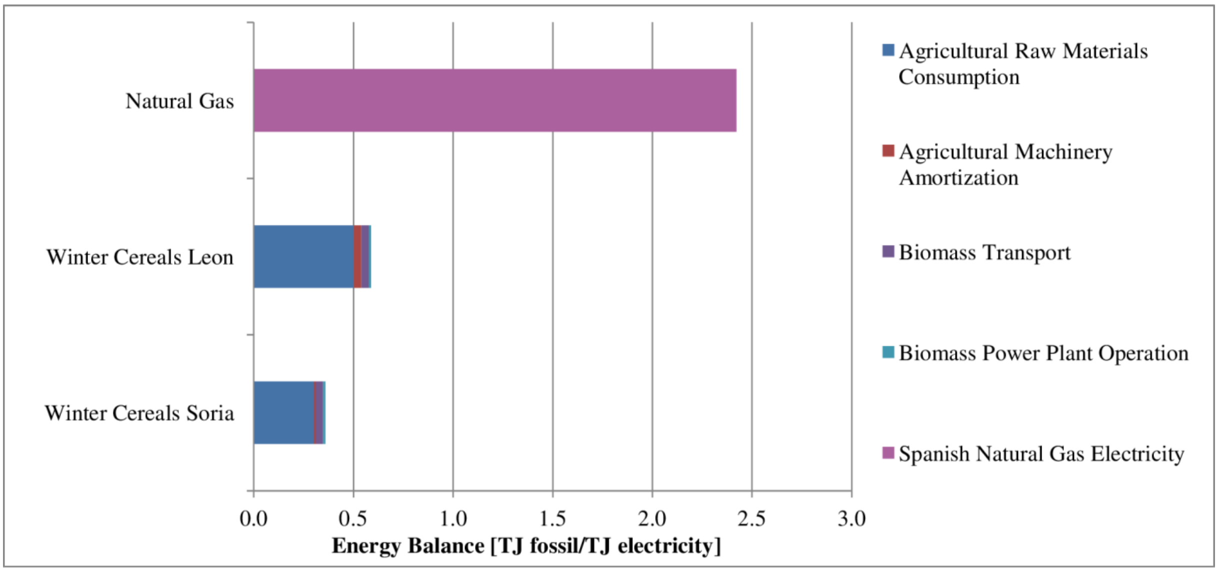

Fig. 7 Fossil energy consumption generated in the production of electricity from winter cereals of the two studied sites compared to natural gas Spanish plants (average scenarios).

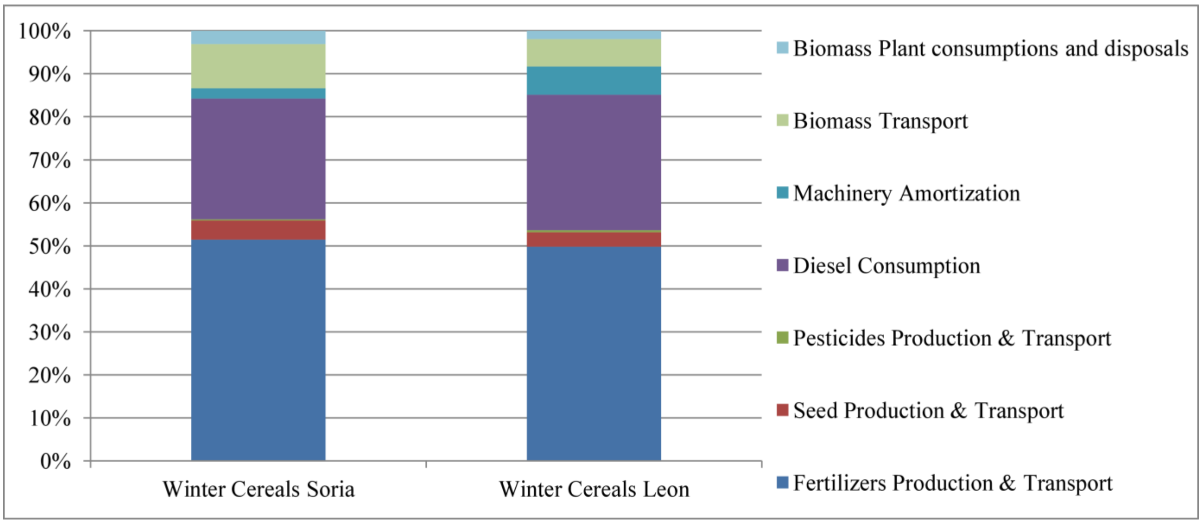

Fig. 8 Fossil energy consumption shares of average scenarios in Soria and León for biomass electricity production.