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1 **Global warming and energy yield evaluation of Spanish wheat straw electricity generation**  
2 **– A LCA that takes into account parameter uncertainty and variability.**

3  
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10  
11 **Abstract**

12 This paper aims to provide more accurate results in the life cycle assessment (LCA) of  
13 electricity generation from wheat straw grown in Spain through the inclusion of parameter  
14 uncertainty and variability in the inventories. We fitted statistical distributions for the all the  
15 parameter that were relevant for the assessment to take into account their inherent uncertainty  
16 and variability. When we found enough data, goodness of fit tests were performed to choose the  
17 best distribution for each parameter and, when this was not possible, we adjusted triangular or  
18 uniform distributions according to data available and expert judge. To obtain a more complete  
19 and realistic LCA, we considered the consequences of straw exportation for the agricultural  
20 system, specially the loss of soil organic carbon and the decrease of future fertility. We also  
21 took into account all the inputs, transformations and transports needed to generate electricity in  
22 a 25 MWe power plant by straw burning. The inventory data for the agricultural, the transport  
23 and the transformation phases were collected considering their most common values and ranges  
24 of variability for the Spanish case. We used Monte Carlo simulation and sensitivity analysis to  
25 obtain global warming potential (GWP) and fossil energy (FOSE) consumption of the system.  
26 These results were compared with those of the electricity generated from natural gas in Spanish  
27 power plants, as fossil reference energy system. Our results showed that for the majority of the  
28 simulations electricity from wheat straw biomass combustion produced less greenhouse gases  
29 (GHG) emissions and consumed less fossil energy than electricity from natural gas. However,  
30 only 58 % of the simulations achieved the sustainability threshold of 60 % GHG savings  
31 proposed by the European Union (EU). Our analysis showed that agricultural field works and  
32 the loss of soil organic carbon due to straw exportation were the most important phases for  
33 FOSE consumption and GWP respectively. According to parameters sensitivity analysis, the  
34 loss of soil organic carbon was completely dependent on the isohumic coefficient and the soil  
35 carbon content factor values. Due to this fact, local and specific estimates of these parameters  
36 are relevant tasks to be performed in order to reduce uncertainties and provide a definitive  
37 answer to the compliance of the EU sustainability criteria.

38

39 Keywords: bioenergy; crop residues; life cycle assessment (LCA); global warming potential;

40 uncertainty; sustainability criteria

41

## 42 **1. Introduction**

43 With the purpose of reducing greenhouse gases (GHG) emissions and depletion of non  
44 renewable energy sources, the European Union (EU) Member States have committed  
45 themselves to increase the share of renewable energy in the EU's energy mix to 20% and reduce  
46 GHG emissions by 20% by 2020 [1]. Bioenergy is intended to play a central role in the  
47 accomplishment of these objectives accounting for more than half of projected 2020 Europe's  
48 energy output [2]. Potential GHG reductions of different pathways to produce bioenergy from  
49 solid [3,4] and liquid [5-8] are being evaluated intensively [9]. Several studies suggest that  
50 lignocellulosic biomass sources for heat and electricity production may perform better in GHG  
51 assessments when compared with crops used as feedstock for first generation liquid biofuels  
52 [10-13]. Crop residues [14-17] and dedicated crops [3,4] can be used as source of  
53 lignocellulosic biomass for bioenergy whereas the first ones usually offer higher resource  
54 efficiency [2]. Furthermore, the use of dedicated energy plantations for bioenergy in Europe  
55 could produce indirect land use changes rising food prices in other countries. For these reasons,  
56 the use of crop residues as lignocellulosic feedstock for heat and electricity production can be  
57 considered as a techno-economic feasible option [18-24] that helps to accomplish previously  
58 mentioned objectives [16,25].

59 Wheat is one of the most important Spanish rainfed crops in terms of its cropping surface and  
60 total production per year with 2.0 million ha and 5.3 dry Mt in average over the last decade [26],  
61 thereby approximately 5.3 dry Mt of wheat straw corresponding to 90 PJ of biomass energy are  
62 jointly produced every year. In most of the Spanish regions, there is an excess of straw due to  
63 the small relevance of ruminant livestock and/or the preference for barley as source of energy  
64 for its feeding. In this situation, the surplus wheat straw is usually incorporated into the soil  
65 aiming to maintain or to increase soil organic matter stock. In the described framework, wheat  
66 straw could be alternatively sold to biomass power plants as feedstock for electricity generation,  
67 instead of being incorporated into the soil. This alternative use of straw can help to reduce the  
68 current national energy dependence and to accomplish EU objectives of GHG reduction and  
69 renewable energies share. Nevertheless, a Life Cycle Assessment (LCA) of this use should be  
70 performed to evaluate environmental impacts and in particular GHG emissions reduction, as the  
71 European Commission recommends for solid biomass production for electricity generation,  
72 heating and cooling [27]. Special attention should be paid to the effect of straw exportation in  
73 GHG emissions due to the possible future decrease of crop fertility and soil carbon stocks  
74 [14,28]. When straw is left into the field a fraction of its carbon content ends up forming humus  
75 (effective organic matter) and consequently a carbon loss should be accounted when straw is  
76 removed. Besides, compensation should be given to the loss of fertility due to the positive effect  
77 of this humus in crop fertility and the nutrients that straw supplies for future crops. There is a  
78 huge uncertainty regarding these facts among others like wheat straw yields, straw humidity and

79 energy content, N<sub>2</sub>O emissions [29,30], diesel consumption of field works, etc. Uncertainty and  
80 variability has been discussed as an important aspect to deal with in the field of LCA in general  
81 [31-33] as well as for the particular case of bioenergy LCAs [7,8,34]. In this study we made a  
82 systematic consideration of parameter uncertainty and variability of all the parameters affecting  
83 all the previous aspects, retrieving data from all the references we found that were valid for our  
84 case. We adjusted statistical distributions for all parameters that have a significant effect in the  
85 results performing goodness of fit tests to choose the best option among distributions when  
86 enough data were available. When data were scarce for a parameter we adjusted triangular or  
87 uniform distributions taking into account the data available and our knowledge of the  
88 phenomenon being studied. There are several LCAs that evaluate use of wheat straw for  
89 combined heat and power (CHP) [14-17] but we are not aware of any published LCA including  
90 parameter uncertainty and variability systematically for all the aspects described previously.  
91 The objective of this study is to perform an accurate evaluation of the environmental  
92 sustainability of the use of wheat straw for electricity generation in Spain. To this end, we  
93 conducted an uncertainty LCA of energy balances and GHG emissions of electricity obtained  
94 from wheat straw and compared the results with those of electricity obtained from natural gas in  
95 Spanish power plants. Monte Carlo simulation and sensitivity analysis were implemented to  
96 incorporate uncertainty and variability affecting to the LCAs produced. GHG savings of  
97 Spanish straw electricity were calculated and compared with thresholds suggested by the EU as  
98 sustainability criteria [27]. Shares of the phases considered in the assessment and critical  
99 parameters affecting results were discussed suggesting possible improvements.

100

## 101 **2 Energy and environmental assessment methodology**

102

### 103 **2.1. Goal, scope and evaluation of data sources and tools**

104 We selected LCA as the environmental assessment tool to determine energetic and  
105 environmental performance (GHG emissions) of the use of wheat straw to generate electrical  
106 energy and its comparison with a fossil reference energy system.

107 LCA involves a systematic set of procedures for compiling and examining the inputs and  
108 outputs of materials and energy and the associated environmental impacts directly attributable to  
109 the functioning of a product or service system throughout its life cycle [35]. This environmental  
110 management tool is regulated by ISO 14040 [35] and ISO 14044 [36] standards, and according  
111 to them, LCAs should follow four steps: (1) goal and definition, (2) inventory analysis, (3)  
112 impact assessment and (4) interpretation.

113 The most important data sources used for the modelling of the inventories of bioenergy system  
114 were: FAOSTAT [26] for wheat yields, ECN Phyllis 2 database [37] for straw energy content,  
115 BIOBID database [38] for straw nutrient contents, the Spanish platform of agricultural

116 machinery for machinery amortization and for diesel and motor oil consumptions of field works  
117 [39], the IPPC [40] and The RSB Methodology [41] for N<sub>2</sub>O emissions and real data of a  
118 Spanish 25 MWe straw power plant for the generation of electricity.

119 We used previous data sources to include parameter uncertainty and variability in order to  
120 provide more accurate results which try to be representative of the different Spanish agricultural  
121 realities. The generation of electricity from natural gas under Spanish conditions has been  
122 chosen as the reference system for comparisons to be one of the cleanest fossil energy sources  
123 for electricity generation [42].

124 Simapro 7.3 software tool and Ecoinvent 2.2 [43] European database have been selected to  
125 conduct the LCAs in this study. For both, the bioenergy system and the natural system  
126 parameter uncertainty and variability were incorporated in the inventories.

127

## 128 **2.2. Functional unit**

129 The generation of 1 TJ of electrical energy from Spanish straw burned in a 25 MWe power plant  
130 have been selected as functional unit for the biomass energy system. The generation of 1 TJe  
131 from natural gas in Spanish conditions has been chosen for the reference fossil system (see **Fig.**  
132 **1**).

133

## 134 **2.3 Systems description**

135 The characteristics and burdens of the bioenergy system and the natural gas system are  
136 described in this section. We chose natural gas Spanish electricity as reference system for  
137 comparisons because is the cleanest fossil energy source available.

138

### 139 **2.3.1 Bioenergy system**

140 The bioenergy system is composed of three subsystems: wheat straw production (agricultural  
141 system), biomass power plant and transport that are going to be explained in detail. The **Fig 1**.  
142 summarises the processes included in the bioenergy system.

143

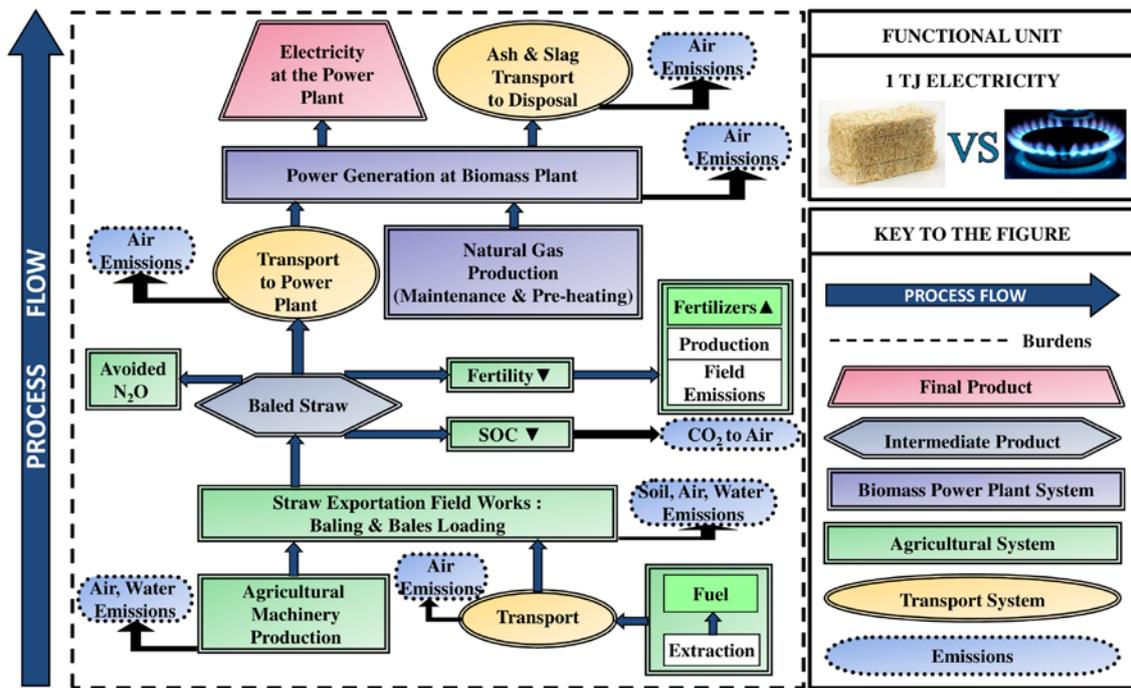


Fig. 1 Bioenergy system burdens and phases included in the analysis.

144  
145

146

147 (1) Wheat straw production subsystem.

148 The objective of wheat cultivation is obtaining grain usually for alimentary purposes. Due to  
149 this fact, wheat straw is considered as a residue and all the inputs and field works needed to  
150 grow wheat in order to produce grain are not considered. Only differences between the wheat  
151 cultivation reference system (straw incorporated in the soil) and the studied system (straw  
152 exported to generate electricity) should be accounted in the LCA of electricity production from  
153 wheat straw.

154 There are some differences in the field works due to straw exportation that should be borne in  
155 mind. During the harvesting the straw is not chopped because is going to be baled and  
156 operations of baling and bale loading are needed. The amount of machinery amortized in these  
157 field works as well as the diesel and motor oil consumption and combustion emissions have  
158 been accounted (see later Sections 2.4.2 and 2.4.3).

159 Other difference is the reduction of N<sub>2</sub>O emissions due to the lower amount of straw left in the  
160 field (see later Section 2.4.4). Straw nitrogen content is crucial for the estimation of these  
161 emissions.

162 One more difference is the reduction of crop fertility in future years due to the effect of the loss  
163 of humus and N, P and K nutrients that straw supplies in the wheat cultivation reference system.  
164 This loss of fertility of the soil has been compensated in our modelling through crop  
165 intensification by the use of more fertilizers. Cherubini states that straw fertilizer effect ranges  
166 from 25% to 75% of its N, P and K straw contents [14], so we consider uniform distributions  
167 following this figures and log-normal distributions for N, P and K straw contents (see later

168 section **2.4.5**). The intensification by the use of nitrogen fertilizer produces a raise in N<sub>2</sub>O  
 169 emissions that have been also accounted (see later Section **2.4.4**).

170 The last and most remarkable difference is the loss of soil organic carbon (SOC) due to straw  
 171 exportation. We consider in our modelling the loss of SOC due to one year of straw exportation  
 172 as follows:

173 
$$CO_2SOC \text{ (kg CO}_2\text{/ha)} = 44/12 \cdot GY \cdot SG \cdot IHC \cdot CSOM$$

174 where CO<sub>2</sub>SOC (kg CO<sub>2</sub>/ha) are the CO<sub>2</sub> emissions due to land use changes in soil organic  
 175 carbon; 44/12 is the factor to convert C in CO<sub>2</sub>; GY(kg grain/ha) is the wheat grain yield in dry  
 176 basis; SG(kg straw/Kg grain) is the straw / grain ratio for Spanish conditions; IHC(kg OM/kg  
 177 Straw) is the isohumic coefficient and measures the amount of straw that turns into humus  
 178 (effective Organic Matter); CSOM(Kg C/kg OM) is the carbon content of soil organic matter.

179 The values that previous parameters take for this study including the uncertainty and variability  
 180 considered for them can be shown in the section **2.4.5**.

181

182 (2) Biomass power plant subsystem.

183 The biomass power plant is modelled using real data from a 25 MWe Spanish straw power plant  
 184 supplied by power plant officers. This plant is considered representative of other existing  
 185 biomass power plants in Spain.

186 The straw power plant consumes small amounts of natural gas in start-up and pre-heating and  
 187 generates ashes and slags as residues of straw burning. Natural gas average consumption and  
 188 ash and slag average generation per kg from straw burned are shown in **Table 1**. Aerial  
 189 emissions are submitted online to regional authorities and its average values are presented in  
 190 **Table 1** as well. The emissions accounted in the assessments are only those which affect the  
 191 global warming potential (GWP). Fossil carbon dioxide emissions of natural gas burning are  
 192 taken into account. The emissions of carbon dioxide from straw combustion have not been  
 193 accounted because CO<sub>2</sub> was previously fixed from the air by the crop no more than one year  
 194 before being burned.

195  
 196  
 197

**Table 1**  
 Biomass power plant consumptions, residues and emissions

Items	Type	Amount	Units
Natural gas	Consumption	0.0389	MJ/Kg Dry Biomass
Slags	Residue	93.72	g/Kg Dry Biomass
Ashes	Residue	9.38	g/Kg Dry Biomass
Carbon Dioxide from natural gas	Emission	2.16	g/Kg Dry Biomass
Nitrogen oxides	Emission	1.85	g/Kg Dry Biomass
Carbon monoxide	Emission	1.05	g/Kg Dry Biomass
Sulphur dioxide	Emission	0.36	g/Kg Dry Biomass
Particulates	Emission	0.27	g/Kg Dry Biomass

198

199 All the factors of uncertainty and variability affecting the power generation subsystem  
 200 parameters are described in section **2.4.5**.

201

202 (3) Transport subsystem.

203 The main characteristics of transport system are shown in **Table 2**, the information shown  
204 includes: materials to transport, origin and destination points, distances, and means of transport  
205 used.

206 Transport distances and transport means of agricultural inputs until regional storehouses are  
207 considered as in Ecoinvent [44]. We assumed 10 km as a good estimate of the average transport  
208 distance for agricultural inputs from the storehouse to farmer's plots. Officers in charge of the  
209 power plant operation provided average transport distances and transport means for straw bales,  
210 ashes and slags.

211 The biomass transport distance from farmer's plots to biomass power plant is calculated as  
212 follows:

$$213 \text{SBTD(km)} = ((\text{CSYN}/100)/(2 \cdot \pi \cdot \text{CLA}))^{0.5}$$

214 where SBTD(km) is straw bales transport distance; CSYN(ha) is the crop surface needed to  
215 achieve the annual electricity production of the biomass plant working 330 days uninterruptedly  
216 per year and CLA(available ha/total ha) is the crop land available in the region to grow wheat  
217 and collect the straw for bioenergy purposes.

218 **Table 2**  
219 Transport system characteristics

Material	From	To	Distance	Vehicle
Fertilizers	Manufacturer	Regional storehouse	600 km	Train
			100 km	Lorry >16t
	Regional storehouse	Plot	10 km	Tractor and Trailer
Straw bales	Farmer plot	Biomass plant	56 km	Lorry 16-32t
Ash and slag	Biomass power plant	Disposal site	37 km	Lorry 16-32t

220

221 The output of the whole bioenergy system is the electrical energy generated. This energy output  
222 is calculated as follow:

$$223 E(\text{MJe/ha}) = \text{GY} \cdot \text{SG} / (1 - \text{H}) \cdot (1 - \text{SL}) \cdot \text{NHV}_{\text{CP,H}} \cdot \eta$$

224 where E(MJe/ha) is the electrical energy generated; GY(kg grain/ha) is the wheat grain yield in  
225 dry basis; SG(kg straw/kg grain) is the ratio between the straw and the grain production; H(kg  
226 water/kg wet straw) is the water content of wheat straw in a per unit basis; SL(kg loss/kg straw)  
227 are the losses of straw due to bales storage in the plot in a per unit basis;  $\text{NHV}_{\text{CP,H}}$ (MJ/kg) is the  
228 net heating value of wheat straw at constant pressure at water content (H);  $\text{NHV}_{\text{CP,H}}$ (MJ/kg) =  
229  $\text{NHV}_{\text{CP,0}} \cdot (1 - \text{H}) - 2,444 \cdot \text{H}$  and  $\eta$ (MJe/MJ straw) is the conversion efficiency of wheat straw into  
230 electricity in a per unit basis.

231 The values that prior parameters take for this assessment are presented in **Table 3**.

232

233

### 234 **2.3.2 Natural Gas System**

235 The natural gas system models the generation of electricity using natural gas in power plants  
236 under Spanish conditions. The system considers the exportation of natural gas to Spain of main  
237 exporter countries (Algeria 73% and Norway 27%), including the gas field operations for  
238 extraction, the losses, the emissions, and the purification. The long distance travel to Spain as  
239 well as the transportation to Spanish power plants is considered, including energy consumption,  
240 losses and emissions. Average efficiencies as well as inputs needed and typical emissions of  
241 Spanish natural gas power plant are taken into account [42]. LCI of the previous system  
242 considers parameter uncertainty according to Ecoinvent modelling.

243

### 244 **2.4. Life cycle inventory structure**

245 The inventories used to consider natural gas consumption of the biomass power plant and the  
246 transportation of agricultural inputs, biomass and power plant residues are taken from Ecoinvent  
247 v2.2. The methods used for the inventory analysis of the agricultural system mainly follow  
248 those proposed in the life cycle inventories of agricultural production systems [44]. The  
249 calculation of N<sub>2</sub>O emissions is based on the guidelines of the RSB GHG Calculation  
250 Methodology v 2.1 [41].

251

#### 252 **2.4.1 Fertilizers production**

253 The inventories for fertilizers production include the consumption and transport of raw  
254 materials and intermediate products as well as the energy consumption and the emissions  
255 generated in the production processes [44].

256

#### 257 **2.4.2 Diesel and motor oil consumption and combustion emissions of agricultural 258 machinery**

259 The diesel and motor oil consumption of agricultural machinery are obtained from the Spanish  
260 platform for the knowledge of agricultural machinery [39]. We considered the difference in field  
261 works between incorporating the straw into the soil and exporting it. This implies subtracting  
262 the consumption of chopping straw and accounting the consumptions for baling and bale  
263 loading. The platform provides for each fieldwork, lifetime of tractor or harvester and  
264 implements used, power of the tractor or harvester, operation time and diesel and motor oil  
265 consumption per hectare. Changing the conditions in operations performed from best to worst  
266 (more consuming) possible ones is how we establish the range for diesel and oil consumption  
267 factor (DOCF) shown in **Table 3**. Diesel and oil consumption depend on biomass productivity  
268 and this is taken into account apart from the DOCF. According to the Spanish platform [39] the  
269 consumption of motor oil for tractors is 1 % of the diesel consumption.

270 The inventories for the extraction, the transportation of crude oil, its transformation into diesel,  
271 and its distribution are taken from Ecoinvent [45]. Exhaust emissions from agricultural  
272 machinery engines are also taken into account [46].

273

#### 274 **2.4.3 Agricultural machinery manufacture**

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

277 The amount of machinery (AM) consumed for carrying out a specific agricultural operation was  
278 calculated by multiplying the weight (W) of the machinery by the operation time (OT) and  
279 dividing the result by the lifetime of the machinery (LT) [44]:

$$280 \text{AM (kg/FU)} = W(\text{kg}) \cdot \text{OT} \cdot (\text{h/FU}) / \text{LT}(\text{h})$$

281 where FU (see former Section 2.2) is the functional unit of the LCA. The operation time, the  
282 lifetime and the weights of the machinery considered for all operations are obtained from the  
283 Spanish platform for the knowledge of agricultural machinery [39].

284

#### 285 **2.4.4 Field and fertilizers derived emissions (Nitrous oxide emissions)**

286 There is debate regarding methodologies [40,41,44] and factors that should be used for the  
287 estimation of N<sub>2</sub>O emissions. This debate has been raised in several bioenergy life cycle  
288 assessments and reviews [47-49] given that its importance is critical when assessing GWP  
289 reductions [50]. To provide a good estimation of N<sub>2</sub>O emissions we follow the RSB GHG  
290 Calculation Methodology v 2.1 [41] given that it reflects the present state of research and it is  
291 based on methods which provide detail and consistency. Nitrate leaching emissions affecting to  
292 N<sub>2</sub>O emissions have not been included because its estimation is based on the interrelation  
293 several local parameters and is difficult to obtain meaningful estimates for Spain as a whole.

294 The calculation of the N<sub>2</sub>O emissions proposed by the RSB [41] is based on the formula in  
295 Nemecek et Kägi [44] and adopts the IPCC guidelines [40]:

$$296 \text{N}_2\text{O}(\text{Kg N}_2\text{O/ha}) = 44/28 \cdot (\text{EF}_1 \cdot (\text{N}_{\text{tot}} + \text{N}_{\text{cr}}) + \text{EF}_4 \cdot 14/17 \cdot \text{NH}_3)$$

297 where N<sub>2</sub>O(kg N<sub>2</sub>O/ha) are emissions of N<sub>2</sub>O; 44/28 is the conversion factor of N-N<sub>2</sub>O in N<sub>2</sub>O;  
298 EF<sub>1</sub>(Kg N-N<sub>2</sub>O/kg N inputs) is the factor that gives the fraction of N inputs that is converted  
299 into N<sub>2</sub>O (see **Table 3**); N<sub>tot</sub>(kg N/ha) is the total nitrogen input from fertilizers; N<sub>cr</sub> is the  
300 nitrogen contained in the crop residues (kg N/ha); EF<sub>4</sub> is the factor that gives the fraction of N-  
301 NH<sub>3</sub> that is converted in N-N<sub>2</sub>O (Kg N-N<sub>2</sub>O/kg N-NH<sub>3</sub>) (see **Table 3**); 14/17 is conversion  
302 factor of NH<sub>3</sub> in N-NH<sub>3</sub>; NH<sub>3</sub> are the losses of nitrogen in the form of ammonia (kg NH<sub>3</sub>/ha)  
303 calculated as proposed in the RSB [41] and Nemecek et Kägi [44] methodologies.

304

305

306

#### 307 **2.4.5 Parameter uncertainty and variability**

308 Results obtained from LCA can have high uncertainties due to the considerable amounts of  
309 measured and simulated data and the simplification of models that try to represent complex  
310 environmental cause-effect chains [51]. There are several examples of quantitative uncertainty  
311 assessments in LCA that deal with this problem [32] and more are appearing over time.  
312 However, the incorporation of uncertainty through the use of a stochastic modeling with Monte  
313 Carlo Simulation is not yet a common practice for recent LCA studies, despite of the  
314 recommendations that were made years ago [52].

315 We systematically included parameter uncertainty and variability for all the inventories that  
316 have a significant importance for the results and then we performed Monte Carlo simulations.  
317 When enough data was available a distribution was fitted to the parameter sample following a  
318 scientific procedure. In order to fit the best possible distribution goodness of fit tests were  
319 performed in combination with graphical tests as quantile-quantile plot. When the amount of  
320 data was not enough to adjust a distribution following previous procedure, simpler distributions  
321 (uniform or triangular) were chosen. We chose between triangular and uniform distributions and  
322 adjusted them taking into account the values retrieved from the references we found and authors  
323 knowledge of the phenomenon being studied (see **Table 3**). Percentiles of 5 % (P05) and 95 %  
324 (P95) were calculated for each distribution in order to perform a sensitivity analysis to  
325 determine the most influencing parameters (See **Fig 5** and **Fig 9**). The ideal situation when  
326 dealing with uncertainty and variability [31] is to separate their effects for each parameter and  
327 perform a tiered Monte Carlo simulation [53]. However, it is not possible to separate the effects of  
328 uncertainty and variability for all the parameters defined in this study, due to this fact and for  
329 consistency reasons, the distributions shown in **Table 3** consider the effects of uncertainty and  
330 variability together.

331

332  
333

**Table 3**  
Uncertainty and variability of LCI parameters

	Parameter	Units	Distribution <sup>1</sup>	P05 <sup>2</sup>	P95 <sup>3</sup>	Data Sources and Explanations	Refs
	GY Wheat grain yield	kg/ha	LN (2462,582)	1633	3516	Last 15 years wheat yields available for Spain. 11 % Humidity of grains was subtracted from data	[26]
	SG Straw/grain	kg/kg	U (0.9, 1.1)	0.91	1.09	Adapted to Spanish typical yields and cutting heights	[54]
	SL Straw storage losses	kg lost/ kg stored	U (0.01, 0.03)	0.011	0.029	2 % can fit well for Spanish dry weather. A ± 50 % variation was considered appropriate.	[55]
NHV <sub>CP,0</sub>	Straw NHV 0% Humidity	MJ/kg	LN (16.94, 0.99)	15.4	18.6	37 wheat straw samples from ECN Phyllis 2 database	[37]
	SH Straw humidity	% wb	T (12, 10, 16)	10.8	14.9	Based on officers from a Spanish 25 MW biomass power plant	
	PE Power plant efficiency	MJe/ MJ straw	T (0.30, 0.29, 0.31)	0.293	0.307	Based on officers from a Spanish 25 MW biomass power plant	
	IHC Isohumic coefficient	kg SOM/ kg straw	T (0.10,0.08, 0.15)	0.088	0.137	Appropriate for Spain when straw is buried without nitrogen fertilizers application.	[56-59]
CSOM	Soil carbon factor	kg SOC/ kg SOM	U (0.50, 0.56)	0.503	0.557	Usually 0.58 value is used for this factor but this value is more a maximum than an average.	[60]
	SFC Straw exportation fertility compensation	kg Fertilizer/ Nutrient Content	U (0.25, 0.75)	0.275	0.725	Based on Cherubini LCAs.	[14]
	SN Straw N	kg Nutrient/	LN (0.568, 0.180)	0.0326	0.901	18, 18 and 20 samples were used from BIOBID database. Negative values of distributions were converted to zero.	
	SK Straw P <sub>2</sub> O <sub>5</sub>	kg Straw	T(0.188, -0.027, 0.221)	0.0247	0.201	Straw K and P contents were transformed to K <sub>2</sub> O and P <sub>2</sub> O <sub>5</sub> as fertilizers doses are given this way.	[38]
	SP Straw K <sub>2</sub> O		T (1.63, -0.23, 1.63)	0.186	1.583		
	EF <sub>1</sub> IPCC Factor 1	Kg N-N <sub>2</sub> O/	T (0.01, 0.003, 0.03)	0.0061	0.0248	IPCC Factors for N <sub>2</sub> O emissions. For both factors triangular distributions with the typical values as modes and extreme values of IPCC interval as maximum and minimum were used.	[40]
	EF <sub>4</sub> IPCC Factor 4	kg N inputs	T (0.01, 0.002, 0.05)	0.0064	0.0402		
DOCF	Diesel & Oil Consumption Factor		U (0.75, 1.25)	0.775	1.225	Good estimate for consumption variation when conditions for and specific operation change.	[39]
CLA	Crop Land availability	ha available/ ha total	T(0.03, 0.015, 0.045)	1.97	4.03	Own estimation based on average biomass transport distance provided by power plant owners.	
NGF	Natural Gas Factor		U(0.5, 1.5)	0.55	1.45	A ± 50 % variation from data provided by 25 MW power plant owners was considered appropriate.	
ASPF	Ash & Slag production		U(0.75, 1.25)	0.775	1.225	A ± 25 % variation from data provided by 25 MW power plant owners was considered appropriate.	
ASTF	Ash & Slag transport		U(0.75, 1.25)	0.775	1.225	A ± 25 % variation from data provided by 25 MW power plant owners was considered appropriate.	
PPEF	Power plant emissions		U(0.75, 1.25)	0.775	1.225	A ± 25 % variation from data provided by 25 MW power plant owners was considered appropriate.	

334 <sup>1</sup>LN: Log-Normal(average, standard deviation) U: Uniform(minimum, maximum) T: Triangular(mode, minimum, maximum).

335 <sup>2</sup>Percentile of 5 %

336 <sup>3</sup>Percentile of 95%

337

## 338 2.5. Life cycle impact assessment

339 In the Life Cycle Impact Assessment (LCIA) phase of an LCA the inputs and outputs of  
340 elementary flows that have been collected and reported in the inventory are translated into  
341 impact indicator results [61]. LCIA includes mandatory and optional steps. We carried out  
342 mandatory steps of classification and characterization and avoided optional steps of  
343 normalization and weighting optional steps.

344

### 345 2.5.1. Environmental impact assessment method

346 The impact assessment method chosen to evaluate the GWP is the IPCC 2007 100 years' time  
347 horizon [62]. The method calculates the cumulative radiative forcing caused by a unit mass  
348 emission of a GHG, integrated over a 100 year time horizon, as compared with the cumulative

349 radiative forcing due to emission of a unit mass of carbon dioxide (CO<sub>2</sub>) over the same time  
350 horizon.

351

### 352 2.5.2. Energy assessment method

353 Cumulative Energy Requirement Analysis (CERA) [63] was the method chosen to assess the  
354 energy consumed to generate electricity from wheat straw biomass and from natural gas. This  
355 method aims to calculate the energy use throughout the life cycle of a good or service.

356

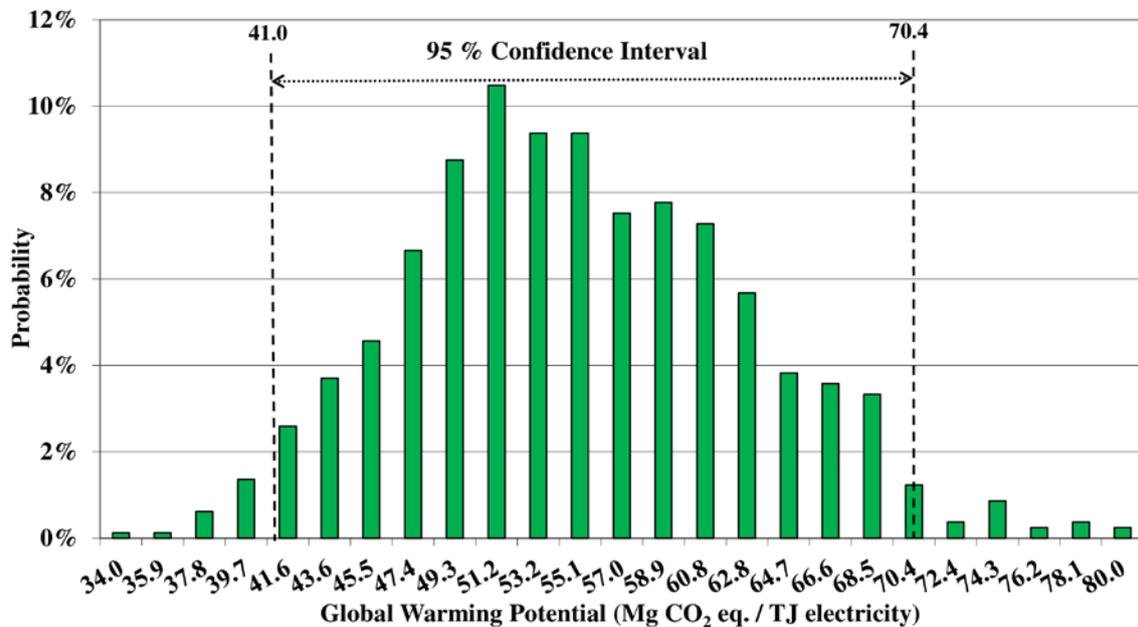
## 357 3 Results

358

### 359 3.1 Global Warming Potential

360 In the Fig. 2 can be shown the probability distribution of the GWP generated in the production  
361 of 1 TJe from wheat straw. The results were within the confidence interval that goes from 41 to  
362 70 Mg CO<sub>2</sub>eq/TJe with a 5 % significance level. The mean value obtained was 55 Mg CO<sub>2</sub>eq/TJe,  
363 this is a 62 % less than the 143 Mg CO<sub>2</sub>eq/TJe obtained when Spanish natural gas electricity was  
364 simulated. When 1 TJe of natural gas electricity was compared with the same amount of  
365 electricity coming from wheat straw, in 100 % of the simulations the GWP generated by natural  
366 gas was higher.

367



368

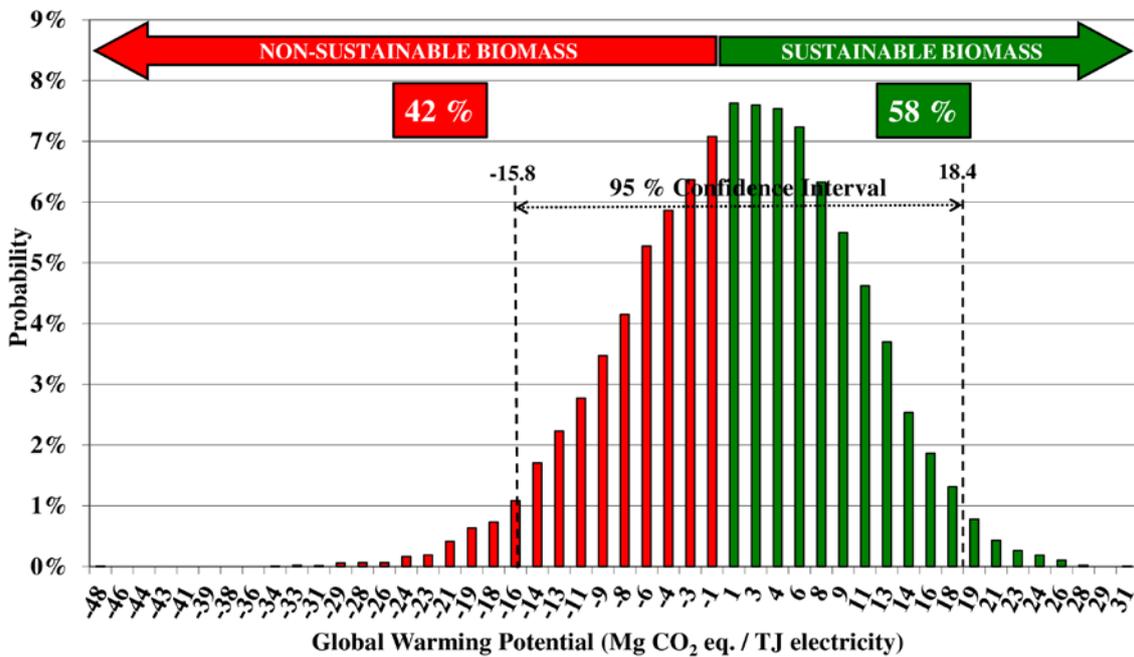
369 Fig. 2. Probability distribution of GWP incurred in the generation of 1TJ of electricity from wheat straw in Spain. Monte Carlo  
370 simulation needed 811 number of runs to obtain as standard error of the mean lower than 0.5 % of the average.

371

372 The European Commission recommends following the same sustainability criteria for solid and  
373 gaseous biofuels [27] as the binding criteria established by the RED [64] for liquid biofuels.

374 Due to this fact, we have assumed that sustainable electricity production from wheat straw

375 should have at least 60% of GHG savings compared to the reference, as this is the amount  
 376 required by the RED for liquid biofuels after 2017. **Fig. 3** shows in positive (green) the  
 377 exceeding GWP reduction of the simulations that accomplished the 60 % of GHG savings  
 378 criteria and in negative (red) the missing GWP to accomplish the same criteria. The results were  
 379 between -16 and 18 Mg CO<sub>2</sub>eq/TJe with a 5 % significance level. The generation of electricity  
 380 by straw burning under Spanish conditions accomplished the EU biomass sustainability criteria  
 381 for 58% of the 17205 simulations done. According to these results, production of electricity  
 382 from Spanish wheat straw was sustainable in the majority of cases but it should be borne in  
 383 mind that there is a probability of 38 % of being outside the EU sustainability zone.  
 384



385  
 386 **Fig. 3.** Probability distribution of the GWP of the simulations that saved more (in green) and less (in red) than the 60 % GHG saving  
 387 threshold in the comparisons of wheat straw electricity and natural gas electricity under Spanish conditions. Monte Carlo simulation  
 388 needed 17205 runs to obtaining a standard error of the mean lower than 0.5% of the average value of the simulations.  
 389

390 The GPW shares of the different phases of the production of straw electricity are shown in **Fig.**  
 391 **4.** The loss of soil organic carbon was the most contributing phase with 39.8 Mg CO<sub>2</sub> eq./TJe  
 392 electricity followed by the compensation of fertility decrease with 9.0 Mg CO<sub>2</sub> eq./TJe  
 393 electricity. The avoided N<sub>2</sub>O emissions due the lower amount of crop residues that remain into  
 394 the field had a remarkable negative contribution of 5.5 Mg CO<sub>2</sub> eq./TJe. The phases of biomass  
 395 transport and the power plant operation had limited impact compared to others.  
 396

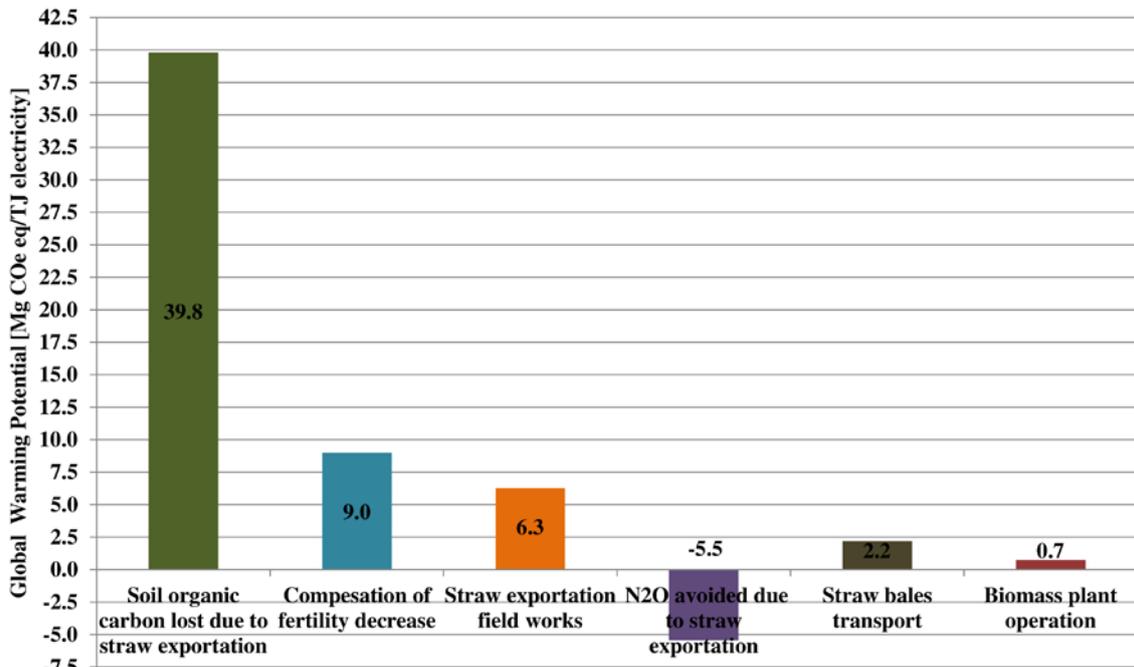
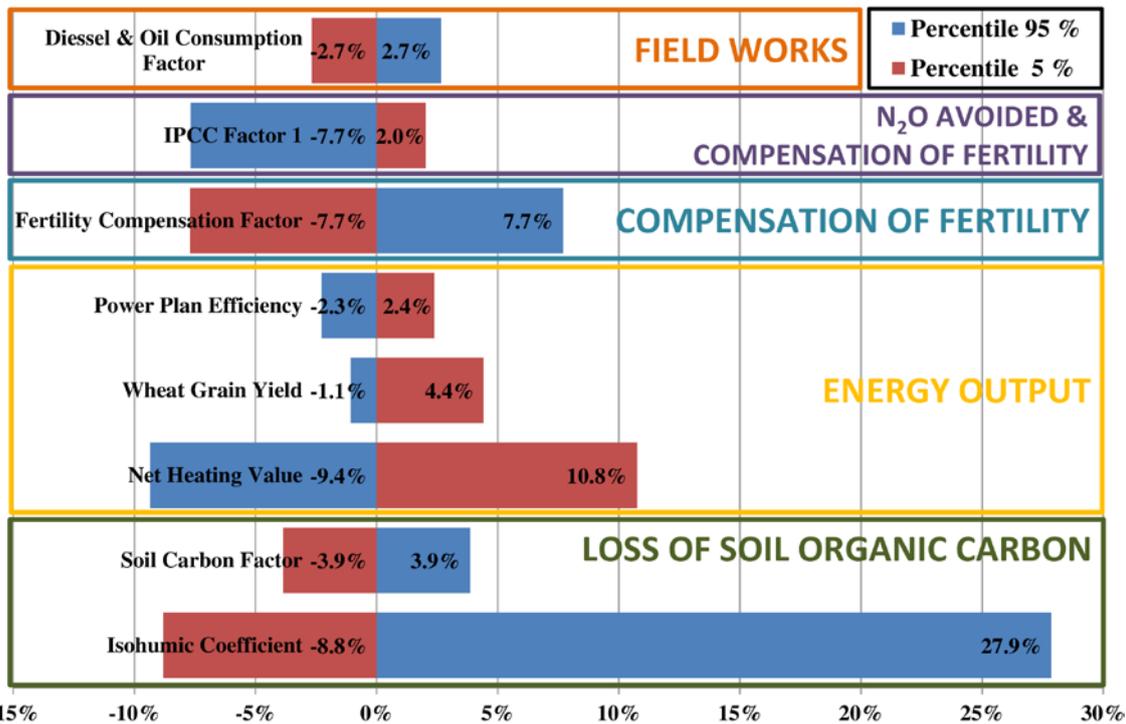


Fig. 4. GPW shares of Spanish wheat straw electricity for average values.

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398  
399

400 The sensitivity analysis of the most influencing parameters for the GWP and the phases of the  
 401 analysis that they are affecting can be shown in **Fig. 5**. It can be observed that for parameters  
 402 which are modelled with non- symmetric distributions (see **Table 4**) the upper (P95) and the  
 403 lower (P05) percentiles influences had remarkable differences between them. This is the case of  
 404 isohumic coefficient, net heating value, grain yield and IPCC factor 1. Isohumic coefficient was  
 405 the most sensitive parameter especially for the 95% percentile. The net heating value and the  
 406 fertility compensation factor also had big influences in the sensitivity analysis with a P05-P95  
 407 range that is more than 10 % the GWP of the average case.



408  
 409 **Fig. 5.** Sensitivity analysis of parameters which P05-P95 percentile ranges are more than 5 % of the average straw electricity GWP.  
 410 The phases which parameters contribute to are shown in colored squares.  
 411

### 412 3.2 Cumulative Energy

413 The **Fig. 6** shows in red the percentage of the simulations in which electricity from wheat straw  
 414 consumed more energy than electricity from natural gas for each type of energy source, the  
 415 opposite situation is presented in green. Total primary energy was higher for straw electricity in  
 416 more than 95 % of the simulations because the biomass energy content of the straw has been  
 417 included in the calculations. Nevertheless, non renewable fossil energy consumption was always  
 418 higher for natural gas electricity, being also the most consumed of the three non-renewable  
 419 sources of energy evaluated.

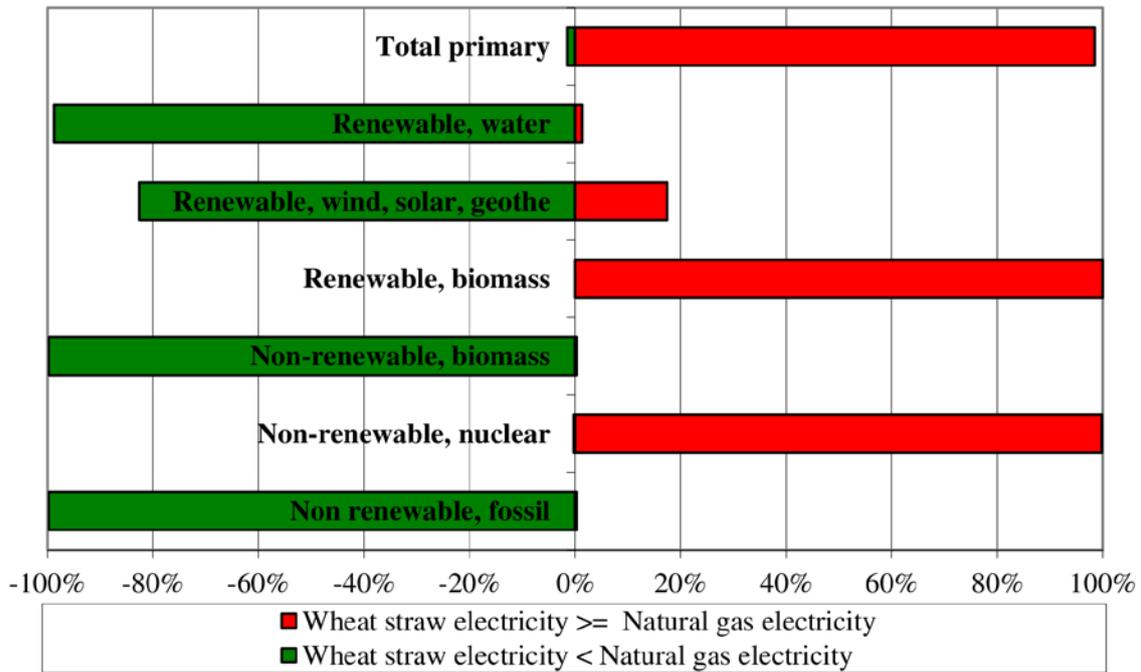
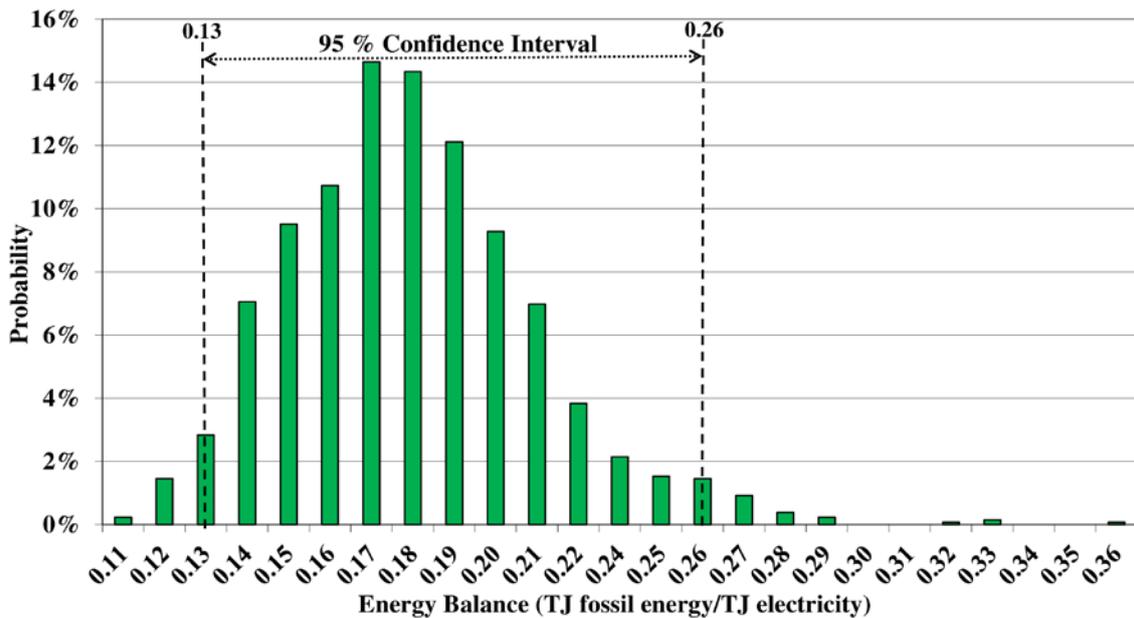


Fig. 6. Uncertainty analysis of the different sources of primary energy consumed in the generation of 1 TJ of electricity natural gas electricity minus 1 TJ of electricity from wheat straw.

420  
421  
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423

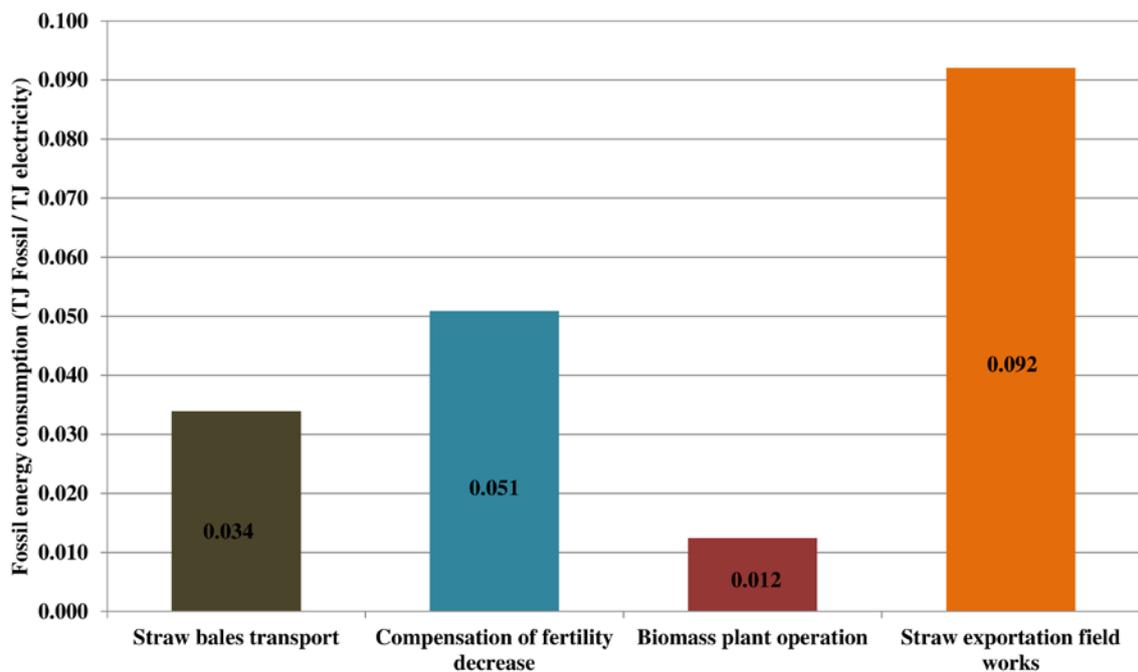
424 The probability distribution of the fossil energy consumed to produce 1 TJ of electricity from  
425 wheat straw is show in **Fig. 7**. The fossil energy consumption was studied separately due to the  
426 non renewable and scarceness characteristics of fossil fuels. The fossil energy consumption for  
427 straw electricity was within the confident interval that goes from 0.13 to 0.26 TJ fossil/TJ  
428 electricity with a 5 % significance level. The mean value obtained was 0.18 TJ fossil/TJ  
429 electricity, this is more than ten times less than the 2.44 TJ fossil/TJ electricity obtained for  
430 natural gas electricity. The mean value of fossil energy consumption obtained for straw  
431 electricity implies that the production of electrical energy was more than five times higher than  
432 the fossil energy consumed for its generation.

433



434  
 435 Fig. 7. Probability distribution of fossil energy consumed in the generation of 1TJ of electricity from wheat straw in Spain. Monte  
 436 Carlo simulation needed 1304 number of runs to obtain as standard error of the mean lower than 0.005.  
 437

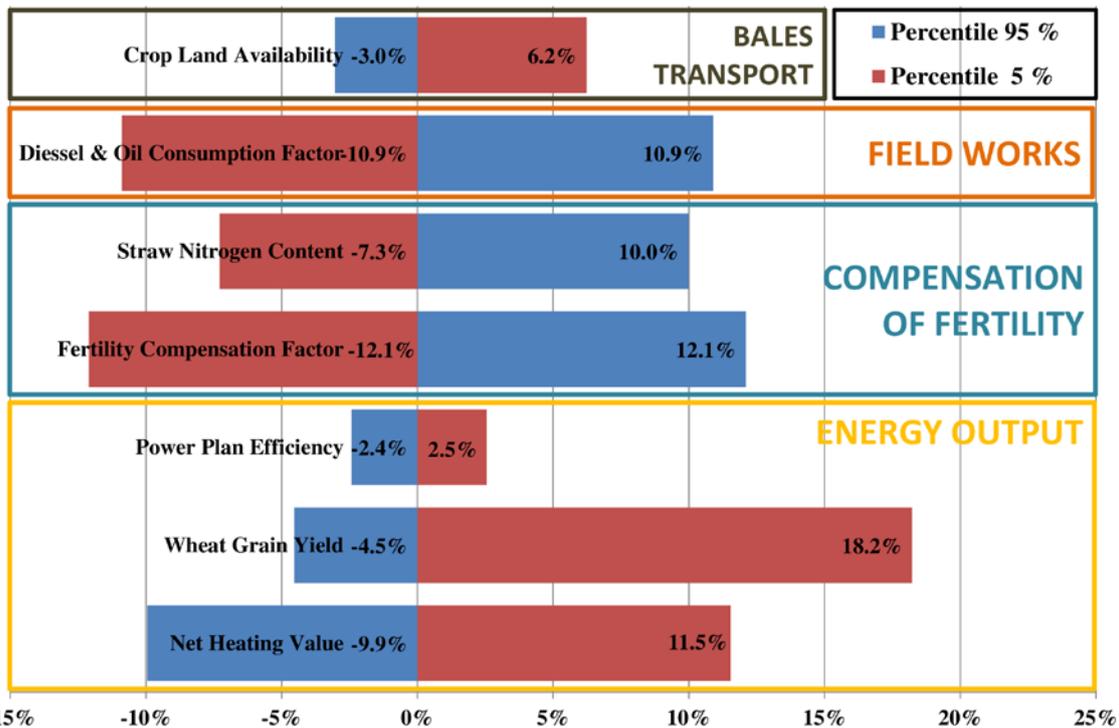
438 The Fig. 8 shows the fossil energy shares of the production of straw electricity. The most fossil  
 439 energy consuming phase was the extra field works needed to export straw bales with 49 % of  
 440 the total. The fertilizers intensification to compensate fertility loss was the second phase in order  
 441 importance with 27% of the total. Bales transport and biomass plant operation accounted  
 442 together for 24 % of total fossil energy consumed.  
 443



444  
 445 Fig. 8. Fossil energy shares of Spanish wheat straw electricity for average values.  
 446

447 The sensitivity analysis of the most influencing parameters for the fossil energy consumption  
 448 and the phases that they are affecting can be shown in Fig. 9. The fertility compensation factor

449 was one of the most sensitive parameters for fossil energy, raising or lowering its consumption  
 450 in more than 12 % for both the 95 % and the 5 % percentile. The wheat grain yield was the  
 451 second parameter in order of influence, when it took the value of the 5 % percentile fossil  
 452 energy consumption raised more than 18 %. Diesel consumption factor and net heating value  
 453 had similar importance in this sensitivity analysis producing variations of around 10 % for 5%  
 454 and 95 % percentiles values with respect to average figures.  
 455



456 -15% -10% -5% 0% 5% 10% 15% 20% 25%  
 457 Fig. 9. Sensitivity analysis of parameters which P05-P95 percentile ranges are more than 5 % of the average straw electricity fossil  
 458 energy demand. The phases which parameters contribute to are shown in colored squares.  
 459

#### 460 4. Discussion

461  
 462 The average results presented in this article for the GWP assessment of wheat straw electricity  
 463 (55 Mg CO<sub>2</sub> eq/TJe ) were very similar to previously published results for winter cereals grown  
 464 as dedicated energy crop for electricity generation in the Spanish province of Soria (52 Mg CO<sub>2</sub>  
 465 eq/TJe) [4] and slightly higher than the ones obtained for *Brassica Carinata* (47 Mg CO<sub>2</sub>  
 466 eq/TJe) cultivated also in Spain [65]. Upon comparing these values it should be borne in mind  
 467 that the methodologies used and the burdens of these studies have some differences between  
 468 them. The accounting of the loss of soil organic carbon due to wheat straw exportation is the  
 469 main reason for obtaining a higher GWP value for the LCA of a crop residue than for the LCAs  
 470 of previously mentioned dedicated energy crops.

471 Loss of soil organic carbon is the main driver of GWP in the production of electricity from  
 472 straw and its value is crucial to know if more than 60 % of GHG savings can be obtained when

473 comparing straw electricity with natural gas electricity in Spain. The isohumic coefficient and  
474 the soil carbon factor are the parameters which influence the most this carbon loss. They depend  
475 on local factors as crop residue and soil characteristics, rainfall, temperature, etc., and can be  
476 estimated more precisely for a specific plot of terrain. Due to this fact, we recommend using  
477 local parameters if available or develop local experiments to guess about them since the  
478 accomplishment of EU sustainability criteria is highly dependent of these factors according to  
479 our modelling. This is in line with the recommendations of recent studies [51,66] that  
480 emphasized the importance of local aspects and case-specific conditions in LCAs results.

481 The selection wheat varieties more adapted to bioenergy with higher neat heating value and  
482 lower straw nitrogen content can provide better results especially for fossil energy consumption.  
483 In the selection of these varieties it should be borne in mind that the main objective of growing  
484 wheat is grain production so varieties selection for bioenergy should respect grain quality and  
485 productivity. Provided that the nitrogen content is a requirement for grains to achieve good  
486 quality and high productivity, harvesting in the optimal moment when all nitrogen has migrated  
487 to grains can be as well a good strategy that will help to minimize nitrogen content in straw.  
488 Higher nitrogen content in straw is negative for fossil energy consumption because more  
489 inorganic fertilizer will be used to compensate the loss of fertility due to straw exportation.  
490 Nevertheless, higher nitrogen content in straw has opposing effects for GWP. The higher  
491 nitrogen content in straw the more nitrous oxide is avoided due to lower emissions of crop  
492 residues that are not left into the field any more. However, more inorganic nitrogen fertilisers  
493 are needed to compensate fertility loss because of straw exportation and also more nitrous oxide  
494 is emitted due to the application of these fertilizers. Doing further research to reduce the  
495 uncertainty of the fertility compensation factor could help to provide more precise results.  
496 Although many companies are not very willing to share information about their production  
497 processes, LCA practitioners should try to obtaining country specific recent data on fertilizer  
498 production systems [7]. This usually provides more precise inventories and results in lower  
499 impacts due to the effect of more efficient production processes and new technologies that  
500 capture GHGs. The probability of having high humidity in bales in Spain is not as high as in  
501 other countries with higher precipitations in summer but using tarped cover storage could also  
502 minimize storage losses and reduce straw humidity in case of rain [67].

503 Field works optimization is other important task to be performed to minimise GWP and energy  
504 consumption. Proper sizing and maintenance of the tractor as well as performing field works at  
505 the optimal velocity could help to reduce diesel consumption and therefore reduce GWP and  
506 fossil energy consumption.

507 More efficient power plants will reduce impacts on GWP and fossil energy consumption.  
508 However, a trade of exists since more efficient plants are usually bigger and they require more  
509 biomass that is transported from further locations. A possible solution to minimise this raise of

510 the biomass transport distance could be to choose the best possible location for the plant and  
511 stimulate more the local farmers established near the power plant to grow wheat sell their bales to  
512 this industry.

513

#### 514 **4 Conclusions**

515

516 The systematic inclusion of parameter uncertainty and variability for most influencing  
517 parameters of the LCAs of bioenergy systems is an important task to be performed in the search  
518 of more accurate results that help decision makers to give more supported answers to bioenergy  
519 sustainability criteria accomplishment.

520 The production of electricity from wheat straw in Spain resulted in lower GHG emissions than  
521 Spanish natural gas electricity for 100% of the simulations. However, only 58 % of the  
522 simulation accomplished EU sustainability criteria of 60% GHG savings when compared with  
523 natural gas electricity. This result implies that although production of electricity from straw is  
524 sustainable for the majority of the cases, there is also a big probability of not accomplishing the  
525 EU threshold, in which case most influencing phases should be analyzed searching ways to  
526 minimize impacts.

527 The optimization of field works performed for straw exportation in combination with the  
528 reduction of storage losses and bale humidity could slightly increase the GHG savings and  
529 reduce the fossil energy consumption. The selection of wheat varieties with higher straw net  
530 heating value could also be an improvement. However, as the sensitivity points out, the  
531 parameters that affect the calculation of the soil organic carbon losses due to straw exportation  
532 are the most influencing for GWP assessment and therefore they are crucial to clarify if the EU  
533 sustainability criteria of 60 % GHG savings is accomplished for Spanish straw electricity. Due  
534 to this fact, we understand that local and case specific estimation of soil carbon factor and  
535 especially isohumic coefficient are unavoidable tasks to reduce the uncertainty and provide a  
536 definitive answer to the accomplishment of EU sustainability criteria of a crop residue harvested  
537 in a specific location.

538

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545

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