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1                   **Life Cycle Assessment of a Small-Scale Anaerobic Digestion Plant**  
2                   **from Cattle Waste**

3  
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5

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10  
11                   **ABSTRACT**

12                   This paper outlines the results of a comprehensive life cycle study of the production  
13                   of energy, in the form of biogas, using a small scale farm based cattle waste fed  
14                   anaerobic digestion (AD) plant. The Life Cycle Assessment (LCA) shows that in  
15                   terms of environmental and energy impact the plant manufacture contributes very  
16                   little to the whole life cycle impacts. The results show that compared with alternative  
17                   energy supply the production and use of biogas is beneficial in terms of greenhouse  
18                   gases and fossil fuel use. This is mainly due to the replacement of the alternative,  
19                   kerosene, and from fertiliser production from the AD process. However, these  
20                   benefits come at a cost to ecosystem health and the production of respiratory  
21                   inorganics. These were found to be a result of ammonia emissions during the  
22                   production phase of the biogas. These damages can be significantly reduced if further  
23                   emission control measures are undertaken.

24  
25                   **KEYWORDS**

26                   Life Cycle Assessment, Biogas, Anaerobic Digestion  
27

28                   **INTRODUCTION**

29                   The use of bioenergy may help meet our renewable energy and carbon reduction  
30                   targets set by the Renewable Energy Directive [1] and Kyoto [2]. Bioenergy is of  
31                   particular interest amongst renewable energy, as it doesn't suffer from some of the  
32                   intermittency or weather dependency that some other renewable technologies do, such  
33                   as wind or solar. It is proposed by DECC that bioenergy might be able to produce half  
34                   of our renewable energy target requirements by 2020 [3]. In addition, AD is useful to  
35                   produce energy in remote areas, including farms, which in the UK are often off the  
36                   main gas grid. This means that their energy production is often through the use of oil  
37                   or kerosene boilers/burners that have higher impact in terms of greenhouse gas  
38                   emissions and fossil fuel depletion than the use of, for example, natural gas.

40  
41                   However, studies of LCA for biogas production were found to be limited and  
42                   incomplete within the literature [4-7]. Although there have been studies examining  
43                   LCA of biogas, these do not always follow the methodology of standard LCA  
44                   procedure [8,9]. LCA has been more widely used for other bioenergy techniques,  
45                   rather than biogas production individually [10-13]. In addition, small farm operations  
46                   do not always only use AD to produce energy, but it is one of many benefits  
47                   associated with AD, including waste disposal and fertiliser production. It is of  
48                   particular benefit in areas of nitrate vulnerability where manure spreading is limited.

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49  
50 The majority of published biogas analyses focus on energy and carbon balances [4,5,  
51 6] as opposed to a holistic environmental appraisal. Studies which did focus on wider  
52 environmental impacts suggested that emissions from the AD process can vary  
53 significantly depending on feedstock utilisation and end-use of biogas [5]. Other  
54 studies compared biogas against other transport fuels and showed that biogas from  
55 manure produced the largest reduction in greenhouse gas emissions [7]. However,  
56 biogas from maize silage offered the largest greenhouse gas reductions for heat and  
57 power [7]. A recent British study highlighted a detailed examination of the  
58 environmental impacts of a large-scale AD plant in the UK [15]. However, the study  
59 did not examine the environmental impacts in-line with the relevant ISO standards for  
60 LCA making this study difficult to interpret and compare against other future LCAs.  
61 Similarly, a number of the biogas LCA studies mentioned above have not clearly  
62 defined the study system boundaries.  
63

64 As a result, it appeared that a detailed LCA study of UK biogas production had not  
65 been carried out. It was concluded that a holistic LCA of a UK biogas plant should be  
66 undertaken in order to model the environmental implications of using this technology.  
67 The plant reported in this paper is based on a farm in the UK. It is supplied with 100%  
68 dairy cattle waste from a herd of 130 cattle. Primary data was collected from site, and  
69 supplementary material data was obtained from LCA databases.  
70

## 71 **METHODOLOGY**

72 Life Cycle Assessment methodology was followed in this study. The commonly  
73 accepted methodology for LCA was produced by the Society of Environmental  
74 Toxicology and Chemistry (SETAC) in the 1990's. This method has been adapted into  
75 an ISO series for LCA [8,9].  
76

77 There are four main steps (shown in Figure 1): Goal definition is the stage in which  
78 the scope of the project is outlined. Here the study boundaries are established and the  
79 environmental issues that will be considered are identified. The inventory stage is  
80 where the bulk of the data collection is performed. This can be done via literature  
81 searches, practical data gathering or, most commonly, a combination of the two.  
82 Impact assessment is where the actual effects on the chosen environmental issues are  
83 assessed. This stage is further subdivided into three elements: classification,  
84 characterisation and valuation. The first two of these are fairly well established,  
85 although there is still ongoing research. However, the valuation stage is fairly  
86 subjective and still arouses debate in the literature.  
87

88 Classification is where the data in the inventory is assigned to the environmental  
89 impact categories. In each class there will be several different emission types, all of  
90 which will have differing effects in terms of the impact category in question. A  
91 characterisation step is therefore undertaken to enable these emissions to be directly  
92 compared and added together. The characterisation stage yields a list of  
93 environmental impact categories to which a single number can be allocated. These  
94 impact categories are very difficult to compare directly and so the valuation stage is  
95 employed so that their relative contributions can be weighted. This is subjective and  
96 difficult to undertake and many studies omit this stage from their assessment. Instead  
97 they employ normalisation as an intermediate step. Improvement assessment is the  
98

99 final phase of an LCA in which areas for potential improvement are identified and  
100 implemented.

101  
102  
103 Many people employ the use of LCA software in order to help process inventory data.  
104 Software also often includes some life cycle inventory databases. In this study  
105 SimaPro[17] software was used, and numerous databases were employed. EcoInvent  
106 [18] is the primary database used, but where data were not available from this, other  
107 sources were obtained. There are also a number of commercially available impact  
108 assessment tools. These employ datasets, such as the IPCC data for greenhouse gases,  
109 in order to undertake the classification, characterisation, normalisation and valuation  
110 stages. For this study the EI 99 [19] method was adopted using the hierarchical data in  
111 the impact assessment.

#### 112 113 **GOAL AND SCOPE**

114 The goal of this assessment was to examine and identify the life cycle environmental  
115 impacts from small-scale anaerobic digestion of cattle waste (AD). The objective was  
116 to identify the most important factors that affected the environmental load of a biogas  
117 generation plant. From these factors, the damages caused by the process were  
118 analysed, including the damages avoided from the displacement of a fossilised fuel.  
119 By determining the environmental load of biogas production from AD, it was possible  
120 to identify whether the process had beneficial or detrimental effects on the  
121 environment. This was assessed using a number of environmental impact categories,  
122 including damage to human health, damage to ecosystems and the depletion of global  
123 resources. The assessment examined the production, delivery and the use of the  
124 biogas (cradle to grave). The by-product of the AD process (the digestate), used as a  
125 source of natural fertiliser, was also examined as a displacement of mineral-based  
126 fertilisers. Throughout the assessment, the production of the plant was accounted for  
127 and linked to the biogas and natural fertiliser outputs. The environmental impacts  
128 were assessed using EI99 LCIA methodology. The plant assessed was based on a UK  
129 farm and was supplied with 100% dairy cattle waste from a herd of 130. The waste  
130 was collected during the winter months and during the milking period when the cows  
131 were indoors. The digester was 240m<sup>3</sup> and digested 653m<sup>3</sup> of cattle waste per annum  
132 (a mix of slurry and manure). The plant retention time (RT) was 20 days and the  
133 biogas production was measured hourly. On average approximately 8.9m<sup>3</sup> per hour of  
134 biogas was produced during RT. The feedstock intake rate was 12.5m<sup>3</sup>/day.

#### 135 **FUNCTIONAL UNIT**

136 The functional unit of the analysis was a cubic metre of biogas. As the methane-  
137 quality was known, this was easily converted to an equivalent cubic metre of  
138 methane. The process of AD was described to be a multi-output process; as a result,  
139 the second output (fertiliser) had a functional unit of mass (kilogram). This could be  
140 converted into a biogas equivalent as it was calculated that one cubic metre of biogas  
141 produced 58.47 kg of natural fertiliser (digestate). This was calculated from the total  
142 annual biogas output and the total annual digestate output from the plant.

#### 143 **SYSTEM BOUNDARIES**

144 The system boundary of the assessment is shown in Figure 2. The analysis system  
145 boundary commenced when the feedstock was collected from the cattle

149 housing/milking parlour. The use of biogas was considered up to the point of use for  
150 heating energy. The boundaries did not consider the transport and spreading of the  
151 digestate as it was unclear as to how the digestate was distributed. Emissions  
152 associated with the AD plant construction were considered in terms of material use  
153 (mass) and some key manufacturing processes. The disposal of the plant was not  
154 considered, as the expected operational lifetime was unknown.

155  
156 The biogas was understood to displace kerosene heating oil as a fuel, whilst the  
157 fertiliser was considered up to production and substitution of artificial fertiliser. The  
158 system boundary included the digestate as a potential artificial fertiliser replacement.  
159 The artificial fertiliser displacement was based on the available N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O from  
160 the digestate.

161

## 162 **LIFE CYCLE INVENTORY ANALYSIS**

163 The direct inputs into the AD process were the feedstock material, the electricity use  
164 within the plant and the heat energy required to heat the feedstock. Indirect inputs  
165 included the energy consumed in the farming machinery. This was treated as on-site  
166 feedstock handling energy requirements. Other indirect inputs included the water  
167 consumption used to wash the milking parlours and cattle housing. This was carried  
168 out primarily for hygiene purposes, although the addition of water to the feedstock  
169 was beneficial to the AD process. However, it was considered outside the system  
170 boundaries, as the AD process did not affect the quantity of water used.

171

172 Under normal operating conditions, the plant produced 8.89m<sup>3</sup>/hr of biogas. Of this,  
173 around 58-64% was methane (CH<sub>4</sub>). Using an intake of 12.5m<sup>3</sup> per day of feedstock  
174 and knowing that the total annual feedstock input was 653 tonnes, resulted in a plant  
175 operational time of 52.24 days per year (1,253 hours per year). The findings suggested  
176 that the capacity factor of the AD plant was as low as 14%. This meant that the  
177 impacts of the manufacturing stage were distributed over a lower output of biogas.  
178 This resulted in a higher environmental impact per unit output of biogas from the  
179 plant manufacture emissions.

180

181 The feedstock used was a mix of farmyard manure (FYM) and cattle slurry. A ratio of  
182 55:45 was chosen, in accordance with other UK studies [20,21]. This was denoted as  
183 'cattle waste' within this study. The Total Solids (TS) and Volatile Solids (VS) of the  
184 waste were 8% and 85% respectively. Using data obtained from the site visit, it was  
185 calculated that for every 12.5m<sup>3</sup> of waste entering the plant; approximately 214m<sup>3</sup> of  
186 biogas was produced over a 24-hour period. Therefore, the biogas production rate was  
187 17.1m<sup>3</sup><sub>biogas</sub>/m<sup>3</sup><sub>waste</sub>.

188

## 189 **ENVIRONMENTAL IMPACTS OF AD PLANT MANUFACTURE –** 190 **CHARACTERISED RESULTS**

191 The characterised results for the production of the plant only (therefore excluding  
192 use), is shown in Figure 3. The largest contributors towards the impact categories  
193 were the digester and digestate tank manufacturing. These two tanks made a relatively  
194 large contribution towards impact categories: carcinogens, respiratory inorganics,

195 respiratory organics, climate change, radiation, ozone layer depletion, ecotoxicity,  
196 acidification & eutrophication, minerals and fossil fuel resources.

197 The reception tank was the third highest contributor (overall) towards the impact  
198 categories. As the construction materials for these three tanks were the same, this  
199 showed that a common material or manufacturing processes could be contributing  
200 towards the impact categories. The heat exchanger unit contributed towards all the  
201 impact categories, with a greater contribution towards ecotoxicity. Although  
202 'miscellaneous pumps' and 'miscellaneous motors' represented 16 separate  
203 assemblies, the contribution towards the impact categories was insignificant.

204 The largest contributors to nearly all the impact categories were the largest sub-  
205 assemblies within the plant. Both of these assemblies had the highest material usage  
206 (a combined consumption of over 60 tonnes of steel). The impact on carcinogenic  
207 effects was affected greatly by the steel use within the plant. This was due to the  
208 disposal of dust by-products from steel production, which was assumed to be 100%  
209 virgin material. Other contributors to carcinogenic effects were due to the disposal of  
210 coal ash into landfill, which was used for electricity production. The emissions from  
211 iron ore extraction, used for steel production, affected the impact category of  
212 respiratory inorganics. This was due to the particulates emitted from the iron  
213 extraction process. Particulate matter can be generated by crushing, conveyance of  
214 crushed ore, blasting and transportation[22].

215 Finally, the impact category 'land use' was mostly contributed to by the  
216 transformation of the land (around 700m<sup>2</sup>) into industrial land. The land was assumed  
217 to be converted from normal grazing land for cattle to industrial land. This caused  
218 damage to ecosystems, because of the change in land use. The unit for measuring the  
219 effects of land-use was the potential disappeared fraction of a species on land per year  
220 per square metre (PDF\*m<sup>2</sup>yr).

221 Whilst the characterised data shows the relative contribution of the stages of the LCA  
222 to it doesn't show the relative significance of the impacts. In order to show this a  
223 normalisation step was undertaken, the result of which are shown in Figure 4. The  
224 most significant impacting categories are shown to be respiratory inorganics and  
225 fossil fuel resource depletion. These were nearly three times greater when combined  
226 than the other impact categories. Respiratory organics, carcinogens, radiation, ozone  
227 layer depletion and acidification/eutrophication were considered to have minimal  
228 impact compared to the other categories.

229 Depletion in fossil fuel resources occurred through the use of heavy oils, natural gas  
230 and hard coal consumed for electricity production. These resources were also used for  
231 heat generation, for manufacturing of steel components and transportation  
232 requirements. These processes were considered necessary within the manufacturing of  
233 the AD plant. However, efficiency implementations, such as using recycled steel,  
234 reducing overall steel use, minimising transport distances etc. could reduce the impact  
235 on fossil fuel depletion.

236 The use of insulation material within the digester (polyurethane) was also found to  
237 have an impact on the depletion of fossil fuels, although does play a key part in the

238 process. It was estimated that the plant used over 600 kg of polyurethane. If other  
239 materials were used such as cork or sheep's wool (organic materials), the fossil fuel  
240 consumption in the digester tank may have been reduced by over 70%. Polyurethane  
241 requires 85.2 MJ/kg of fossil fuels, whilst sheep wool and cork require around  
242 20MJ/kg of material.

243 Damages to human respiratory systems can be caused through the emissions of a  
244 number of inorganic substances. In this study these were found to include particulate  
245 matter (PM), nitrate and sulphate, sulphur trioxide ( $\text{SO}_3$ ), ozone ( $\text{O}_3$ ), carbon  
246 monoxide (CO) and nitrous oxide ( $\text{NO}_x$ ). These substances were found to cause  
247 chronic health effects and mortality. The majority of the contribution towards  
248 respiratory inorganics during the plant manufacture was due to the initial stages of  
249 steel manufacture. When obtaining iron ore, blasting techniques were used in order to  
250 separate the ore from the original source. The blasting created particulates of 2.5-10  
251  $\mu\text{m}$  in diameter. This particle size is sufficiently small to penetrate the human  
252 respiratory system and bring about serious health effects. Diesel combustion was also  
253 found to generate particulates, which may have led to similar health effects.

254 **ENVIRONMENTAL IMPACTS OF THE AD PLANT USE PHASE – BIOGAS  
255 PRODUCTION**

256 As there were two outputs from the plant an allocation process was undertaken. Over  
257 all, using an economic allocation 12% of the impacts were allocated to the biogas  
258 production. Using a mass allocation 40% of the results were allocated to the biogas  
259 production [4]. The results from this with an additional unallocated (total impact)  
260 impact are shown in Figure 5.

261 The allocation methodology was found to have a very large effect on the scale of the  
262 environmental impacts for biogas production. For some impact categories such as  
263 respiratory inorganics, the difference in allocation percentage had a significant effect  
264 on the damage towards that impact category. The most significant environmental  
265 impact from the normalised results was the effect on respiratory inorganic from  
266 biogas production. Over 70% of the total impact was contributed by the biogas  
267 production and the remaining 29% affected by the plant manufacture. The emissions  
268 contributing towards respiratory inorganics were primarily found to be a result of the  
269 air emissions from the digestate storage. Other emissions from kerosene combustion  
270 at start-up, diesel and biogas combustion for digester heating, also contributed to this  
271 impact category. Emissions such as particulates and sulphur dioxide contributed  
272 towards the high impact on respiratory inorganics.

273 The production of biogas showed a negative effect on the impact category of climate  
274 change. This was due to the potential carbon dioxide emissions sequestered from the  
275 organic matter. The  $\text{CO}_2$  fixation was accounted for as a consumption of the  $\text{CO}_2$   
276 resource. This theory assumed that carbon dioxide was consumed to generate the  
277 feedstock (animal feedstock production) and therefore was required within the plant.  
278 The  $\text{CO}_2$  is stored within the biogas in the form of  $\text{CH}_4$  (and some  $\text{CO}_2$ ) until the  
279 biogas is combusted.

281 Another area in which the production of biogas contributed significantly towards the  
282 environment was through the detrimental effect on fossil fuel reserves. This was due  
283 to the depletion of kerosene and diesel fuel used in the process.

284

## 285 **WHOLE LIFE CYCLE IMPACT ASSESSMENT**

286 For the whole life impact assessment a mass based allocation has been selected. This  
287 is because during the 25 year operational life of the system the mass will not fluctuate,  
288 whereas the economics may fluctuate significantly. Figure 6 shows that over the  
289 whole life of biogas production, the emissions from the plant use contributed the most  
290 towards three environmental impact categories: respiratory inorganics,  
291 acidification/eutrophication and fossil fuel resource depletion. The plant construction  
292 was also found to have insignificant contributions towards the environmental impacts,  
293 when compared to the use phase of the AD plant. These emissions were produced  
294 only once within the lifetime of the plant, whilst plant use had reoccurring emissions.

295 The most significant result came from the consequential displacement of the kerosene  
296 production, using biogas. The energy equivalent of kerosene showed a significant  
297 reduction in fossil fuel resource depletion over the life of the AD process.  
298 Additionally, savings in CO<sub>2</sub> emissions also contributed towards a reduction in  
299 climate change impact, giving the plant an overall (net) negative output on climate  
300 change.

301 Figure 7 shows the whole life normalised environmental impacts for the digestate  
302 output of the AD process. These results also highlighted that the AD plant use phase  
303 contributed significantly towards respiratory inorganics, acidification/eutrophication  
304 and fossil fuels resource depletion. However, due to the mass allocation, the  
305 emissions allocated towards the digestate production were higher. As a result, the  
306 overall contribution of the emissions towards these environmental impact categories  
307 was more significant. Over the life of the plant the emissions associated with the plant  
308 construction had minimal contribution towards the environmental impact categories,  
309 which was similar to the biogas production lifecycle.

310 The most significant contribution towards the whole-life cycle of the digestate output  
311 from AD was the consequential savings in displacing inorganic fertiliser. Based on  
312 the same quantity of fertiliser (in terms of N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O properties) the  
313 displacement of inorganic fertiliser resulted in a significant reduction in impacts  
314 towards four main environmental impact categories: carcinogenic effects, respiratory  
315 inorganics, climate change and fossil fuel resource depletion.

316 Overall the key benefits from digestate displacing inorganic fertiliser were savings in  
317 fossil resources which also led to a reduction in carbon emissions (and a lower impact  
318 on climate change). Additionally, other smaller benefits across most of the  
319 environmental impacts were also seen.

320 The common factor between both lifecycles (Figures 6 & 7) was the high emissions  
321 contributing towards respiratory inorganics and acidification/eutrophication. These  
322 emissions, produced during the use phase of the AD plant, could have a detrimental  
323 impact towards human health and ecosystem quality. It also appeared that although

324 there were savings in kerosene and inorganic fertilisers, these impact categories were  
325 still significant.

326 The emissions leading to respiratory inorganics were from the digestate storage, the  
327 combustion of kerosene, diesel and biogas. These emissions can cause smog leading  
328 to respiratory effects such as asthma, chest infections and bronchitis amongst other  
329 chronic obstructive pulmonary disorders. As a result, these emissions could have  
330 potentially serious effects on human health. This was primarily due to the ammonia  
331 emissions during the production phase of biogas, the diesel and kerosene combustion  
332 and emissions from the biogas combustion (used for the production of further biogas).  
333 Ammonia release was especially significant as it contributed towards both impact  
334 categories. These emissions could have been avoided if ammonia filters were put in  
335 place such as the ANAstrip process [23]. This could significantly reduce the impact  
336 of these environmental concerns, as it eliminates traces of ammonia within the  
337 process. Another technique would be to prolong the digestion period so that less  
338 ammonia is emitted during the digestate stage. A final recommendation would be to  
339 create a cover over the digestate tank in order to trap the post digestion emissions.  
340 This would not only reduce air emissions but also recover some of the remaining  
341 biogas.

342 Acidification can have an impact on ecosystems through the increase in the pH acidity  
343 of waters and soils. Air emissions can also lead to acid rain which can have  
344 detrimental effects especially on vegetation (for example conifer trees can deteriorate  
345 in health through acid rain). Eutrophication can lead to an abnormal increase in  
346 nutrient concentration over specific soil or water volume. The increase in nutrient  
347 availability increases the growth of aquatic plants and algae. An overproduction of  
348 algae and blooms causes an increase of plant life on the water surface, which can lead  
349 to reduced sunlight and oxygen penetrating the top layer of water. Increased nutrients  
350 in soil can lead to leaching into water streams causing eutrophication of lakes, rivers  
351 or bathing waters [24].

352 This shows how emissions from an industrial process such as AD could have  
353 detrimental impacts on the delicate balance of natural species and also human health.  
354 The detrimental environmental impacts affected by the use of AD can have direct or  
355 indirect impacts towards human health and ecosystem quality. Measures should be  
356 taken to minimise the emissions within the AD process. Reducing emissions via a  
357 desulphurisation plant could minimise the overall environmental impact of the AD  
358 process, which is significant if the technology were to be used on a large scale. This  
359 would eliminate the hydrogen sulphide within the biogas and subsequently eliminate  
360 the sulphur dioxide emissions from hydrogen sulphide combustion. These systems  
361 can range from very crude devices such as a container of iron filings acting as a filter  
362 for the biogas to pass through; to more expensive computer controlled gas cleaning  
363 processes [25].

## 364 **CONCLUDING REMARKS**

365 The study analysed the environmental impacts of biogas production and utilisation  
366 through the technique of life cycle assessment (LCA). LCA enabled an understanding  
367 of the factors which contributed most towards detrimental impacts on the  
368 environment, during the life cycle of biogas production. The study also examined the

369 environmental benefits of using biogas as a domestic heat source, subsequently  
370 displacing the use of domestic heating kerosene fuel. The key findings from the LCA  
371 results can be summarised:

- 373 • The emissions created from the plant manufacture contributed very little  
374 towards the whole life cycle environmental impacts. This would have been  
375 further reduced if a higher operating capacity factor were obtainable.
- 376 • The use phase of the AD plant created emissions which appeared to have  
377 significant impacts towards human respiratory systems and  
378 acidification/eutrophication issues within ecosystems.
  - 379 ○ The impacts were a result of emissions such as ammonia from the  
380 digestate storage, sulphur dioxide, nitrous oxide and particulates from  
381 the combustion of biogas, kerosene or diesel.
- 382 • The production of biogas and fertiliser both created significant impacts  
383 towards fossil fuel depletion due to the use of diesel and kerosene. However,  
384 over the whole life cycle, the consequential displacement of kerosene as an  
385 end-use energy source and inorganic fertilisers, showed a net-benefit in fossil  
386 fuel depletion.
- 387 • The study concluded that it is essential to cover the digestate storage tank as  
388 biological reactions are still occurring thus emitting, methane, ammonia and  
389 carbon dioxide. Globally a number of AD units do not cover the digestate  
390 storage.
- 391 • Desulphurisation and ammonia removal processes were also considered to be  
392 crucial within the AD system in order to remove these emissions either  
393 entering the atmosphere directly or undergoing the combustion process.
- 394 • Ammonia is also released during the spreading of digestate. However, as the  
395 lifecycle system boundary terminated at the fertiliser production stage, this  
396 was not included. This could however be included as a further analysis.

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