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1 CLIMATE BENEFITS FROM ALTERNATIVE ENERGY USES OF BIOMASS
2 PLANTATIONS IN UGANDA

3

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23 ABSTRACT

24

25 The establishment of tree plantations in rural areas in Uganda could provide renewable energy
26 to rural communities, while decreasing greenhouse gas emissions from conventional
27 electricity sources and unsustainable forest use. The study evaluates the greenhouse gas
28 benefits that could be produced by biomass based energy systems in Anaka, a rural settlement
29 in the Amuru district in northern Uganda. Two alternative energy uses are explored: a)
30 electricity production through wood gasification and b) traditional fuelwood use. It is
31 estimated that a small-scale wood gasifier could provide electricity for basic community
32 services by planting less than 10 hectares of new short rotation coppices (SRCs). The
33 gasification system could save 50-67% of the GHG emissions produced by traditional diesel
34 based electricity generators in terms of CO₂-eq. (0.61-0.83 t MWh⁻¹ or 7.1 t y⁻¹ per hectare of
35 SRCs). It was also estimated that traditional use of fuelwood in households is currently
36 unsustainable, i.e. the consumption of wood is higher than the annual growth from natural
37 wood resources in the study area. It is estimated that 0.02-0.06 ha per capita of plantations
38 could render the current consumption of wood sustainable. In this way, the CO₂ emissions
39 produced through unsustainable extraction of wood could be avoided (2.0-7.3 t per capita per
40 year or 50-130 t y⁻¹ per hectare of SRCs).

41

42 KEYWORDS:

43 Bioenergy; Gasification; GHG Balance; Sustainability; Uganda; Short Rotation Coppice

44

45 1 INTRODUCTION

46

47 Biomass is the main source of energy in Uganda. National statistics report that 91.5% of
48 energy consumption is derived from the combustion of biomass sources such as fuelwood,
49 charcoal and residues. A very limited share of energy use is covered by electricity (1.1%) and
50 the remaining 7.4% is produced by fossil fuels [1].

51 Wood biomass will likely remain the dominant household energy source for cooking and
52 heating for several decades in Uganda due to low accessibility to alternative energy sources
53 [2]. In addition, biomass is seen as an option to provide electricity to rural areas where only
54 1% of the population has access to the grid. High electricity prices, frequent power outages,
55 and high line losses pose hurdles to increasing access to the grid over the short to medium
56 term.

57 At the same time, forest statistics report that wood resources in Uganda are constantly
58 decreasing [3]. Consequently, biomass based electricity generation or traditional energy from
59 fuelwood can be expected to be constrained by a decreasing availability of wood from forests
60 and other wooded lands. By contributing to the degradation of natural wood resources,
61 biomass based energy also contributes to increase greenhouse gas (GHG) emissions in the
62 atmosphere and to climate change.

63 The establishment of new plantations in developing countries could guarantee wood
64 availability for the future, supply feedstock to renewable energy systems that are accessible to
65 rural communities and produce GHG benefits as compared to fossil fuel based systems and
66 unsustainable wood extraction.

67 This study assesses the climate mitigation benefits produced by alternative uses of wood
68 plantations, when new Short Rotation Coppices (SRCs) are established on non-forested, low
69 carbon-stock land in Uganda. The comparison of GHG benefits from alternative uses of a

70 certain bioenergy source is important to support the most efficient strategies to achieve GHG
71 emission reductions [4] [5]. To the knowledge of the authors, this is the first attempt to make
72 such an assessment from wood plantations in Uganda.

73 Two alternative energy uses of wood plantations in a rural area in Uganda are considered:

74 a) Electricity from wood gasification; and

75 b) Firewood for traditional use in households.

76 The climate mitigation benefits of wood gasification are assessed by applying a GHG balance
77 based on a Life Cycle Assessment methodology. The balance compares the GHG impacts of
78 the gasifier to the impacts of a typical fossil fuel based electricity generation.

79 In parallel, we assessed the area of SRC plantations needed to supply fuelwood to the rural
80 community. The plantations would avoid degradation of natural biomass resources and thus
81 avoid increasing GHG in the atmosphere. An estimate of the avoided emissions is provided.

82

83 2 METHODS

84

85 2.1 STUDY AREA

86

87 The study area is located in the Amuru district in the Northern part of Uganda (02°36'0"N,
88 31°57'0"E). The CLIMWAT database [6] reports an annual precipitation of about 1,500 mm
89 y^{-1} and an average annual temperature of 23°C for the meteorological station in Gulu.

90 Climatic measurements taken in 2005-2007 in Aswa-Lolim, Amuru suggest that the average
91 rainfall could be lower in certain areas of the Amuru district, around 900 to 1,000 mm per
92 annum. [7].

93 The Anaka refugee camp in Amuru is the settlement chosen for the installation of the gasifier
94 and the assessment of the impacts of traditional use of fuelwood. The Anaka internally
95 displaced people camp (IDP camp) hosts about 22,450 people. Main electricity users in the
96 camp are the hospital and shops. Anaka is located in the north-western part of a water
97 catchment in which the main land uses are grasslands (727 km²), followed by agricultural land
98 (214 km²) and forests (192 km²) [8]. Currently, grasslands are used for hunting. Most likely,
99 in the near future land will return to small holder agriculture and cattle ranching, as they were
100 before the civil war.

101

102 2.2 BIOMASS FOR ELECTRICITY

103

104 Previous investigations showed that small-scale wood gasifiers could be an economically and
105 socially feasible energy system to produce electricity in rural Uganda [9]. This study
106 integrates previous analysis by assessing the mitigation potential of wood gasifiers in Uganda.
107 The GHG benefits of electricity generation by wood gasification as compared to electricity

108 originating from diesel generators in the IDP camp of Anaka are evaluated through a GHG
109 balance based on a Life Cycle Assessment methodology.

110

111 2.2.1 GHG BALANCE

112

113 A GHG balance, based on a Life Cycle Assessment (LCA) methodology, includes all
114 processes, which influence GHG emissions from *cradle to grave* [10]. The GHGs included in
115 the study are carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). Global Warming
116 Potentials (GWP) on a 100 year time horizon are used to express the contribution of CO₂, CH₄
117 and N₂O to global warming in terms of equivalent amount of CO₂ (CO₂-eq.) [11].

118 The GHG balance is performed with the Global Emission Model of Integrated Systems
119 (GEMIS), version 4.5 [12] and project specific data are added to the GEMIS standard data set
120 version 4.5. Two different systems for electricity production are analysed:

- 121 ▪ “Electricity wood gasifier – E-WG”: Production of electricity with a centralized wood
122 gasification system. The biomass used is supplied from Short Rotation Coppices
123 (SRCs) of *Eucalyptus grandis* Hill ex Maiden.
- 124 ▪ “Electricity diesel generator – E-DG”: Production of the electricity with decentralized
125 diesel generators.

126 The GHG balance is based on process chains which are designed for each investigated
127 system: the wood gasification and the reference fossil fuel system (diesel generator). A
128 process chain describes the complete life cycle, starting with the production of raw materials
129 and ending with the supply of energy to the end user (Figure 1). Emissions or removals from
130 the conversion of grassland to SRCs are also included.

131

132 Figure 1

133

134 2.2.2 INPUT DATA

135

136 The electricity demand for the Anaka camp is estimated based on a study conducted in the
137 refugee camp of Kyangwali, Uganda within the project BIOSYRCA [13]. Electricity is used
138 by the hospital and the trading centre of the Anaka camp. In Kyangwali, the electricity
139 demand is estimated to be 25.5 MWh y⁻¹. In this study, a demand of 30 MWh y⁻¹ is assumed
140 as a conservative estimate to include a possible increase of demand in the near future and
141 higher electricity needs for the hospital.

142 The data on the electricity generators are reported in Table 1. The gasifier powers a modified
143 diesel engine that runs on a dual fuel mode. The fuel gas provides 75% of the primary energy
144 input.. Diesel is required for start-up operations and to support the systems. A small power
145 grid must be constructed to supply electricity from the gasifier to the main buildings of the
146 refugee camp. The length of transmission lines is assumed to be 2 km to connect the hospital
147 and shops of the trading centre. In the case of diesel generators each of the buildings that
148 require electricity is equipped with a separate diesel generator.

149

150 Table 1

151 ^aType Ankur Gasifier WBG-15/GAS-9; data according to [14] and expert judgment.

152 ^bDecentralized units in the main buildings type PRAMAC P4500-PF322SYA; data according
153 to product specification (www.pramac.com)

154

155 The wood for gasification is supplied by Short Rotation Coppices (SRCs) of *E. grandis*. It is
156 assumed that the plantation density is 2.5 x 2.5 m or equal to a stem density of 1600 ha⁻¹ the

157 maximum rotation length is 6 years [15] and that the annual productivity of the stands ranges
158 between 5 to 15 t ha⁻¹ y⁻¹ on an oven dry basis [13]. It is also assumed that the productivity of
159 the plantations corresponds to the biomass that can be harvested.

160 The total planted area needed for the SRCs is calculated based on the productivity of the
161 plantations and the total amount of wood required by the gasification system. The lower
162 heating value of wood is assumed equal to 18 GJ t⁻¹ and the electrical conversion efficiency
163 15% [13]. It is calculated that a wood supply of 30 t y⁻¹ is needed to produce an electricity
164 output of 30 MWh y⁻¹ from the gasifier, if wood contributes to 75% of the energy input of the
165 dual-mode system. By assuming an annual productivity of 5 to 15 t ha⁻¹ y⁻¹, the final harvest
166 produces 30-90 t ha⁻¹. Therefore the annual demand is met by harvesting 1.0 to 0.33 hectares
167 each year. To guarantee a constant annual supply of wood, a total area of 2.0 to 6.0 ha needs
168 to be converted to Eucalyptus plantations and 1/6 of it is cut every year.

169 Plantations should be established on areas not used for agricultural production in order to
170 exclude competition with other major land uses, primarily food production. Therefore, the
171 SRCs are planted on an area currently covered by grasslands.

172 The annual emissions from planting and harvesting are calculated as an average over 20 years,
173 taking into account that harvesting starts in year six and that the plantations are renewed every
174 three rotation periods. The transport emissions are assessed by assuming a maximum distance
175 of 30 km between the plantations and the gasifier. The emissions caused by transportation for
176 planting and harvesting are calculated based on a daily productivity of a team of 3 to 6
177 workers. It is assumed that each worker plants 220 seedlings per day and harvests 120 trees
178 per day. The fuel consumption of the truck is assumed to be at 0.165 dm³ km⁻¹, i.e. 9.9 dm³ d⁻¹
179 ¹. The harvesting is done with chainsaws. A fuel consumption of 12.8 dm³ and an oil
180 consumption of 2.9 dm³ per working day are assumed. The emissions caused by use of
181 herbicide and fertilizer before planting are also included. It is assumed that a manual chipping

182 system is used to chip the wood used for the gasifier. Motor driven chippers are very
183 effective, but they require a substantial initial investment, besides constant service and
184 maintenance. Hand operated or spring activated scissors or axes were considered a more
185 suitable option in rural Uganda.

186 An inventory table of the inputs and outputs of the gasification system is reported in the
187 Appendix.

188

189 2.2.3 LAND USE CHANGE EMISSIONS AND REMOVALS

190

191 The carbon (C) stock changes due to the conversion of grasslands to Eucalyptus plantations
192 are included in the GHG balance. The change is calculated as the difference between the
193 carbon stock of the Eucalyptus plantations and the carbon stock of grasslands on hectare
194 basis. The annual change over a conversion period of 20 years is considered [11]:

195 (1)
$$\Delta C = \frac{(C_E - C_R)}{20}$$

196 Where:

197 ΔC : carbon stock change due to land use change ($\text{t ha}^{-1} \text{y}^{-1}$)

198 C_E : carbon stock in Eucalyptus SRCs (t ha^{-1})

199 C_R : carbon stock in grasslands (t ha^{-1})

200

201 Only the carbon stock changes in the biomass are included in the calculation. The conversion
202 of cropland or grassland to plantations will likely increase or maintain unaltered the amount
203 of carbon in soils [16]. Therefore, it is conservatively assumed that the carbon stock changes
204 in the soil are equal to zero [11]. The biomass carbon content of grasslands is derived from
205 IPCC default values (8 t ha^{-1} of C). The biomass in the SRCs is assessed based on a stand

206 productivity of 5-15 t ha⁻¹ and an IPCC default root-to-shoot ratio of 0.24 to convert
207 aboveground biomass to root biomass. A carbon fraction in the biomass of 0.47 is assumed
208 [11]. It was assessed that the new SRCs accumulate 9.3-27.8 t ha⁻¹ of C after 20 years when
209 belowground biomass is included and when the carbon loss from conversion is not taken into
210 account (8 t ha⁻¹ of C). Therefore, the conversion produces a net C sequestration in living
211 biomass of 0.06-1.0 t ha⁻¹ y⁻¹ or a sequestration of 0.4-2.0 t y⁻¹ over the entire area.

212

213 2.3 BIOMASS FOR TRADITIONAL USE

214

215 Most rural households in Uganda strongly depend on fuel wood and the collection of wood
216 for traditional use (mainly cooking) significantly contributes to deforestation and forest
217 degradation in Uganda [8] [17]. Additional plantations may be used to cover a share of this
218 traditional demand for wood. Using the Anaka IDP camp and the district of Gulu as examples,
219 we assess the area of additional plantations needed to supply sufficient wood for traditional
220 use without causing deforestation or degradation of existing forests, i.e. make the use of wood
221 sustainable and help avoiding GHG emissions to the atmosphere. Maintaining the balance
222 between annual forest growth and annual fellings of wood is one of the major indicators of the
223 sustainability concept [18]. When supplying energy from wood in Uganda, it is assumed that
224 the concept of sustainability can be translated as *renewability* of the energy source.

225 As a first step, data on wood demand are compared to the biomass growth of natural resources
226 to assess the fraction of non-renewable biomass extracted in the study area. We define the
227 non-renewable biomass fraction, $FRAC_{NRB}$ as the fraction of wood removals exceeding the
228 vegetation growth on total removals:

$$229 \quad (2) \quad FRAC_{NRB} = \frac{(BD - G)}{BD}$$

230 Where:

231 *BD*: biomass demand in a certain area ($t\ y^{-1}$)

232 *G*: biomass growth in the same area ($t\ y^{-1}$)

233

234 Second, the emissions caused by the non-renewable biomass extracted annually are calculated
235 by converting the non-renewable biomass to CO₂ emissions. A wood carbon fraction of 0.47
236 is assumed. Therefore, each tonne of non-renewable biomass burnt releases 1.83 t of CO₂ in
237 the atmosphere.

238 Third, the area of plantations needed to substitute the non-renewable biomass and to avoid the
239 related emissions is calculated. The plantation area needed depends on the productivity, the
240 amount of fuelwood that can be extracted from the total biomass and the rotation length of the
241 plantation. The area is estimated by assuming that plantations are similar to the Eucalyptus
242 SRCs previously described with an average productivity of $10\ t\ ha^{-1}\ y^{-1}$ on an oven dry basis.
243 It is assumed that the total demand of wood in the region remains constant over time and that
244 the renewable fraction of wood is still supplied by natural wood resources.

245 The non-renewable biomass fraction is assessed for the entire Gulu district and for the Anaka
246 IDP camp by using the two following alternative methods.

247 The Amuru district was still part of the Gulu district before 2006 and the available statistics
248 refer to the old administrative borders. Therefore, the assessment of the $FRAC_{NRB}$ is done for
249 Gulu and it includes the area of Amuru. The non-renewable biomass fraction in the Gulu
250 district is assessed by using national removal statistics by FAO, representing the demand, and
251 biomass growth data from the National Biomass Study (NBS) of Uganda [8].

252 Since data on wood removals are not available at the regional level, the national statistics are
253 regionalized to assess the amount of wood demand in Gulu. The fuelwood demand is strongly
254 related to the population residing in a certain area. Therefore, the proportion of the national

255 amount of fuelwood extracted in Gulu is calculated by using the percentage of the population
256 in the district (2%). The industrial roundwood extraction in Gulu, instead, is assessed by
257 calculating the proportion of forest biomass in the district of the total forest biomass in
258 Uganda and by assuming that the percentage of industrial roundwood removed would be the
259 same. The wood removals are converted to total biomass with IPCC default factors [11].
260 The biomass growth is calculated based on information from the NBS of Uganda (Table 2).
261 The total annual growth is equal to the aboveground annual increment converted to total
262 biomass. Also in this case, we used IPCC default factors.

263

264 Table 2

265

266 Alternatively, the $FRAC_{NRB}$ is assessed also for the area around the Anaka IDP camp by using
267 a second method. In this area, the fuelwood demand is calculated based on a wood
268 consumption of 601-692 kg of fuelwood per capita [19] [20] and the Anaka population of
269 22,450 people. Based on these data, it is calculated that the total fuelwood demand in Anaka
270 is 13,500 to 15,500 t y⁻¹. The fuelwood demand is converted to biomass affected by
271 harvesting with IPCC conversion factors.

272 A land use map of the study area and the National Biomass Study (NBS) data on the biomass
273 growth are used to estimate the biomass resources available to the IDP camp. Fuelwood is
274 collected within a certain walking distance usually of one kilometre, but people can cover a
275 20 km distance if needed. Three different areas with radii from the IDP camp of 5 km, 10 km
276 and 15 km respectively are selected to calculate the available amount of wood within variable
277 distances and $FRAC_{NRB}$ (Figure 2). It is assumed that all the wood collected or purchased is
278 available within these distances.

279

280 Figure 2

281

282 3 RESULTS

283

284 3.1 BIOMASS FOR ELECTRICITY GENERATION

285

286 The GHG Balance shows that the wood gasification system produces less GHG emissions
287 than the reference fossil fuel system of diesel generators (Figure 3). When the plantation
288 productivity is low ($5 \text{ t ha}^{-1} \text{ y}^{-1}$), the gasification system produces about half of the GHG
289 emissions produced by the fossil fuel system (51%). The emissions are even lower if SRCs
290 have higher productivity, i.e. if the average carbon stock of the SRCs is higher. When the
291 plantation produces $15 \text{ t ha}^{-1} \text{ y}^{-1}$ of wood, the installation of a gasifier produces about 1/3 of
292 the emissions produced by diesel generators. Therefore, the gasification system saves 18.1-
293 24.6 t y^{-1} or $0.61\text{-}0.83 \text{ t MWh}^{-1}$ of $\text{CO}_2\text{-eq.}$ emissions.

294

295 Figure 3

296

297 The overall GHG balance of the gasification system is given by different components (Figure
298 4). Emissions are produced by the management of SRCs (harvesting, fertilization, transport of
299 workers and seeds), the transport of wood, the gasifier (construction material, diesel for the
300 operation of the system), and the construction and operation of the electricity grid. These
301 emissions are partially offset by carbon sequestration due to conversion from grasslands to
302 Eucalyptus plantations (Land Use Change). The extent to which emissions are offset depends
303 on the productivity of the plantations.

304

305 Figure 4

306

307 3.2 BIOMASS FOR TRADITIONAL USE

308

309 The National Biomass Study (NBS) clearly shows that the biomass stock of natural wood
310 resources is decreasing all over Uganda. The trend is mainly caused by the gap between the
311 high demand for fuelwood and the biomass increment [8].

312 By regionalising the national statistics, it is assessed that 722,000 m³ of fuelwood and 19,100
313 m³ of roundwood were removed in Gulu in 2005. By converting these figures to total
314 biomass, it is estimated that 4.84 Mt y⁻¹ of biomass was harvested or 3.23 Mt y⁻¹ when only
315 aboveground biomass is considered. From the supply side, we calculate that the total annual
316 biomass growth in Gulu is equal to 3.82 Mt y⁻¹ (2.55 Mt y⁻¹ aboveground growth).

317 Based on these numbers, the non-renewable fraction of biomass extracted in Gulu ($FRAC_{NRB}$)
318 is 21.1%.

319

320 Similar results are produced for the Anaka IDP camp with the alternative approach described
321 in the Methods.

322 The difference between biomass demand in Anaka and biomass produced on land around the
323 camp shows that the net biomass balance is negative within a distance of 10 km radius from
324 the IDP camp. If the biomass would be extracted homogenously in the 15 km radius area, the
325 fuelwood extracted would be all renewable, but within a 15 km radius there is higher
326 competition of use with other settlements (Figure 2). The percentage of non-renewable
327 biomass that is extracted ranges between 88-89% in the 5 km radius to 18-29% in the 10 km
328 radius (Table 3).

329

330 Table 3

331

332 The non-renewable biomass extracted for fuelwood around the Anaka camp produces an
333 annual amount of CO₂ emissions equal to:

- 334 • 151.5 – 177.6 x 10³ t y⁻¹ if fuelwood is collected within 5 km; or 7.3 t y⁻¹ per capita on
335 average.
- 336 • 31.6 – 57.8 x 10³ t y⁻¹ if fuelwood is collected within 10 km; or 2.0 t y⁻¹ per capita on
337 average.
- 338 • zero CO₂ emissions if fuelwood is collected within 15 km.

339 These results do not take into account that biomass is declining and that the percentage of
340 non-renewable biomass increases with time.

341 In the Gulu district, the calculated 21% of non-renewable biomass releases each year 1.76 Mt
342 of CO₂ emissions in the atmosphere. These emissions could be avoided by promoting the
343 establishment of dedicated plantations or tree farming (e.g. trees around fields) that would
344 substitute the use of non-renewable biomass.

345 By assuming a productivity of 10 t ha⁻¹ y⁻¹, and a per capita fuelwood demand of 647 kg y⁻¹,
346 the required plantation area is 1283 ha within a 5 km radius for a *FRAC_{NRB}* of 88%, while
347 only 348 ha would be required within a 10 km radius for a *FRAC_{NRB}* of 24%.

348 The use of wood in the area would change from unsustainable use to sustainable use due to
349 the additional wood supply from these plantations.

350 Based on the results from the GHG Balance for the wood gasifier, it can be conservatively
351 assumed that the balance between carbon sequestration and emissions due to installation and
352 management of the plantations is zero.

353

354 3.3 EFFICIENCY IN PRODUCING EMISSIONS SAVINGS

355

356 The previous sections showed that fast growing plantations could help achieving GHG
357 emission reductions in rural Uganda either if the wood is used to produce electricity or as
358 fuelwood. The efficiency of these two activities in producing emission savings can be
359 compared by calculating the emission reductions achievable on a per hectare basis.

360 A) Gasification system

361 The gasification system saves on average 21.3 t y^{-1} of $\text{CO}_2\text{-eq.}$ ($18.1\text{-}24.6 \text{ t y}^{-1}$) compared
362 to diesel generators by planting a total area of 3 ha of SRCs. Therefore the emissions
363 saved by the gasifier are equal to 7.1 t y^{-1} per hectare of SRCs.

364 B) Fuelwood production

365 A fuelwood demand of $14,515 \text{ t y}^{-1}$ annually required for the Anaka IDP camp produces
366 $44,680 \text{ t y}^{-1}$ of CO_2 emissions if the fuelwood is converted to total biomass extracted
367 within a distance of 10 km radius from the camp ($FRAC_{NRB}=24\%$). The total area of SRCs
368 needed to offset these emissions is equal to 348 ha, meaning that the plantations for
369 fuelwood save $128.2 \text{ t ha}^{-1} \text{ y}^{-1}$ of $\text{CO}_2\text{-eq}$ emissions. The same result in terms of GHG
370 saving per hectare is obtained when fuelwood is extracted within an area of 5 km radius
371 from the camp.

372 Therefore, in terms of GHG savings on a per hectare basis, the most efficient use of fast
373 growing plantations in rural Uganda is to replace fuelwood collected in forests managed
374 unsustainably. However, the services provided by the gasification system and the fuelwood
375 plantations are very different. Even if replacement of fuelwood is much more efficient from
376 the point of view of GHG savings per hectare, the electricity services provided by the
377 gasification system bring additional benefits (e.g. social development) that might render the
378 use of plantations for electricity production more beneficial from a socio-economic point of
379 view. The great difference of GHG savings might also depend on the IPCC factors that
380 convert fuelwood to total biomass. According to these factors and the calculations made, the

381 collection of fuelwood from natural wood resources is very inefficient, i.e. the amount of
382 biomass affected by harvesting is 3.2 to 8.1 times higher than the amount used for fuelwood
383 (the highest factor of 8.1 is for woodlands). In fact, only certain parts of the trees are collected
384 for fuelwood, but the remaining biomass of the harvested tree remains in the field and starts to
385 decay. Under a more efficient use, when most of the aboveground biomass from natural wood
386 resources is used for fuelwood (about 70%) the CO₂ savings would be around 50 t ha⁻¹ y⁻¹.

387

388 4 DISCUSSION

389

390 According to the results in this study, wood gasification for electricity production could
391 provide a valid alternative in terms of GHG impacts to diesel generation in rural communities
392 in Uganda. The overall carbon balance shows that wood gasification could provide energy in
393 rural communities that produces at least 50% less GHG emissions than the traditional diesel
394 generators. The GHG balance improves if the productivity of the plantations increases.

395 The productivity of plantations is dependent on the tolerance of the tree species to local
396 climate conditions and to the mortality rate due to fires and pests. In Amuru a short-term trial
397 study showed that the productivity of Eucalyptus in the area could be very low and that a high
398 mortality rate can occur because of fire, low peaks of rainfall and pests [7]. However, more
399 detailed information would be needed to state that Eucalyptus is unsuitable in the study area.

400 Alternative species to *E. grandis* more adapted to the Amuru area or hybrid Eucalyptus clones
401 that are more resistant to dry conditions, such as *E. grandis* x *E. camaldulensis*, could be used.
402 In addition, a different management, such as a different rotation length and tree density, could
403 strongly influence the productivity of the SRCs.

404 Another parameter that should be considered to choose suitable tree species is its water use. It
405 is recognized that Eucalyptus is a species that can produce high evapotranspiration. If planted
406 on large scale areas, Eucalyptus could have negative impacts on the water balance in the
407 catchment and limit water availability [21]. This problem should be addressed especially in
408 zones, such as major parts of Africa, where scarcity of water for human consumption is an
409 important issue.

410 We investigated the possibility to plant a native species such as *Markhamia lutea*, but data on
411 its productivity were not robust enough to be used in the study. The use of native species
412 could have the advantage to be more resistant to local conditions and therefore guarantee a

413 more constant and secure wood supply. In addition negative effects on biodiversity and water
414 balance could be avoided.

415 Major limits to the presented results emerge from the uncertainty of the input data. As
416 illustrated in the previous paragraphs, more precise information on the productivity of the
417 plantations could narrow down the variability of the final results. Emissions or removals in
418 the soil pool from land conversion should also be included, whereas they were neglected in
419 this study due to the lack of more specific data for similar regions. In addition, large part of
420 the input data to the model GEMIS were not specific for Uganda. A further limit of the study
421 is that we focused only on the GHG impact of the gasification system. A complete
422 environmental impact assessment, including more impact categories, would improve the
423 understanding of the sustainability of such systems. Factors that affect the feasibility of
424 implementation of gasification systems in rural areas should also be taken into account.

425 Barriers to technical implantation could be: mechanical and technical problems when running
426 the gasification system, unavailability of dried and chipped wood and social problems [22].

427 Moreover, public and private investments that provide the initial capital to establish the
428 gasification system and the plantations should be identified to evaluate the feasibility of such
429 installations (e.g. soft loans, microcredits, Clean Development Mechanism projects) [23].

430 This study encourages further investigations of social, economic and technical viability of
431 such small scale biomass gasification systems for rural electricity production in Uganda.

432 Small-scale biomass gasification systems providing basic electricity services can have many
433 economic and social advantages towards other renewable and non-renewable electricity
434 sources and often constitute the only current economic alternative to diesel generators in rural
435 Uganda. As little as 68 kg of dry wood per capita and year can already provide significant
436 increases in life standards for rural residents in Uganda when used for electricity generation
437 thus keeping the additional environmental pressures low [9].

438

439 The study assessed that the present use of wood for fuel in Amuru district is most likely
440 unsustainable. However, the background data are highly uncertain, in particular the data on
441 removals and the conversion factors to assess the total biomass affected by fuelwood
442 extraction. It is also likely that a significant share of the wood removals is not reported by
443 official statistics. If this is the case, the gap between wood removals and forest growth would
444 be higher. Consequently the non-renewable fraction of biomass would be higher than the one
445 estimated in this study and a larger area of plantations would be needed. In addition, the study
446 does not take into account that the non-renewable fraction of biomass will increase over time
447 if natural wood resources will continue to shrink. On these grounds, the estimates of $FRAC_{NRB}$
448 should be considered conservative. On the other hand, conversion factors to assess the total
449 biomass affected by fuelwood extraction might overestimate $FRAC_{NRB}$.

450 Since wood will still be the main source of energy in Uganda, at least in the short to medium
451 term, solutions to decrease pressure on natural resources should be proposed, including the
452 increase of wood resources through additional forest plantations. An alternative to plantations
453 is the increase of energy use efficiency through, e.g., the use of improved wood stoves.
454 However, it is reported that increased efficiency does not necessarily lead to a decrease of
455 wood consumption [2]; this phenomenon is known as the Jevons paradox [24].

456 An additional problem linked to the use of woody biomass is indirect land use change. When
457 plantations are established on land that would have been used for other purposes, it is possible
458 that the other uses are displaced somewhere else. The displacement can produce land use
459 changes elsewhere and consequent negative environmental impacts (e.g. GHG emissions,
460 biodiversity loss). For this reason, we suggested to establish the plantations on areas
461 extensively used or that are marginal (grasslands). However, re-distribution of land after the

462 civil war could re-convert large areas to agricultural use and compete with the establishment
463 of new plantations.

464

465 5 CONCLUSIONS

466

467 The establishment of new tree plantations for energy production could be beneficial for rural
468 communities in Uganda for both GHG emission reductions and the sustainability of biomass
469 supply.

470 The analysis of the GHG benefits of a small-scale gasification system showed that it would be
471 a valid alternative in terms of GHG impact to the diesel generators for areas that will not have
472 access to hydropower or other forms of electricity generation in the short to medium term due
473 to their distance to established electricity grids, low population density, and biophysical and
474 geographical features. Wood gasification could provide electricity for basic community
475 services by planting less than 10 hectares of new Short Rotation Coppices and it could save
476 50-67% of the CO₂-eq.emissions produced by traditional diesel based electricity generators
477 (18.1-24.6 t y⁻¹ or 0.61-0.83 t MWh⁻¹).

478 Wood plantations should also be considered to reduce pressure on natural resources due to
479 traditional use of wood in households in Uganda. It was assessed that the fuelwood removals
480 in a rural area in Uganda are unsustainable because the demand for wood exceeds the annual
481 growth from existing forests and other wooded lands. This situation substantially contributes
482 to the degradation of natural biomass resources and, as a consequence, to GHG emissions.

483 The non-renewable fraction of biomass that is extracted (21% in the Gulu district) could be
484 replaced with wood from new plantations to render the overall balance of fuelwood removals
485 sustainable and reduce emissions to the atmosphere. It was assessed that 0.02-0.06 ha per
486 capita of plantations in a rural community in Uganda could avoid the GHG emissions
487 produced through unsustainable extraction of wood (approximately 2.0-7.3 t of CO₂ per capita
488 per year).

489

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493 [APPENDIX]

494

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TABLES

Table 1 – Basic data on the power generation systems

Technology	Efficiency	Life span	Operation	Capacity	Steel	Concrete
	(%)	(y)	hours (h y ⁻¹)	(kW)	(kg)	(kg)
Wood gasifier ^a (bioenergy system)	15	15	3.257	9	500	200
Diesel generator ^b (Reference system)	28	10	3.257	3	100	-

^aType Ankur Gasifier WBG-15/GAS-9; data according to [12] and expert judgment.

^bDecentralized units in the main buildings type PRAMAC P4500-PF322SYA; data according to product specification (www.pramac.com)

Table 2 – Data on vegetation types in the Gulu District. The data refer only to the aboveground biomass (source: NBS)

Vegetation	Area	Biomass		Biomass change		Biomass increment	
	km ²	kt	t ha ⁻¹	kt y ⁻¹	%	t ha ⁻¹ y ⁻¹	kt y ⁻¹
Forest	8	99	131.0	-0.2	-0.2	13.0	9.8
Woodland	4686	14363	30.6	-737.5	-5.1	5.0	2343.1
Bushland	359	420	11.7	-13.6	-3.2	1.0	35.9
Grasslands	1624	1801	11.1	-3.4	-0.2	1.0	162.4
Total	6677	16683	25.0	-754.6	-4.5	n.a.	2551.2

Table 3 – Fraction of non-renewable biomass removed within a certain distance from the Anaka IDP camp. The ranging values are determined by different fuelwood demands per capita.

	15 km	10 km	5 km
Fuelwood demand (kt y ⁻¹)		13.5 - 15.5	
Tot biomass demand (kt y ⁻¹)		100.4 - 115.6	
Biomass growth (kt y ⁻¹)	198.5	82.1	12.5
Net biomass balance (1000 t y ⁻¹)			
- Low	98.0	-18.3	-87.9
- High	82.9	-33.5	-103.1
<i>FRAC_{NRB}</i> (%)			
- Low	0	18	88
- High	0	29	89

APPENDIX

Inventory table for the wood gasification systems

	Unit	Eucalyptus 15 t	Eucalyptus 5 t
SRC Cultivation and Harvesting			
INPUT			
Auxiliary energy			
<i>Diesel</i>	MWh MWh ⁻¹	0.0014	0.0029
<i>Petrol</i>	MWh MWh ⁻¹	0.004	0.012
Auxiliary material			
<i>Engine Oil</i>	kg MWh ⁻¹	0.083	0.250
<i>Phosphate</i>	kg MWh ⁻¹	0.05	0.15
<i>Herbicides</i>	kg MWh ⁻¹	0.01	0.04
OUTPUT			
Eucalyptus			
<i>Yield (fresh matter)</i>	t ha ⁻¹ y ⁻¹	154	51
<i>Water Content</i>	%	41.5	41.5
<i>Heating Value</i>	MWh t ⁻¹	2.64	2.64
SRC Transport			
Vehicle Type		Small Truck	
Loading Capacity	t	3.5	
Fuel Consumption	dm ³ km ⁻¹	0.165	
Distance	km	60	
Gasifier			
INPUT			
Eucalyptus	MWh MWh ⁻¹	4.87	
Auxiliary energy			
<i>Diesel</i>	MWh MWh ⁻¹	1.79	
Construction material			
<i>Steel</i>	t MW ⁻¹	56	
<i>Concrete</i>	t MW ⁻¹	22	
OUTPUT			
Electricity			
Power Grid			
Transmission Losses	% km ⁻¹	0.04	
Construction material			
<i>Steel</i>	t km ⁻¹	550	
<i>Concrete</i>	t km ⁻¹	45	

FIGURE CAPTIONS

Figure 1 – Process chains for the centralized wood gasification system and the fossil reference system with decentralized diesel generators.

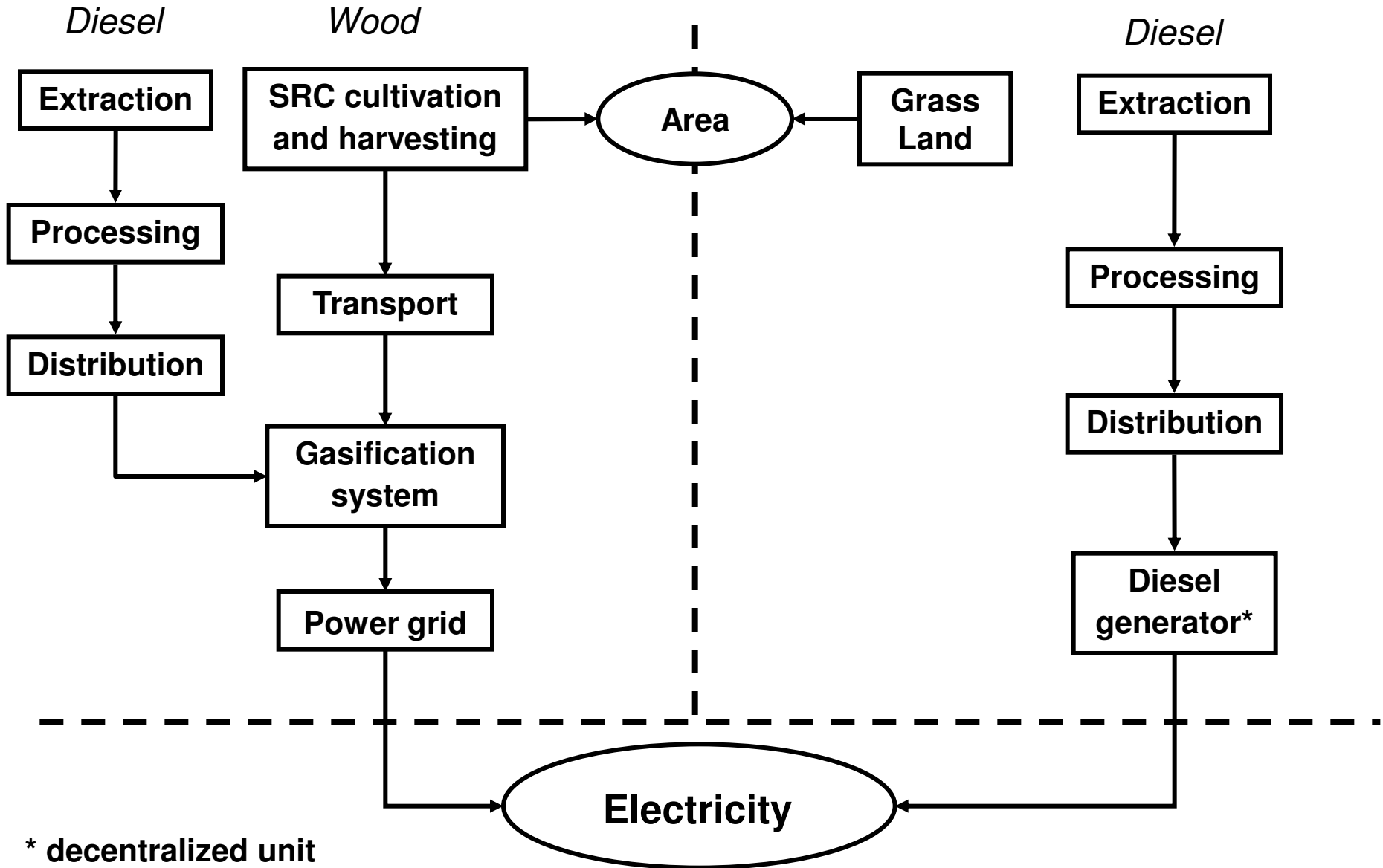
Figure 2 – Land use map of the water catchment in which the Anaka camp is located [8]. The dotted circles around the camp define the wood supply areas within variable distances.

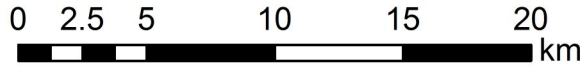
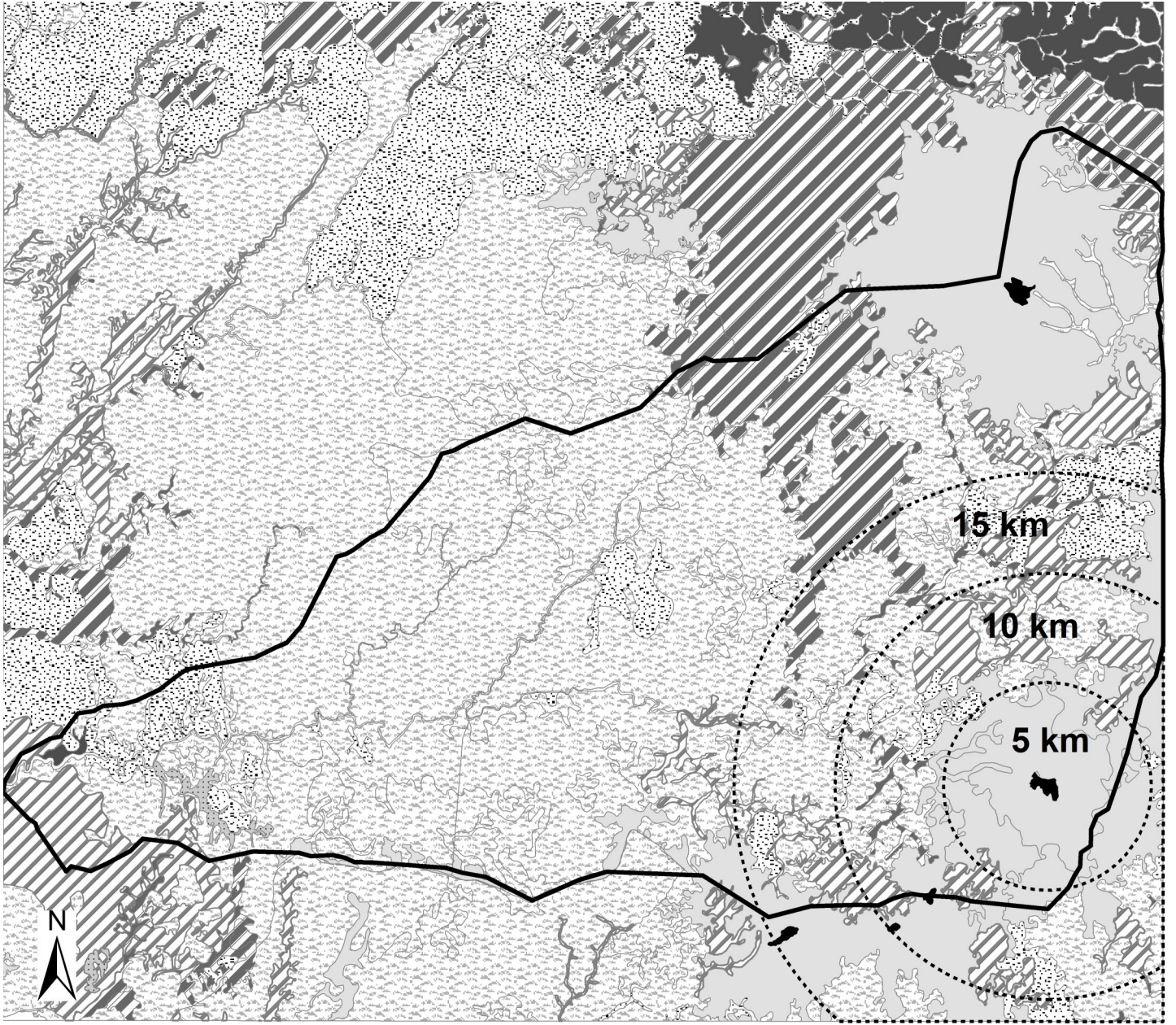
Figure 3 – Comparison of GHG emissions from the diesel generators (E-DG) and the wood gasifier (E-WG). The emissions from the gasifier are shown for different levels of productivity of the plantations (5 and 15 t ha⁻¹ y⁻¹).

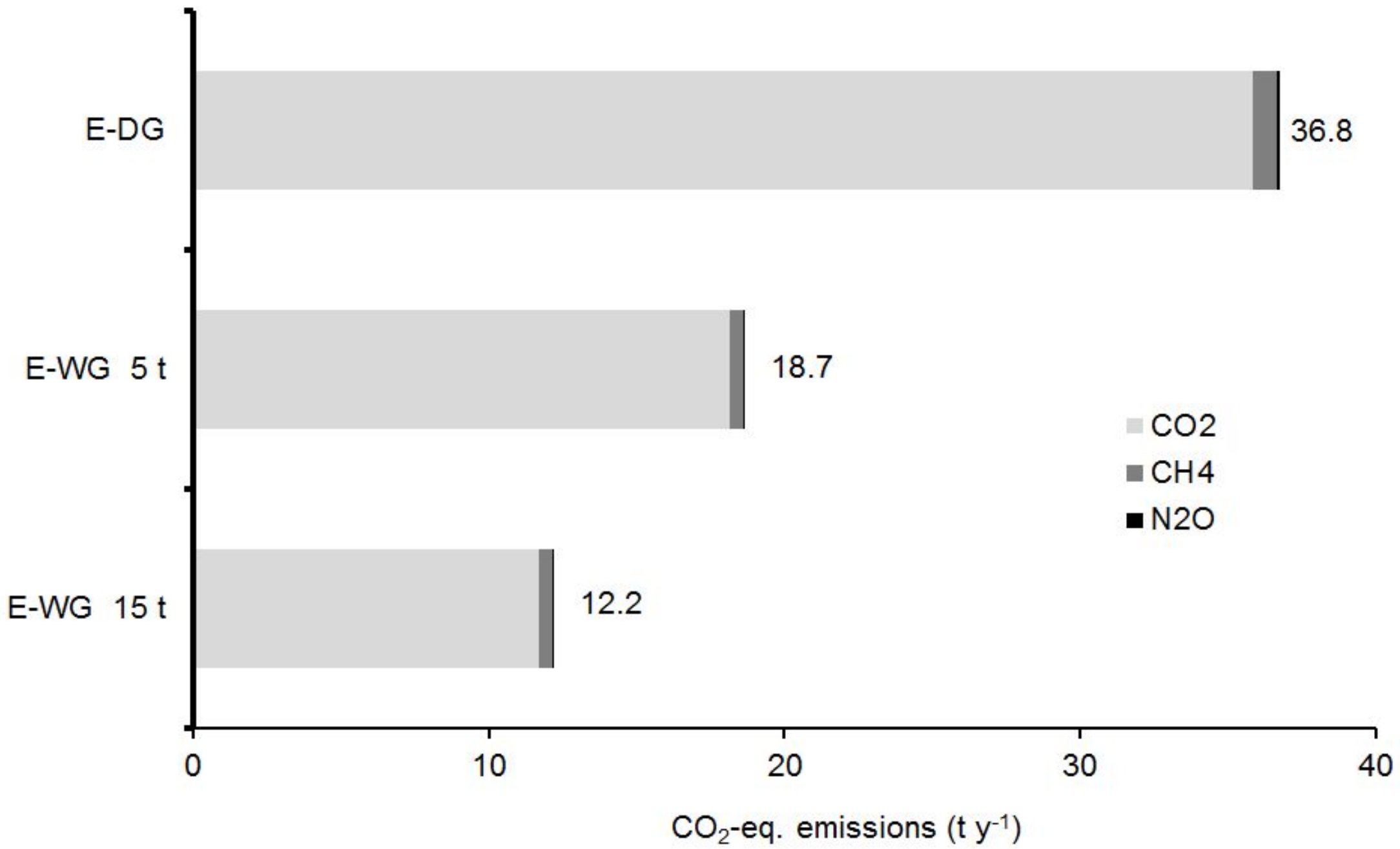
Figure 4 – Emission components of the gasification system (E- WG) according to different productivities of the Short Rotation Coppices (SRCs).

Gasification system

Diesel Generator







Process Steps

