

Life Cycle Assessment of Hydrogenated Biodiesel Production from Waste Cooking Oil Using the Catalytic Cracking and Hydrogenation Method

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Highlights

- LCA with uncertainty analysis was conducted for BDF production from waste cooking oil.
- HBD production scenario reduced total environmental impacts by 50–71% compared with incineration.
- FAME-type BDF provides limited future benefit compared with fossil-derived diesel.
- A shift from FAME-type BDF to HBD would more effectively reduce total environmental impacts.

1 **Abstract**

2 There is a worldwide trend towards stricter control of diesel exhaust emissions, however
3 presently, there are technical impediments to the use of FAME (fatty acid methyl esters)-type
4 biodiesel fuel (BDF). Although hydrogenated biodiesel (HBD) is anticipated as a new diesel
5 fuel, the environmental performance of HBD and its utilization system have not been
6 adequately clarified. Especially when waste cooking oil is used as feedstock, not only biofuel
7 production but also the treatment of waste cooking oil is an important function for society. A
8 life cycle assessment (LCA), including uncertainty analysis, was conducted to determine the
9 environmental benefits (global warming, fossil fuel consumption, urban air pollution, and
10 acidification) of HBD produced from waste cooking oil via catalytic cracking and
11 hydrogenation, compared with fossil-derived diesel fuel or FAME-type BDF. Combined
12 functional unit including “treatment of waste cooking oil” and “running diesel vehicle for
13 household waste collection” was established in the context of Kyoto city, Japan. The
14 calculation utilized characterization, damage, and integration factors identified by LIME2,
15 which was based on an endpoint modeling method. The results show that if diesel vehicles
16 that comply with the new Japanese long-term emissions gas standard are commonly used in
17 the future, the benefit of FAME-type BDF will be relatively limited. Furthermore, the
18 scenario that introduced HBD was most effective in reducing total environmental impact,
19 meaning that a shift from FAME-type BDF to HBD would be more beneficial.

20

21 **Keywords**

22 Waste-to-fuel, Biodiesel fuel (BDF), Hydrogenated biodiesel (HBD), Waste cooking oil,
23 Catalytic cracking method, Life cycle assessment (LCA)

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27 **1. Introduction**

28 To develop a low-carbon society, it is important to promote the production of biofuels
29 such as biodiesel fuel (BDF). Biofuels are produced worldwide: Biofuel consumption in road
30 transport accounted for 1.3 Mboe/day (million barrels of oil equivalent per day) as of 2011,
31 and is expected to increase to 4.1 Mboe/day in 2035, an increase from 3% of road transport
32 fuel demand in 2011 to 8% in 2035. Of this, biodiesel consumption accounted for 0.4
33 Mboe/day and is estimated to be 1.1 Mboe in 2035 (IEA, 2013). The fuels that are currently
34 under development utilize non-food feedstock, including waste (Naik et al., 2010; Sims et al.,
35 2010; Takamizawa et al., 2013). Such fuels are thought to be more environmentally desirable,
36 because biofuels derived from food crops such as soybeans are associated with a number of
37 problems: competition with food agriculture for land and water use, and widely varying
38 assessments of net greenhouse gas (GHG) reductions once land-use change is taken into
39 account (Fargione et al., 2008; Searchinger et al., 2008).

40 In Kyoto city, Japan, waste cooking oil has been collected from households since 1998,
41 and used to produce BDF since 2004. The BDF production facility operated by Kyoto city has
42 a capacity of 5 kL/day (1,500 kL/yr), and is the largest facility managed by a local
43 government in Japan. The alkali catalysis method is commonly used to convert waste cooking
44 oil to BDF, which consists of fatty acid methyl esters (FAME) (Meher, 2006; Salvo, 2012).
45 As of fiscal year (FY) 2012, approximately 1,300 kL of FAME-type BDF has been produced
46 annually from waste cooking oil (approximately 196 kL from households and 1,110 kL from
47 businesses). Considering that the generation of waste cooking oil from households was
48 estimated to be approximately 1,140 kL within Kyoto city, this represents a collection rate of
49 17% waste cooking oil from households for BDF production. The produced BDF has been
50 used as fuel for city buses (B20) and household waste collection vehicles (B100) within
51 Kyoto city.

52 From the standpoint of air pollution, there has been an increasing focus globally on the
53 control of gas emissions from diesel vehicles (EC, 2007). As shown in Table 1, Japan has also
54 established and enforced gas emission standards that regulate pollutants such as NO_x and
55 particulate matter (PM) emissions in a number of stages (DELPHI, 2014). For instance, in the
56 case of NO_x emissions, the standard value for vehicles of gross weight more than 3.5 tons is
57 3.38 g-NO_x/kWh for the new short-term emissions gas standard (2002–2004), 2.00
58 g-NO_x/kWh for the new long-term standard (2005–2008), and 0.700 g-NO_x/kWh for the post
59 new long-term standard (2009 onward). However, FAME-type BDF is occasionally
60 problematic when used in diesel vehicles (Fukuda et al., 2008; WFCC, 2013). In particular,
61 some technical problems have arisen in terms of the suitability of BDF for new-model diesel
62 vehicles equipped with diesel particulate filters and NO_x reduction devices after
63 implementation of the new long-term emissions standard.

Table 1

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These problems, which include the mixing of fuel with engine oil and the poor performance of NO_x reduction devices, have become major impediments to BDF use. Therefore, there are some challenges involved in producing new diesel fuels. HVO (hydrotreating of vegetable oils) has been developed and commercially supplied to mainly EU regions. HVO is also known as renewable diesel or HDRD (hydrogenation derived renewable diesel) in the USA, and as HBD (hydrogenated biodiesel) in the Far East including Japan (Neste Oil, 2014). HVO consists mainly of paraffins and is free of aromatics, oxygen, and sulfur. HVO generally shows higher cetane index and higher oxidation stabilities compared to FAME-type BDF (Bezergianni et al., 2013). HVO can be applied not only to vegetable oil but also to animal fats. Therefore, the HVO production method is expected to contribute to the expanding feedstock of BDF and resulting increases in fuel supplies. Neste Oil is the world’s largest producer of HVO, which it supplies under the brand name “NExBTL.” Its production capacity is approximately 2 million ton/yr from four facilities. HVO is made by hydrotreatment of vegetable oils and animal fats, but additionally, waste and residues such as waste animal fat accounted for over half of feedstocks (Neste Oil, 2013). The OPTIBIO project operated for 3.5 years, between autumn 2007 and December 2010, to demonstrate the use of NExBTL for city buses in Helsinki. The project confirmed that HVO can replace fossil-derived diesel without any modifications to the vehicles or refueling system (Nylund et al., 2011). The Worldwide Fuel Charter (WWFC) now evaluates HVO as being highly suited as a blendstock for diesel fuel (WWFC, 2013).

HVO has been also developed in Japan, where it is often called HBD. Attention has been given to the production method, namely catalytic cracking and hydrogenation (Tani et al., 2011a, 2011b), and a three-year demonstration project for this new method, involving Kyoto city, ASTEM, and other companies, was operational between April 2012 and March 2015 (ASTEM, 2013; Kakuta, 2014; Takasuga, 2014). Unlike the general methods, the catalytic cracking process promotes decarbonization, which has the notable benefit of reducing the consumption of energy and H₂. Hydrogenation after cracking requires normal pressure and temperature conditions (1.0 MPaG at 150°C) and less H₂, whereas direct hydrogenation requires high pressure and temperature (4–6 MPaG at 300–350°C) and consumes 10 times the amount of H₂. Therefore, hydrogenation after cracking is suitable for small- and mid-sized production facilities that utilize regional feedstocks such as waste cooking oil. The produced HBD has similar characteristics to those of diesel fuel, including calorific content and boiling point. The characteristics of some fuels, including HBD produced in the demonstration project at Kyoto city (ASTEM, 2013), are summarized in the electronic supplementary material.

101 A life cycle assessment (LCA) was performed to evaluate the effectiveness of BDF use in
102 reducing negative environmental impacts. Liang et al. (2013) quantitatively showed that
103 feedstocks had different environmental performances by comparing seven feedstocks
104 including waste cooking oil. Dufour et al. (2012) used LCA to evaluate six environmental
105 impacts for four types of free fatty acid-rich wastes (used cooking oil, animal fats, sewage
106 sludges), and concluded that biodiesel fuel from used cooking oil potentially achieved the
107 most favorable environmental performance. On the other hand, when waste cooking oil was
108 used for BDF production, the treatment (BDF production) method was also an important
109 factor in environmental performance (Morais, 2010; Varanda, 2011). The environmental
110 performance of HBD and its utilization system has not been adequately clarified. Garraín et al.
111 (2014) showed that HBD blend diesel (13% blend) from soybean oil could reduce fossil fuel
112 consumption by 2% and GHG emissions by 9% at well-to-tank stage compared with FAME
113 blend diesel. Neste Oil (2014) estimated that the GHG reduction effects of NExBTL
114 compared with fossil-derived diesel were 47%, 49%, and 91% for palm oil, rapeseed oil, and
115 animal fat feedstocks, respectively; and, by conducting exhaust gas emission tests, showed
116 that emissions of PM were reduced by approximately 30–40%. Evaluating exhaust gas
117 emissions such as NO_x and PM from HBD production and its utilization system by means of a
118 life cycle approach is also necessary to determine environmental performance compared with
119 the FAME-type BDF that is generally used. Arvidsson et al. (2011) conducted an LCA of
120 HBD production from rapeseed oil, palm oil, and Jatropha considering four environmental
121 impacts: fossil fuel consumption, global warming, acidification, and eutrophication. The
122 functional unit of the analysis focused on fuel supply (1 kWh of energy output). However,
123 biofuel production and the treatment of waste cooking oil are important functions for society,
124 especially when waste cooking oil is used as feedstock.

125 The purpose of this study was to clarify the effects of HBD on reducing environmental
126 impacts compared with fossil-derived diesel fuel, or FAME-type BDF. An LCA including
127 characterization, damage assessment, integration assessment, and uncertainty analysis was
128 conducted to evaluate a number of environmental impacts including global warming and air
129 pollution.

130

131 **2. Materials and methods**

132 **2.1. Functional unit and system boundary**

133 Table 2 shows the characteristics of the waste cooking oil considered in this study.
134 Combined functional unit including “treatment of waste cooking oil” and “running diesel
135 vehicle for household waste collection” was established. The first functional unit was
136 assumed to be the treatment of 1,142 kL/yr and 1,108 kL/yr of waste cooking oil from
137 households and businesses, respectively. The second functional unit assumed that 41.1 TJ of

138 diesel fuel (fossil-derived diesel fuel, FAME-type BDF, and HBD) was consumed by diesel
139 vehicles used to collect household waste within Kyoto city. Both amounts reflected the actual
140 situation in Kyoto city as of FY2012. Only waste cooking oil was considered as feedstock,
141 although animal fats could be also used to produce HBD.

142 The system boundary included the collection of waste cooking oil, treatment or recycling
143 (BDF production), and fossil-derived diesel fuel and/or BDF consumption of a
144 diesel-powered collection vehicle. With regard to fossil fuel consumption, the system
145 boundary considered the stages from raw material extraction to final use (combustion), and
146 associated environmental impacts were allocated to the process that consumed the fossil fuel.

147

Table 2

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149 **2.2. Environmental impacts**

150 LIME1, a Japanese life-cycle impact assessment method, was developed for the first term
151 (1998–2003) of a national LCA project, whereas LIME2 was developed for the second term
152 (2003–2006) (JLCA, 2012). LIME2 was based on an endpoint modeling method, and
153 considered environmental conditions, such as weather and population density, in Japan such
154 as weather and population density. Therefore, LIME2 is mainly applied in Japan (European
155 Commission, 2010).

156 LIME2 comprises 19 category endpoints that are connected by 15 environmental impact
157 categories (JLCA, 2012). These environmental impact categories are assessed by integration,
158 following characterization and damage assessment. Characterization is the first step, in which
159 potential environmental impacts are assessed for each impact category. It is possible to
160 compare or integrate the impacts of two or more environmentally damaging substances on the
161 specific impact category. Damage assessment is the second step in assessing the amount of
162 damage that can occur for each object of protection. In LIME, four items were defined as
163 objects of protection: human health, social assets, biodiversity, and primary production. The
164 Disability Adjusted Life Year (DALY), which is used internationally for health statistics, was
165 defined as the damage index for human health. An economic index in Japan, that can
166 comprehensively measure the impact on various components (agricultural products, forests,
167 marine products, and resources), was defined as the damage index for social assets. EINES,
168 which was originally based on the methodology for assessing extinction risk in the field of
169 conservation ecology, was defined as the damage index for biodiversity. Net primary
170 production (NPP), which is widely used as an index of ecosystem richness in the fields of
171 biology and landscape architecture, was defined as the damage index for primary production.
172 Integration is the final step, in which the results of the four objects of protection are converted
173 into a single index by means of weighting factors. In LIME2, conjoint, analysis was adopted
174 for weighting the area of protection.

175 The considered environmental impacts in this study were fossil fuel consumption, global
176 warming, urban area air pollution, and acidification. The calculation utilized characterization,
177 damage, and integration factors identified by LIME2. These factors were retrieved from the
178 website of the Life Cycle Assessment Society of Japan (JLCA). The impact categories and
179 their objects are listed in Table 3. With regards to global warming, CO₂ emissions derived
180 from biomass are regarded as carbon-neutral, and were therefore excluded from the
181 calculation. Table 4 shows a list of impact categories and corresponding damage factors.

182
183

Table 3

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Table 4

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186 **2.3. Scenario setting**

187 The scenarios in this study are listed in Table 5. As a base scenario, all waste cooking oil
188 from households and businesses was assumed to be collected with mixed waste and then
189 incinerated, while diesel fuel was used to operate household waste collection vehicles. With
190 regard to a baseline scenario, two sub-scenarios were considered, based on the diesel vehicle
191 types covered by the Japanese emission gas standard: one where diesel vehicles complied
192 with the new short-term emissions gas standard (scenario S1-short), and the other where
193 diesel vehicles complied with the new long-term emissions gas standard (scenario S1-long).
194 S1-short is the scenario that reflects the general, current situation in Japan, while S1-long
195 reflects the future exhaust gas control situation.

196 For the BDF utilization scenarios, 196 kL/yr of waste cooking oil from households (17%
197 as collection efficiency) and 1,108 kL/yr from businesses were collected separately, from
198 which BDF was produced by the alkali catalysis method (scenario S2-short), or the catalytic
199 cracking and hydrogenation method (scenario S3-long). The remaining 947 kL/yr from
200 households was incinerated with mixed waste. Because of the above-mentioned technical
201 problems for diesel particulate filters required for the long-term emissions gas standard, it was
202 assumed that FAME-type BDF was used only for diesel vehicles that complied with the new
203 short-term emissions gas standard (S2-short). It could be said that S2-short reflects the current
204 situation in Kyoto city; on the other hand, HBD could be used for diesel vehicles that comply
205 with both the new short-term and the new long-term emission gas standards. However, HBD
206 was used for diesel vehicles that only complied with the new long-term emissions gas
207 standard in S3-long, in order to evaluate the more desirable HBD utilization system.

208 Fig. 1 shows the system flow of each scenario, and each process setting is explained in
209 section 2.4.

210

211

Table 5

212 Fig. 1

213

214 **2.4. Unit processes and data collection**

215 Important parameters used in this study are listed in Table 6, and each process is briefly
216 introduced below. The later sections also discuss the uncertainties that were considered for
217 some parameters.

218

219 **2.4.1. Collection**

220 A grid city model (Ishikawa, 1996) was used for calculating the annual collection distance
221 and diesel fuel consumption. Direct emissions of CO₂ and CH₄, N₂O, SO_x, NO_x, PM_{2.5}, and
222 PM₁₀ from household waste collection vehicles were then estimated.

223 In S1-short and S1-long, all waste cooking oil from households was assumed to be
224 collected twice a week with mixed waste, and the weight of waste cooking oil accounted for
225 0.50% of household waste. Therefore, the estimated amount of diesel fuel consumption was
226 allocated based on weight. In S2-short and S3-long, 947 kL/yr of waste cooking oil, which
227 was failed to be collected separately, was also assumed to be collected with mixed waste.

228 In S2-short and S3-long, FAME-type and HBD could both be used to power household
229 waste collection vehicles. However, this benefit was not included in the “collection” process,
230 but rather in the “running household waste collection vehicle” process, as will be explained
231 later. Only fossil-derived diesel fuel was consumed in this process.

232

233 **2.4.2. Incineration with energy recovery**

234 In this process, it was assumed that waste cooking oil and waste glycerin, which was
235 co-generated by the FAME-type BDF production process using an alkali-catalyzed method
236 (S2-short), were incinerated with household waste in the incineration facility within Kyoto
237 city. Direct emissions of CH₄, N₂O, SO_x, NO_x, PM_{2.5}, and PM₁₀ from waste combustion were
238 calculated. CO₂ emissions from fossil-derived carbon were also counted because waste
239 glycerin contained unreacted methanol. It was assumed that there was no residue, as nearly all
240 the waste cooking oil was combustible.

241 Electricity was considered as energy consumption and calculated using an empirical
242 formula based on household waste composition (NIES, 2008). At the same time, an electricity
243 production facility with an efficiency of 15% was assumed to be associated with the
244 incineration facility. Both consumption and substituted electricity refer to commercial
245 electricity from utility companies. The weighted average emission factors for 10 companies in
246 Japan were used in this analysis.

247

248 **2.4.3. FAME-type BDF production by alkali catalysis method**

249 Waste cooking oil and methanol were used for BDF production by an alkali-catalyzed
250 method. Electricity and paraffin oil were considered as energy consumption. Inventory data
251 were obtained from the BDF production facility in Kyoto city. It should be noted that
252 fossil-derived carbon in the produced FAME-type BDF accounted for approximately 7.0% of
253 the total carbon content because methanol, which was produced from natural gas, was used
254 for FAME-type BDF. Co-generated waste glycerin contained KOH as a catalyst, unreacted
255 methanol, and waste cooking oil. Waste glycerin was assumed to be treated during
256 incineration with the energy recovery process mentioned previously. The characteristics of
257 waste glycerin are presented in the electronic supplementary material.

258

259 **2.4.4. HBD production by catalytic cracking and hydrogenation method**

260 The HBD production process can be described as follows: Firstly, waste cooking oil was
261 degraded at around 400–500°C, and the organic acids contained in the decomposed oil were
262 decomposed for conversion into hydrocarbons at the reactor. Offgas consisting of CO₂, CO,
263 H₂, CH₄, and other hydrocarbons, was also produced at this stage. Secondly, the produced
264 hydrocarbons were separated into high-, intermediate- (biodiesel), and low-boiling-point oils
265 using two condensers. Thirdly, a minor amount of acid contained in the biodiesel was
266 removed, and the biodiesel was refined for long-term stability. Finally, the refined biodiesel
267 was hydrogenated using H₂ at 150–250°C in order to improve stability for oxidation and heat.
268 This study refers to hydrogenated diesel fuel as HBD. In total, 90.7% of the input waste
269 cooking oil on an energy basis could be recovered in the form of HBD, other oils, and offgas.
270 The HBD showed an energy yield of 52.8%, which was lower than that of FAME-type BDF.

271 Inventory data were obtained from a demonstration project by ASTEM. Electricity was
272 considered as energy consumption. Offgas, and high- and low-boiling-point oils, which were
273 co-generated in this process, were combusted for heating supply. Of these types, only the
274 low-boiling-point oil could be exported from the facility as surplus energy after heating.
275 Therefore, it was assumed that naphtha was substituted by surplus low-boiling-point oil on a
276 heating value basis.

277

278 **2.4.5. Diesel fuel production**

279 The production of diesel fuel as commercially used in Japan was assumed in this process.
280 Inventory data provided by JLCA (JLCA, 2012) were used to calculate CO₂, SO₂, NO₂, and
281 PM₁₀ emissions. All PM emissions were regarded as PM₁₀ in this process because of a lack of
282 data.

283

284 **2.4.6. Running household waste collection vehicle**

285 Direct emissions of CO₂, SO_x, NO_x, PM_{2.5}, and PM₁₀ were calculated in this process. CO₂

286 and SO_x emissions were calculated using the elemental composition of the fuels. The other
287 emission factors (EFs) were assumed to differ according to the types of diesel vehicles
288 covered by the Japanese emission gas standards: the new short-term emissions gas standard
289 (S1-short, S2-short), and the new long-term emissions gas standard (scenario S1-long,
290 S3-long). The type of fuel also affected the EFs. Therefore, the results of emission testing
291 from the vehicles currently used for household waste collection by Kyoto city, which
292 considered the type of fuel, were adopted as EFs (Kyoto city) after converting the data from
293 g/kWh to g/L. The proportions of PM₁₀ and PM_{2.5} were based on a previous study by
294 Motoshita (2008), since these data were absent from the emission testing in Kyoto city.
295 However, it was assumed that there was no difference between EFs in HBD and those in
296 diesel fuel, because there were no actual data for HBD. The demonstration project by ASTEM
297 plans to include a fleet running test.

298
299

Table 6

300 **3. Results and Discussion**

301 **3.1. Characterization**

302 The estimated characterization results are shown in Fig. 2. With regard to global warming
303 and fossil fuel consumption, there are no differences between S1-short and S1-long. In every
304 scenario, CO₂ emission was the dominant contributor to global warming compared with other
305 emissions, CH₄, and N₂O. The running household waste collection vehicle process
306 contributed to increases in GHG emissions in S1 and S3-long, because the process consumed
307 fossil-derived diesel fuel. GHG emissions from the incineration process in S2-short exceeded
308 those in S1 and S3-long, because the production of FATE-type BDF in S2-short incinerated
309 waste glycerin containing carbon from fossil-derived methanol. Nevertheless, net total GHG
310 emissions from S2-short showed a negative value (-150 t-CO₂ eq/yr), indicating that the use of
311 waste cooking oil for FAME-type BDF could help reduce net GHG emissions. On the
312 contrary, in S1 and S3-long, net total GHG emissions were estimated to be 1561 t-CO₂ eq/yr
313 and 547 t-CO₂ eq/yr respectively. GHG reduction effects from energy recovery in incineration
314 and substituted naphtha were not sufficiently large to cancel out the GHG emissions, which
315 were mainly derived from the running of household waste collection vehicles. GHG
316 emissions in S3-long were reduced by 65% compared with S1, which used fossil-derived
317 diesel. On the other hand, RED (European Commission, 2009: Directive 2009/28/EC)
318 introduced GHG reduction effects of 47% and 65% by HVO from rapeseed oil and sunflower,
319 respectively. NExBTL from palm oil, and rapeseed oil reduced GHG emissions by 47% and
320 49%, respectively, compared with fossil-derived diesel (Neste Oil, 2014). It was implied that
321 HBD production from waste cooking oil and its utilization system in this study could achieve
322 equivalent GHG reduction, despite the different system boundaries employed by the two

323 studies.

324 Fossil fuel consumption in S2-short and S3-long could be reduced by 120% and 58%, as
325 compared with S1. The FAME-type BDF production process consumed more fossil fuels than
326 HBD, because the latter could use by-products such as offgas for heating supply. Surplus
327 low-boiling-point oil also contributed to reductions in the net consumption of fossil fuel.

328 Urban area air pollution and acidification showed similar results, which indicated that the
329 type of diesel vehicle covered by the Japanese emission gas standard had the largest impact on
330 urban area air pollution. Although NO_x emission was the dominant contributor to urban area
331 air pollution and acidification in every scenario, the emission amounts differed by the type of
332 diesel vehicle. In S1-short and S2-short, NO_x emissions from household waste collection
333 vehicles that complied with the new short-term emissions gas standard were dominant. On the
334 contrary, it was apparent that a shift to vehicle types that complied with the new long-term
335 emissions gas standard could dramatically reduce NO_x emissions. As net results, urban area
336 air pollution and acidification in S1-long were decreased by 90% and 78% respectively,
337 compared with S1-short. Energy recovery during incineration also contributed to reducing
338 emissions of air pollutants especially SO_x , which was one factor that made S1-short and
339 S1-long superior to S2-short and S3-long, respectively, in terms of urban area air pollution
340 and acidification. In S3-long, reductions of 76% in urban area air pollution and 75% in
341 acidification were achieved compared with S1-short.

342 

343

344 **3.2. Damage assessment**

345 Fig. 3 shows the estimated damage for the four endpoints (in all endpoints, lower values
346 indicate less damage). NO_x emissions from household waste collection vehicles affected
347 human health. NO_x emissions accounted for 42% and 67% of overall damage in the S1-short
348 and S2-short scenarios, compared with 18% and 34% in S1-long and S3-long. $\text{PM}_{2.5}$ emission
349 from incineration also affected human health in all scenarios. SO_x emissions showed negative
350 value as a result of the substitution effect of the electricity production in incineration with
351 energy recovery process, although their effect was small. In S2-short, CO_2 emission also
352 showed negative value because this scenario consumed no fossil-derived diesel to operate the
353 household waste collection vehicles. These results imply that, as a treatment for waste
354 cooking oil, a shift from incineration to BDF production contributes to protecting human
355 health, mainly as a result of avoiding the emission of $\text{PM}_{2.5}$.

356 Crude oil extraction for diesel production, and subsequent emission of NO_x by operating
357 household waste collection vehicles, were the dominant sources of damage to social assets. In
358 S2-short, NO_x emissions accounted for 92% of the total impact on social assets. The result
359 indicated that shifting from incineration of waste cooking oil as in S1-short to FAME-type

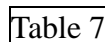
360 BDF production as in S2-short had more benefits than shifting from diesel vehicles compliant
361 with the new short-term gas standard (such as S1-short) to those compliant with the new
362 long-term gas standard (such as S1-long).

363 Biodiversity was affected only by coal consumption. Electricity produced via incineration
364 with energy recovery process was the dominant factor even if the electricity consumed in the
365 other processes was considered.

366 There were two major factors in primary production: one was the coal reduction effect
367 achieved by electricity substitution at incineration with energy recovery process, and the other
368 was NO_x emission associated with operating household waste collection vehicles. Because
369 S1-long could benefit from both these factors, the scenario showed the least impact on
370 biodiversity.

371 The results are also summarized in Table 7. Comparing the four scenarios, S3-long
372 showed the best environmental performance for human health and social assets; S1-short and
373 S1-long were the best for biodiversity. S1-long also showed the best performance for net
374 primary production. It is important to evaluate these four endpoints in combination, which is
375 discussed in the next section.

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377 

378

379 **3.3. Integration**

380 The estimated integration results from each scenario are shown in Fig. 4. Compared with
381 S1-short, S1-long could reduce urban area air pollution and acidification, whereas S2-short
382 could reduce global warming and fossil fuel consumption. In terms of the net results, the use
383 of FAME-type BDFs in S2-short could reduce environmental impacts by 42% compared with
384 S1-short, while S1-long also reduced environmental impact by 42%.

385 These results imply that if diesel vehicles compliant with the new long-term emissions gas
386 standard are commonly used in the future, as was considered in S1-long, the benefit of using
387 FAME-type BDF (S2-short) will apparently be relatively low. This is because FAME-type
388 BDF cannot be used for vehicles that comply with the long-term emissions gas standard.
389 However, if HBD is produced using the catalytic cracking and hydrogenation method,
390 environmental impacts could be reduced by 71% and 50% compared with those in S1-short
391 and S1-long, respectively. Therefore, it was concluded that a shift from FAME-type BDFs to
392 HBD in the future would be effective in reducing environmental impacts, including not only
393 global warming but also fossil fuel consumption, urban air pollution, and acidification.

394

395 

396

397 **3.4. Uncertainty analysis**

398 Some parameters include uncertainties, which must therefore be considered in the LCA.
399 Clavreul et al. (2012) reviewed and categorized uncertainties in LCAs for waste management
400 systems into three uncertainties using the framework introduced by Huijbregts et al. (1998),
401 one of which is parameter uncertainty. In this study, uncertainty analysis was conducted for
402 the four parameters in Table 8, which strongly influenced the results.

403 Electricity was the largest energy source, followed by diesel fuel. The range was taken as
404 the minimum to maximum EFs of electricity consumption during 5 years (FY2008–2012).
405 The default value was accordingly the maximum value in 5 years.

406 The efficiency of energy recovery is one of the fundamental factors for determining the
407 environmental performance of incineration processes (Gentil et al., 2010). The limitations
408 imposed by technical issues or treatment capacity mean that an incineration facility might not
409 include an electricity production facility. In Japan, approximately 310 of 1,100 incineration
410 facilities include electricity production facilities, and electricity production efficiency was
411 11.7% as of FY2011 (MOE, 2013a). The Japanese Ministry of the Environment (MOE,
412 2013b) aims to achieve 21% average electricity production efficiency for incineration
413 facilities that will be constructed during FY2013–2017. Therefore, 0% (no electricity
414 production facility) and 20% were considered as minimum and maximum values.

415 The EF of NO_x derived from exhaust gas from household waste collection vehicles
416 depends not only on fuel type but various factors: carrying capacity, running speed, etc. The
417 actual EF of HBD produced by the catalytic cracking and hydrogenation method will be
418 clarified via the proposed fleet running test during the demonstration project by ASTEM.
419 Therefore, to establish the tendency of uncertainty derived from the EF, the minimum and
420 maximum EFs of NO_x were determined by comparing the average value reported in some
421 previous studies (JPEC, 2005; Koyano et al., 2009). Due to lack of data, it was assumed that
422 the EF of HBD equaled that of diesel fuel.

423 The EFs of PM_{2.5} and NO_x at an incineration facility depend on the flu gas treatment
424 system installed at the facility (Møller et al., 2011; Shiota et al., 2011). The EF range of PM_{2.5}
425 was determined using the range of four facilities (Shiota et al., 2011). The EF of NO_x was not
426 included in uncertainty analysis because NO_x emissions during incineration had smaller
427 impacts compared with other emissions.

428

Table 8

429
430 The results are shown in Fig. 5 and Fig. 6. With regard to the EF of electricity
431 consumption, CO₂ emission factor affected global warming, human health, and integration,
432 whereas the other EFs (NO_x and SO_x) had smaller effect. The EFs had significant impact on
433 the ranking between S1-long and S2-short.

434 Electricity production efficiency had a large effect on all impact categories except
435 acidification, and on all endpoints and the integration result. It had larger impact on the results
436 for S1-short and S1-long than in the other scenarios because there was greater use of
437 incineration. It was also indicated that the inclusion of an electricity production facility
438 contributed to reducing environmental impacts in all scenarios. In the absence of an electricity
439 production facility, the integration results in each scenario increased by 30%, 53%, 28%, and
440 45%, respectively.

441 The EF of exhaust gas from household waste collection vehicles compliant with the new
442 long-term standard had a bigger impact on the results than vehicles compliant with the new
443 short-term standard. This was because the range (3.32–10.1 g/L) was wider in S1-long and
444 S3-long than those in S1-short (16.2–17.3 g/L) and S2-short (16.2–18.3 g/L).

445 The EFs of PM_{2.5} in incineration facilities tended to give wider ranges for the integration
446 results in all scenarios compared with the other three parameters used in the uncertainty
447 analysis. This was because the EF had a large effect on human health. It should be noted that
448 the EF might include sufficient uncertainty to reverse the ranking between the S1-long and
449 S2-short scenarios.

450 Electricity production efficiency and EF of PM_{2.5} at incineration facility had larger
451 impacts than the other parameters on result of integration. Therefore, the treatment of waste
452 cooking oil is the significant factor in determining the results. The results of uncertainty
453 analysis indicated that ranking between S1-long and S2-short might be reversed. However, it
454 could be also said that S1-short, which reflects the current situation in Japan, was the worst
455 scenario, and that S3-long was the desired scenario.

456 This study focused on four parameters for uncertainty analysis. However, there remain
457 further uncertainties, as follows:

- 458 • Actual EFs of exhaust gas from household waste collection vehicles using HBD are
459 currently unknown. Exhaust gas sampling and analysis will therefore be required during
460 the proposed fleet running test.
- 461 • The exhaust gas emission standard has been getting stricter than that in the new long-term
462 standard in Japan. Therefore, when those diesel vehicles currently in use are exchanged
463 for vehicles using HBD that meet stricter performance criteria than the new long-term
464 standard, further reduction of the environmental impacts will be possible. On the other
465 hand, blending FAME-type BDF with fossil-derived diesel fuel such as B5 is one solution
466 to extend the future use of diesel vehicles that comply with the new short-term standard.
467 However, in such case, the environmental impacts associated with the exhaust gas
468 emissions will not be reduced.
- 469 • Due to salting during cooking, waste cooking oil might contain higher Cl content than
470 other feedstock such as unused vegetable oil and animal fats. Cl contents in both waste

471 cooking oil and in cracking oil before hydrogenation are less than 10 ppm. Because the
472 Cl content could contribute to acidification, more detailed Cl behavior will also need to
473 be considered in future studies.

474 

475 

476

477 **4. Conclusions**

478 There is a worldwide trend towards stricter control of exhaust emissions from diesel
479 vehicles. Certain technical issues have become major impediments to the use of FAME-type
480 BDF in diesel vehicles that comply with the new long-term emissions standard. The purpose
481 of this study was to clarify the reduction effects of HBD produced by the catalytic cracking
482 and hydrogenation method on environmental impacts, as compared with fossil-derived diesel
483 fuel or FAME-type BDF. An LCA including uncertainty analysis was conducted to evaluate
484 four environmental impacts: global warming, fossil fuel consumption, urban area air pollution,
485 and acidification. Both the operation of diesel vehicles and the treatment of waste cooking oil
486 were also considered as functional units.

487 Our conclusions are as follows:

- 488 • If diesel vehicles that comply with the new long-term emissions gas standard are
489 commonly used in the future, the benefit of using FAME-type BDF will be relatively
490 modest.
- 491 • The results including uncertainty analysis indicate that S1-short, which reflects the
492 current situation in Japan, was the least optimal scenario, and that S3-long, which
493 introduced HBD, was most effective in terms of reducing environmental impact.
- 494 • Therefore, a shift from FAME-type BDF to HBD in the future would be more effective in
495 reducing total environmental impacts comprising not only global warming but also fossil
496 fuel consumption, urban air pollution, and acidification.

497

498 **Abbreviations list**

499	BDF	: biodiesel fuel
500	DALY	: disability-adjusted life year
501	DAP	: deposition-oriented acidification potential
502	EINES	: expected increase in number of extinct species
503	FAME	: fatty acid methyl esters
504	FY	: fiscal year
505	GHG	: greenhouse gas
506	GWP	: global warming potential
507	HBD	: hydrogenated biodiesel

- 508 HDRD : hydrogenation derived renewable diesel
509 HVO : hydrotreating of vegetable oils
510 LCA : life cycle assessment
511 NPP : net primary productivity
512 PM : particulate matter
513 UAF : urban air pollution characterization factor
514

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523

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648

Table 1 Exhaust gas emission standards for heavy commercial vehicles in Japan

Version of standard	Short-term	Long-term	New short-term	New long-term	Post new long-term
Implementation date	1994	1997	2003	2005	2009
Test mode	13 mode	13 mode	13 mode	JC08	JC08
Regulation value					
NO _x (g/kWh)	6.8	4.50	3.38	2.0	0.7
PM (g/kWh)	0.96	0.25	0.18	0.027	0.010
CO (g/kWh)	9.20	7.40	2.22	2.22	2.22
HC, NMHC (g/kWh)	3.80	2.90	0.87	0.17	0.17

The heavy commercial vehicle category has a gross vehicle weight > 3.5 tons (> 2.5 tons before 2005).

Implementation dates refer to new vehicle models.

Table 2 Characteristics of waste cooking oil

Density	0.92	ton/kL
Moisture content	0.2	wt%
Lower heating value	36.6	MJ/kg
Elemental composition		
C	78.1	wt%
H	11.5	wt%
O	9.8	wt%
S	2.2	ppm

Table 3 Impact categories, their objects, and units of characterization factors

Impact category	Object	Unit of characterization factor
Fossil fuel consumption	Crude oil, Coal, Natural gas	Consumption energy [MJ]
Global warming	CO ₂ , CH ₄ , N ₂ O	GWP [kg-CO ₂ eq]
Urban area air pollution	SO _x , NO _x , PM _{2.5} , PM ₁₀	UAF [kg-SO ₂ eq]
Acidification	SO ₂ , NO _x	DAP [kg-SO ₂ eq]

GWP: global warming potential, UAF: urban air pollution characterization factor, DAP: deposition-oriented acidification potential.

For PM_{2.5} and PM₁₀, characterization factor was not available in LIME2.

Table 4 Impact categories and corresponding objects of protection

Impact category	Human health	Social assets	Biodiversity	Primary production
	[DALY]	[Yen]	[EINES]	[NPP]
Fossil fuel consumption		✓	✓	✓
Global warming	✓	✓		
Urban area air pollution	✓			
Acidification		✓		✓

DALY: disability-adjusted life year, Yen: Japanese yen, EINES: expected increase in number of extinct species, NPP: net primary productivity

Table 5 Scenario setting

		S1-short	S1-long	S2-short	S3-long
<i>Functional unit 1: Treatment of waste cooking oil (kL/yr)</i>					
Waste cooking oil from households	Incineration	1,142	1,142	947	947
	FAME-type BDF or HBD production	—	—	196	196
Waste cooking oil from businesses	Incineration	1,108	1,108	—	—
	FAME-type BDF or HBD production	—	—	1,108	1,108
<i>Functional unit 2: Running diesel vehicle for household waste collection (kL/yr)</i>					
Diesel vehicle complied with:		short	long	short	long
Fossil-derived fuel consumption		1,157	1,157	—	502
FAME-type BDF consumption		—	—	1,252	—
HBD consumption		—	—	—	652

short: the new short-term emission gas standard

long: the new long-term emission gas standard

Table 6 Important parameters for unit processes

Process and parameters		Values	Units	Specific features	References
<i>Collection</i>					
Diesel consumption	Collected as mixed waste	0.109	L/kL of WCO	Allocated basing on weight	Estimated
	Source separation	11.4	L/kL of WCO	From households	Estimated
	Source separation	9.07	L/kL of WCO	From businesses	
<i>Incineration with energy recovery</i>					
Electricity consumption		158	kWh/ton of WCO		NIES, 2008; and calculation
Electricity production efficiency		15.0	%	Produced by steam turbine	Assumed
Emission factor	CH ₄	0.120	kg/ton of carbon		Yasuda, 1997
	N ₂ O	0.565	kg/ton of WCO		MOE, 2009
	SO _x	150	g/ton of WCO	All sulfur (S) content in waste cooking oil was assumed to be emitted in this process	Calculation
	NO _x	500	g/ton of WCO		Hirai et al., 2001
	PM _{2.5}	798	g/ton of WCO		Shiota, 2011; and calculation
	PM ₁₀	108	g/ton of WCO		Shiota, 2011; and calculation
	CO ₂	100	kg/ton of waste glycerin		Calculation
<i>FAME-type BDF production by alkali catalysis method</i>					
Waste cooking oil consumption		1.04	L/L of BDF		Data obtained from Kyoto city
Methanol consumption		0.131	kg/L of BDF		Data obtained from Kyoto city
KOH consumption		7.60	g/L of BDF		Data obtained from Kyoto city

Paraffin consumption		0.0274	L/L of BDF		Data obtained from Kyoto city
Electricity consumption		0.184	L/L of BDF		Data obtained from Kyoto city
Waste glycerin generation		0.396	L/L of BDF		Data obtained from Kyoto city
<i>HBD production by catalytic cracking and hydrogenation method</i>					
Wastewater generation		0.0400	L/L of WCO		Data by demonstration test
Electricity consumption		0.240	kWh/L of WCO		Data by demonstration test
H ₂ consumption		0.0926	m ³ /L of WCO		Data by demonstration test
N ₂ consumption		0.125	kg/L of WCO	Used as carrier gas	Data by demonstration test
Heat energy consumption		9.07	MJ/L of WCO	Supplied by high- and low-boiling oils, and offgas	Data by demonstration test
Products and produced energy	HBD	0.50	L/L of WCO		Data by demonstration test
	High-boiling-point oil	0.04	L/L of WCO		Data by demonstration test
	Low-boiling-point oil	0.16	L/L of WCO		Data by demonstration test
	Offgas	0.13	m ³ /L of WCO		Data by demonstration test
Emission factor	CH ₄	0.00590	kg/m ³ of wastewater		MOE et al., 2012
<i>Diesel fuel production</i>					
Electricity consumption		0.0075	kWh/L		JLCA, 2013
Emission factor	CO ₂	0.091	g/L		JLCA, 2013
	SO _x	0.087	g/L		JLCA, 2013
	NO _x	0.071	g/L		JLCA, 2013
	PM	9.0×10 ⁻⁵	g/L	All PM was regarded as PM ₁₀	JLCA, 2013
<i>Running household waste collection vehicle</i>					
Emission factor	CO ₂	2.62	kg/L		MOE, 2009
(diesel fuel, new short-term st.)	SO _x	1.16	g/L	All sulfur (S) content in diesel fuel was assumed to be emitted in this process	Calculation
	NO _x	18.8	g/L		Emission testing, calculation

	PM _{2.5}	2.85	mg/L		Emission testing; Motoshita, 2008; and calculation
	PM ₁₀	1.29	mg/L		Emission testing; Motoshita, 2008; and calculation
Emission factor (diesel fuel, new long-term st.)	CO ₂	2.62	kg/L		MOE, 2009
	SO _x	1.16	g/L	All sulfur (S) content in diesel fuel was assumed to be emitted in this process	Calculation
	NO _x	4.29	g/L		Emission testing, calculation
	PM _{2.5}	1.08	mg/L		Emission testing; Motoshita, 2008; and calculation
	PM ₁₀	4.91	mg/L		Emission testing; Motoshita, 2008; and calculation
Emission factor (FAME-type BDF, new short-term st.)	CO ₂	0.133	kg/L	Carbon derived from methanol was considered	Calculation
	SO _x	0.00405	g/L	All sulfur (S) content in waste cooking oil was assumed to be emitted in this process	Calculation
	NO _x	17.3	g/L		Emission testing, calculation
	PM _{2.5}	5.92	mg/L		Emission testing; Motoshita, 2008; and calculation
	PM ₁₀	26.8	mg/L		Emission testing; Motoshita, 2008; and calculation
Emission factor (HBD, new long-term st.)	SO _x	0.00405	g/L	All sulfur (S) content in waste cooking oil was assumed to be emitted in this process	Calculation
	NO _x	4.29	g/L	Assumed to be equal to the factor in fossil-derived diesel case	Calculation

			PM _{2.5}	1.08 mg/L	Assumed to be equal to the factor in fossil-derived diesel case	Assumed
			PM ₁₀	4.91 mg/L	Assumed to be equal to the factor in fossil-derived diesel case	Assumed
<i>Common parameter</i>						
Emission factor for electricity consumption			CO ₂	0.570 g/kWh	Weighted average value of 10 commercial utility companies as of FY2012.	Calculation
			SO _x	0.195 g/kWh	Weighted average value of 10 commercial utility companies as of FY2012.	Calculation
			NO _x	0.225 g/kWh	Weighted average value of 10 commercial utility companies as of FY2012.	Calculation
			PM ₁₀	0.0117 g/kWh	Weighted average value of 10 commercial utility companies as of FY2012.	Calculation

WCO: waste cooking oil.

Table 7 Summary of damage assessment

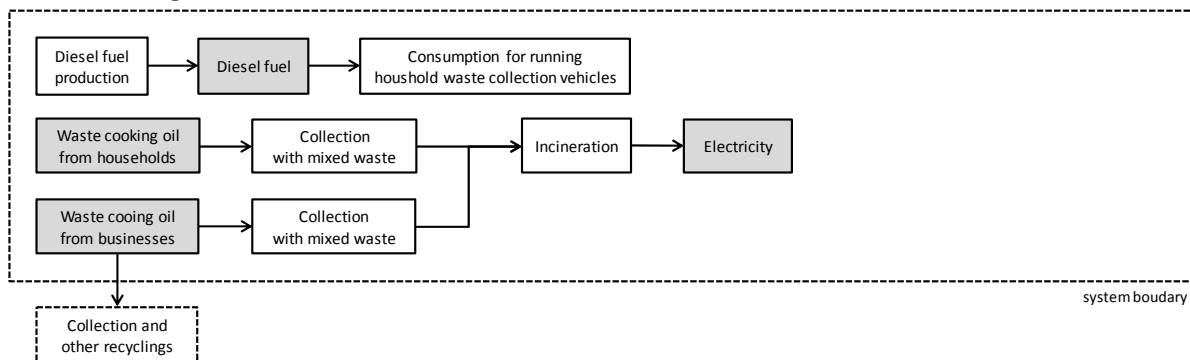
		S1-short	S1-long	S2-short	S3-long
Human health	[DALY]	1.10	0.60	0.69	0.32
Social assets	[Million Yen]	5.08	3.64	2.02	1.43
Biodiversity	[$\times 10^{-10}$ EINES]	-27.4	-27.4	-9.87	-8.40
Primary Production	[$\times 10^3$ NPP]	2.49	-1.51	4.21	0.48

Table 8 Parameters considered in uncertainty analysis

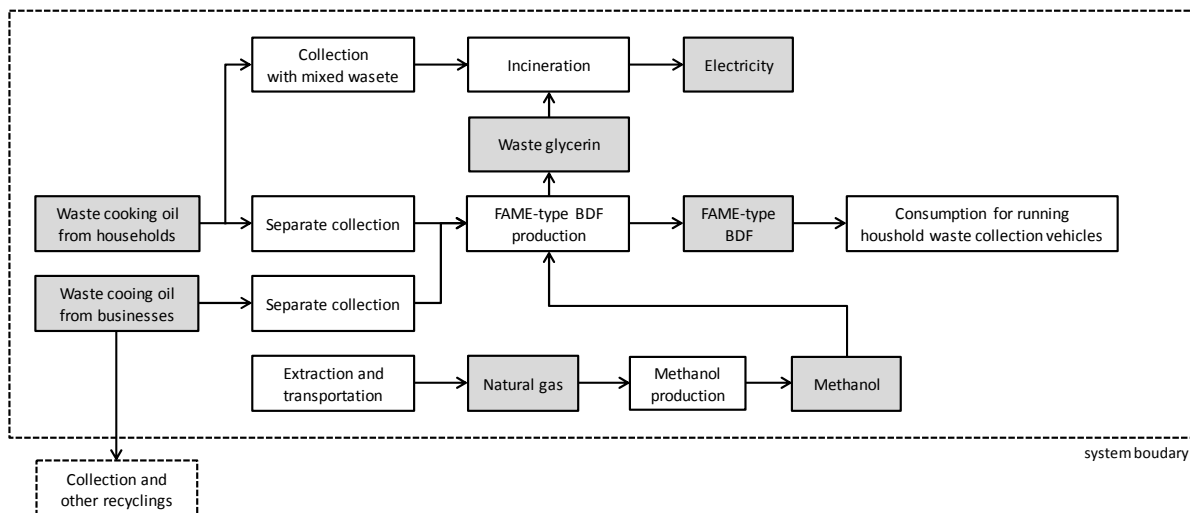
	Min.	Default	Max.
A) EFs: electricity consumption (g/kWh)			
CO ₂	0.412	0.570	0.570
SO _x	0.138	0.195	0.195
NO _x	0.170	0.225	0.225
B) Electricity production efficiency at incineration facility			
	0%	15%	20%
C) EF of NO _x : exhaust gas from household waste collection vehicle (g/L)			
Diesel, the new short-term st.	16.2	18.8	-
Diesel, the new long-term st.	3.32	4.29	10.1
FAME-type BDF, the new short-term st.	16.2	17.3	-
HBD, the new long-term st.	3.32	4.29	10.1
D) EF of PM _{2.5} : incineration facility (mg/ton of WCO)			
	37.2	798	1999

EF: emission factor. WCO: waste cooking oil.

<S1-short, S1-long scenarios>



<S2-short scenario>



<S3-long scenario>

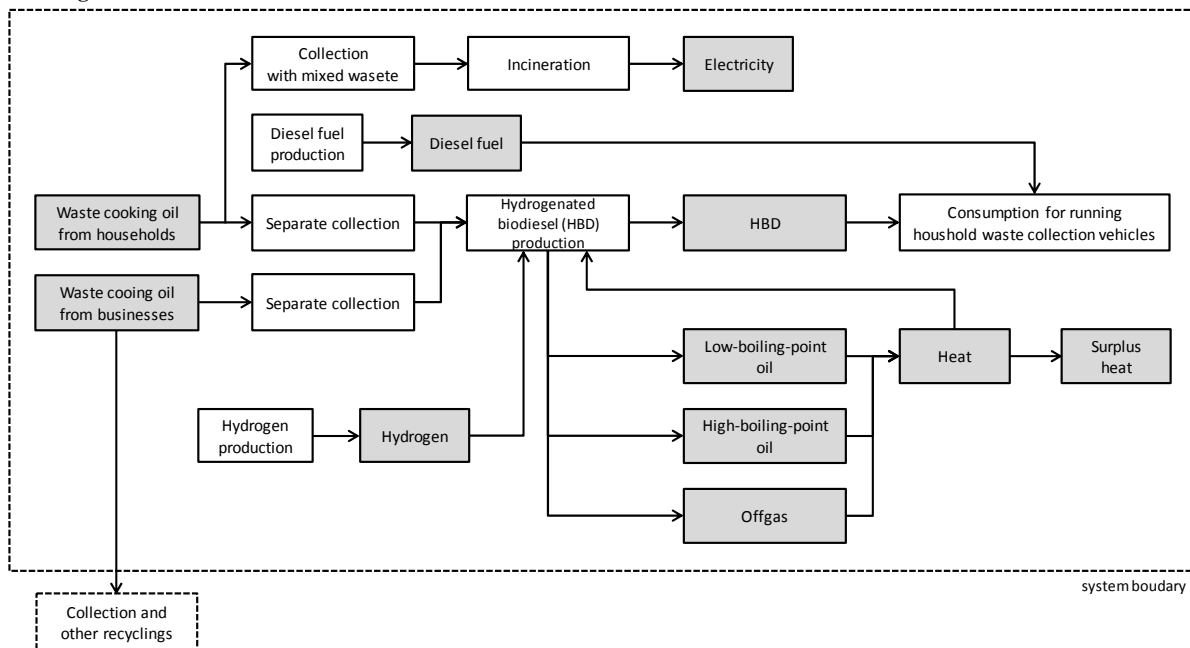
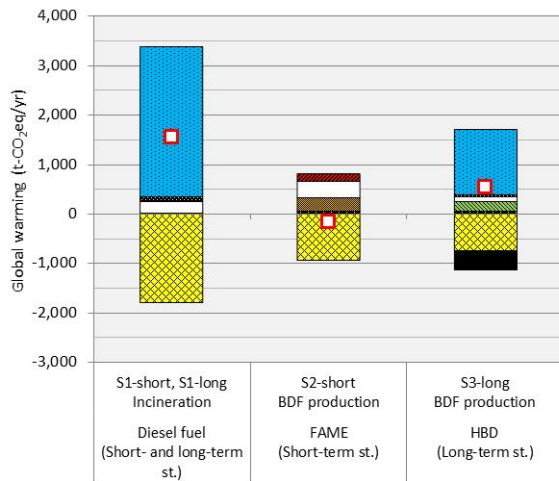
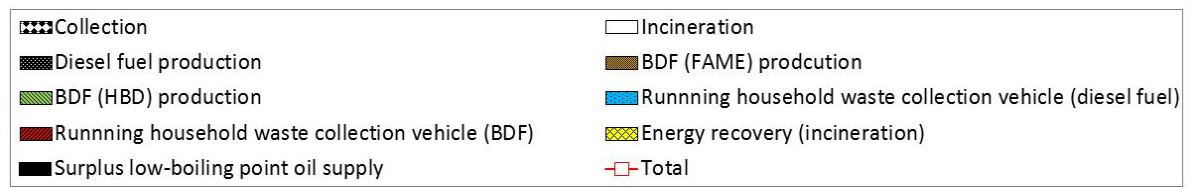
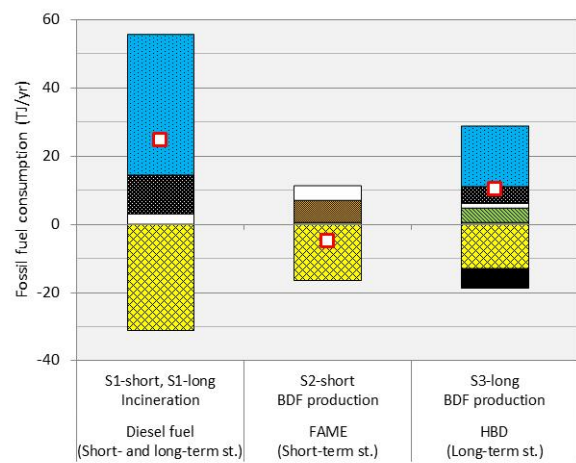


Fig. 1 System flow of each scenario

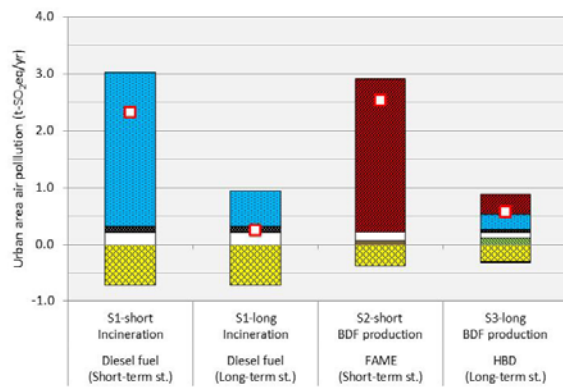
White boxes: processes, black boxes: products and energy, dotted white boxes: excluded processes.



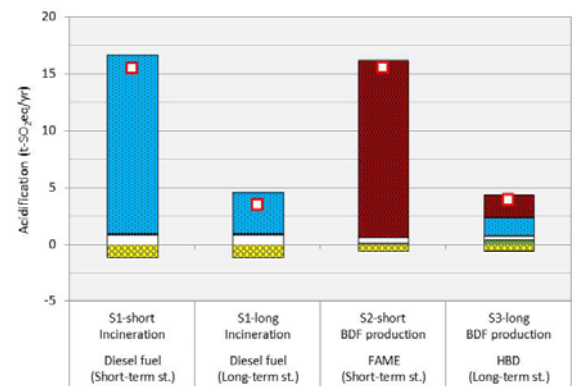
(a) Global warming



(b) Fossil fuel consumption

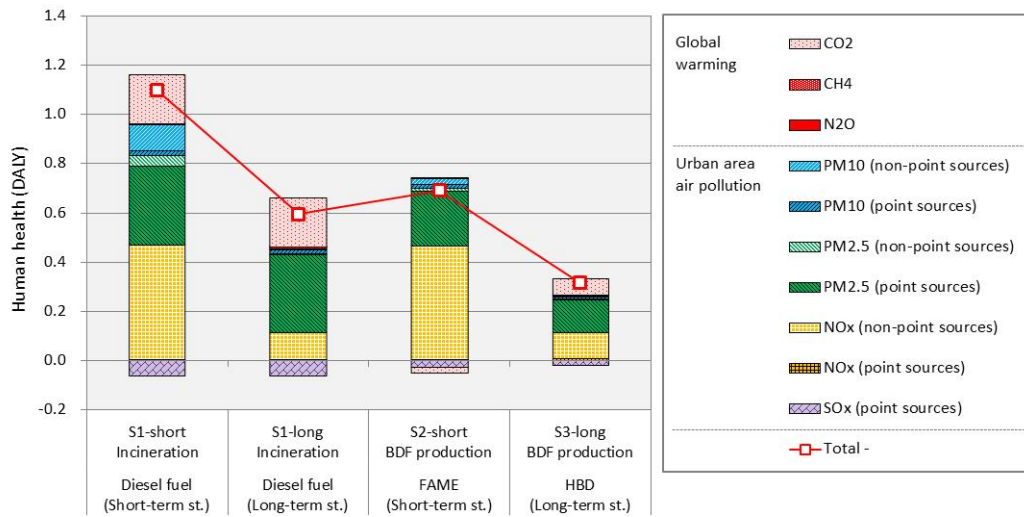


(c) Urban area air pollution

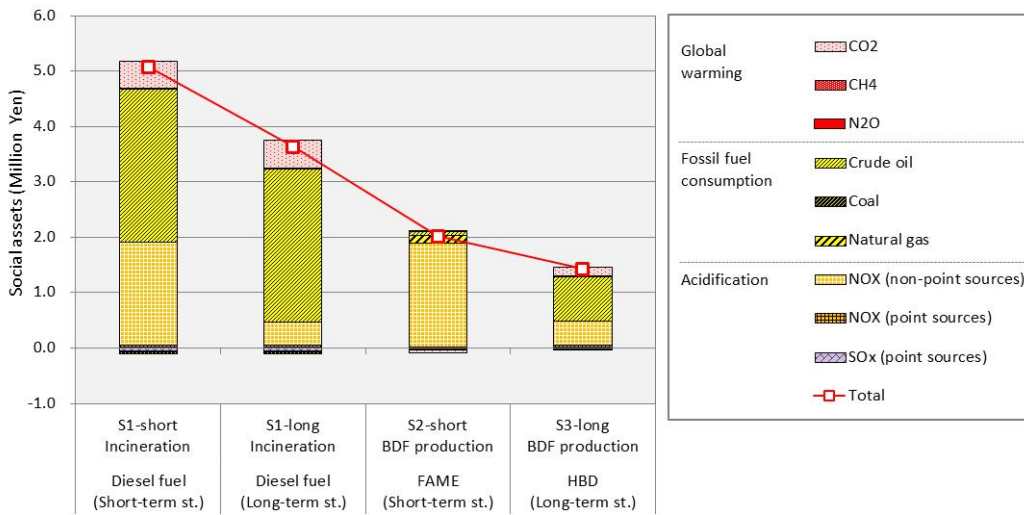


(d) Acidification

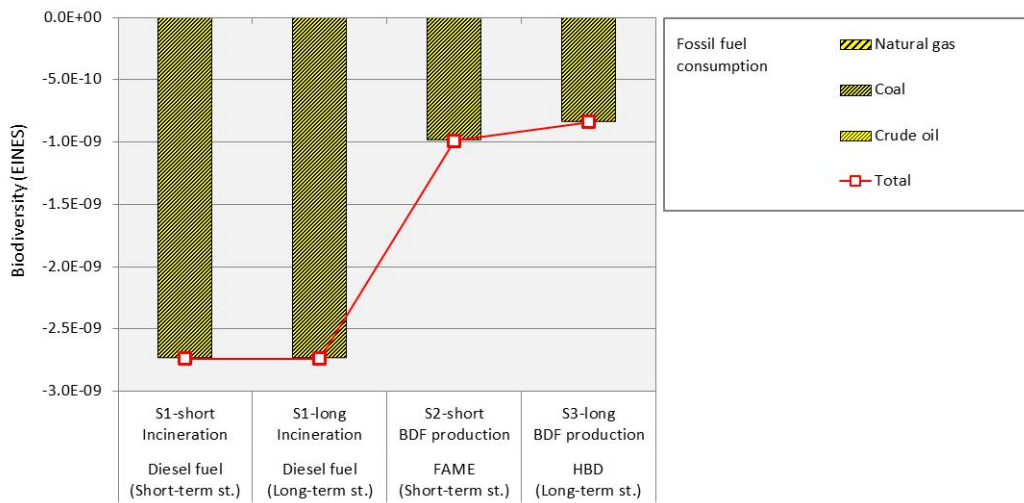
Fig. 2 Results of characterization



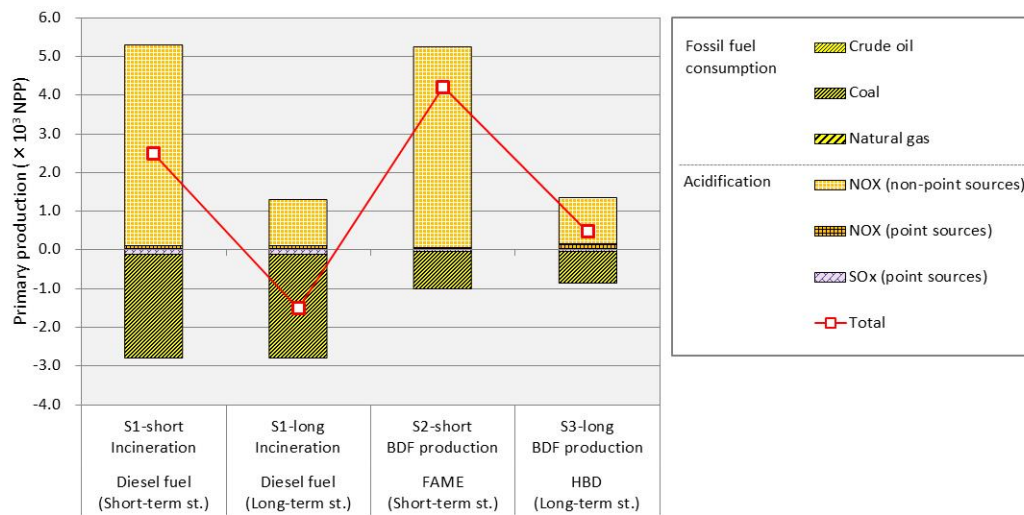
(a) Human health



(b) Social assets



(c) Biodiversity



(d) Primary Production

Fig. 3 Results of damage assessment

Point sources: emissions from facilities, non-point sources: emissions from diesel vehicles.

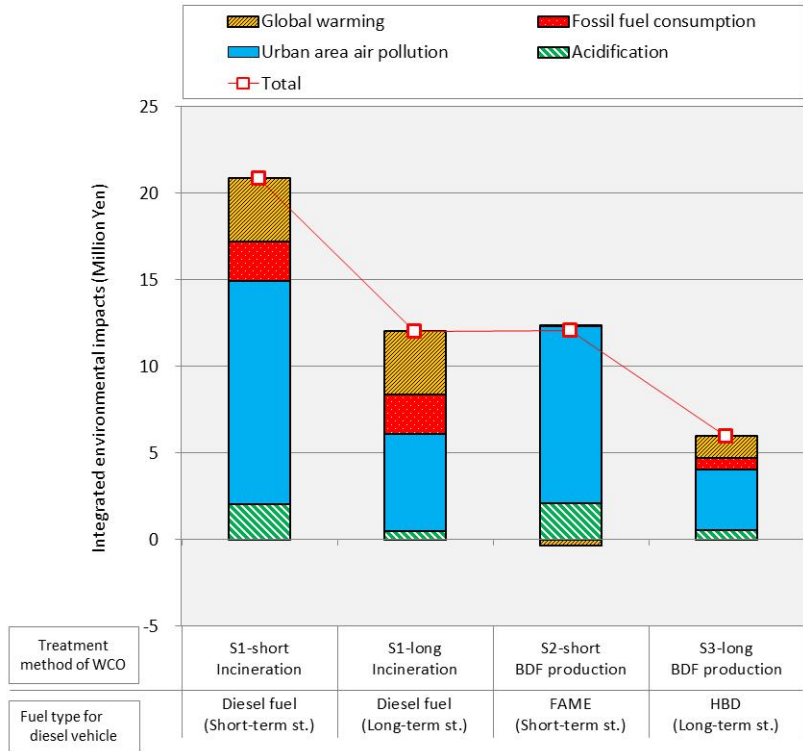


Fig. 4 Integrated environmental impact of each scenario

WCO: waste cooking oil, Short-term st.: new short-term emissions gas standard, Long-term st.: new long-term emissions gas standard.

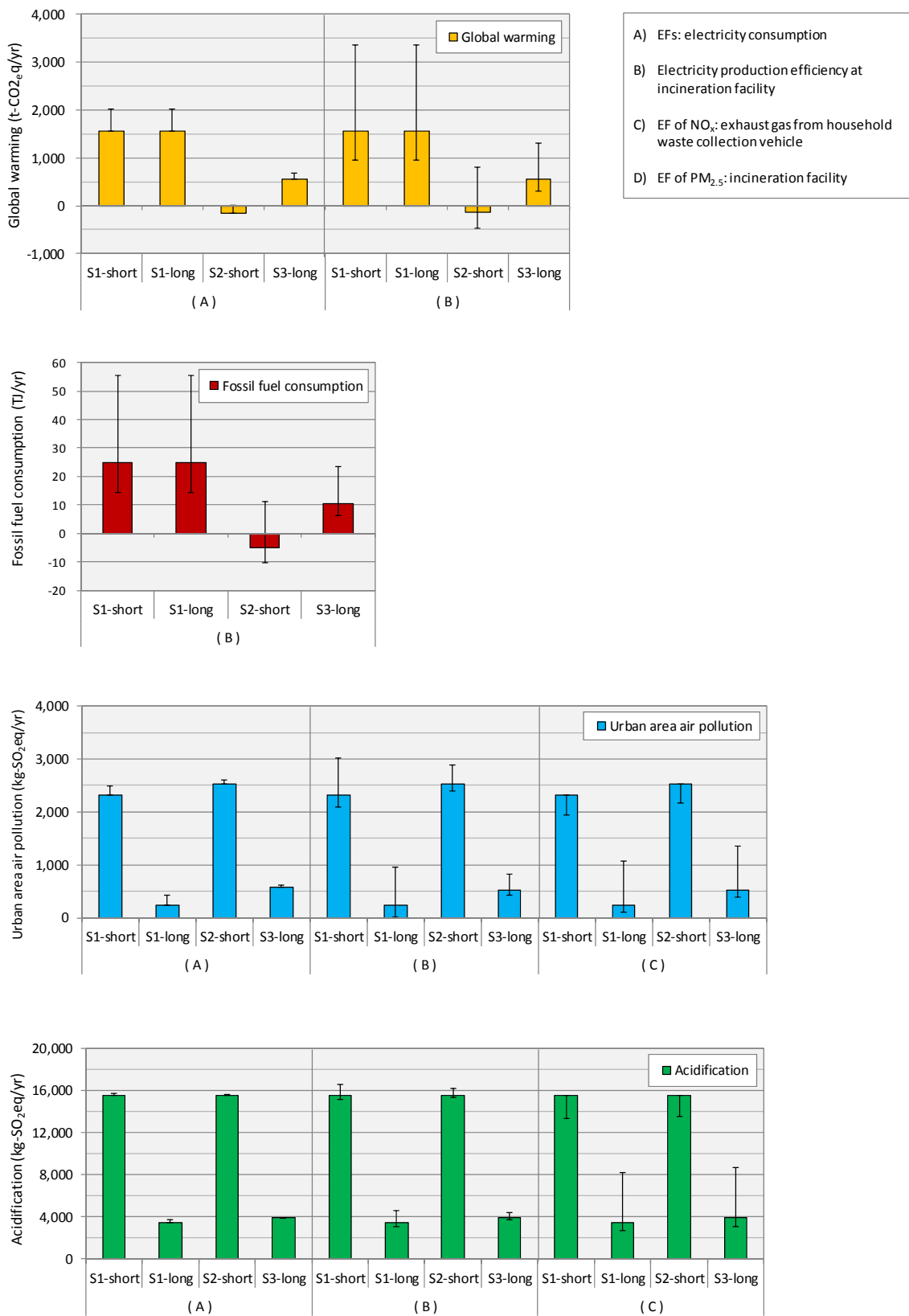


Fig. 5 Results of uncertainty analysis (Characterization)

Uncertainties are shown as a range (Min.-Max.).

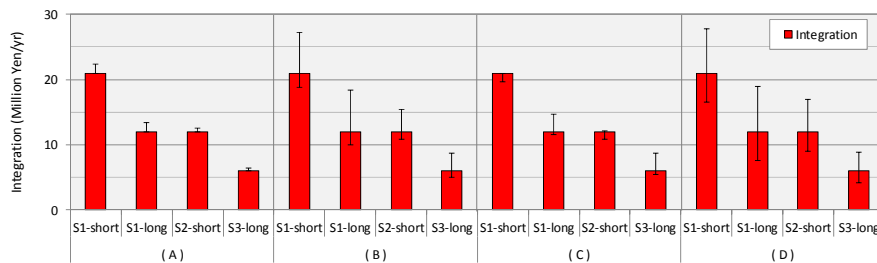
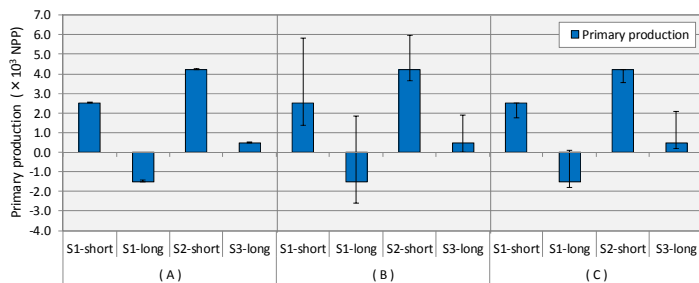
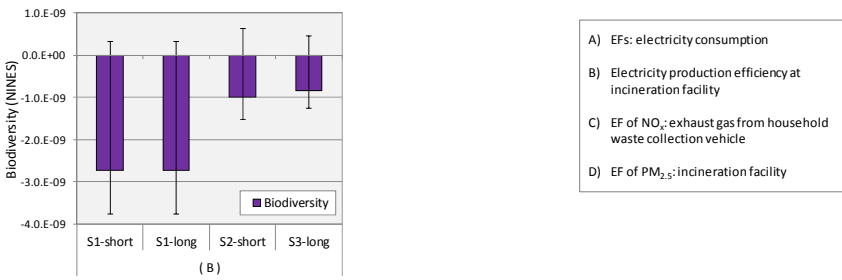
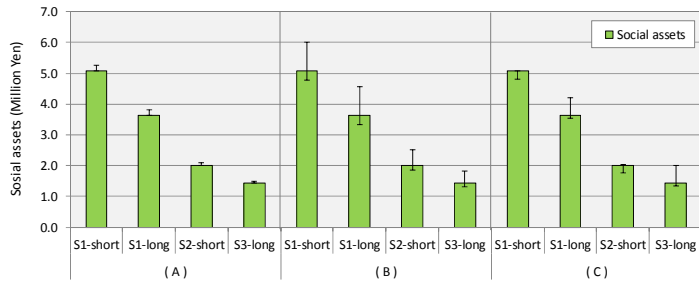
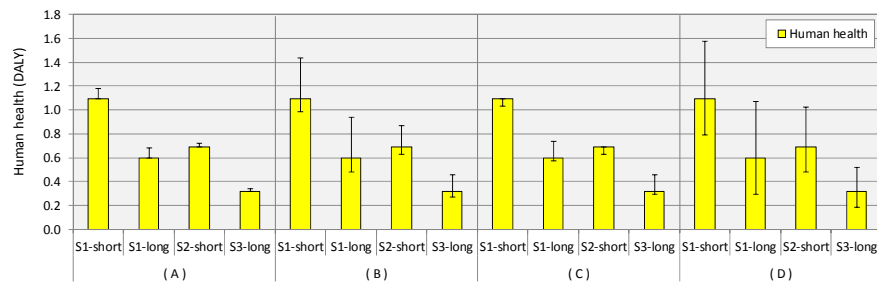


Fig. 6 Results of uncertainty analysis (Damage assessment and integration)

Uncertainties are shown as a range (Min.–Max.).

<Electronic supplementary material>

Life Cycle Assessment of Hydrogenated Biodiesel Production from Waste Cooking Oil Using the Catalytic Cracking and Hydrogenation Method

Waste Management, <http://www.journals.elsevier.com/waste-management/>

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Table 1 Characteristics of fossil-derived diesel fuel and BDFs

	Fossil-derived diesel fuel	FAME	HBD	HVO
	JIS2	Produced at Kyoto city	Produced in the demonstration project at Kyoto city* (ASTEM, 2013)	NExBTL (Neste Oil, 2014)
Density at 15°C (kg/L)	0.823	0.884	0.844	0.77–0.79
Kinetic viscosity at 40°C (-)	4.3	4.59	3.2	2.0–4.0
Flash point (°C)	-	135	50	> 61
Cetane index	56.3	52.5	51.7	> 70.0
90% distillation point (°C)	329	-	360	< 320 (95% distillation)
Oxidation stability (Rancimat method)	> 48	5.9	> 36	< 25
Pour point (°C)	-	-2.5	-13.1	-
Clogging point (°C)	-	-5	-4	-
Lower heating value (MJ/kg)	44.1	37.2	42.6	44.1
C (wt%)	86.0	77.1	85.9	-
H (wt%)	12.5	11.9	12.6	-
O (wt%)	< 0.5	10.8	< 0.5	-

*Produced by the catalytic cracking and hydrogenation method

Table 2 Characteristics of waste glycerin

Moisture content	22.0	wt%
Glycerin	47.3	wt%
Methanol	5.2	wt%
Potassium (K)	3.2	wt%
Oily fraction	22.4	wt%
Elemental composition		
Biomass-based carbon (C)	93.0	wt%
Fossil-derived carbon (C)	7.0	wt%

References

- ASTEM, 2013. Report on R&D towards the utilization of 2nd generation biodiesel suitable for vehicles. Kyoto, Japan (in Japanese).
- Neste Oil, 2014. Hydrotreated vegetable oil (HVO) – premium renewable biofuel for diesel engines.