

# Rewarding of extra-avoided GHG emissions in thermochemical biorefineries incorporating Bio-CCS

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## ABSTRACT

The incorporation of Bio-CCS, which involves an increase in investment and operating costs, would not be of interest in thermochemical biorefineries unless some economic benefit were provided. The rewarding of extra-avoided emissions encourages larger savings of GHG emissions in thermochemical biorefineries incorporating Bio-CCS. Therefore, there is a need for policies which reward of Bio-CCS incorporation, and in a broader sense, all extra-avoided emissions. In this study, we analyze how the geological storage of already captured CO<sub>2</sub> (i.e. the incorporation of Bio-CCS) could be rewarded, taking different policy scenarios in the EU into consideration. Since thermochemical biorefineries achieve a GHG saving above the minimum target in the EU, the sale of all extra-avoided GHG emissions (not only from the geological storage of captured CO<sub>2</sub>) from energy carriers and chemicals is analyzed. Two different configurations of thermochemical biorefineries are analyzed: a biorefinery producing an energy carrier and a biorefinery co-producing an energy carrier and chemicals.

26 Considering the sale of CO<sub>2</sub> allowances in the European Emissions Trading Scheme  
27 (EU-ETS), current prices (5-15 €/t) would not make Bio-CCS incorporation profitable.  
28 However, it would be profitable compare with current sequestration costs for  
29 conventional power plants (50-100 €/t). If the sale of extra-avoided emissions from the  
30 production of energy carriers were included in the EU-ETS, the CO<sub>2</sub> sequestration cost  
31 would be reduced, although not enough to enhance the process economy. If chemicals  
32 were included, the sequestration cost would decrease significantly.

33

34 **Keywords:** thermochemical biorefinery; Bio-CCS; CO<sub>2</sub> allowances; European  
35 Emissions Trading Scheme

36

## 37 NOMENCLATURE

38

39 BR: biomass reduction from the co-feeding of a fossil fuel in the biorefinery (%)

40  $CC_i$ : carbon content of  $i$  (g CO<sub>2</sub> eq. / MJ of product)

41 EA: extra-avoided emissions (t/h CO<sub>2</sub>)

42  $EA^{Bio-CCS}$ : extra-avoided emissions from Bio-CCS (t/h CO<sub>2</sub>)

43  $EA^{w/o Bio-CCS}$ : extra-avoided emissions excluding Bio-CCS (t/h CO<sub>2</sub>)

44  $e_{CCS}$ : emissions saving from Bio-CCS (g CO<sub>2</sub> eq. / MJ of total products from the biorefinery)

45  $E_{CS,i}$ : equivalent carbon storage in  $i$  (%)

46  $e_{ec}$ : emissions from the extraction or cultivation of raw materials (g CO<sub>2</sub> eq. / MJ of total products  
47 from the biorefinery)

48  $E_{F,i}$ : GHG balance of fossil reference/fuel  $i$  (g CO<sub>2</sub> eq. / MJ of fossil reference/fuel)

49  $E_i$ : GHG balance of  $i$  (g CO<sub>2</sub> eq. / MJ of  $i$ )

50  $e_l$ : annualized emissions from carbon stock changes caused by land-use change (g CO<sub>2</sub> eq. /  
51 MJ of total products from the biorefinery)

52  $e_p$ : emissions in the biorefinery (g CO<sub>2</sub> eq. / MJ of total products from the biorefinery)

53  $e_{td}$ : emissions from transport and distribution (g CO<sub>2</sub> eq. / MJ of total products from the  
54 biorefinery)

55  $e_{u,i}$ : emissions in the final use of  $i$  (g CO<sub>2</sub> eq. / MJ of  $i$ )

56  $GS_i$ : grade of substitution for  $i$  (MJ of fossil reference / MJ of  $i$ )

57 INPUT: biomass feedstock to the biorefinery (MW<sub>th</sub>)

58 PC: plant capacity (MW of total products from the biorefinery)

59  $saving_i$ : individual saving for  $i$  (%)

60  $saving_i^{w/o Bio-CCS}$ : individual saving for  $i$  excluding Bio-CCS (%)

61  $x_i$ : fraction of  $i$  in total plant production (low heating value basis)

62

## 63 1. Introduction

64 In the EU, Directive 2009/28/EC of the European Parliament and Council, also known

65 as Renewable Energy Directive (RED), regulates the certification of energy carriers

66 produced from biomass (biofuels and bioliquids) imposing a minimum saving of

67 greenhouse gas (GHG) emissions [1]. These energy carriers can be produced in a

68 thermochemical biorefinery, which is a facility which processes biomass by means of

69 pyrolysis and/or gasification to produce one or several products (commonly energy  
70 carriers: transportation fuel or fuel for heat or electricity generation; but also chemicals)  
71 and services (heat, electricity) [2]. In the calculation of the GHG saving, the GHG  
72 emissions associated with the production and use of the energy carrier, i.e. the GHG  
73 balance, should be calculated and compared with the corresponding fossil reference.  
74 The fulfillment of the minimum GHG saving in the production of energy carriers makes  
75 them eligible for tax exemptions or reductions according to national support schemes in  
76 the EU [1].

77  
78 The capture and storage of biogenic CO<sub>2</sub> (Bio-CCS) refers to the capture, compression  
79 and transport of a biogenic CO<sub>2</sub>-rich stream to an onshore or offshore geological  
80 storage facility (sequestration). Regarding the incorporation of Bio-CCS, previous  
81 literature has analyzed its technical feasibility on biochemical and thermochemical  
82 biorefineries [3-8]. Möllersten et al. analyzed the case of electricity production with CO<sub>2</sub>  
83 capture in the Swedish pulp and paper industry [4,5]. The incorporation of Bio-CCS in  
84 the production of substitute natural gas (SNG) has been analyzed including the use of  
85 black liquor [6,7]. Arasto et al. compared the different processing technologies for the  
86 production of biofuels, such as ethanol, SNG and Fisher-Tropsch diesel [8].

87  
88 The need of a removal of CO<sub>2</sub> (negative emissions) from the atmosphere is widely  
89 accepted in the literature in order to limit global warming to 2°C over pre-industrial levels  
90 [8-14]. Bio-CCS is recognized as the only large-scale technology which can remove  
91 CO<sub>2</sub> from the atmosphere [15-18]. Therefore, the development of biorefineries

92 incorporating Bio-CCS is crucial for the achievement of negative emissions. An  
93 interesting topic, out of the scope of this work, is the study of the GHG mitigation  
94 potential of Bio-CCS. The modeling of Bio-CCS in forecasting energy scenarios is  
95 described elsewhere using different methodologies [19-29].

96

97 Thermochemical biorefineries are, without incorporating Bio-CCS, above the minimum  
98 target of GHG saving in the EU for 2018 [2]. Therefore, the incorporation of Bio-CCS,  
99 which involves an increase in investment and operating costs, would result in extra-  
100 avoided GHG emissions (avoided GHG emissions above the minimum target in  
101 European regulation). However, such an incorporation would not be of interest in  
102 thermochemical biorefineries, unless some economic benefit were provided. The idea of  
103 rewarding biorefineries for their reduction of GHG emissions has been previously  
104 proposed in the literature, especially in the case of biorefineries incorporating Bio-CCS  
105 [30-34]. Nevertheless, previous studies have not analyzed rewarding in terms of current  
106 and/or future regulation. For example, Kalt et al. assumed all emissions below the  
107 corresponding fossil reference might be sold as CO<sub>2</sub> emission allowances [32]. If so,  
108 there would be double rewarding of the reduction of GHG emission subsidies for  
109 biofuels (depending on regulation in each member state) and the sale of CO<sub>2</sub>  
110 allowances. Schmidt et al. assumed only emissions within the biorefinery should be  
111 considered in the GHG balance (while other factors e.g. kind of biomass feedstock were  
112 neglected) [33]. Ricci proposed the rewarding of CO<sub>2</sub> allowances from Bio-CCS  
113 incorporation [34]. Therefore, the GHG balance is not considered, even if it involves  
114 GHG savings above the minimum target. Based on these proposals, some authors have

115 economically assessed the rewarding of Bio-CCS incorporation into different  
116 configurations of thermochemical biorefineries producing energy carriers [3,33,35-43].  
117 In all cases, the rewarding was via the sale of CO<sub>2</sub> allowances. However, such  
118 rewarding is not included in the European Emissions Trading Scheme (EU-ETS) [18,44]  
119 and nor is CCS in conventional facilities (e.g. power plants, refineries, etc.). Therefore,  
120 there is a need for policies which reward Bio-CCS incorporation, and in a broader  
121 sense, all extra-avoided emissions. Considering current regulation in the EU, an  
122 alternative reward for extra-avoided emissions is the co-feeding of a fossil fuel.  
123 However, it depends on fossil fuel price compared to biomass. Several studies have  
124 analyzed this [45-50].

125

126 In this study, we analyze how the incorporation of Bio-CCS into thermochemical  
127 biorefineries could be rewarded, taking the results of the GHG balance (cradle-to-grave)  
128 and different policy scenarios in the EU into account. To the best of our knowledge,  
129 there is no previous studies of this kind in the literature. Unlike previous studies  
130 [3,33,35-43,45-50], in this study a general analysis is presented, where the main factors  
131 affecting the update of the techno-economic assessment are described. Since  
132 thermochemical biorefineries achieve a GHG saving above the minimum target in the  
133 EU, the sale of all extra-avoided GHG emissions (not only from Bio-CCS) is analyzed.  
134 Moreover, since the co-production of chemicals in thermochemical biorefineries is as  
135 yet unregulated, the impact of future regulation is estimated. Two different  
136 configurations of thermochemical biorefineries are selected for the assessment: a

137 biorefinery producing an energy carrier (ethanol) and electricity, and a biorefinery co-  
138 producing an energy carrier (DME) and chemicals (methyl acetate and hydrogen).

139

## 140 **2. Modeling**

### 141 2.1. Calculation of extra-avoided emissions in thermochemical biorefineries

142 The calculation of the GHG balance in thermochemical biorefineries has been described  
143 in a previous publication of the authors [2]. The GHG balance is the sum of all cradle-to-  
144 grave anthropogenic GHG emissions (net emitted to the atmosphere) from the process  
145 (see Scheme 1) [1,2]. It is expressed in g of CO<sub>2</sub> equivalent per MJ of products leaving  
146 the biorefinery (lower heating value basis) in accordance with European regulation [1].  
147 The emissions from cultivation ( $e_{ec}$ ), land-use ( $e_l$ ), and biorefinery ( $e_p$ ) are allocated for  
148 each product. Carbon capture and geological storage ( $e_{ccs}$ ) constitutes a negative  
149 contribution in the GHG balance. The emissions in the transport and distribution ( $e_{td}$ )  
150 and final use ( $e_u$ ) are set for each product. The GHG balance is a simplified version of a  
151 carbon footprint assessment (cradle-to-grave), which aims to be useful for the  
152 calculation of the saving of anthropogenic GHG emissions in a non-commercial process  
153 like thermochemical biorefineries [2]. In the case of co-producing chemicals and  
154 regarding their final use (e.g. production of plastics), there could be long-term storage of  
155 biogenic carbon (for example, a period of 100 years, as stated by LCA standards)  
156 [51,52]. An equivalent storage of biogenic carbon ( $E_{cs}$ ), is used to model this long-term  
157 storage [2]. The value for the corresponding fossil reference is regulated in the EU  
158 (Scheme 1) [1]. In the case of chemicals, the fossil reference is not currently regulated.  
159 However, data can be found in the literature [2].

160

$$161 \quad E_i = x_i \cdot (e_{ec} + e_l + e_p - e_{ccs}) + e_{td,i} + e_{u,i} \text{ [energy carriers]}$$

$$162 \quad E_i = x_i \cdot (e_{ec} + e_l + e_p - e_{ccs}) + e_{td,i} + e_{u,i} + E_{CS,i} \cdot CC_i \text{ [chemicals]}$$

$$163 \quad E_i^{w/o \text{ Bio-CCS}} = E_i + e_{ccs} \cdot x_i$$

$$164 \quad E_{F,i} = 83.8 \text{ (g CO}_2 \text{ eq. / MJ) [regulated, transportation fuel]}$$

$$165 \quad E_{F,i} = 77.0 \text{ (g CO}_2 \text{ eq. / MJ) [regulated, heat generation]}$$

$$166 \quad E_{F,i} = 91.0 \text{ (g CO}_2 \text{ eq. / MJ) [regulated, electricity generation]}$$

$$167 \quad E_{F,i} = e_{u,i} + (1 - E_{CS,i}) \cdot CC_i \text{ [not regulated, chemicals]}$$

168

Scheme 1

169

170 The GHG saving is calculated regarding the final use of the energy carrier as a  
171 transportation fuel (biofuel), or for the generation of electricity or heat (bioliquids). The  
172 grade of substitution (GS) allows for a better comparison of the GHG balance with the  
173 corresponding fossil reference [2]. The saving is calculated as shown in Scheme 2. The  
174 value of the GHG saving excluding Bio-CCS will be necessary for the calculation of the  
175 extra-avoided GHG emissions.

176

$$177 \quad \text{saving}_i \text{ (\%)} = (E_{F,i} - E_i / GS_i) / E_{F,i}$$

$$178 \quad \text{saving}_i^{w/o \text{ Bio-CCS}} \text{ (\%)} = (E_{F,i} - (E_i + e_{ccs} \cdot x_i) / GS_i) / E_{F,i}$$

179

Scheme 2

180

181 Extra-avoided emissions are the avoided GHG emissions above the minimum target in  
182 European regulation. In this study, we consider the 2018 target (i.e. 60%) as the



183 required saving for thermochemical biorefineries [1]. The extra-avoided emissions are  
184 calculated by adding the extra-avoided emissions of each regulated co-product  
185 (Scheme 3). The extra-avoided emissions from Bio-CCS do not depend on production  
186 in the biorefinery.

187

$$EA = 3.6 \cdot 10^{-3} \cdot PC \cdot \sum [(saving_i^{w/o \text{ Bio-CCS}} - 60\%) \cdot E_{F,i} \cdot x_i] + EA^{Bio-CCS}$$

188

$$EA^{Bio-CCS} = 3.6 \cdot 10^{-3} \cdot PC \cdot e_{CCS}$$

189

190

Scheme 3

191

## 192 2.2. Policy scenarios for the rewarding of extra-avoided emissions

193 The proposed policy scenarios are:

- 194 • Current regulation in the EU. There is no incentive for the incorporation of Bio-  
195 CCS. Therefore, the rewarding of extra-avoided emissions is possible only via  
196 the co-feeding of fossil fuels in the biorefinery.
- 197 • Bio-CCS is included in the EU-ETS. The International Energy Agency has  
198 declared Bio-CCS would represent significant removal of CO<sub>2</sub> from the  
199 atmosphere in the future and, therefore, should be included in future regulation  
200 [16]. The Fifth Assessment Report on Climate Change recognizes the  
201 importance of carbon dioxide removal (CDR) from the atmosphere, including Bio-  
202 CCS [17]. In this scenario, extra-avoided emissions from Bio-CCS ( $EA^{Bio-CCS}$ ) are  
203 rewarded via the EU-ETS.

- 204 • All extra-avoided emissions are included in the EU-ETS. The rewarding of extra-  
205 avoided emissions is not limited to Bio-CCS incorporation, but to all extra-  
206 avoided emissions from the process [2,44]. In this scenario, extra-avoided  
207 emissions (EA) are rewarded via the EU-ETS.
- 208 • Chemicals are regulated and included in the EU-ETS. The EU aims to  
209 progressively reduce and finally eliminate all for-free emission allowances within  
210 the EU-ETS, including the petrochemical sector [53]. Besides, materials made  
211 from biomass represent long-term storage of biogenic carbon and constitute,  
212 therefore, CDR from the atmosphere [5]. Thus, regulation of chemicals may be  
213 real in the near future [34,54,55,56]. In this study, we propose biomass-derived  
214 chemicals will be regulated like energy carriers, i.e. imposing a minimum GHG  
215 saving. In this scenario, all extra-avoided emissions including chemicals are  
216 rewarded via the EU-ETS. The same target for GHG saving is used for energy  
217 carriers and chemicals (60%).

218

### 219 2.3. Update of the techno-economic assessment for the incorporation of Bio-CCS

220 The incorporation of Bio-CCS in thermochemical biorefineries has been modeled in the  
221 literature [3,33,35-43]. In the design of thermochemical biorefineries, it is common to  
222 have a unit for the removal of CO<sub>2</sub> from the syngas (equivalent to pre-combustion CO<sub>2</sub>  
223 capture in IGCC power plants) in order to meet the requirement of the synthesis section  
224 [42]. In such a case, the installation and operating costs of the CO<sub>2</sub> removal unit would  
225 be included in the original assessment. Therefore, the incorporation of Bio-CCS, would  
226 add only the compression (multi-stage) and conditioning (de-watering) of the CO<sub>2</sub>

227 stream. In the case of a biorefinery without CO<sub>2</sub> removal, the capture of CO<sub>2</sub> from  
228 several sources has the same technical consideration as for conventional power plants  
229 (post-combustion CO<sub>2</sub> capture). Both investment and operating costs of the CO<sub>2</sub>  
230 removal unit should be included.

231

232 Regarding the transport of CO<sub>2</sub> to the geological storage (sequestration), in contrast to  
233 a commercial power plant incorporating CCS (which would capture 800-1600 t/h of CO<sub>2</sub>  
234 [57]), the flowrate of captured CO<sub>2</sub> in a thermochemical biorefinery is much lower [2].  
235 Therefore, the costs associated with the transport of CO<sub>2</sub> in the literature for power  
236 plants could be out of range. However, no specific analysis has been carried out in  
237 previous studies on Bio-CCS [9,15,16,30,58-60].

238

#### 239 2.4. Rewarding of extra-avoided GHG emissions

240 In this section, we describe how extra-avoided emissions are rewarded and  
241 incorporated into the techno-economic assessment.

242

243 For the co-feeding of fossil fuels, the design of the biorefinery has to be update, thereby  
244 becoming more complex. In the case of coal, the co-feeding fuels constitute a  
245 substantial modification of the configuration involving the installation of a coal gasifier  
246 along with the modification of gas cleaning and conditioning sections. Only if the plant  
247 originally had an entrained-flow (EF) gasifier, might the co-feeding of coal be done in  
248 the same gasifier. The co-feeding of natural gas requires modification of the  
249 conditioning section in order to process natural gas into syngas. If there was not a

250 reformer in the original design, a reforming unit has to be included. There are different  
251 alternatives for the reforming of natural gas: steam methane reforming (SMR), auto-  
252 thermal reforming (ATR) and partial oxidation (POx) [61-68]. All cases except SMR  
253 require an air separation unit (ASU), which penalizes the process economy.

254

255 Regardless of the fossil fuel, the co-feeding leads to a reduction of extra-avoided  
256 emissions (limited to fulfill the minimum GHG saving). The reduction of biomass  
257 feedstock and the amount of fossil fuel co-feeding are calculated, maintaining constant  
258 energy output from the biorefinery (Scheme 4).

259

$$BR (\%) = \frac{EA}{INPUT \cdot \left( \frac{E_{F,i}}{GS_i} + \frac{EA}{INPUT} \right)}$$

260

$$261 \quad \text{Co-feeding (MW of fossil fuel } i) = \frac{EA}{\frac{EA \cdot GS_i}{INPUT} + E_{F,i}}$$

262

Scheme 4

263

264 The sale of CO<sub>2</sub> allowances does not require modifications in the biorefinery. CO<sub>2</sub>  
265 becomes a co-product of the biorefinery thereby adding revenue. The sale price of the  
266 CO<sub>2</sub> is assumed to be equal to the price of CO<sub>2</sub> allowances in the EU-ETS.

267

268 **3. Assessment of two configurations of thermochemical biorefineries**  
269 **incorporating Bio-CCS**

270 In a previous study, the authors proposed and assessed several configurations of  
271 thermochemical biorefineries [69]. The main innovation of the study was the design of a  
272 biorefinery using DME as a platform chemical (intermediate compound, which can be a  
273 product or converted into other products). The design of the process led to  
274 multiproduction configurations, where energy carriers and chemicals were co-produced.  
275 The co-production of methyl acetate, a high-value chemical for the petrochemical  
276 industry, improved the process economy making the biorefinery profitable [69]. A  
277 detailed description of the process configurations (design basis and technical  
278 description) is given in Appendix A. Figure 1 shows a general overview of the selected  
279 configurations in this study: a thermochemical biorefinery producing an energy carrier  
280 (ethanol) and electricity, and a thermochemical biorefinery co-producing an energy  
281 carrier (DME) and chemicals (methyl acetate and hydrogen). The capture of CO<sub>2</sub> was  
282 included in the original design of both configurations because of the conditioning  
283 requirements of downstream catalysts [69]. The captured CO<sub>2</sub> represents 12.8% of  
284 carbon (biomass) input to the plant in both configurations because of identical syngas  
285 conditioning (see Appendix A). However, the differences in downstream processing  
286 result in slightly higher CO<sub>2</sub> emissions for the configuration producing ethanol and  
287 electricity. Table 1 shows the original results from the techno-economic assessment  
288 without Bio-CCS. It is remarkable that in spite of the high energy efficiency of the  
289 configurations, less than a quarter of biomass carbon goes to final products (see Figure  
290 1). Table 2 shows the update in total capital investment (TCI) and total operating cost  
291 (TOC), when Bio-CCS is incorporated into the configurations (for already captured  
292 CO<sub>2</sub>). The update of the techno-economic assessment for Bio-CCS incorporation is

293 carried out using original results from energy and material balances (see [69] for further  
 294 details in the methodology) and economic assumptions from the original assessment  
 295 (see Appendix B). The GHG balance of the selected configurations was analyzed in a  
 296 previous study [2]. Table 3 shows the GHG balance and saving for the two selected  
 297 configurations. The values for extra-avoided emissions are calculated for the policy  
 298 scenarios described in section 2.2.

299

300

301 Figure 1. General overview and carbon balance of selected configurations: (a)  
 302 producing an energy carrier and electricity; (b) co-producing an energy carrier and  
 303 chemicals. i-CFB: indirectly-heated circulating fluidized bed gasifier.

304

305 Table 1. Results of the original techno-economic assessment for the two selected  
 306 configurations of thermochemical biorefineries.<sup>a</sup>

	<b>Producing an energy carrier (a)</b>	<b>Co-producing energy carrier and chemicals (b)</b>
<b>Inputs to the biorefinery (MW<sub>th,e</sub>)</b>	Biomass: 500	Biomass: 500 Electricity: 1
<b>Energy efficiency (%)<sup>b</sup></b>	43.6	49.1
<b>Products (MW<sub>th,e</sub>)</b>	Ethanol: 157	DME:118

	Electricity: 61	Hydrogen: 77 Methyl acetate: 51
<b>Biomass price (€/GJ)</b>	2.4	2.4
<b>Total capital investment, TCI (M€<sub>2010</sub>)</b>	363.5	360.3
<b>Total operating cost, TOC (M€/year)</b>	61.8	61.6
<b>Price and final use of products (€/GJ)</b>	Ethanol: 24.5 (transportation fuel) Electricity: 10.3	DME: 22.5 (transportation fuel) Methyl acetate: 64.0 (chemical) Hydrogen: 6.0 (chemical)
<b>Internal rate of return, IRR (%)</b>	5.4	23.9

307 <sup>a</sup> The data is taken from our previous study [69]. The configuration “thermochemical  
308 biorefinery producing an energy carrier” corresponds to configuration TR-01 and  
309 “thermochemical biorefinery co-producing an energy carrier and chemicals” to  
310 configuration TR-05.

311 <sup>b</sup> Calculated using the formula  $\eta_{th,total} = \frac{products (MW_{th}) + net^{output} electricity (MW_e)}{biomass (MW_{th}) + \frac{net^{input} electricity (MW_{th})}{\eta_e}}$  as

312 described in [44,69].  $\eta_e = 35\%$ .

313

314 Table 2. Update of TCI, TOC and revenue for the two configurations of thermochemical  
 315 biorefineries after Bio-CCS incorporation (geological storage of already captured CO<sub>2</sub>).

	<b>Producing an energy carrier (a)</b>	<b>Co-producing energy carrier and chemicals (b)</b>
<b>Change in TCI (M€)<sup>a</sup></b>	4.5	4.4
<b>Change in TOC (M€/year)<sup>a</sup></b>	2.9	5.7
<b>Reduction of revenue (M€/year)<sup>b</sup></b>	2.9	-

316 <sup>a</sup> See Appendix B.

317 <sup>b</sup> The export of electricity is reduced through compression of the CO<sub>2</sub> for transport. The  
 318 sale of CO<sub>2</sub> allowances is not included.

319

320 Table 3. GHG balance and saving for the two configurations of thermochemical

321 biorefineries, and extra-avoided GHG emissions for each policy scenario [2].

		<b>Producing an energy carrier (a)</b>	<b>Co-producing energy carrier and chemicals (b)</b>
<b>GHG balance(g CO<sub>2</sub> eq. / MJ)<sup>a</sup></b>	w/o Bio-CCS <sup>b</sup>	7.4	7.9
	w Bio-CCS <sup>b</sup>	-22.7	-17.1
	Chemicals included <sup>c</sup>	-	-16.5/-29.5
<b>GHG saving</b>	w/o Bio-CCS <sup>b</sup>	Ethanol: 94.0	DME: 91.3
	w Bio-CCS <sup>b</sup>	Ethanol: 119.6	DME: 106.6



	Chemicals included <sup>c</sup>	-	DME: 106.6 Methyl acetate: 96.3- 195.3
<b>Extra-avoided emissions (t/h)</b>	Current regulation <sup>b</sup>	38.5	34.1
	Bio-CCS is included in EU-ETS	23.4	23.4
	All extra-avoided emissions <sup>b</sup>	38.5	34.2
	Chemicals included <sup>c</sup>	-	37.5-47.1

322 <sup>a</sup> The biomass feedstock is farmed wood (poplar chips) from non-degraded land and the  
323 emissions in the final use of energy carriers are considered neutral, as stated in  
324 European regulation [1].

325 <sup>b</sup> Calculated only for regulated products (ethanol and DME).

326 <sup>c</sup> For methyl acetate, the E<sub>cs</sub> is set from 0 to 90%. Hydrogen has no carbon content and  
327 is not included since processing would be as a secondary feedstock. The associated  
328 GHG emissions to hydrogen (after Bio-CCS incorporation) are -4.1 g CO<sub>2</sub> eq. / MJ.

329

### 330 3.1. Current regulation in the EU

331 In the original configurations, there was neither an EF gasifier nor a reforming unit.  
332 Therefore, the co-feeding of coal or natural gas would involve the installation of a  
333 gasifier or a reformer, respectively. In order to achieve the best comparison with the  
334 original assessment, natural gas is chosen as the fossil fuel since it involves fewer  
335 modifications in processing units. The selected reforming unit is SMR. The original

336 configurations are updated using the calculated grade of substitution of biomass by  
337 natural gas (see Appendix C).

338  
339 Table 4 shows the update of original assessments for the co-feeding of natural gas. The  
340 economic results have been updated taking into account the reduction of biomass  
341 feedstock. Therefore, gasification and conditioning sections are sized-reduced from the  
342 original assessment. However, there is a new section for the reforming of natural gas.  
343 The change in the TCI is equal for the two configurations (increase of 4.6%) since the  
344 greater co-feeding of the biorefinery producing an energy carrier is balanced by the  
345 larger total capital investment of the original design of the biorefinery co-producing  
346 energy carrier and chemicals.

347  
348 Table 4. Update of the techno-economic assessment for the co-feeding of natural gas  
349 (Bio-CCS is already incorporated in the biorefinery).

	<b>Producing an energy carrier (a)</b>	<b>Co-producing energy carrier and chemicals (b)</b>
<b>Natural gas co-feeding (MW<sub>th</sub>)<sup>a</sup></b>	153.0	139.4
<b>BR (% biomass feedstock)</b>	24.5	22.3
<b>Change in TCI (M€)<sup>b</sup></b>	17.6	17.6

350 <sup>a</sup> The anthropogenic GHG emissions ( $E_{F, \text{natural gas}}$ ) associated with the co-feeding are  
351 52.81 g CO<sub>2</sub> eq. / MJ of natural gas (complete combustion of natural gas). The grade of  
352 substitution (GS) is 0.80 (See Appendix C).

353 <sup>b</sup> See Appendix B.

354

355 Figure 2 shows the impact of the price of natural gas on the process economy. In spite  
356 of having lower profitability, the configuration producing an energy carrier is the only one  
357 which might be favored with the co-feeding of natural gas. However, the required  
358 natural gas price would be 1 €/GJ, which is below current prices in the EU and US. The  
359 configuration co-producing an energy carrier and chemicals fares worse in comparison  
360 since it has less extra-avoided emissions and imports more electricity after Bio-CCS  
361 incorporation. In order to analyze the impact of biomass price on the process economy,  
362 the change in the IRR is presented for the configuration co-producing an energy carrier  
363 and chemicals. It can be seen that the impact is greater than from the price of natural  
364 gas. Therefore, the co-feeding would only have a slight impact on the process economy.

365

366

367 Figure 2. Impact of the price of natural gas on IRR (current regulation). Data for  
368 European and US gas prices are taken from [70,71]. Biomass price from the original  
369 assessment (2.4 €/GJ).

370

371 3.2. Bio-CCS is included in the EU-ETS

372 Figure 3 shows the locus for constant IRR (original assessment) varying biomass and  
373 price of CO<sub>2</sub> allowances. The resulting value for CO<sub>2</sub> allowances is the equivalent  
374 sequestration cost in the biorefinery since it includes the cost of CO<sub>2</sub> compression within  
375 the plant, transport and geological storage. For the biomass price used in the original  
376 assessment (2.4 €/GJ), the resulting cost of sequestration is lower than in conventional  
377 power plants (around 50 to 100 €/t of CO<sub>2</sub>, according to the literature [57,72-74]).  
378 However, it is higher than the latest price of CO<sub>2</sub> allowances in the EU-ETS [75].

379

380 Figure 4 shows the impact of the price of CO<sub>2</sub> allowances on the process economy.  
381 Once again, the impact of biomass price is greater than the price of CO<sub>2</sub> allowances.  
382 Only if they are above 110 €/t, would the IRR of the configuration producing an energy  
383 carrier be above 10%.

384

385

386 Figure 3. Equivalent cost of sequestration as a function of biomass price (Bio-CCS  
387 included in the EU-ETS).

388

389

390 Figure 4. Impact of the price of CO<sub>2</sub> allowances (Bio-CCS included in the EU-ETS) on  
391 the IRR (biomass 2.4 €/GJ).

392

393 3.3. All extra-avoided emissions are included in the EU-ETS

394 Figure 5 shows the equivalent sequestration cost taking the sale of all extra-avoided  
395 GHG emissions (not limited to Bio-CCS) in the EU-ETS into consideration. Although  
396 sequestration costs are lower than in section 2.2, they are still above prices in the EU-  
397 ETS. However, they constitute half the sequestration cost for power plants, which  
398 represents an important advantage compared with CCS.

399

400 Figure 6 shows the impact of the price of CO<sub>2</sub> allowances on the process economy.  
401 Once again, the impact of biomass price is greater than the price of CO<sub>2</sub> allowances.  
402 Only if they are above 75 €/t, would the IRR of the configuration producing an energy  
403 carrier be above 10%.

404

405

406 Figure 5. Equivalent cost of sequestration as a function of biomass price (all extra-  
407 avoided emissions are included in the EU-ETS).

408

409

410 Figure 6. Impact of the price of CO<sub>2</sub> allowances (all extra-avoided emissions included in  
411 the EU-ETS) on the IRR (biomass 2.4 €/GJ).

412

413 3.4. Chemicals are regulated and included in the EU-ETS

414 Figure 7 shows the equivalent cost of sequestration for the sale of all extra-avoided  
415 emissions including chemicals. This storage in chemicals only affects the configuration  
416 of the thermochemical biorefinery co-producing an energy carrier and chemicals. For

417 the equivalent storage of biogenic CO<sub>2</sub>, three cases are studied: no carbon storage,  
418 50% and 90% equivalent carbon storage. As explained in Table 3, hydrogen has no  
419 carbon content, so only the storage in methyl acetate is analyzed. Taking the price from  
420 the original assessment for biomass (2.4 €/GJ), the case of 90% carbon storage  
421 decreases the sequestration cost 10 €/t. However, the sequestration cost is still above  
422 current prices in the EU-ETS.

423

424 Figure 8 shows the impact of the price of CO<sub>2</sub> allowances on the process economy.  
425 Only if the price of CO<sub>2</sub> allowances were above 20-35 €/t (regarding the carbon  
426 storage), would the IRR be slightly enhanced.

427

428

429 Figure 7. Cost of sequestration as a function of biomass price for the configuration of  
430 thermochemical biorefinery co-producing energy carrier and chemicals (chemicals are  
431 included in the EU-ETS and there is Bio-CCS incorporation).

432

433

434 Figure 8. Impact of the price of CO<sub>2</sub> allowances for the configuration of thermochemical  
435 biorefinery co-producing energy carrier and chemicals (chemicals are included in the  
436 EU-ETS and there is Bio-CCS incorporation) on the IRR via rewarding of extra-avoided  
437 emissions (biomass 2.4 €/GJ).

438

439 **4. Discussion**

440 Figure 9 shows the impact of studied policy scenarios on the process economy for each  
441 configuration of a thermochemical biorefinery. The sale of CO<sub>2</sub> allowances from Bio-  
442 CCS would profit the configurations only at high prices. In such a case, the  
443 thermochemical biorefinery producing an energy carrier would reach 7% IRR, making it  
444 almost profitable. If all extra-avoided emissions could be sold, this configuration would  
445 compare better since it produces regulated products. Only if chemicals were regulated  
446 and the equivalent carbon storage were high (90%), would the impact of the sale of CO<sub>2</sub>  
447 allowances be significant for the configuration co-producing chemicals. Therefore, an  
448 interesting result of this study is that the incorporation of Bio-CCS cannot make a  
449 thermochemical biorefinery profitable unless it was either already profitable or high CO<sub>2</sub>  
450 prices were considered.

451

452

453 Figure 9. Summary of the impact of studied policy scenarios on the process economy.

454 (a) Thermochemical biorefinery producing an energy carrier and (b) thermochemical  
455 biorefinery co-producing energy carrier and chemicals. Biomass price from the original  
456 study: 2.4 €/GJ.

457

458 Figure 10 compares the impact of changing capital investment (TPI), operating cost  
459 (TOC) and selling prices of products (ethanol, DME and methyl acetate) in the original  
460 assessment along with the impact of incorporating Bio-CCS. For the configuration of  
461 thermochemical biorefinery producing an energy carrier, the sale of CO<sub>2</sub> allowances in  
462 the best policy scenario (all extra-avoided emissions are sold in the EU-ETS) would

463 have a positive effect. In the case of 50 €/t, the impact would be equivalent to a  
464 reduction of 21% of TPI or 15% of TOC, or to an increase of ethanol selling price of  
465 14%. For the configuration of thermochemical biorefinery co-producing energy carrier  
466 and chemicals, the sale of CO<sub>2</sub> allowances in the best policy scenario (chemical  
467 included in the EU-ETS) would be also positive. In the case of 50 €/t, the impact would  
468 be equivalent to a reduction of 9% of TPI or 17% of TOC, or to an increase of the selling  
469 price of DME and methyl acetate of 11% and 15%, respectively.

470

471

472 Figure 10. Sensitivity analysis of IRR considering a change on TPI, TOC, selling prices,  
473 and Bio-CCS incorporation into selected configurations: (a) thermochemical biorefinery  
474 producing an energy carrier and (b) thermochemical biorefinery co-producing energy  
475 carrier and chemicals.

476

477 Regarding the accuracy of this study, there are several limitations and uncertainties  
478 when calculating the extra-avoided emissions of thermochemical biorefineries. The  
479 temporal impact of biogenic GHG emissions are not analyzed since current information  
480 is still limited. The rewarding of the sale of extra-avoided emissions from the production  
481 of electricity is not included, since they are excluded from the GHG saving calculation  
482 [76]. The diverse final use of bio-products is not analyzed. The actual values for the  
483 equivalent carbon storage in chemical derived-products depends on regional constraints  
484 (recycling, landfilling, incineration rates). Finally, the fossil references are likely to  
485 change with future regulation, as is the GHG saving target.



486

## 487 **5. Conclusions**

488 Bio-CCS represents net removal of CO<sub>2</sub> from the atmosphere and if incorporated into  
489 thermochemical biorefineries, leads to extra-avoided GHG emissions, which can be  
490 rewarded. The rewarding of extra-avoided emissions encourages the incorporation of  
491 Bio-CCS into thermochemical biorefineries thanks to a larger saving of GHG emissions.  
492 The rewarding of Bio-CCS incorporation into thermochemical biorefineries is possible  
493 via the co-feeding of fossil fuels (considering current regulation) or the sale of CO<sub>2</sub>  
494 allowances (not included in current regulation). We have updated two previously  
495 assessed configurations of a thermochemical biorefinery, which were ready for Bio-CCS  
496 incorporation. In view of current prices, the co-feeding of natural gas would not be  
497 profitable in the studied configuration of thermochemical biorefineries. Considering the  
498 sale of CO<sub>2</sub> allowances in the EU-ETS, current prices (5-15 €/t) would not make Bio-  
499 CCS incorporation profitable. It would be positive only at high CO<sub>2</sub> prices (50 €/t).  
500 However, these prices are still in the range of current sequestration cost for  
501 conventional power plants (50-100 €/t).

502

503 In this study, we have analyzed the sale of extra-avoided emissions coming not only  
504 from Bio-CCS, but also from the process. If the sale of extra-avoided emissions from the  
505 production of energy carriers were included in the EU-ETS, the CO<sub>2</sub> sequestration cost  
506 would be reduced, although not enough to enhance the process economy. If chemicals  
507 were regulated and included in the EU-ETS, the sequestration cost would decrease  
508 significantly. However, even at high CO<sub>2</sub> prices the impact of rewarding extra-avoided

509 GHG emissions on the assessed configurations is slight since the geological storage is  
510 limited to already captured CO<sub>2</sub> in the biorefinery.

511

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518

## 519 **Appendix A. Description of selected configurations of thermochemical biorefinery** 520 **(reproduced from [69])**

521 Biomass feedstock (poplar chips) with 30 wt% moisture is dried in a rotary dryer, where  
522 moisture is reduced to 12 wt% with combustion gases from the gasifier. The gas has  
523 been previously cooled from 800°C down to 450°C to produce high pressure (HP)  
524 steam in a heat recovery steam generator (HRSG). Dried poplar chips are sent to a  
525 hammer mill for particle reduction. The selected gasifier is an atmospheric indirectly-  
526 heated atmospheric Circulating Fluidized Bed Gasifier (iCFBG). The performance data  
527 of the iCFBG is given in [69]. The raw syngas from the gasifier contains dust, tars,  
528 nitrogen and alkali compounds, and halogens which must be removed in order to  
529 prevent damage to equipment and the poisoning of catalysts. Removal of particles is  
530 carried out in both cases by high-temperature cyclones. The raw syngas enters a tar

531 cracker, which is modeled using recent experimental data [77]. The outlet stream is  
532 cooled and the remaining impurities (dust, alkalis, residual ammonia, etc.) are removed  
533 by water scrubbing. Sulphur compounds are removed by a liquid phase oxidation  
534 process (LO-CAT®) and bed filtration (ZnO). The syngas is then conditioned to meet  
535 the requirements of the downstream catalysts in the reaction loop: a H<sub>2</sub>/CO ratio of 1, a  
536 low content of CO<sub>2</sub> (<10%v/v) and hydrocarbons (mainly methane) in the DME  
537 conversion section, and syngas dewatering. In the syngas conditioning section, there is  
538 no reforming unit since the tar cracker unit also converts (partially) methane into H<sub>2</sub> and  
539 CO. The selected technology for CO<sub>2</sub> removing is an amine system, due to the low  
540 partial pressure of CO<sub>2</sub> in the gas. A pressure swing adsorption (PSA) system is  
541 selected for recovering the excess of H<sub>2</sub> (co-product of the biorefinery).

542

543 The DME synthesis section is modeled using a one-step DME reactor, where CO, H<sub>2</sub>  
544 and some CO<sub>2</sub> are converted into DME, and methanol and water to a lesser extent. The  
545 reactor uses a dual catalyst, i.e. Cu-ZnO and a kind of zeolite or alumina, suspended in  
546 a solvent (slurry reactor); one catalyst synthesizes methanol from syngas and the other  
547 dehydrates the methanol to DME. Produced methanol in the process (DME  
548 hydrocarbonylation, Figure A.1) can be fed to the reactor and converted into DME. The  
549 DME conversion section is designed as multi-stage reactors with DME shots. This  
550 configuration fits process requirements best because it enables high DME conversion in  
551 the reactor and does not require syngas recirculation to fulfill the high CO/DME ratio  
552 required, like in the case of using a single reactor. For the design of the configuration of  
553 thermochemical biorefinery producing ethanol and electricity (Figure A.1), a CO/DME

554 molar ratio of 10 is used. Collected liquid products from the reactors (methanol, ethanol  
555 and small amounts of methyl acetate) are mixed and sent to the product separation  
556 section. For the design of the configuration of thermochemical biorefinery producing  
557 DME, methyl acetate and hydrogen (Figure A.2), a CO/DME molar ratio of 47.1 is used.

558

559 In the configuration of thermochemical biorefinery producing ethanol and electricity  
560 (Figure A.1), ethanol is distilled to meet fuel-grade specifications and the methanol  
561 recycled to the DME synthesis section, where it is dehydrated in the reactor. In the  
562 configuration of thermochemical biorefinery producing DME, methyl acetate and  
563 hydrogen (Figure A.2), the produced methyl acetate is recovered in a stabilizer column  
564 as liquid distillate. The outlet stream from the DME synthesis reactor is condensed and  
565 CO<sub>2</sub> is recovered by distillation in a stabilizer column. Methanol is separated from water  
566 by distillation and recycled to the DME synthesis reactor. The DME product stream  
567 contains 99.5%v/v of DME, with CO<sub>2</sub> and methanol as the main impurities. The effluent  
568 from the DME carbonylation and the effluent from the DME synthesis reactor are cooled  
569 using the cryogenic refrigeration (CR) system.

570

571

572 Figure A.1. Process flowchart of the configuration of thermochemical biorefinery  
573 producing an energy carrier (ethanol) and electricity. Originally case TR-01 in reference  
574 [69].

575

576

577 Figure A.2. Process flowchart of the configuration of thermochemical biorefinery co-  
578 producing an energy carrier (DME) and chemicals (methyl acetate and hydrogen).

579 Originally case TR-05 in reference [69].

580

## 581 Appendix B. Data for the update of the techno-economic assessment

582 The data for the update of the purchase and installation of equipment is shown in Table  
583 B.1. The TCI is 189.8% of costs of the purchase and installation of equipment [69]. The  
584 data for the update of the operating cost is shown in Table B.2. Fixed operating cost is  
585 assumed to be 8.4% of TCI [69]. The economic assumptions for the calculation of the  
586 IRR are shown in Table B.3.

587

588 Table B.1. Data for the update of the purchase and installation of equipment.

	Base purchase cost (MUS\$ <sub>2010</sub> ) <sup>a</sup>	Reference year	Scale factor	Units	Base Scale	Installation factor <sup>b</sup>	Reference
<b>SMR<sup>c</sup></b>	41.0	2002	0.6	kmol reformed/h	1277	1	[78]
<b>Compressor (CO<sub>2</sub> conditioning)</b>	5.85	2009	0.7	MW <sub>e</sub>	5.44	1.32	Supplier
<b>De-watering</b>	0.097	2008	-	MW <sub>th</sub>	1.81	1	Supplier

<b>(CO<sub>2</sub> conditioning)</b>							
--------------------------------------	--	--	--	--	--	--	--

589 <sup>a</sup> A conversion rate of 1.35 US\$/€ has been used in this study.

590 <sup>b</sup> The installation factor is 1 if the base cost already includes the indirect costs.

591 <sup>c</sup> Natural gas supply pressure is above 16 bar according to European standards for gas  
592 grid (industrial consumers) [79]. Therefore, compression is not necessary and it is not  
593 included in the capital investment.

594

595 Table B.2. Data for the update of TOC.

<b>CO<sub>2</sub> transport (€/t)</b>	4 [74]
<b>CO<sub>2</sub> geological storage (€/t)</b>	10 [74]
<b>Import of electricity (€/GJ)</b>	16 [69]

596

597 Table B.3. Economic assumptions for discounted cash flow analysis [69].

<b>Parameter</b>	<b>Value</b>
Debt/Equity	0/100%
Plant life	20 years
Depreciation (linear)	10 years
Salvage value	0 M€
Construction period	1 year
Income tax	30%

Working capital	1-month operating costs
Land	6% TCI

---

Working capital and cost of land are recovered at the end of plant life.

598

599 **Appendix C. Calculation of the grade of substitution**

600 From the update of the process simulation, the grade of substitution has been  
601 calculated (Table C.1). All configurations have the same grade of substitution since the  
602 H<sub>2</sub>/CO molar ratio of the bio-syngas is equal. Therefore, these values cannot be used  
603 as a general reference for the co-feeding of natural gas in thermochemical biorefineries.  
604 The inefficiency of natural gas substitution is due to high energy consumption by the  
605 SMR unit (approx. 50% is combusted to provide the heat for reforming), which was not  
606 included in the original design (there was a tar-reformer). In the case where a SMR unit  
607 was included in the original design (i.e. there was no tar reformer), natural gas co-  
608 feeding would enhance energy efficiency [45].

609

610 Table C.1. Results of the co-feeding of natural gas in selected configurations.<sup>a</sup>

	<b>Value</b>
<b>Steam/methane (molar)</b>	3.00
<b>Steam/CO<sub>2</sub> (molar)</b>	1.54
<b>H<sub>2</sub>/CO molar ratio of bio-syngas</b>	1.61
<b>GS (MJ biomass / MJ natural gas)</b>	0.80

611 <sup>a</sup> The composition of natural gas corresponds to an energy content of 38 MJ/Nm<sup>3</sup>.

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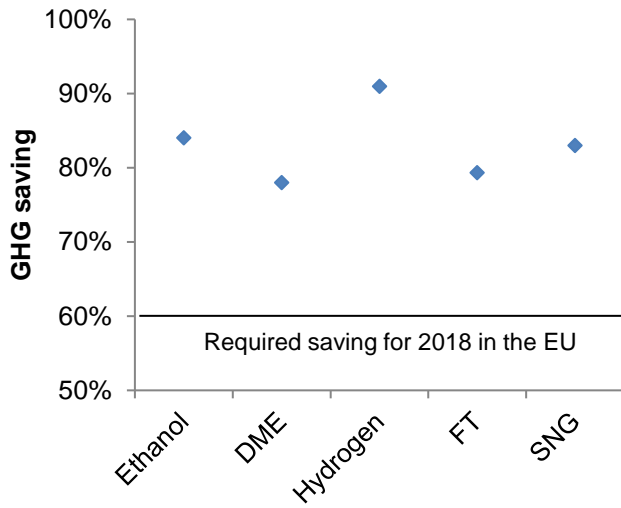
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Figure 1.

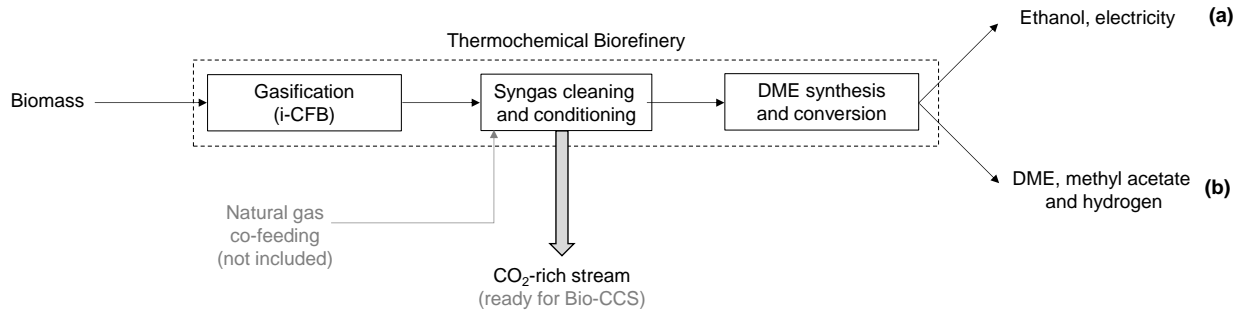


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Figure 2.



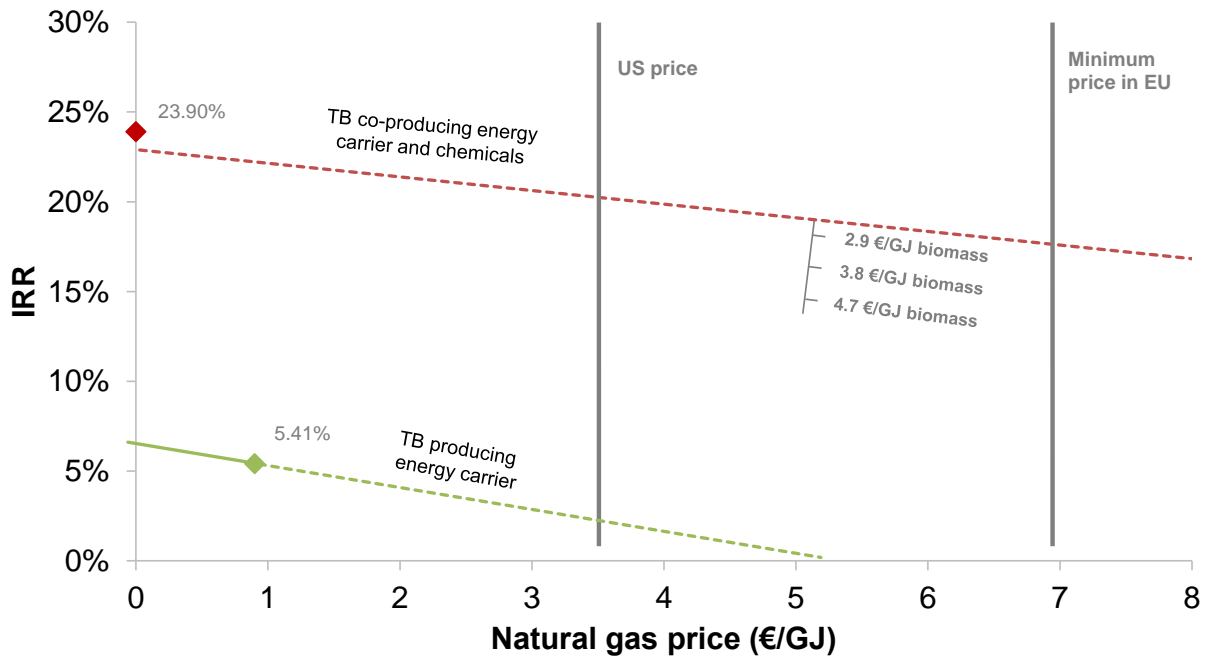
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Figure 3.

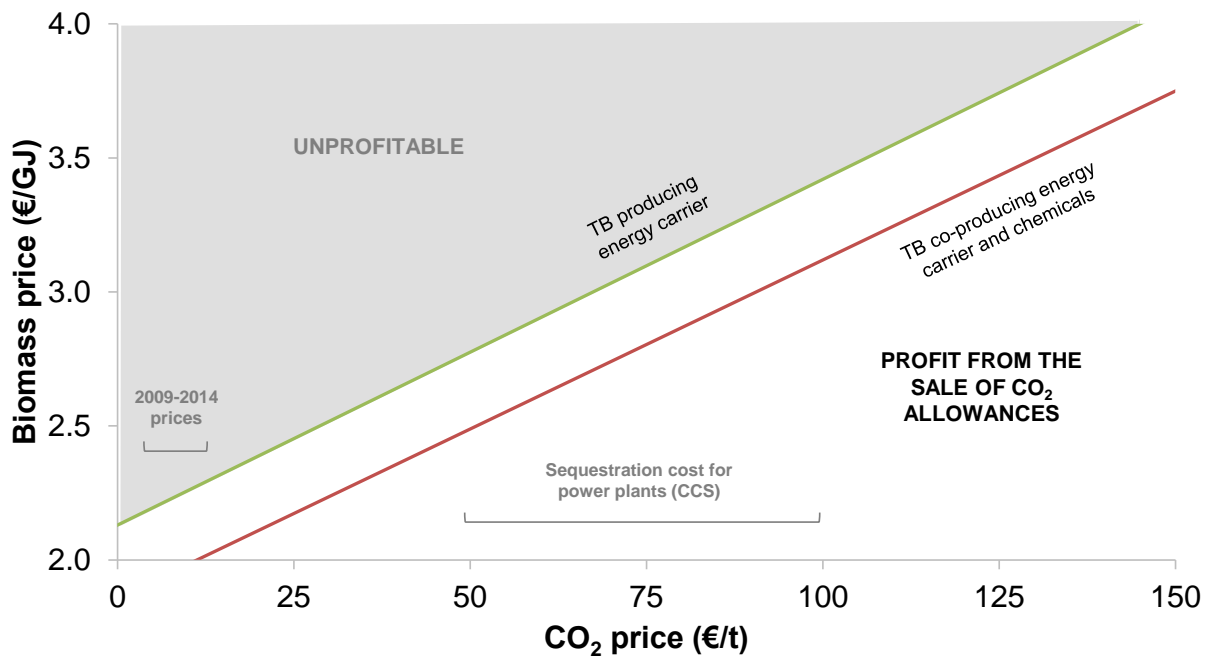


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Figure 4.



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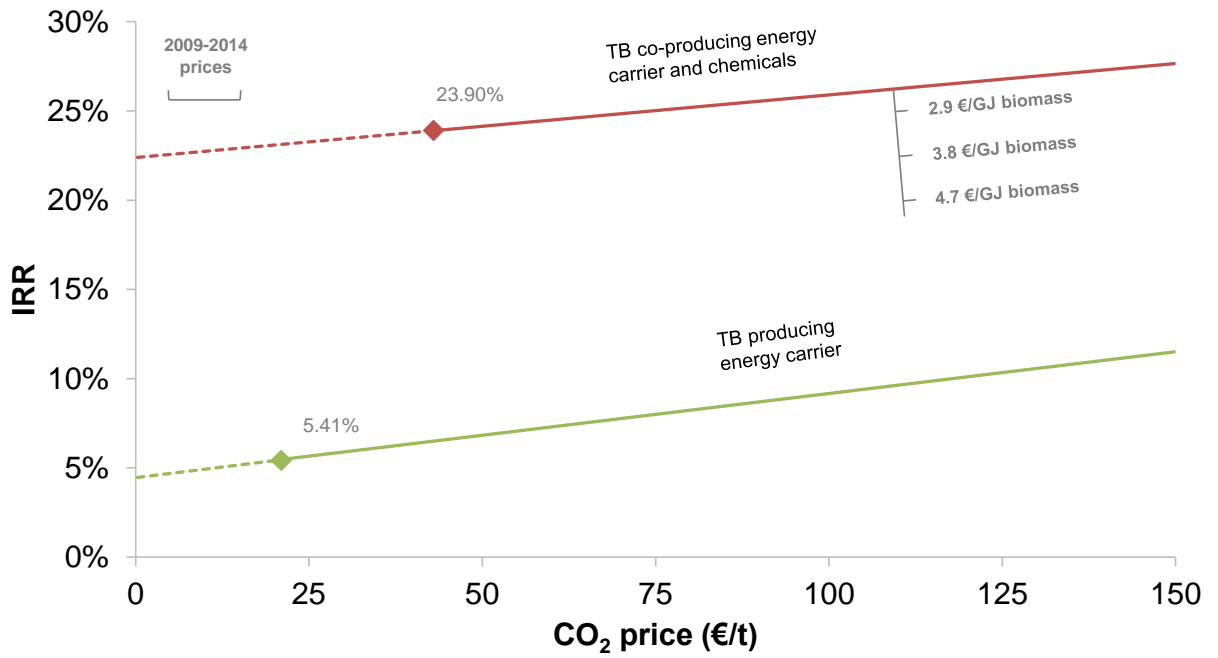
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Figure 5.

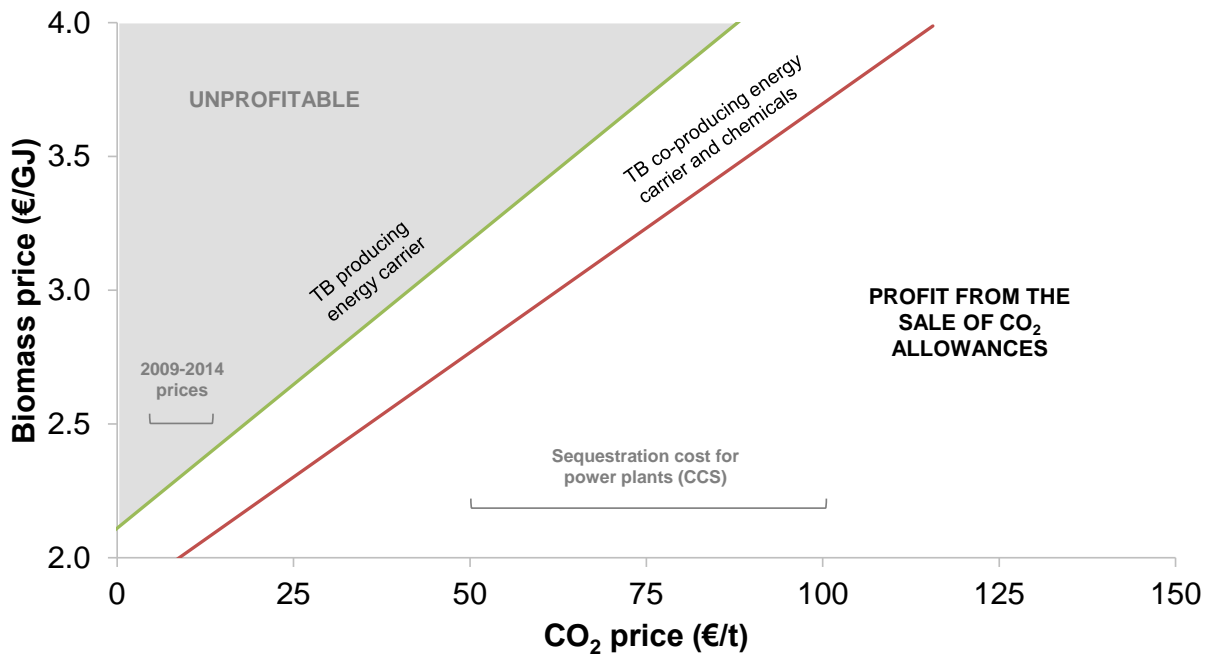


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Figure 6.



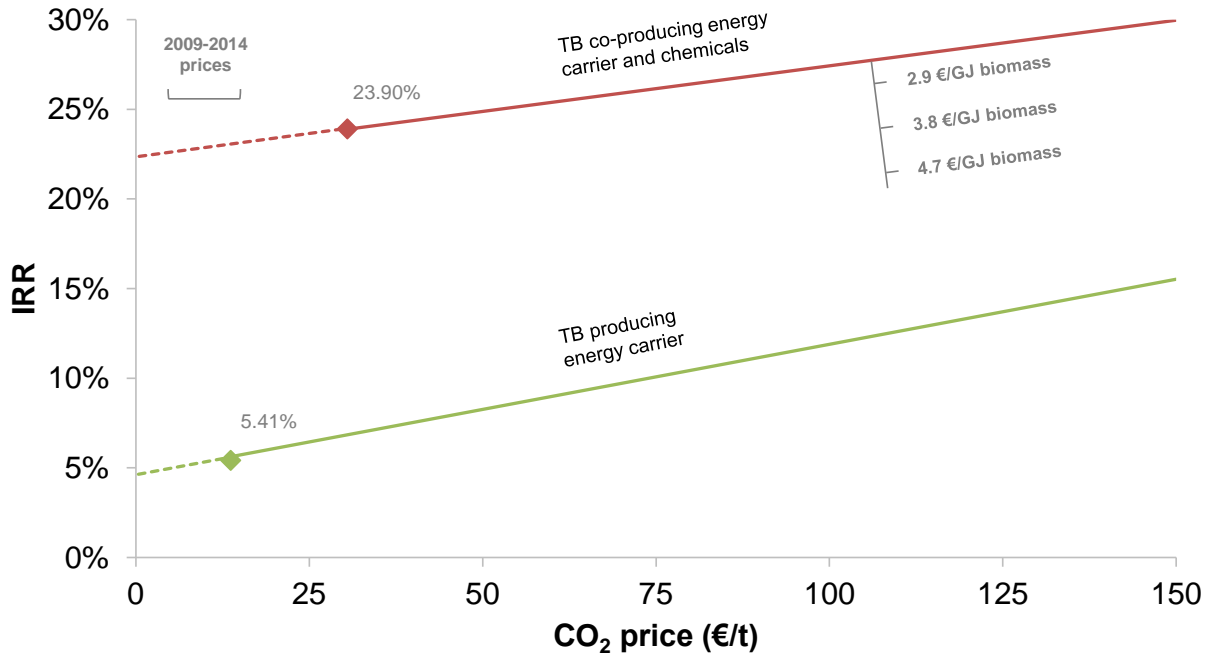
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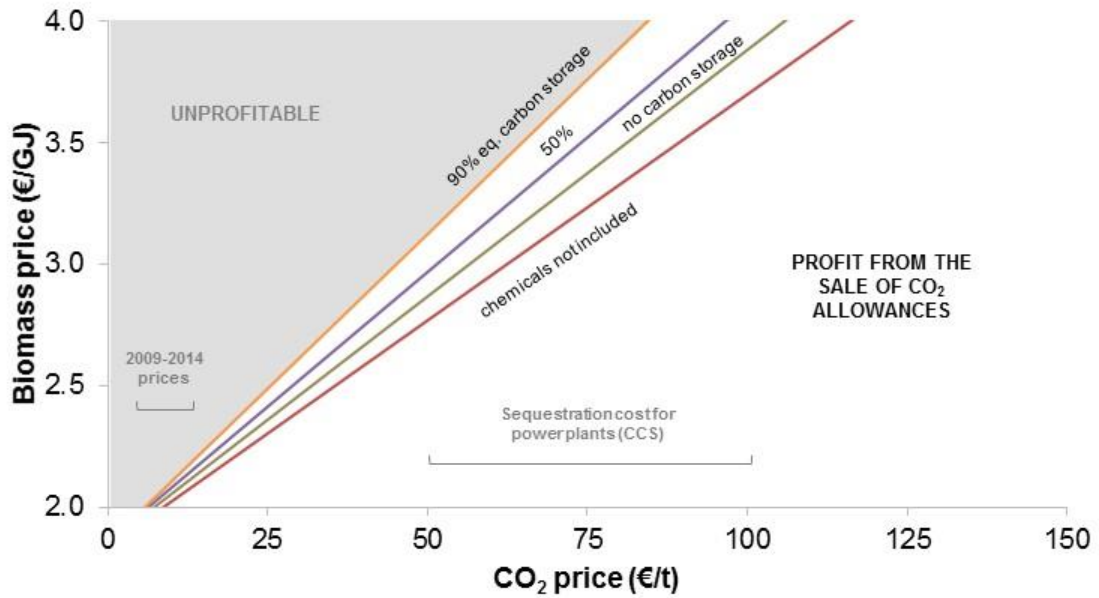
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Figure 7.



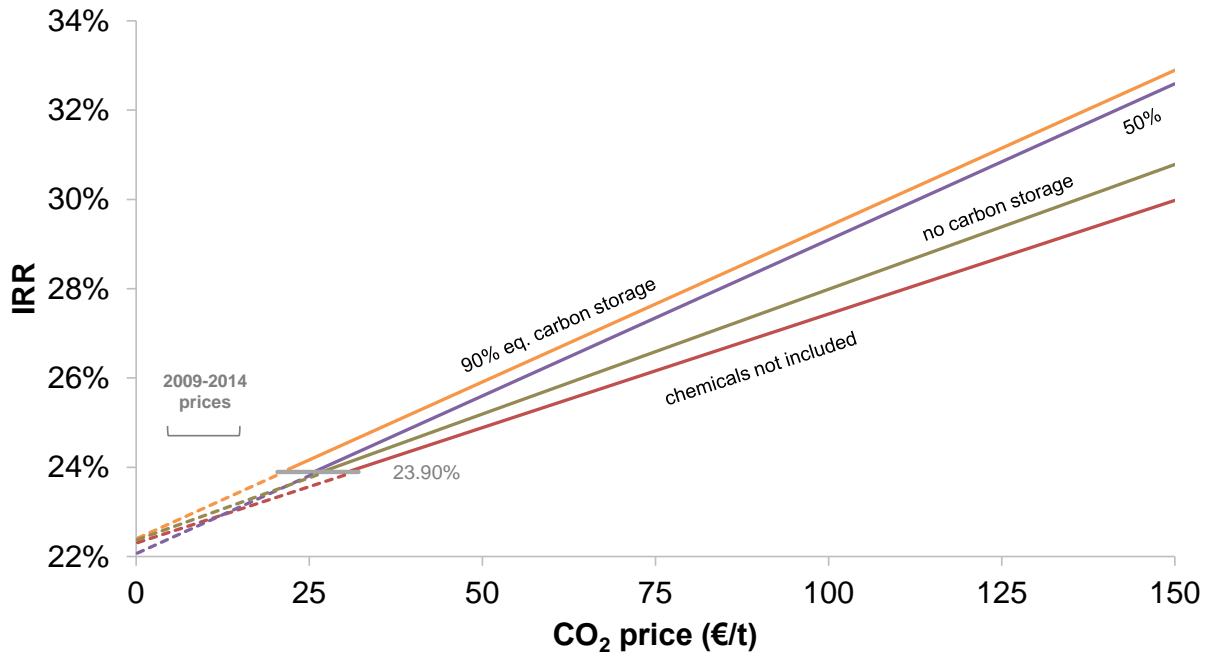
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Figure 8.



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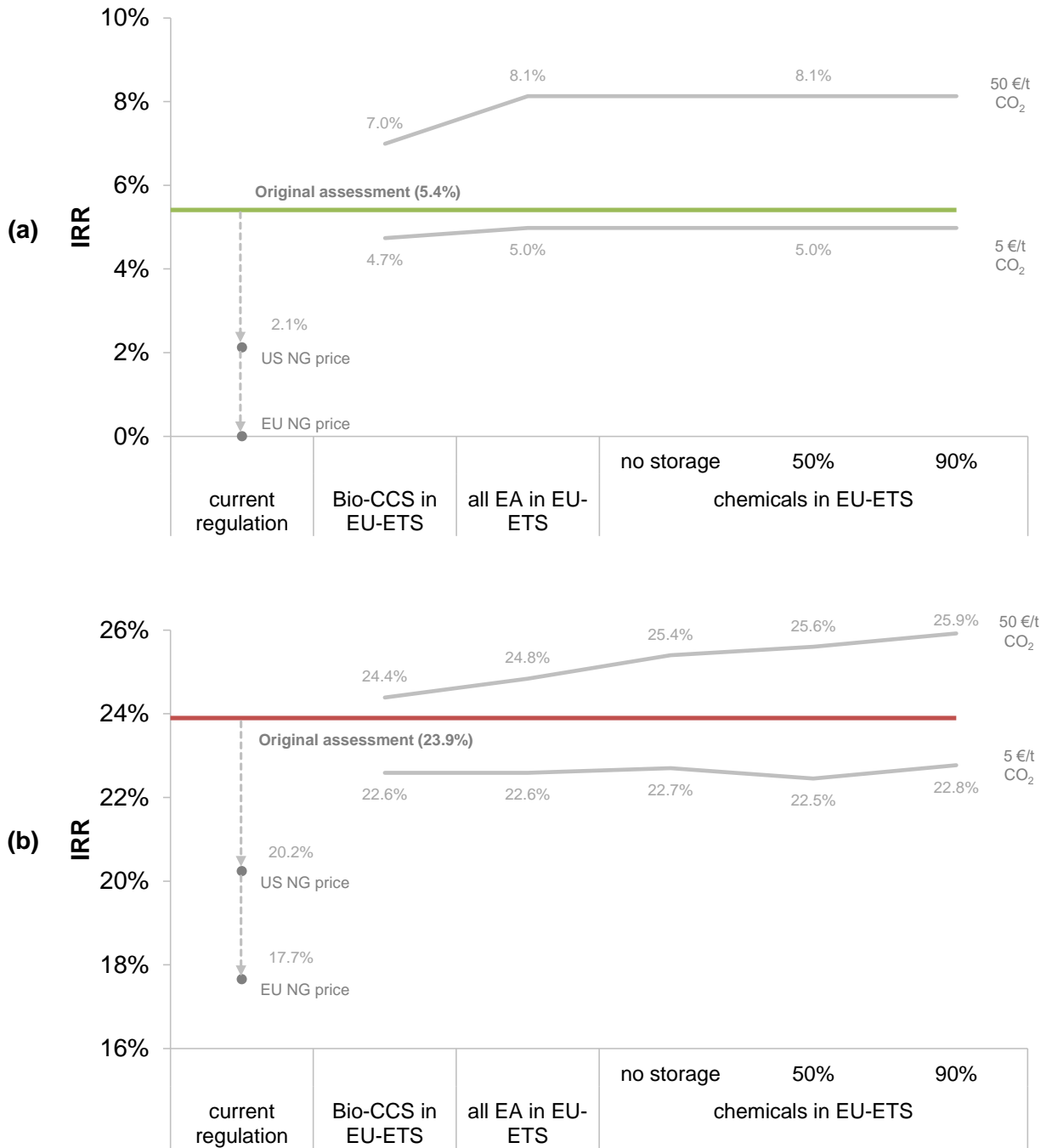
894 Figure 9.  
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Figure 10.



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