

# 1            **Balance and saving of GHG emissions in thermochemical biorefineries**

2            Pedro Haro<sup>a,\*</sup>, Cristina Aracil<sup>a,b</sup>, Fernando Vidal-Barrero<sup>b</sup>, Pedro Ollero<sup>b</sup>

3            <sup>a</sup> Andalusian Association for Research & Industrial Cooperation (AICIA). Camino de los  
4 Descubrimientos s/n. 41092 Seville, Spain

5            <sup>b</sup> Bioenergy Group, Chemical and Environmental Engineering Department. Escuela Técnica  
6 Superior de Ingeniería, Universidad de Sevilla. Camino de los Descubrimientos s/n. 41092  
7 Seville, Spain

8            \* corresponding author. E-mail: [pedrogh@us.es](mailto:pedrogh@us.es)

## 10          **ABSTRACT**

11          In this study, a simplified methodology for the calculation of the balance of greenhouse  
12 gas (GHG) emissions and corresponding saving compared with the fossil reference is  
13 presented. The proposed methodology allows the estimation of the anthropogenic GHG  
14 emissions of thermochemical biorefineries (net emitted to the atmosphere). In the  
15 calculation of the GHG balance, all relevant factors have been identified and analyzed  
16 including multiproduction, emissions from biogenic carbon capture and storage (Bio-  
17 CCS), co-feeding of fossil fuels (secondary feedstock) and possible carbon storage in  
18 biomass-derived products (chemicals). Therefore, it is possible to calculate the balance  
19 of GHG emissions of a hypothetical thermochemical biorefinery considering different  
20 alternatives of land-use, biomass feedstock, co-feeding of fossil fuels, Bio-CCS  
21 incorporation and final use of the products. The comparison of the estimated GHG  
22 balance with the corresponding fossil reference for each product is of special relevance  
23 in the methodology since it is the parameter used in European regulation for the fulfillment  
24 of sustainability criteria in biomass-derived fuels and liquids. The proposed methodology  
25 is tested using a previously assessed set of different process concepts of thermochemical  
26 biorefineries (techno-economic analysis). The resulting GHG balance and saving are  
27 analyzed to identify uncertainties and provide recommendations for future regulation. In  
28 all process concepts, the GHG savings are above the minimum requirement of GHG

29 emissions for 2018. In the case of incorporating Bio-CCS, cradle-to-grave negative GHG  
30 emissions are obtained. However, in order to assess the role of chemical co-production  
31 from biomass, they need to be included in future regulation.

32

33 **Keywords:** thermochemical biorefinery; balance of GHG emissions; saving of GHG  
34 emissions; multiproduction; Bio-CCS

## 35 **NOMENCLATURE**

- 36 A: factor scaling to the area concerned
- 37 CC: carbon content (g of CO<sub>2</sub> eq. / MJ of chemical)
- 38 CS<sub>A</sub>: carbon stock per unit area associated with the actual land use
- 39 CS<sub>R</sub>: carbon stock per unit area associated with the reference land use
- 40 C<sub>VEG</sub>: above and below ground vegetation carbon stock
- 41 E: GHG balance (g CO<sub>2</sub> eq. / MJ of all products)
- 42 e<sub>B</sub>: bonus of 29 g CO<sub>2</sub> eq. / MJ energy carrier if biomass is obtained from restored degraded land
- 43 e<sub>CCS</sub>: emissions saving from Bio-CCS (g CO<sub>2</sub> eq. / MJ of all products)
- 44 E<sub>CS</sub>: equivalent carbon storage in chemicals (%)
- 45 e<sub>ec</sub>: emissions from the extraction or cultivation of raw materials (g CO<sub>2</sub> eq. / MJ of all products)
- 46 E<sub>F</sub> = anthropogenic emissions of the fossil reference: transportation fuel, heat or electricity  
47 generation (g CO<sub>2</sub> eq. / MJ of fossil reference)
- 48 E<sub>i</sub>: GHG balance of product i (g CO<sub>2</sub> eq. / MJ of i)
- 49 e<sub>i</sub>: annualized emissions from carbon stock changes caused by land-use change (g CO<sub>2</sub> eq. / MJ  
50 all products)
- 51 e<sub>p</sub>: emissions in the biorefinery (g CO<sub>2</sub> eq. / MJ of all products)
- 52 e<sub>td</sub>: emissions from transport and distribution (g CO<sub>2</sub> eq. / MJ of all products)
- 53 e<sub>u,i</sub>: emissions in the final use of i (g CO<sub>2</sub> eq. / MJ of i)
- 54 F<sub>i</sub>: input factor (soil organic carbon)
- 55 F<sub>LU</sub>: land use factor
- 56 F<sub>MG</sub>: management factor
- 57 GS<sub>i</sub> = grade of substitution for product i (MJ of fossil reference / MJ of i)
- 58 P: productivity of the crop (MJ/ha)
- 59 saving<sub>i</sub> : individual saving of product i
- 60 SOC: soil organic carbon
- 61 SOC<sub>ST</sub>: standard soil organic carbon in the 0-30 centimeter topsoil layer
- 62 x<sub>i</sub>: fraction of product i in total plant production (lower heating value basis)
- 63

64 **1. Introduction**

65 A thermochemical biorefinery is a facility which processes biomass by means of pyrolysis  
66 and/or gasification to produce one or several products (commonly energy carriers:  
67 transportation fuel or fuel for heat or electricity generation; but also chemicals) and  
68 services (heat, electricity). The thermochemical conversion of biomass leads to syngas  
69 (gasification) or bio-oil (pyrolysis), which are processed in a similar fashion to  
70 conventional refineries or petrochemical plants. For instance, the technologies and know-  
71 how from the petrochemical industry apply to the design of thermochemical biorefineries  
72 [1]. However, nowadays, thermochemical biorefineries are not yet commercial. Important  
73 efforts are being made for their commercialization by Enerkem Company in Canada  
74 (gasification of municipal solid waste and production of ethanol) [2]. There are also  
75 several public demonstration plants producing dimethyl ether (DME) in Sweden (BioDME  
76 project) and Germany (bioliq<sup>®</sup> project), and substitute natural gas (SNG) in Sweden  
77 (GoBiGas project) [3-5]. All these examples are of thermochemical biorefineries  
78 producing a single product.

79

80 The success of thermochemical biorefineries depends on the combination of three pillars  
81 of sustainability: economic (the biorefinery must be profitable), environmental (there must  
82 be a significant saving of greenhouse gas, GHG) and societal/regulation (there should be  
83 public promotion through supranational regulation). The fulfillment of these three pillars  
84 leads to a sustainable process able to reduce fossil fuel dependence.

85

86 Regarding the economic pillar, energy carriers produced in thermochemical biorefineries  
87 cannot compete with fossil fuels unless public financial support is offered (e.g. subsidies).  
88 Conventional refineries require less processing and have larger energy efficiencies (from  
89 feedstock to final products) [1,6-9]. However, biomass is the only source for renewable  
90 carbon. In order to enhance plant economics, a different approach was proposed in the  
91 design of thermochemical biorefineries with multiproduction (co-producing energy  
92 carriers and chemicals) [10]. Like in refineries, there is potentially large energy and  
93 material integration in these plants, so product diversification would neither adversely  
94 affect energy efficiency, nor process economics. These biorefineries could achieve high  
95 profitability if low-value high-volume products (energy carriers and/or commodities for the  
96 petrochemical sector) are co-produced along with high-value low-volume products (high-  
97 value chemicals) [1,10].

98

99 Focusing on the environmental pillar, thermochemical biorefineries usually have a higher  
100 saving of GHG emissions (cradle-to-grave) compared to biochemical biorefineries (Figure  
101 1). Figure 1 shows the GHG saving (cradle-to-grave) of thermochemical and biochemical  
102 biorefineries from the literature. The saving for ethanol is the average from references  
103 [24,25] (thermochemical biorefinery) and [26-30] (biochemical biorefinery). The values for  
104 DME, Fisher-Tropsch (FT) and SNG are taken from references [9,30-32]. The value for  
105 H<sub>2</sub> are taken from [9] (thermochemical biorefinery) and [33-36] (biochemical biorefinery).  
106 However, the values presented in Figure 1 are based on data resulting from the different  
107 conditions of, e.g. biomass cultivation and land-use change, and methodology from the  
108 references does not follow any regulations on biofuels. The incorporation of biogenic

109 carbon capture and storage (Bio-CCS), i.e. a biogenic CO<sub>2</sub>-rich stream is captured,  
110 pressurized and transported to an onshore or offshore geological storage facility  
111 (sequestration), can lead to significant removal of CO<sub>2</sub> from the atmosphere [11,12] and  
112 the impact of the sale of captured CO<sub>2</sub> has been analyzed in several techno-economic  
113 assessments [13-23]. Nonetheless, a cradle-to-grave GHG balance of the process is  
114 necessary before considering storage (sequestered) CO<sub>2</sub> as a negative emission of the  
115 process [1]. Biogenic carbon capture and replacement (Bio-CCR), i.e. a biogenic CO<sub>2</sub>-  
116 rich stream is captured and used for the production of other products e.g. urea, requires  
117 further analysis with regard to the products made from the reutilized CO<sub>2</sub> [37-41].

118

119

120 Figure 1. GHG saving (cradle-to-grave) of thermochemical and biochemical  
121 biorefineries from the literature [9,24-36].

122

123 Concerning the regulation pillar, governments have regulated the bioenergy sector in  
124 order to secure investment and promote the best available technologies for greatest GHG  
125 saving and the reduction of fossil fuels dependence. To date, regulation has been limited  
126 to financial support for energy carriers, and in the European Union (EU) to the  
127 implementation of minimum GHG saving. Neither Bio-CCS nor rewarding for the  
128 achievement of substantial GHG saving (above the regulated target) have been included  
129 in the European Emissions Trading Scheme (EU-ETS) [1,42].

130

131 The fulfillment of current regulation is core in the design of thermochemical biorefineries.

132 In order to check fulfillment, the first step is calculation of the GHG balance. The GHG

133 balance has a physical meaning and its calculation should be accurate and simple if easy-  
134 way utilization by stakeholders is desired. However, there are alternatives and  
135 uncertainties in the calculation. The value assigned to emissions from cultivation and  
136 transportation, the grade of substitution of the fossil-product and the use of fossil fuels as  
137 secondary feedstock in the biorefinery are common to all biorefineries at early stage of  
138 development. Product allocation, co-production of chemicals and the diverse final use of  
139 co-products are inherent to thermochemical biorefineries with multiproduction. The  
140 second step involves the comparison of the emissions assigned to the bio-product(s) with  
141 the corresponding fossil reference(s). The way this comparison is carried out is regulated  
142 and, therefore, different GHG savings could be assigned to the same bio-product  
143 according to different regulations.

144

145 In this paper, the main aim is to describe and discuss the calculation of the GHG balance  
146 and saving of thermochemical biorefineries. The proposed methodology is based on  
147 current and expected EU regulation including all relevant contributions, such as the  
148 impact of multiproduction (energy carriers and/or chemicals) and Bio-CCS. To the best of  
149 our knowledge, there is no previous studies of this kind in the literature. The methodology  
150 is applied to a previously assessed set of process concepts of thermochemical  
151 biorefineries. The resulting GHG balance and saving are analyzed to provide a set of  
152 recommendations for future regulation. Special attention is given to the co-production of  
153 chemicals, since they could represent a long-term storage of biogenic carbon and  
154 improve the process economy [1,43].

155

## 156 2. GHG balance and saving

### 157 2.1. GHG balance

158 The GHG balance is the sum of all cradle-to-grave anthropogenic GHG emissions (net  
159 emitted to the atmosphere) from the process (Equation 1, see Figure 2.b). It is expressed  
160 in g of CO<sub>2</sub> equivalent. The functional unit is MJ of product(s) leaving the biorefinery (lower  
161 heating value basis). The GHG balance is, therefore, a measure of the emissions of the  
162 whole process including all products from the biorefinery and has a physical meaning.

163

$$164 \quad E = e_{ec} + e_l + e_p - e_{ccs} + \text{sum}[x_i \cdot (e_{td} + e_{u,i})] \quad (\text{Equation 1})$$

165

166 An individual GHG balance can also be defined for each co-product. This value is useful  
167 for the calculation of the saving of a specific product:

168

$$169 \quad E_i = x_i \cdot (e_{ec} + e_l + e_p - e_{ccs}) + e_{td} + e_{u,i} \quad (\text{Equation 2})$$

170

171

172 Figure 2. Balance of GHG emissions using fossil fuels (a) or biomass (b).

173

### 174 2.2. Differences between carbon footprint assessment and GHG balance

175 The calculation of the cradle-to-grave GHG emissions of a process using biomass can be  
176 carried out using different methods [44,45]. A conventional environmental assessment  
177 (carbon footprint assessment) would be carried out using a life cycle assessment (LCA)  
178 limited to the GHG emissions (cradle-to-grave). LCA is a well-known tool, which analyzes



179 all relevant emissions and resources consumed and the related environmental and health  
180 impacts and resource depletion issues that are associated with any goods or services  
181 [46]. The carbon footprint assessment is a useful method for the comparison of new  
182 products and technologies, which requires precise data (inventory) and well-defined  
183 system boundaries. Therefore, it is necessary to have detailed knowledge of the full life  
184 cycle of the product (from the extraction of resources, through production, use, and  
185 recycling, up to the disposal of remaining waste [46]) and the reference system  
186 (comparing different alternatives to produce the same functional product). LCA requires  
187 a relevant functional unit and well-defined system boundaries. Since the GHG balance  
188 uses MJ of products as a functional unit and does not analyze the reference system, it  
189 would not be a consistent method compared to LCA standards [46].

190

191 The GHG balance can be seen as a simplified version of a carbon footprint assessment,  
192 which aims to be useful for the calculation of the GHG saving of a process (in our case a  
193 thermochemical biorefinery). In a GHG balance, we do not aim for the comparison of  
194 different processes for the production of the same functional unit. Moreover, we want to  
195 apply this method to new process concepts still far from commercial. The results of the  
196 GHG balance are used to check the fulfillment of the imposed GHG saving (compared to  
197 the fossil reference). We do not have a carbon footprint for the reference fossil-product  
198 (e.g. gasoline), but a value assigned by supranational regulation, which may or may not  
199 be in keeping with the results of a carbon footprint assessment. Emissions from biomass  
200 cultivation, transportation and land-use change are estimated.

201

202 2.3. Calculation of the GHG balance and saving according to European regulation  
 203 Directive 2009/28/EC of the European Parliament and Council also known as Renewable  
 204 Energy Directive (RED) regulates the certification of energy carriers (biofuels and  
 205 bioliquids) imposing a minimum GHG saving (Table 1). According to RED, the saving is  
 206 calculated regarding the final use of the energy carrier as a transportation fuel (biofuel),  
 207 or for the generation of electricity or heat (bioliquids) [41]. The grade of substitution (GS)  
 208 allows a better comparison with the fossil reference or for rewarding the use of some  
 209 biomass feedstock (see Equation 3). Therefore, thermochemical biorefineries co-  
 210 producing an energy carrier are forced to observe RED, which regulates how to account  
 211 for the individual GHG balance of each energy carrier. The production of electricity from  
 212 (solid) biomass is still not regulated in the EU [47]. Therefore, electricity exported to the  
 213 grid from the biorefinery has no GHG saving requirement.

214

215 Table 1. Required GHG saving for new biorefineries producing energy carriers in the EU  
 216 [41].

<b>Time</b>	<b>Saving</b>
<b>until 2017</b>	35%
<b>2017-2018</b>	50%
<b>after 2018</b>	60%

217

218

219 
$$\text{Saving (\%)} = (E_F - E/GS)/E_F \quad \text{(Equation 3)}$$

220

221 For the calculation of the GHG balance, RED states that each term can be either  
 222 calculated using actual data or using a set of default values provided by the European  
 223 Commission. When assessing new process concepts, only emissions from the biorefinery

224 are known, so the use of default values for the remaining steps is mostly recommended.  
225 RED considers zero the emissions in the final use of energy carriers produced from  
226 biomass [41]. In the case of co-producing more than one energy carrier, other products  
227 and/or electricity (multiproduction), the individual GHG balance of the energy carrier has  
228 to be used, where common emissions to all products are allocated to their energy content  
229 (determined by lower heating value except for electricity) [41]. However, the calculation  
230 of the GHG saving is limited to energy carriers and is not currently regulated for other  
231 products (including electricity).

232

### 233 **3. GHG balance and saving of thermochemical biorefineries producing an energy** 234 **carrier**

235 In this section, we deal with the calculation of the GHG balance of thermochemical  
236 biorefineries producing one energy carrier: biomass feedstock, land-use change (direct  
237 and indirect), grade of substitution, fossil reference, impact of biogenic GHG emissions,  
238 co-feeding of fossil fuels and Bio-CCS incorporation. The impact of these contributions is  
239 analyzed using a previously published process concept [10].

240

#### 241 3.1. Biomass feedstock, and the transport and distribution of biomass and products

242 A thermochemical biorefinery (opposite to biochemical biorefineries) can process a wide  
243 range of biomass feedstock: edible biomass, all kind of lignocellulosic biomass (wood,  
244 energy crops, forest and agricultural residues), sewage sludge, and refuse-derived fuel  
245 (RDF).

246

247 RED provides a set of default values for the use of farmed and waste wood, whereas for  
 248 energy crops actual emission values are required (Table 2). In the case of RDF  
 249 (biodegradable fraction), sewage sludge, forest or agriculture residues, RED considers  
 250 no associated emissions [41]. The transport of biomass is also regulated, especially for  
 251 biomass produced in EU. However, RED aggregates these values with the emissions  
 252 from the distribution of final products [41].

253

254 Table 2. Default values for cultivation ( $e_{ec}$ ) and transport ( $e_{td}$ ) in g CO<sub>2</sub> eq. / MJ (all  
 255 products) [41].

		$e_{ec}$	$e_{td}^a$
<b>Wasted wood</b>		1.0	4.0
<b>Farmed wood</b>	non-degraded land	5.0	2.0
	severe degraded land	7.5 <sup>b</sup>	2.0
<b>RDF (biodegradable fraction), sewage sludge, forest and agriculture residues</b>		0	Actual values are required
<b>Energy crops</b>		Actual values are required	

256 <sup>a</sup> It includes the distribution of final products as liquids (road transport).

257 <sup>b</sup> Assumed to be 50% higher than for non-degraded land.

258

### 259 3.2. Land-use change (direct and indirect)

260 First, we must distinguish between direct and indirect land-use change. Direct land-use  
 261 change means any change in the use of a piece of land from one to another of the six  
 262 IPCC land cover categories (forest land, cropland, grazing land, wetlands, settlements,  
 263 other land) plus a seventh category for perennial crops, covering in particular multiannual  
 264 crops whose stem is usually not annually harvested [48]. Indirect land-use change means  
 265 where pasture or agricultural land previously destined for the food, feed and fiber markets  
 266 is diverted to biofuel production, the non-fuel demand will still need to be satisfied either

267 through intensification of current production or by bringing non-agricultural land into  
268 production elsewhere [48].

269

270 The value of direct land-use change depends on the region, the kind of soil and the  
271 previous use of the land [41]. However, in the case of a managed forest, there is no  
272 difference between distinct regions if the forest previously managed for wood production  
273 is managed for energy crop production [41]. The use of forest and agricultural residues  
274 has no associated emissions if there is no reduction in the stock of carbon soil. The use  
275 of waste wood, RDF and sewage sludge have no associated emissions [41].

276

277 As an illustrative example, two cases of direct land-use change are proposed in this study:

- 278 • Severe degraded land (Mediterranean country).
- 279 • Managed forest (Mediterranean or Nordic country).

280

281 The default values for land-use change have been calculated using the value of  
282 productivity from reference [10], as explained in European guidelines [41,48,49]. The  
283 emissions associated with the severe degraded land in a Mediterranean country are -42.8  
284 g CO<sub>2</sub> eq. / MJ (total production). There are no associated emissions in the case of  
285 managed forests. The details of the calculation of the direct land-use change emissions  
286 are shown in Annex A.

287

288 Regulation of indirect land-use change is considered crucial for sustainable development  
289 in the bioenergy sector. However, the major impact is associated with biorefineries using

290 edible biomass or energy crops [50]. Although indirect land-use change is still under  
 291 discussion, lignocellulosic biomass, wastes and residues are not included in the  
 292 regulation of indirect land-use change [48,51].

293

### 294 3.3. Grade of substitution

295 The calculation of the GHG saving uses the MJ as a functional unit for both the fossil  
 296 reference and energy carrier. However, RED states that the energy content may not be  
 297 applicable if important differences are found in the final use. In such a case, the grade of  
 298 substitution should be used [41]. An estimation of the grade of substitution is shown in  
 299 Table 3, where ethanol, Fisher-Tropsch diesel (FT), SNG and DME are compared with  
 300 their fossil references.

301

302 In the case of using lignocellulosic biomass, wastes or residues, the energy carrier is  
 303 considered to have twice its actual energy content [41]. However, expected regulation in  
 304 EU could eliminate this bonus [48].

305

306 Table 3. Maximum differences for the grade of substitution.

	<b>Grade of substitution (GS<sub>i</sub>)<sup>a</sup></b>			
	<b>Transportation fuel<sup>b</sup></b>	<b>Heat generation</b>	<b>Electricity generation</b>	<b>References</b>
<b>Ethanol</b>	1.1 (2.2)	-	-	[52]
<b>FT</b>	0.95 (1.9)	-	-	[53]
<b>SNG</b>	0.8 (1.6)	1 (2) <sup>c</sup>	1 (2) <sup>c</sup>	[54,55]
<b>DME</b>	0.7 (1.4)	1 (2)	-	[56]

307 <sup>a</sup> The values of energy content used are 21.3 MJ/L for ethanol, 34.2 MJ/L for FT, 46.6  
 308 MJ/kg for SNG and 28.0 MJ/kg for DME. The values in brackets refer to the case of having  
 309 twice its energy content [41].

310 <sup>b</sup> It depends on the car engine. Future development in technology will change these  
311 values.

312 <sup>c</sup> SNG properties do not differ from conventional natural gas.

313

#### 314 3.4. Fossil reference

315 Table 4 shows the default values for the fossil reference regarding the final use of the  
316 energy carrier, which are the latest available actual average emissions from the European  
317 Commission. The main uncertainty surrounding current regulation is the estimation of the  
318 evolution of the diesel/gasoline split in EU [50].

319

320 Table 4. Emissions of the fossil reference ( $E_F$ ) [41,50].

	<b>g CO<sub>2</sub> eq. / MJ</b>
<b>Transportation fuel<sup>a</sup></b>	83.8 (90.3)
<b>Heat generation</b>	77.0
<b>Electricity generation<sup>b</sup></b>	91.0

321 <sup>a</sup> In brackets the value estimated for 2020.

322 <sup>b</sup> The value given for electricity generation does not apply to electricity production in the  
323 biorefinery (see section 2.3).

324

#### 325 3.5. Impact of biogenic GHG emissions

326 RED assumes the use of energy carriers has a neutral impact on global carbon balance  
327 if they are produced from biomass [41]. This would be right for CO<sub>2</sub> emissions from the  
328 complete combustion of the energy carrier. However, during combustion, other gases  
329 with global warming potential (GWP) like methane, N<sub>2</sub>O and CO are emitted. These gases  
330 should not be neglected. Table 5 shows the corresponding anthropogenic GHG  
331 emissions in the final use of some energy carriers.

332

333

Table 5. GHG emissions of biofuels with GWP impact.

	<b>Anthropogenic emissions (g CO<sub>2</sub> eq. / MJ of product)<sup>a</sup></b>			
	Transportation fuel <sup>b</sup>	Heat generation	Electricity generation	References
<b>Ethanol</b>	5.36	-	-	[57]
<b>FT</b>	2.30	-	-	[58]
<b>SNG</b>	4.11	4.11	0.95	[58]
<b>DME</b>	3.76	3.76	-	[59]

334 <sup>a</sup> Total GHG emissions from the final use (combustion) – CO<sub>2</sub> emissions from complete  
335 combustion.

336 <sup>b</sup> For conventional car engines. The fraction of N<sub>2</sub>O in the exhaust gases are taken from  
337 [60].

338

339 There is controversy surrounding the temporal impact of biogenic emissions [45], and  
340 they are usually not considered in order to avoid double counting [61]. However, some  
341 references have assessed the importance of the timing of CO<sub>2</sub> fluxes on the balance of  
342 GHG emissions [61,62]. Regarding biomass feedstock, the climate outcome may still be  
343 undesirable when the carbon is sourced from slow-growing biomass [62]. Current  
344 information is still limited and the subject is not expected to be regulated in the medium  
345 term.

346

### 347 3.6. Co-feeding of fossil fuels (secondary feedstock)

348 The co-feeding of fossil fuels is common in biochemical biorefineries, where natural gas  
349 is often combusted in cogeneration units. In the case of thermochemical biorefineries, the  
350 co-feeding of fossil fuels (a secondary feedstock in the biorefinery) is seldom analyzed



351 [63,64]. In the case of coal, the best option is to use it in a gasifier producing more syngas.  
352 In the case of natural gas, it could be reformed (producing more syngas) or use for the  
353 production of heat and power (cogeneration). Regardless of the fossil fuel, the co-feeding  
354 of fossil fuels always increases the GHG emissions of the biorefinery (see Annex B).

355

### 356 3.7. Bio-CCS

357 The capture of CO<sub>2</sub> is technically favored in thermochemical biorefineries compared to a  
358 conventional power plant [12,22,42,65]. It is also favored from an environmental  
359 perspective since it is the only technology able to remove biogenic CO<sub>2</sub> from the  
360 atmosphere [12]. Therefore, the flux of CO<sub>2</sub> storage is a negative contribution in the GHG  
361 balance (for further details see [1]). In the case of the co-feeding of a fossil fuel, only a  
362 fraction of the CO<sub>2</sub> would be biogenic (see Annex B). Nevertheless, there are also  
363 associated GHG emissions. The compression and conditioning of the CO<sub>2</sub> requires  
364 electricity thereby affecting the GHG balance (see Annex B). In this study, only CO<sub>2</sub>  
365 capture and geological storage (sequestration) is analyzed.

366

### 367 3.8. Example of a process concept of thermochemical biorefinery producing one 368 energy carrier

369 Table 6 shows the inventory of a thermochemical biorefinery producing ethanol. The GHG  
370 balance and saving of the process concept are calculated considering different case  
371 studies (see Table 7).

372

373 Table 6. Inventory of a process concept of thermochemical biorefinery producing  
374 ethanol.<sup>a</sup>

	<b>Value</b>
<b>Biomass input</b>	500 MW <sub>th</sub>
<b>Electric balance<sup>b</sup></b>	-61 MW <sub>e</sub>
<b>Ethanol production</b>	157 MW <sub>th</sub>
<b>Emissions in the biorefinery, e<sub>p</sub><sup>c</sup></b>	0.4 g CO <sub>2</sub> eq. / MJ
<b>Bio-CCS (optional)<sup>c</sup></b>	23.4 t/h CO <sub>2</sub>

375 <sup>a</sup> Corresponding to process concept TR-01 of our previous publication (8000 operating  
376 hours per year) [10].

377 <sup>b</sup> A negative value means that electricity is exported to grid.

378 <sup>c</sup> The calculation is detailed in Annex B.

379

380 Table 7. Description of the case studies (thermochemical biorefinery producing ethanol).

<b>Case</b>	<b>Biomass</b>	<b>Land</b>	<b>GHG emissions in the final use</b>	<b>Bio-CCS</b>	<b>According to current EU regulation?</b>
<b>A</b>	Farmed wood	Severe degraded land in a Mediterranean country	Neutral	No	Yes
<b>B</b>	Farmed wood	Managed forest	Neutral	No	Yes
<b>C</b>	Wasted wood	N/A	Neutral	No	Yes
<b>D</b>	Forest and agriculture residues <sup>b</sup>	N/A	Neutral	No	Yes <sup>a</sup>
<b>E</b>	Farmed wood	Severe degraded land in a Mediterranean country	As stated in Table 5	No	No
<b>F</b>	Farmed wood	Severe degraded land in a	Neutral	Yes	Yes

		Mediterranean country			
<b>G</b>	Farmed wood	Managed forest	Neutral	Yes	Yes
<b>H</b>	Wasted wood	N/A	Neutral	Yes	Yes
<b>I</b>	Forest and agriculture residues <sup>b</sup>	N/A	Neutral	Yes	Yes <sup>a</sup>

381 <sup>a</sup> The directive does not give default values for the transportation of residues. The same  
382 value as for wasted wood have been assumed.

383 <sup>b</sup> The same value for  $e_{td}$  as for wasted wood has been assumed.

384  
385 For each case study, the corresponding values for emissions from previous sections have  
386 been used except for lignocellulosic biomass, which has not been considered as twice its  
387 energy content (according to expected future regulation, see section 3.3).

388 Figure 3 shows that the highest emissions corresponds to the use of farmed wood from  
389 a managed forest as feedstock (case B). The use of severe degraded land (cases A, E  
390 and F) always give negative emissions. However, these cases are unlikely because of  
391 the increase in the production cost of biomass. The use of forest and agriculture residues  
392 (cases C-D and H-I) produces the same result due to the simplifications in the calculation  
393 of the GHG balance. The incorporation of Bio-CCS (cases F-I) dramatically reduces the  
394 emissions and it is a more viable option compared to the use of severe degraded land.  
395 The impact of considering anthropogenic emissions in combustion (case E) has a greater  
396 impact than the use of wasted wood or other residues instead of farmed wood in the GHG  
397 balance. The resulting GHG saving, in general, exhibits the opposite behavior. In all  
398 cases, the saving is above the minimum required for 2018, i.e. 60%. The highest saving  
399 is achieved using farmed wood from severe degraded land and incorporating Bio-CCS  
400 (Case F). However, in the cases of forest and agriculture residues (cases C, D, H and I),

401 the saving is higher because of the consideration of double energy content. Therefore,  
402 although having 2 g CO<sub>2</sub> eq./MJ of difference, the savings of cases H and I are 22 points  
403 above case G.

404

405

406 Figure 3. Results of GHG balance and saving of the process concept producing ethanol.

407

#### 408 **4. GHG balance and saving of thermochemical biorefineries with multiproduction**

409 In a thermochemical biorefinery with multiproduction, the design of the plant is similar to  
410 conventional refineries, where not only several energy carriers but also chemicals  
411 (commodities and high-value chemicals) are co-produced. Therefore, the calculation of  
412 the GHG balance requires the allocation of emissions up to the biorefinery for each co-  
413 product (including chemicals, which are not regulated). In a thermochemical biorefinery  
414 with multiproduction, it is not possible to calculate a single GHG saving for the whole  
415 process if there is more than one energy carrier with different fossil references. An  
416 alternative analyzed in this study is the definition of an average saving. In some cases,  
417 the same co-product can have different final uses: energy carrier (transportation fuel,  
418 generation of heat and/or electricity) and/or chemical.

419

##### 420 4.1. Co-production of several energy carriers

421 If several energy carriers are co-produced, each co-product would have its individual  
422 saving. However, if a co-product were not able to meet the minimum saving required, the  
423 environmental sustainability of the remaining energy carriers would be in jeopardy.

424 Therefore, each individual saving of GHG emissions should be above the minimum  
425 saving.

426

#### 427 4.2. Co-production of chemicals

428 The production of chemicals in thermochemical biorefineries offers a different perspective  
429 to that of biochemical biorefineries. In biochemical biorefineries, chemical production is  
430 usually limited to the fine chemistry sector (e.g. succinic acid, hydroxymethylfurfural, lactic  
431 acid and levulinic acid) and the co-production of glycerin in biodiesel plants (a by-product  
432 of the process) [66-77]. A recent review of the GHG balance of biorefineries producing  
433 these chemicals is provided by Kajaste [78]. In a thermochemical biorefinery, the  
434 production of chemicals is on a larger scale; thus potential products are petrochemical  
435 commodities or high-value chemicals for the petrochemical sector [1].

436

437 The production of chemicals represents more than 30% of total industrial energy  
438 consumption [79]. The use of biomass for the production of chemicals constitutes an  
439 opportunity to reduce GHG emissions associated with the use of fossil fuels in the  
440 petrochemical industry [80]. Although emissions from the chemical industry are still not  
441 regulated, some preliminary guidelines have been developed [81].

442

443 Two driving factors can promote future regulation of large-scale chemicals from biomass.  
444 First, the EU aims to progressively reduce and finally eliminate all for-free emission  
445 allowances within the EU-ETS, including the petrochemical sector [82]. In such a case,  
446 an increase in operating costs in the production of chemicals is expected [83]. The use of

447 renewable sources would become of interest and biomass could replace crude oil for  
448 chemicals production. Second, the future promotion of biomass as a feedstock for the  
449 petrochemical sector would be analogous to the current promotion of biofuels. Therefore,  
450 the setting of a minimum GHG saving would also be applicable.

451

452 Considering chemicals are regulated as energy carriers, it would be necessary to know  
453 the corresponding fossil reference, the emissions for further processing (if any) and the  
454 timing of carbon storage (carbon average stock in the long-term) in either the chemicals  
455 or the product made from them. This storage would be similar to carbon storage in  
456 biochar, which is widely accepted and included in EU regulation [41,62,84]. Although the  
457 final use is diverse, the fossil reference and emissions from processing are known if the  
458 chemicals are commodities in the petrochemical sector [85]. However, the timing of  
459 carbon storage raises important uncertainties. First, the use of chemicals is more diverse  
460 than in that of biofuels. Second, the carbon storage depends on the life cycle of the  
461 material, i.e. the final disposal (recycling, landfilling, incineration, etc.) must be known  
462 [40,43,61,84]. Therefore, a detailed analysis is required for each material (final product)  
463 including regional constraints (there are important differences within Europe). Finally, it is  
464 important to avoid double counting in the final disposal of the materials. If they are not  
465 disposed of in a landfill, there are emissions to be considered in the life-cycle of the new  
466 product. For example, if a plastic made from a biomass-derived chemical were  
467 incinerated, the resulting GHG emissions could not be considered neutral. Discussion on  
468 raised implications are outside of the scope of this study.

469

470 We have estimated the timing of GHG emissions using an equivalent biogenic carbon  
 471 storage after a period of 100 years (as stated by the IPCC [58]) for chemicals used in the  
 472 production of biomass-derived materials. The equivalent carbon storage is expressed in  
 473 % of carbon content in the product (expressed in g of CO<sub>2</sub> equivalent per MJ of chemical  
 474 leaving the biorefinery), which is independent of the fossil or biogenic source. In order to  
 475 incorporate the equivalent carbon storage into the GHG saving, the values of the GHG  
 476 balance and the fossil reference should be updated as shown in Eq. 4 and 5. Table 8  
 477 presents the data for the calculation of the GHG saving for some chemicals.

478

479  $E_i = E_i^{\text{w/o carbon storage}} + E_{\text{CS},i} \cdot \text{CC}_i$  (Equation 4)

480  $E_{F,i} = E_{F,i}^{\text{w/o carbon storage}} + (1 - E_{\text{CS},i}) \cdot \text{CC}_i$  (Equation 5)

481

482 Table 8. Data for the calculation of the GHG saving of some chemicals.

<b>Co-product</b>	<b>Processing (use as chemical)</b>	<b>e<sub>u,i</sub> (g CO<sub>2</sub> eq. / MJ of chemical)<sup>a</sup></b>	<b>CC (g CO<sub>2</sub> eq. / MJ of chemical)</b>	<b>E<sub>F,i</sub> (g CO<sub>2</sub> eq. / MJ of fossil reference)</b>
<b>Ethanol</b>	Production of ethylene	3.8 [19]	70.1	25.4 [86]
<b>DME</b>	Production of olefins (ethylene and propylene)	8.0 [22,23]	68.3	73.3 [86]
	Production of synthetic gasoline	0 [22]	68.3	83.8 [41]
<b>Methyl acetate</b>	Production of vinyl chloride	7.0 <sup>b</sup> [88]	90.3	70.0 [87]
<b>H<sub>2</sub></b>	Hydrogenation (conventional refineries) <sup>c</sup>	-	0	-

483 <sup>a</sup> Anthropogenic emissions from the processing, equivalent to the emissions of biofuels  
484 with GWP impact (see Table 5).

485 <sup>b</sup> The emissions are for the conversion of ethylene into vinyl chloride (no better data  
486 available).

487 <sup>c</sup> For the production of fuels, e.g. upgrading of heavy fuel oil. The consumption of fossil  
488 fuel in the processing of H<sub>2</sub> is not included since it is a secondary feedstock in the process.  
489

#### 490 4.3. Average GHG saving

491 Equation 6 shows how to calculate the average GHG saving for a set of bio-products. It  
492 must be noted, that not all bio-products have to be included and electricity is always  
493 excluded.

494

$$495 \text{ Average saving} = \frac{\sum (x_i \cdot \text{saving}_i)}{\sum (x_i)} \quad (\text{Equation 6})$$

496

#### 497 4.4. Diverse final use of co-products

498 The final use of each co-product is difficult to predict and depends on market evolution  
499 and supranational regulation. Regarding the fraction of co-product employed in each use,  
500 the GHG balance would be affected because of the different emissions in each final use.  
501 In the case of an energy carrier that can also be used as a chemical (e.g. ethanol and  
502 DME, see Table 8), the individual GHG saving would only be applicable to the fraction  
503 used as energy carrier.

504

#### 505 4.5. Examples of process concepts of thermochemical biorefineries with 506 multiproduction



507 Table 9 presents the inventory of a process concept co-producing DME and ethanol (two  
 508 energy carriers) and Table 10 a process concept co-producing DME and chemicals  
 509 (methyl acetate and H<sub>2</sub>).

510

511 Table 9. Inventory of a process concept of thermochemical biorefinery co-producing  
 512 ethanol and DME.<sup>a</sup>

	<b>Value</b>
<b>Biomass input</b>	500 MW <sub>th</sub>
<b>Electric balance<sup>b</sup></b>	-32 MW <sub>e</sub>
<b>Ethanol production</b>	111 MW <sub>th</sub>
<b>DME production</b>	32 MW <sub>th</sub>
<b>Emissions in the biorefinery, e<sub>p</sub><sup>c</sup></b>	0.5 g CO <sub>2</sub> eq. / MJ
<b>Bio-CCS (optional)<sup>c</sup></b>	23.4 t/h CO <sub>2</sub>

513 <sup>a</sup> Corresponding to process concept TR-03 of our previous publication (8000 operating  
 514 hours per year) [10].

515 <sup>b</sup> A negative value means that electricity is exported to grid.

516 <sup>c</sup> The calculation is detailed in Annex B.

517

518 Table 10. Inventory of a process concept of thermochemical biorefinery co-producing  
 519 DME and chemicals.<sup>a</sup>

	<b>Value</b>
<b>Biomass input</b>	500 MW <sub>th</sub>
<b>Electric balance<sup>b</sup></b>	1 MW <sub>e</sub>
<b>DME production</b>	118 MW <sub>th</sub>
<b>H<sub>2</sub> production</b>	77 MW <sub>th</sub>
<b>Methyl acetate production</b>	51 MW <sub>th</sub>
<b>Emissions in the biorefinery, e<sub>p</sub><sup>c</sup></b>	0.9 g CO <sub>2</sub> eq. / MJ <sup>b</sup>
<b>Bio-CCS (optional)<sup>c</sup></b>	23.4 t/h CO <sub>2</sub>

520 <sup>a</sup> Corresponding to process concept TR-05 of our previous publication (8000 operating  
 521 hours per year) [10].

522 <sup>b</sup> A positive value means that electricity is imported from the grid.

523 <sup>c</sup> The calculation is detailed in Annex B.

524

525 4.5.1. Thermochemical biorefinery co-producing ethanol and DME

526 The GHG balance and saving of the process concepts are calculated considering the  
527 different case studies from Table 11. All cases use farmed wood from a managed forest.

528

529 Table 11. Description of the case studies (thermochemical biorefinery co-producing  
530 ethanol and DME).

<b>Cases</b>	<b>Final use of ethanol</b>	<b>Final use of DME</b>	<b>Emissions in the final use</b>	<b>Bio-CCS</b>	<b>According to current EU regulation?</b>
<b>J</b>	Transportation fuel (100%)	Transportation fuel (100%)	Neutral	No	Yes
<b>K</b>	Transportation fuel (100%)	Transportation fuel (100%)	As stated in Table 5	No	No
<b>L</b>	Transportation fuel (100%)	Transportation fuel (100%)	Neutral	Yes	Yes
<b>M</b>	Transportation fuel (100%)	Heat generation (100%)	Neutral	No	Yes

531

532

533 Figure 4. Results of GHG balance and savings of the process concept co-producing  
534 ethanol and DME.

535

536 Figure 4 shows the GHG balance, average and individual savings. The highest emissions  
537 correspond to the case including anthropogenic emissions from the combustion of ethanol  
538 and DME (case K). If the emissions were not included, the GHG balance would be 5 g  
539 CO<sub>2</sub> eq./MJ lower, regardless of the final use of DME (cases J and M). The incorporation  
540 of Bio-CCS has a positive impact giving negative emissions. The average saving is

541 always above the required 60% (Table 1) as well as for the individual savings. The impact  
 542 of the multiple final uses of DME is negligible in the average saving and can only be  
 543 appreciated in the DME saving.

544

#### 545 4.5.2. Thermochemical biorefinery co-producing DME and chemicals

546 The GHG balance and saving of the process concepts are calculated considering the  
 547 different case studies from Table 12. All cases use farmed wood from a managed forest.  
 548 The different final uses of each co-product are analyzed.

549

550 Table 12. Description of the case studies (thermochemical biorefinery co-producing  
 551 DME and chemicals).<sup>a</sup>

<b>Cases</b>	<b>Final use of DME</b>	<b>Emissions in the final use</b>	<b>Bio-CCS</b>	<b>According to current EU regulation?</b>
<b>N</b>	Transportation fuel (100%)	Neutral	No	Yes
<b>O</b>	Transportation fuel (50%) Production of olefins (50%)	Neutral only for energy carriers <sup>b</sup>	No	No
<b>P</b>	Transportation fuel (50%) Production of synthetic gasoline (50%)	Neutral only for energy carriers <sup>b</sup>	No	No
<b>Q</b>	Heat generation (50%) Production of olefins (50%)	Neutral only for energy carriers <sup>b</sup>	No	No
<b>R</b>	Transportation fuel (50%) Production of olefins (50%)	Neutral only for energy carriers <sup>b</sup>	Yes	No

<b>S</b>	Transportation fuel (50%) Production of olefins (50%)	As stated in Table 5 and 8	No	No
<b>T</b>	Production of olefins (100%) <sup>c</sup>	As stated in Table 8	No	No
<b>U</b>	Production of olefins (100%) <sup>c</sup>	As stated in Table 8	Yes	No

552 <sup>a</sup> Methyl acetate and H<sub>2</sub> are used as chemicals in all cases.

553 <sup>b</sup> Chemicals as stated in Table 8.

554 <sup>c</sup> Only chemicals are produced.

555

556

557 Figure 5. Results of GHG balance and savings of the process concept co-producing  
558 DME and chemicals.

559

560 In Figure 5, if carbon storage is not considered, the highest emissions would correspond  
561 to the use of DME for olefin production (Case T). Like in Figure 2, the final use of DME  
562 as an energy carrier has no impact on the GHG balance (cases O and Q). The emissions  
563 in the final use as an energy carrier of DME have only a slight impact on the GHG balance  
564 (cases Q and S). If the processing of chemicals were not included in the GHG balance,  
565 as stated in RED, the emissions would be the lowest without incorporating Bio-CCS (case  
566 N). Thus, there is an underestimation of the GHG balance if chemicals are co-produced.  
567 The cases considering carbon storage in chemicals would have negative GHG emissions  
568 if the fraction of biogenic carbon storage is higher than 21% (case T) or than 45% (case  
569 P). The calculation of the average saving including chemicals is done using the data from  
570 Table 8. If so, cases using DME for olefin production are heavily penalized in the average

571 saving (cases O, Q, R and S). However, they are still above the minimum saving required  
572 for energy carriers in 2018.

573

## 574 **5. Discussion**

575 Although current regulation is enough for the calculation of individual savings of energy  
576 carriers produced in a thermochemical biorefinery with multiproduction, important issues  
577 should be addressed in the future. With respect to the calculation of the GHG balance,  
578 we have identified the emissions in the final use of products and the co-production of  
579 chemicals. Regarding the calculation of the GHG saving, the issues are with the average  
580 saving and the diverse use of the products. The co-production of chemicals in the  
581 biorefinery affects GHG balance and saving laterally. Future regulation must consider  
582 these issues, especially if large-scale chemicals are produced (e.g. commodities).  
583 Likewise, in the energy sector, well-defined rules are required for the secure promotion  
584 of biomass-derived products in the petrochemical sector. Therefore, only bioproducts with  
585 a minimum saving of GHG emissions should be candidates for subsidies and financial  
586 support. Considering the regulation of chemicals in terms of GHG saving (as done in this  
587 study), fossil references and minimum savings have to be defined.

588

589 This study has raised some uncertainties in the calculation of the GHG balance and  
590 saving. The diverse final use of energy carriers and chemicals affects the emissions in  
591 final use and could change the fossil reference for the calculation of the saving. In the  
592 case of chemicals, calculation of the emissions in the final use depends on the further  
593 processing into final products (e.g. plastics). The potential impact of carbon storage in

594 these final products is significant (see Figure 5). Nonetheless, the determination of the  
595 most likely fraction of carbon storage requires actual data from the disposal of final  
596 products (e.g. plastics). Finally, the temporal effect of biogenic GHG emissions should be  
597 fully understood before considering its incorporation into future regulation.

598

## 599 **6. Conclusions**

600 The proposed methodology allows the estimation of the anthropogenic GHG emissions  
601 of thermochemical biorefineries. Therefore, it is possible to calculate the balance of GHG  
602 emissions in a hypothetical thermochemical biorefinery considering different alternatives  
603 of land-use, biomass feedstock, co-feeding of fossil fuels, Bio-CCS incorporation and final  
604 use of the co-products. The comparison of the estimated GHG balance with the  
605 corresponding fossil reference for each product is of special relevance in the methodology  
606 since it is the parameter used in European regulation for the fulfillment of sustainability  
607 criteria. This study demonstrates that the calculation of the saving requires a previously  
608 defined value for the emissions of the fossil reference. The proposed methodology is  
609 useful for the assessment of next-generation thermochemical biorefineries for different  
610 regulation scenarios. However, in order to assess the role of chemical co-production from  
611 biomass, they need to be included in future regulation on bioenergy.

612

613 Regarding the assessed examples of thermochemical biorefineries, the following  
614 conclusions are inferred:

- 615 • The incorporation of Bio-CCS brings negative emissions in the GHG balance (a  
616 net removal of CO<sub>2</sub> from the atmosphere).

- 617       • The diversity of final uses of energy carriers (heat, electricity or transportation fuel)  
618       does not affect the average saving.
- 619       • The impact of considering anthropogenic emissions in the combustion of biofuels  
620       has a greater impact than the kind of biomass feedstock in the GHG balance.  
621       However, the anthropogenic emissions in the final use of energy carriers slightly  
622       penalizes the GHG saving.
- 623       • In all cases, the GHG savings are above the requirement of 60% for 2018 (above  
624       100% if Bio-CCS is incorporated).
- 625       • When chemicals are co-produced in the biorefinery, the carbon storage in  
626       materials (e.g. plastics) has a significant impact on the GHG balance. The GHG  
627       saving cannot be properly calculated since chemicals are not regulated.

628

## 629 **Acknowledgements**

630 This work has been funded by the Spanish Ministry of Economy and Competitiveness  
631 and carried out in the framework of the BIOTER project (*Proyecto de Investigación*  
632 *Fundamental No-Orientada*; ENE2012-31598). Pedro Haro thanks the Spanish Ministry  
633 of Economy and Competitiveness for the post-doctoral Grant *Torres Quevedo* (PTQ-13-  
634 06203).

635

## 636 **Annex A. GHG emissions from direct land-use change**

637 RED provides a formula to calculate annualized emissions from carbon stock changes  
638 due to land-use change (expressed in g CO<sub>2</sub> eq. /MJ of all products):

639

$$e_i = (CS_R - CS_A) \cdot 3,664 \cdot 1/20 \cdot 1/P - e_B \quad \text{(Equation A.1)}$$

641

642 The values of  $CS_R$  y  $CS_A$  are obtained from the guidelines of the European Commission  
 643 [49]. This guideline provides a formula to determine the soil organic carbon stock:

644

$$CS_i = A \cdot (SOC + C_{VEG}) \quad \text{(Eq. A.2)}$$

$$SOC = SOC_{ST} \cdot F_{LU} \cdot F_{MG} \cdot F_I \quad \text{(Eq. A.3)}$$

647

648 In this study, the values of  $SOC_{ST}$ ,  $F_{LU}$ ,  $F_{MG}$ ,  $F_I$  y  $C_{VEG}$  are taken from the guidelines  
 649 provided for mineral soils [49].

650

651 **Table A1.** Selected scenarios for the direct land-use change.<sup>a</sup>

	<b>Reference land use (R)</b>		<b>Actual land use (A)</b>	
	Severe degraded land <sup>b</sup>	Mediterranean managed forest	Severe degraded land <sup>b</sup>	Mediterranean managed forest
<b>SOC<sub>ST</sub></b>	Warm temperate and dry climate with high activity clay soils		Warm temperate and dry climate with high activity clay soils	
<b>F<sub>LU</sub></b>	Cultivated	Managed forest	Managed forest	
<b>F<sub>MG</sub></b>	No till	All	All	
<b>F<sub>I</sub></b>	Low	All	All	



<b>C<sub>VEG</sub></b>	All	Temperate continental forest and mountain systems, Asia and Europe broadleaf ≤20 years
------------------------	-----	---

<sup>a</sup> Calculated using the guidelines from European Commission [49].

<sup>b</sup> This case has a bonus of 29 g CO<sub>2</sub> eq. / MJ of all products according to RED [41].

652

653 **Annex B. Calculation of  $e_p$  and  $e_{ccs}$**

654 The value of  $e_p$  is determined by the process concept of the thermochemical biorefinery.

655 In the biorefinery, the potential anthropogenic emissions come from the use of

656 consumables (catalysts, oil, amines, oxygen, etc.) and the import of electricity and/or

657 heat. However, in the case of the co-feeding of fossil fuels,  $e_p$  should be updated to take

658 into account the fraction of anthropogenic carbon leaving the biorefinery as contribution

659 (see Equation B.1).

660

661 
$$e_p = \text{consumables} + \text{import of services (+ co-feeding)} \quad (\text{Eq. B.1.})$$

662

663 **Table B.1.** Emissions in the biorefinery for the studied process concepts of

664 thermochemical biorefinery ( $e_p$ ).

	<b>Thermochemical biorefinery without multiproduction: cases A-I</b>	<b>Thermochemical biorefinery co- producing energy carriers: cases J- N</b>	<b>Thermochemical biorefinery co- producing energy carriers and</b>

	(g CO <sub>2</sub> eq. / MJ of all products)	(g CO <sub>2</sub> eq. / MJ of all products)	chemicals: cases O-V (g CO <sub>2</sub> eq. / MJ of all products)
<b>Consumables</b>	0.44	0.52	0.38
<b>Import of electricity<sup>a</sup></b>	-	-	0.57
<b>TOTAL</b>	<b>0.44</b>	<b>0.52</b>	<b>0.95</b>

665 <sup>a</sup> An emission factor of 0.5 t of CO<sub>2</sub> per MWh has been used.

666

667 For the calculation of  $e_{ccs}$ , not only captured CO<sub>2</sub> has to be considered but also the  
668 consumption of electricity in the biorefinery. The incorporation of Bio-CCS involves  
669 conditioning (compression) of the CO<sub>2</sub>. If required electricity is produced within the plant,  
670 leading to a reduction in the electricity balance. If required, electricity is imported from the  
671 grid, and the associated emissions due to the production of the electricity must be  
672 included.

673

674 **Table B.2.** Update of emissions in the biorefinery from Bio-CCS incorporation ( $e_{ccs}$ ).<sup>a</sup>

	Variation of electricity balance (MW)	Variation of emissions in the biorefinery (g CO <sub>2</sub> eq. /	$e_{ccs}$ (g CO <sub>2</sub> eq./MJ of all products)

		<b>MJ of all products)</b>	
<b>Thermochemical biorefinery without multiproduction (cases F-I)</b>	+2.5	0	-30.1
<b>Thermochemical biorefinery co-producing energy carriers (case L)</b>	+2.5	0	-37.6
<b>Thermochemical biorefinery co-producing energy carriers and chemicals (cases S, V)</b>	+2.5	+1.43	-26.4

675 <sup>a</sup> GHG emissions from transport and geologic storage are not included.

676

## 677 **References**

- 678 1. Haro P, Villanueva Perales AL, Arjona R, Ollero P. Thermochemical biorefineries with  
679 multiproduction using a platform chemical. *Biofuels, Bioproducts and Biorefining*.  
680 2014;8(2):155-70.
- 681 2. Enkern company webpage. [www.enerkem.com](http://www.enerkem.com)
- 682 3. BioDME project webpage. <http://www.biodme.eu/>
- 683 4. Bioliq® project webpage. <http://www.bioliq.de/english/index.php>
- 684 5. GoBiGas project webpage.  
685 [http://www.gotborgenergi.se/English/Projects/GoBiGas\\_Gothenburg\\_Biomass\\_Gasification](http://www.gotborgenergi.se/English/Projects/GoBiGas_Gothenburg_Biomass_Gasification_Project)  
686 [Project](http://www.gotborgenergi.se/English/Projects/GoBiGas_Gothenburg_Biomass_Gasification_Project)
- 687 6. Trippe F, Fröhling M, Schultmann F, Stahl R, Henrich E, Dalai A. Comprehensive techno-  
688 economic assessment of dimethyl ether (DME) synthesis and fischer-tropsch synthesis as  
689 alternative process steps within biomass-to-liquid production. *Fuel Process Technol.*  
690 2013;106:577-86.
- 691 7. Centi G, Lanzafame P, Perathoner S. Analysis of the alternative routes in the catalytic  
692 transformation of lignocellulosic materials. *Catalysis Today*. 2011;167(1):14-30.

- 693 8. Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Eckert CA, et al. The path  
694 forward for biofuels and biomaterials. *Science*. 2006;311(5760):484-9.
- 695 9. Laser M, Larson E, Dale B, Wang M, Greene N, Lynd LR. Comparative analysis of efficiency,  
696 environmental impact, and process economics for mature biomass refining scenarios.  
697 *Biofuels, Bioproducts and Biorefining*. 2009;3(2):247-70.
- 698 10. Haro P, Ollero P, Villanueva Perales AL, Gómez-Barea A. Thermochemical biorefinery based  
699 on dimethyl ether as intermediate: Technoeconomic assessment. *Appl Energy*.  
700 2013;102:950-61.
- 701 11. Combining Bioenergy with CCS: Reporting and Accounting for Negative Emissions under  
702 UNFCCC and the Kyoto Protocol. Working Paper. International Energy Agency (IEA): OECD  
703 Publishing. Paris, 2011. [http://www.oecd-](http://www.oecd-ilibrary.org/docserver/download/5k9h0wd6407k.pdf?expires=1384340056&id=id&accname=quest&checksum=A46076BB6FC5798FF20693E01F08DAE8)  
704 [ilibrary.org/docserver/download/5k9h0wd6407k.pdf?expires=1384340056&id=id&accname=](http://www.oecd-ilibrary.org/docserver/download/5k9h0wd6407k.pdf?expires=1384340056&id=id&accname=quest&checksum=A46076BB6FC5798FF20693E01F08DAE8)  
705 [quest&checksum=A46076BB6FC5798FF20693E01F08DAE8](http://www.oecd-ilibrary.org/docserver/download/5k9h0wd6407k.pdf?expires=1384340056&id=id&accname=quest&checksum=A46076BB6FC5798FF20693E01F08DAE8)
- 706 12. Biomass with CO<sub>2</sub> Capture and Storage (Bio-CCS). European Technology Platform for Zero  
707 Emission Fossil Fuel Power Plant.  
708 [http://www.zeroemissionsplatform.eu/library/publication/206-biomass-with-co2-capture-and-](http://www.zeroemissionsplatform.eu/library/publication/206-biomass-with-co2-capture-and-storage-bio-ccs-the-way-forward-for-europe.html)  
709 [storage-bio-ccs-the-way-forward-for-europe.html](http://www.zeroemissionsplatform.eu/library/publication/206-biomass-with-co2-capture-and-storage-bio-ccs-the-way-forward-for-europe.html)
- 710 13. Schmidt J, Leduc S, Dotzauer E, Kindermann G, Schmid E. Cost-effective CO<sub>2</sub> emission  
711 reduction through heat, power and biofuel production from woody biomass: A spatially explicit  
712 comparison of conversion technologies. *Appl Energy*. 2010;87(7):2128-41.
- 713 14. Johansson D, Franck P-, Pettersson K, Berntsson T. Comparative study of Fischer-Tropsch  
714 production and post-combustion CO<sub>2</sub> capture at an oil refinery: Economic evaluation and  
715 GHG (greenhouse gas emissions) balances. *Energy*. 2013;59:387-401.
- 716 15. Meerman JC, Knoope MMJ, Ramírez A, Turkenburg WC, Faaij APC. Technical and economic  
717 prospects of coal- and biomass-fired integrated gasification facilities equipped with CCS over  
718 time. *International Journal of Greenhouse Gas Control*. 2013;16:311-23.
- 719 16. Carbo MC, Smit R, Van Der Drift B, Jansen D. Bio energy with CCS (BECCS): Large potential  
720 for BioSNG at low CO<sub>2</sub> avoidance cost. *Energy Procedia*. 2011;4:2950-4.
- 721 17. Heyne S, Harvey S. Impact of choice of CO<sub>2</sub> separation technology on thermo-economic  
722 performance of bio-SNG production processes. *Int J Energy Res*. 2014;38(3):299-318.
- 723 18. Meerman JC, Ramírez A, Turkenburg WC, Faaij APC. Performance of simulated flexible  
724 integrated gasification polygeneration facilities, part B: Economic evaluation. *Renewable and*  
725 *Sustainable Energy Reviews*. 2012;16(8):6083-102.

- 726 19. Lindfeldt EG, Westermark MO. System study of carbon dioxide (CO<sub>2</sub>) capture in bio-based  
727 motor fuel production. *Energy*. 2008;33(2):352-61.
- 728 20. Knoope MMJ, Meerman JC, Ramírez A, Faaij APC. Future technological and economic  
729 performance of IGCC and FT production facilities with and without CO<sub>2</sub> capture: Combining  
730 component based learning curve and bottom-up analysis. *International Journal of*  
731 *Greenhouse Gas Control*. 2013;16:287-310.
- 732 21. Laude A, Jonen C. Biomass and CCS: The influence of technical change. *Energy Policy*.  
733 2013;60:916-24.
- 734 22. Haro P, Trippe F, Stahl R, Henrich E. Bio-syngas to gasoline and olefins via DME - A  
735 comprehensive techno-economic assessment. *Appl Energy*. 2013;108:54-65.
- 736 23. Haro P, Ollero P, Trippe F. Technoeconomic assessment of potential processes for bio-  
737 ethylene production. *Fuel Process Technol*. 2013;114:35-48.
- 738 24. Tao L, Tan ECD, McCormick R, Zhang M, Aden A, He X, et al. Techno-economic analysis and  
739 life-cycle assessment of cellulosic isobutanol and comparison with cellulosic ethanol and n-  
740 butanol. *Biofuels, Bioproducts and Biorefining*. 2014;8(1):30-48.
- 741 25. Sustainability Metrics and Life Cycle Assessment for Thermochemical Conversion of Woody  
742 Biomass to Mixed Alcohols. Eric C. D. Tan and Abhijit Dutta. National Bioenergy Center,  
743 National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401,  
744 USA. 2013 2nd International Conference on Environment, Energy and Biotechnology IPCBEE  
745 vol.51 (2013).
- 746 26. Joelsson JM, Gustavsson L. Reduction of CO<sub>2</sub> emission and oil dependency with biomass-  
747 based polygeneration. *Biomass Bioenergy*. 2010;34(7):967-84.
- 748 27. Sheehan J, Aden A, Paustian K, Killian K, Brenner J, Walsh M, et al. Energy and  
749 environmental aspects of using corn stover for fuel ethanol. *J Ind Ecol*. 2004;7(3-4):117-46.
- 750 28. Cherubini F, Jungmeier G. LCA of a biorefinery concept producing bioethanol, bioenergy, and  
751 chemicals from switchgrass. *International Journal of Life Cycle Assessment*. 2010;15(1):53-  
752 66.
- 753 29. González-García S, Iribarren D, Susmozas A, Dufour J, Murphy RJ. Life cycle assessment of  
754 two alternative bioenergy systems involving salix spp. biomass: Bioethanol production and  
755 power generation. *Appl Energy*. 2012;95:111-22.
- 756 30. Wu M, Wu Y, Wang M. Energy and emission benefits of alternative transportation liquid fuels  
757 derived from switchgrass: A fuel life cycle assessment. *Biotechnol Prog*. 2006;22(4):1012-24.

- 758 31. Joelsson JM, Gustavsson L. Reductions in greenhouse gas emissions and oil use by DME  
759 (di-methyl ether) and FT (Fischer-Tropsch) diesel production in chemical pulp mills. *Energy*.  
760 2012;39(1):363-74.
- 761 32. Heyne S, Harvey S. Assessment of the energy and economic performance of second  
762 generation biofuel production processes using energy market scenarios. *Appl Energy*.  
763 2013;101:203-12.  
764 .
- 765 33. Djomo SN, Blumberga D. Comparative life cycle assessment of three biohydrogen pathways.  
766 *Bioresour Technol*. 2011;102(3):2684-94
- 767 34. Djomo SN, Humbert S, Dagnija Blumberga. Life cycle assessment of hydrogen produced from  
768 potato steam peels. *Int J Hydrogen Energy*. 2008;33(12):3067-72.
- 769 35. Ferreira AF, Ribeiro LA, Batista AP, Marques PASS, Nobre BP, Palavra AMF, et al. A  
770 biorefinery from *nannochloropsis* sp. microalga - energy and CO<sub>2</sub> emission and economic  
771 analyses. *Bioresour Technol*. 2013;138:235-44.
- 772 36. Pacheco R, Ferreira AF, Pinto T, Nobre BP, Loureiro D, Moura P, et al. The production of  
773 pigments & hydrogen through a *spirogyra* sp. biorefinery. *Energy Conversion and*  
774 *Management*. 2015;89:789-97.
- 775 37. Yao Y, Graziano D, Riddle M, Cresko J, Masanet E. Greener pathways for energy-intensive  
776 commodity chemicals: Opportunities and challenges. *Current Opinion in Chemical*  
777 *Engineering*. 2014;6:90-8.
- 778 38. Von Der Assen N, Voll P, Peters M, Bardow A. Life cycle assessment of CO<sub>2</sub> capture and  
779 utilization: A tutorial review. *Chem Soc Rev*. 2014;43(23):7982-94.
- 780 39. Van Der Giesen C, Kleijn R, Kramer GJ. Energy and climate impacts of producing synthetic  
781 hydrocarbon fuels from CO<sub>2</sub>. *Environmental Science and Technology*. 2014;48(12):7111-21.
- 782 40. Von Der Assen N, Jung J, Bardow A. Life-cycle assessment of carbon dioxide capture and  
783 utilization: Avoiding the pitfalls. *Energy and Environmental Science*. 2013;6(9):2721-34.
- 784 41. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the  
785 promotion of the use of energy from renewable sources and amending and subsequently  
786 repealing Directives 2001/77/EC and 2003/30/EC. [http://eur-lex.europa.eu/legal-  
787 content/en/ALL/?uri=CELEX:32009L0028](http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:32009L0028)
- 788 42. Potential for Biomass and Carbon Dioxide Capture and Storage. IEA-GHG. July, 2011.  
789 [http://www.ieaghg.org/docs/General\\_Docs/Reports/2011-06.pdf](http://www.ieaghg.org/docs/General_Docs/Reports/2011-06.pdf)

- 790 43. Pawelzik P, Carus M, Hotchkiss J, Narayan R, Selke S, Wellisch M, et al. Critical aspects in  
791 the life cycle assessment (LCA) of bio-based materials - reviewing methodologies and deriving  
792 recommendations. *Resour Conserv Recycling*. 2013;73:211-28.
- 793 44. Yang J, Zhang P. Assessment methods of carbon dioxide emitted from bioenergy utilization.  
794 *Renewable and Sustainable Energy Reviews*. 2011;15(6):2684-9.
- 795 45. Guinée JB, Heijungs R, Van Der Voet E. A greenhouse gas indicator for bioenergy: Some  
796 theoretical issues with practical implications. *International Journal of Life Cycle Assessment*.  
797 2009;14(4):328-39.
- 798 46. European Commission - Joint Research Centre - Institute for Environment and Sustainability:  
799 International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life  
800 Cycle Assessment - Detailed guidance. First edition March 2010. EUR 24708 EN.  
801 Luxembourg. Publications Office of the European Union; 2010.  
802 [http://bookshop.europa.eu/en/international-reference-life-cycle-data-system-ilcd-handbook-](http://bookshop.europa.eu/en/international-reference-life-cycle-data-system-ilcd-handbook-general-guide-for-life-cycle-assessment-detailed-guidance-pbLBNA24708/downloads/LB-NA-24708-EN-C/LBNA24708ENC_002.pdf;pgid=y8dlS7GUWMdSR0EAIMEUUsWb0000ZpeJs5Sw;sid=LoV0TNn8Avp0U4mnCPbq67vZY-ZqPt4vKFY=?FileName=LBNA24708ENC_002.pdf&SKU=LBNA24708ENC_PDF&CatalogueNumber=LB-NA-24708-EN-C)  
803 [general-guide-for-life-cycle-assessment-detailed-guidance-pbLBNA24708/downloads/LB-](http://bookshop.europa.eu/en/international-reference-life-cycle-data-system-ilcd-handbook-general-guide-for-life-cycle-assessment-detailed-guidance-pbLBNA24708/downloads/LB-NA-24708-EN-C/LBNA24708ENC_002.pdf;pgid=y8dlS7GUWMdSR0EAIMEUUsWb0000ZpeJs5Sw;sid=LoV0TNn8Avp0U4mnCPbq67vZY-ZqPt4vKFY=?FileName=LBNA24708ENC_002.pdf&SKU=LBNA24708ENC_PDF&CatalogueNumber=LB-NA-24708-EN-C)  
804 [NA-24708-EN-](http://bookshop.europa.eu/en/international-reference-life-cycle-data-system-ilcd-handbook-general-guide-for-life-cycle-assessment-detailed-guidance-pbLBNA24708/downloads/LB-NA-24708-EN-C/LBNA24708ENC_002.pdf;pgid=y8dlS7GUWMdSR0EAIMEUUsWb0000ZpeJs5Sw;sid=LoV0TNn8Avp0U4mnCPbq67vZY-ZqPt4vKFY=?FileName=LBNA24708ENC_002.pdf&SKU=LBNA24708ENC_PDF&CatalogueNumber=LB-NA-24708-EN-C)  
805 [C/LBNA24708ENC\\_002.pdf;pgid=y8dlS7GUWMdSR0EAIMEUUsWb0000ZpeJs5Sw;sid=Lo](http://bookshop.europa.eu/en/international-reference-life-cycle-data-system-ilcd-handbook-general-guide-for-life-cycle-assessment-detailed-guidance-pbLBNA24708/downloads/LB-NA-24708-EN-C/LBNA24708ENC_002.pdf;pgid=y8dlS7GUWMdSR0EAIMEUUsWb0000ZpeJs5Sw;sid=LoV0TNn8Avp0U4mnCPbq67vZY-ZqPt4vKFY=?FileName=LBNA24708ENC_002.pdf&SKU=LBNA24708ENC_PDF&CatalogueNumber=LB-NA-24708-EN-C)  
806 [V0TNn8Avp0U4mnCPbq67vZY-](http://bookshop.europa.eu/en/international-reference-life-cycle-data-system-ilcd-handbook-general-guide-for-life-cycle-assessment-detailed-guidance-pbLBNA24708/downloads/LB-NA-24708-EN-C/LBNA24708ENC_002.pdf;pgid=y8dlS7GUWMdSR0EAIMEUUsWb0000ZpeJs5Sw;sid=LoV0TNn8Avp0U4mnCPbq67vZY-ZqPt4vKFY=?FileName=LBNA24708ENC_002.pdf&SKU=LBNA24708ENC_PDF&CatalogueNumber=LB-NA-24708-EN-C)  
807 [ZqPt4vKFY=?FileName=LBNA24708ENC\\_002.pdf&SKU=LBNA24708ENC\\_PDF&Catalogu](http://bookshop.europa.eu/en/international-reference-life-cycle-data-system-ilcd-handbook-general-guide-for-life-cycle-assessment-detailed-guidance-pbLBNA24708/downloads/LB-NA-24708-EN-C/LBNA24708ENC_002.pdf;pgid=y8dlS7GUWMdSR0EAIMEUUsWb0000ZpeJs5Sw;sid=LoV0TNn8Avp0U4mnCPbq67vZY-ZqPt4vKFY=?FileName=LBNA24708ENC_002.pdf&SKU=LBNA24708ENC_PDF&CatalogueNumber=LB-NA-24708-EN-C)  
808 [eNumber=LB-NA-24708-EN-C](http://bookshop.europa.eu/en/international-reference-life-cycle-data-system-ilcd-handbook-general-guide-for-life-cycle-assessment-detailed-guidance-pbLBNA24708/downloads/LB-NA-24708-EN-C/LBNA24708ENC_002.pdf;pgid=y8dlS7GUWMdSR0EAIMEUUsWb0000ZpeJs5Sw;sid=LoV0TNn8Avp0U4mnCPbq67vZY-ZqPt4vKFY=?FileName=LBNA24708ENC_002.pdf&SKU=LBNA24708ENC_PDF&CatalogueNumber=LB-NA-24708-EN-C)
- 809 47. Report from the Commission to the Council and the European Parliament on sustainability  
810 requirements for the use of solid and gaseous biomass sources in electricity, heating and  
811 cooling. COM(2010)11. [http://www.emissions-](http://www.emissions-euets.com/attachments/259_Report%20from%20the%20Commission%20of%2025%20February%202010%20COM(2010)11%20final.pdf)  
812 [euets.com/attachments/259\\_Report%20from%20the%20Commission%20of%2025%20Febr](http://www.emissions-euets.com/attachments/259_Report%20from%20the%20Commission%20of%2025%20February%202010%20COM(2010)11%20final.pdf)  
813 [uary%202010%20COM\(2010\)11%20final.pdf](http://www.emissions-euets.com/attachments/259_Report%20from%20the%20Commission%20of%2025%20February%202010%20COM(2010)11%20final.pdf)
- 814 48. European Parliament legislative resolution of 11 September 2013 on the proposal for a  
815 directive of the European Parliament and of the Council amending Directive 98/70/EC relating  
816 to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion  
817 of the use of energy from renewable sources (COM(2012)0595 – C7-0337/2012 –  
818 2012/0288(COD)).  
819 [http://www.europarl.europa.eu/sides/getDoc.do?type=TA&language=EN&reference=P7-TA-](http://www.europarl.europa.eu/sides/getDoc.do?type=TA&language=EN&reference=P7-TA-2013-357)  
820 [2013-357](http://www.europarl.europa.eu/sides/getDoc.do?type=TA&language=EN&reference=P7-TA-2013-357)
- 821 49. Commission Decision of 10 June 2010 on guidelines for the calculation of land carbon stocks  
822 for the purpose of Annex V to Directive 2009/28/EC (notified under document C(2010) 3751).

- 823 2010/335/EU. <http://eur-lex.europa.eu/legal->  
824 [content/EN/TXT/?uri=uriserv:OJ.L\\_.2010.151.01.0019.01.ENG](http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2010.151.01.0019.01.ENG)
- 825 50. Commission staff working document impact assessment accompanying the document  
826 Proposal for a Directive of the European Parliament and of the Council amending Directive  
827 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC  
828 on the promotion of the use of energy from renewable sources.  
829 <http://register.consilium.europa.eu/doc/srv?l=EN&t=PDF&f=ST+15189+2012+ADD+1>
- 830 51. Uslu A, van Stralen J, Elbersen B, Panoutsou C, Fritsche U, Böttcher H. Bioenergy scenarios  
831 that contribute to a sustainable energy future in the EU27. Biofuels, Bioproducts and  
832 Biorefining. 2013;7(2):164-72.
- 833 52. Alvarenga RAF, Dewulf J. Plastic vs. fuel: Which use of the Brazilian ethanol can bring more  
834 environmental gains? Renewable Energy. 2013;59:49-52.
- 835 53. Beer T, Grant T, Morgan G, Lapszewicz J, Anyon P, Edwards J, Nelson P, Watson H, Williams  
836 D. Comparison of transport fuels - final report to the Australian Greenhouse Office on the  
837 stage 2 study of life cycle emissions analysis of alternative fuels for heavy vehicles. CSIRO,  
838 Aspendale, Victoria, Australia. 2001.  
839 <http://www.environment.gov.au/archive/settlements/transport/comparison/>
- 840 54. [http://www.audi.com/content/com/brand/en/vorsprung\\_durch\\_technik/content/2013/10/audi-](http://www.audi.com/content/com/brand/en/vorsprung_durch_technik/content/2013/10/audi-)  
841 [a3-sportback-g-tron.html](http://www.audi.com/content/com/brand/en/vorsprung_durch_technik/content/2013/10/audi-a3-sportback-g-tron.html)
- 842 55. <http://www.ngvjournal.com/new-seat-leon-tgi-and-mii-ecofuel-cars-now-available-in-the->  
843 [spanish-market/](http://www.ngvjournal.com/new-seat-leon-tgi-and-mii-ecofuel-cars-now-available-in-the-spanish-market/)
- 844 56. Salomonsson P. From Wood to wheel. 7<sup>th</sup> Asian DME Conference. 2011.  
845 [www.biodme.eu/about-dme](http://www.biodme.eu/about-dme)
- 846 57. Seggiani M, Prati MV, Costagliola MA, Puccini M, Vitolo S. Bioethanol-gasoline fuel blends:  
847 Exhaust emissions and morphological characterization of particulate from a moped engine.  
848 Journal of the Air and Waste Management Association. 2012;62(8):888-97.
- 849 58. IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National  
850 Greenhouse Gas Inventories Programme, Eggleston HS, Buendia L, Miwa K, Ngara T,  
851 Tanabe K (eds). 2006.
- 852 59. Koponen K, Nylund N-. IEA technology network cooperation: Fuel and technology alternatives  
853 for buses: Overall energy efficiency and emissions. SAE International Journal of Commercial  
854 Vehicles. 2012;5(2):515-33.
- 855 60. Lipman TE, Delucchi MA. Emissions of nitrous oxide and methane from conventional and  
856 alternative fuel motor vehicles. Clim Change. 2002;53(4):477-516.

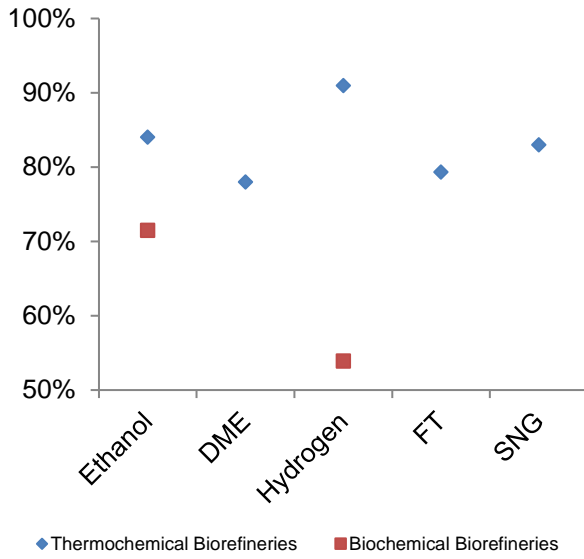


- 857 61. Levasseur A, Lesage P, Margni M, Samson R. Biogenic carbon and temporary storage  
858 addressed with dynamic life cycle assessment. *J Ind Ecol.* 2013;17(1):117-28.
- 859 62. Guest G, Bright RM, Cherubini F, Strømman AH. Consistent quantification of climate impacts  
860 due to biogenic carbon storage across a range of bio-product systems. *Environ Impact Assess*  
861 *Rev.* 2013;43:21-30.
- 862 63. Trippe F, Haro P, Fröhling M, Schultmann F, Stahl R, Henrich E. Techno-Economic  
863 Assessment of Dimethyl Ether (DME) Synthesis and Fischer–Tropsch Synthesis as  
864 Alternative Process Steps within Biomass-to-Liquid Production. 21<sup>st</sup> European Biomass  
865 Conference and Exhibition, ETA-Florence Renewable Energies, Copenhagen (Denmark),  
866 June 3-7 2013.
- 867 64. Haro P, Cutz L, Thunman H, Johnsson F. Co-Feeding of Natural Gas in Pyrolysis Plants  
868 Producing Biofuels - GHG Savings and Economic Impact. 22<sup>nd</sup> European Biomass  
869 Conference and Exhibition, ETA-Florence Renewable Energies, Hamburg (Germany), June  
870 23–26 2014.
- 871 65. McGlashan N, Shah N, Caldecott B, Workman M. High-level techno-economic assessment of  
872 negative emissions technologies. *Process Saf Environ Prot.* 2012;90(6):501-10.
- 873 66. Wery T, Petersen G. Top Value Added Chemicals from Biomass Volume I — Results of  
874 Screening for Potential Candidates from Sugars and Synthesis Gas. Produced by the Staff at  
875 Pacific Northwest National Laboratory (PNNL) National Renewable Energy Laboratory  
876 (NREL), Office of Biomass Program (EERE). 2004.
- 877 67. Corma Canos A, Iborra S, Velly A. Chemical routes for the transformation of biomass into  
878 chemicals. *Chem Rev.* 2007;107(6):2411-502.
- 879 68. Kamm B, Schönlicke P, Kamm M. Biorefining of green biomass - technical and energetic  
880 considerations. *Clean - Soil, Air, Water.* 2009;37(1):27-30.
- 881 69. Clark JH, Deswarte FEI, Farmer TJ. The integration of green chemistry into future  
882 biorefineries. *Biofuels, Bioproducts and Biorefining.* 2009;3(1):72-90.
- 883 70. Tuck CO, Pérez E, Horváth IT, Sheldon RA, Poliakoff M. Valorization of biomass: Deriving  
884 more value from waste. *Science.* 2012;337(6095):695-9.
- 885 71. Holladay JE, Bozell JJ, White JF, Johnson D. Top Value Added Chemicals from Biomass  
886 Volume 2 — Results of Screening for Potential Candidates from Biorefinery Lignin. Produced  
887 by Staff at Pacific Northwest National Laboratory (PNNL) and the National Renewable Energy  
888 Laboratory (NREL). 2007.

- 889 72. Cukalovic A, Stevens CV. Feasibility of production methods for succinic acid derivatives: A  
890 marriage of renewable resources and chemical technology. *Biofuels, Bioproducts and*  
891 *Biorefining*. 2008;2(6):505-29.
- 892 73. Rackemann DW, Doherty WO. The conversion of lignocellulosics to levulinic acid. *Biofuels,*  
893 *Bioproducts and Biorefining*. 2011;5(2):198-214.
- 894 74. van Beilen JB. Transgenic plant factories for the production of biopolymers and platform  
895 chemicals. *Biofuels, Bioproducts and Biorefining*. 2008;2(3):215-28.
- 896 75. Alonso DM, Wettstein SG, Dumesic JA. Bimetallic catalysts for upgrading of biomass to fuels  
897 and chemicals. *Chem Soc Rev*. 2012;41(24):8075-98.
- 898 76. De Jong W, Marcotullio G. Overview of biorefineries based on co-production of furfural,  
899 existing concepts and novel developments. *International Journal of Chemical Reactor*  
900 *Engineering*. 2010;8.
- 901 77. Daoutidis P, Marvin WA, Rangarajan S, Torres AI. Engineering biomass conversion  
902 processes: A systems perspective. *AIChE J*. 2013;59(1):3-18.
- 903 78. Kajaste R. Chemicals from biomass - managing greenhouse gas emissions in biorefinery  
904 production chains - A review. *J Clean Prod*. 2014;75:1-10.
- 905 79. Chemical and Petrochemical Sector Potential of best practice technology and other measures  
906 for improving energy efficiency. IEA information paper. OECD/IEA 2009.  
907 [http://www.iea.org/publications/freepublications/publication/chemical\\_petrochemical\\_sector.](http://www.iea.org/publications/freepublications/publication/chemical_petrochemical_sector.pdf)  
908 [pdf](http://www.iea.org/publications/freepublications/publication/chemical_petrochemical_sector.pdf)
- 909 80. Technology Roadmap. Energy and GHG Reductions in the Chemical Industry via Catalytic  
910 Processes. IEA Report. 2013.  
911 [http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergyand](http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergyandGHGReductionsInTheChemicalIndustryViaCatalyticProcesses.pdf)  
912 [GHGReductionsInTheChemicalIndustryViaCatalyticProcesses.pdf](http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergyandGHGReductionsInTheChemicalIndustryViaCatalyticProcesses.pdf)
- 913 81. Addressing the Avoided Emissions Challenge Guidelines from the chemical industry for  
914 accounting for and reporting greenhouse gas (GHG) emissions avoided along the value chain  
915 based on comparative studies. October 2013. [http://www.icca-](http://www.icca-chem.org/ICCADocs/E%20CC%20LG%20guidance_FINAL_07-10-2013.pdf)  
916 [chem.org/ICCADocs/E%20CC%20LG%20guidance\\_FINAL\\_07-10-2013.pdf](http://www.icca-chem.org/ICCADocs/E%20CC%20LG%20guidance_FINAL_07-10-2013.pdf)
- 917 82. The EU Emissions Trading System (EU ETS). European Union, Publications Office. 2013.  
918 [http://ec.europa.eu/clima/publications/docs/factsheet\\_ets\\_en.pdf](http://ec.europa.eu/clima/publications/docs/factsheet_ets_en.pdf)
- 919 83. Ren T, Daniëls B, Patel MK, Blok K. Petrochemicals from oil, natural gas, coal and biomass:  
920 Production costs in 2030-2050. *Resour Conserv Recycling*. 2009;53(12):653-63.

- 921 84. Wang Z, Dunn JB, Han J, Wang MQ. Effects of co-produced biochar on life cycle greenhouse  
922 gas emissions of pyrolysis-derived renewable fuels. *Biofuels, Bioproducts and Biorefining*.  
923 2014;8(2):189-204.
- 924 85. Ren T, Patel MK. Basic petrochemicals from natural gas, coal and biomass: Energy use and  
925 CO<sub>2</sub> emissions. *Resour Conserv Recycling*. 2009;53(9):513-28.
- 926 86. Vogtländer JG, Van Der Velden NM, Van Der Lugt P. Carbon sequestration in LCA, a proposal  
927 for a new approach based on the global carbon cycle; cases on wood and on bamboo.  
928 *International Journal of Life Cycle Assessment*. 2014;19(1):13-23.
- 929 87. Neelis ML, Patel MK, Bach PW, Haije WG. Analysis of energy use and carbon losses in the  
930 chemical and refinery industries. Report of the Utrecht University, Copernicus Institute for  
931 Sustainable Development and Innovation, Department of Science, Technology and Society  
932 (ECN-I-05-008). 2005.  
933 [http://dspace.library.uu.nl/bitstream/handle/1874/20679/NW%26SE2005-](http://dspace.library.uu.nl/bitstream/handle/1874/20679/NW%26SE2005-60.pdf?sequence=1)  
934 [60.pdf?sequence=1](http://dspace.library.uu.nl/bitstream/handle/1874/20679/NW%26SE2005-60.pdf?sequence=1)
- 935 88. Ostermayer A, Giegrich J. Eco-profiles of the European Plastics Industry: Vinyl Chloride. The  
936 European Council of Vinyl Manufacturers and Plastics Europe. July 2006.  
937  
938

939 Figure 1.

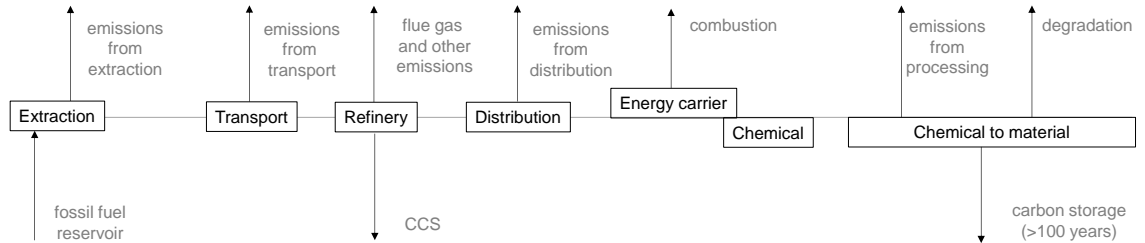


940

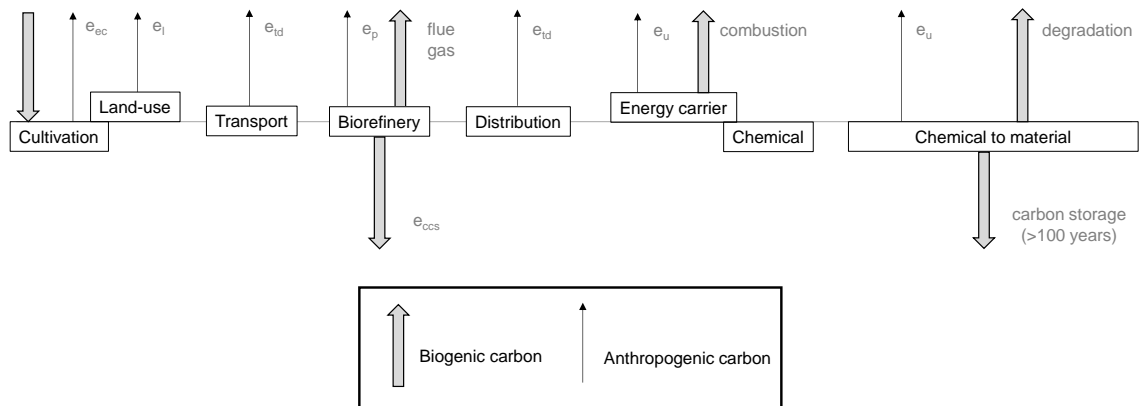
941

942 Figure 2.

a) GHG balance using fossil fuels ( $E_p$ , regulated):



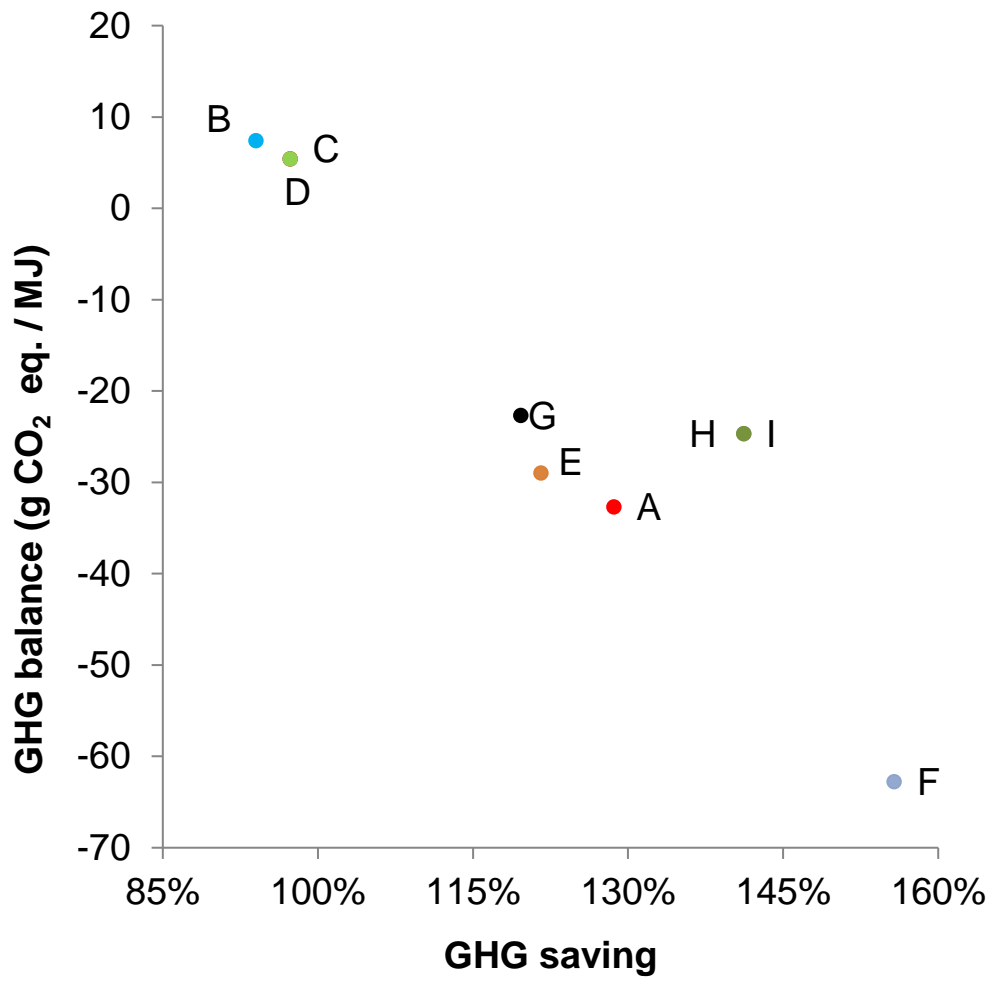
b) GHG balance using biomass ( $E$ , calculated):



943

944

945 Figure 3.

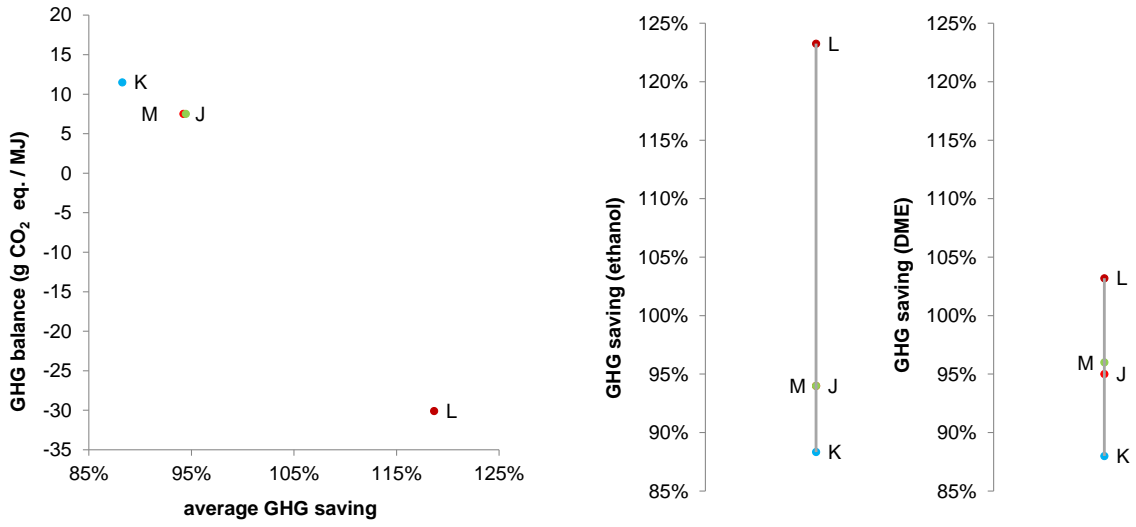


946

947

948

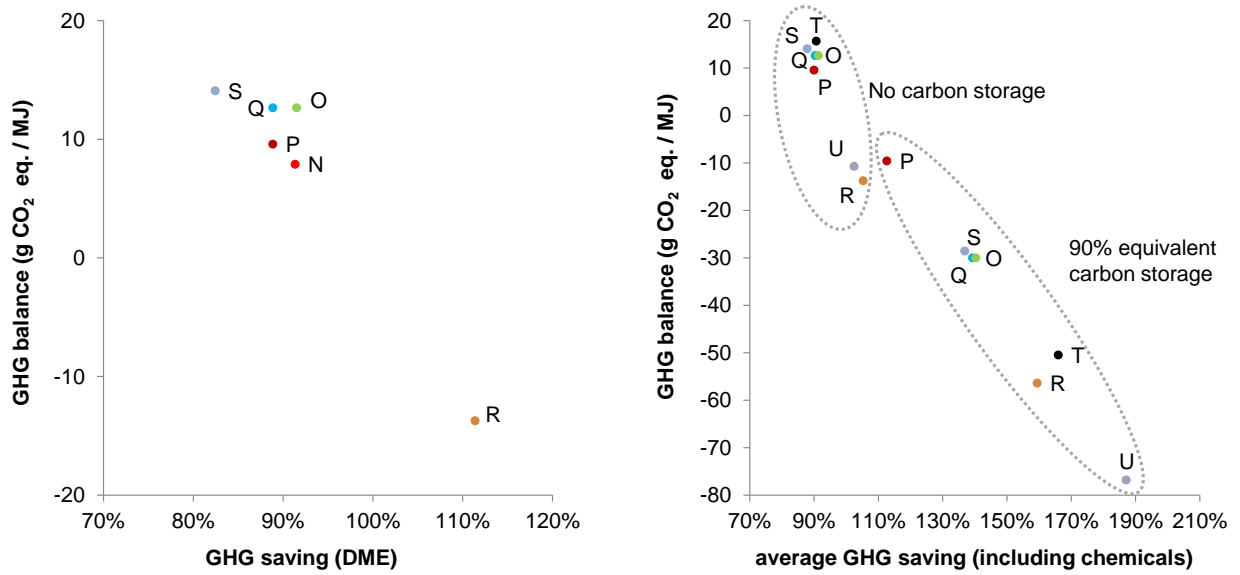
949 Figure 4.



950

951

952 Figure 5.



953

954