Word count: 5973

1   # Process simulation and life cycle assessment of

2   # converting autoclaved municipal solid waste into

3   # butanol and ethanol as transport fuels

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15  **Abstract**

16      In 2015/2016, the total municipal solid waste (MSW) collected by local authority in the U.K.

17  was 26 million tonnes and over 57% is still put into landfill or incinerated. MSW is a promising

18  feedstock for bio-butanol production as it has a high lignocellulosic fibre content such as paper,

19  wood, and food waste, about 50 wt% of a typical MSW stream. The study evaluates acetone,

20  butanol, ethanol and hydrogen production from autoclaved municipal solid waste feedstock.

21  Life cycle assessment is undertaken to evaluate the acetone, butanol, ethanol and hydrogen

22  production process, considering cogeneration of heat and power from residual biogenic waste

23  based on experimental data and process modelling. Acetone, butanol, and ethanol product yield

24  can be achieved at 12.2 kg butanol, 1.5 kg ethanol, 5.7 kg acetone, and 0.9 kg hydrogen per

25  tonne MSW. The product yield is relatively low compared to other lignocellulosic feedstocks

26  primarily because of the lower hydrolysis yield (38% for glucose) achieved in this study;

27  however, hydrolysis yields could be improved in future optimisation work. The conversion

28  shows a net primary energy demand of -1.11 MJ/MJ liquid biofuels (butanol and ethanol) and

29  net greenhouse gas emission of -12.57 g $CO_2$eq/MJ liquid biofuels, achieving a greenhouse gas

30  reduction of 115% compared to gasoline comparator.

31  **Keywords**

32      Municipal solid waste, Waste autoclaving, Enzymatic hydrolysis, ABE fermentation, Life

33  cycle assessment

34 **1    Introduction**

35    The EU transport sector accounted for 25.8% of the total greenhouse gas (GHG) emissions

36 in the EU in 2015 at 1.05 Gt/yr including international aviation and maritime emissions

37 (European Environment Agency, 2017). The EU's climate change targets  have already stated

38 transport emissions must be cut by 60% by 2050 compared with 1990 levels (The European

39 Union, 2014). Renewable energy sources can contribute to climate change mitigation through

40 the reduction of GHG emissions and achieve sustainable development, driving the increased

41 demand for renewable fuels. The EU issued the Renewable Energy Directive (RED), for

42 instance, requires that renewable energy content should account for at least 10% of the energy

43 used in transportation by 2020 (European Commission, 2018).

44    Butanol ($C_4H_9OH$) is an attractive renewable liquid transport fuel. Its superior properties

45 have been well documented: butanol fits the existing fuel infrastructure as it can be stored in a

46 mixture with traditional gasoline and diesel at a varied ratio; it has a better energy density (30%

47 greater than ethanol) and combustion performance  due to similar air: fuel ratio to that of

48 gasoline than ethanol and can be used in higher quantities in a standard petrol engine (up to

49 20% without any engine modifications) but ethanol is limited to 15% (Wu et al., 2007); and

50 exhibits low solubility in water which reduces the risk of groundwater contamination from

51 unintended release. Butanol thus has the potential to substitute both ethanol and biodiesel in

52 the biofuel market to reach $185.3 billion in 2021 as estimated by Pike Research (Microbiology

53 Society, 2013). In addition to being a potential biofuel, butanol is also a valuable C4 feedstock

54 for chemical synthesis (e.g., methacrylate esters, butyl glycol ethers, butyl acetates, and

55 plasticizers) and an industrial solvent or co-solvent for surface coatings (Bankar et al., 2013).

56 However, challenges still need to be addressed, such as high feedstock costs and associated

57 high operational cost requiring cheaper and sustainable feedstocks.

58    Municipal solid waste (MSW) is a promising feedstock for butanol production as it has a

59    high lignocellulosic fibre content such as paper, wood, and food waste, about 50 wt% of a

60    typical MSW stream. Unlike other cellulosic feedstocks, MSW has low/negative feedstock

61    prices, immediate availability, and high potential in reducing GHG emissions of biofuel

62    production compared to first and second generation biofuels from food crop and agricultural

63    or forest residue wastes. Further, diverting the organic content of MSW for biofuel production

64    is also beneficial in addressing MSW waste management issues (Gharfalkar et al., 2015;

65    Jeswani and Azapagic, 2016). In 2015/2016, the total MSW collected by local authority in the

66    U.K. was over 26 million tonnes and over 57% is still put into landfill or incinerated

67    (Department for Environmental Food and Rural Affairs (Defra), 2017b; Science and

68    Technology Select Committee, 2014). The gate fee charged by landfilling in the UK reveal a

69    cost of £19/tonne excluding landfill tax and £102/tonne including landfill tax, while tipping

70    fees for incineration are £86/tonne in 2015/2016 (WRAP (Waste & Resources Action

71    Programme), 2016). Therefore, the production of biofuel from MSW is extremely attractive in

72    terms of environmental and economical perspective.

73    Life cycle assessment (LCA) provides a transparent methodology that can be used to

74    examine lignocellulosic biofuel production as it examines the environmental burdens over the

75    entire life, from production, through use and on to disposal or recycling (McKechnie et al.,

76    2011). Existing LCAs of biofuel production (e.g., ethanol) from various feedstocks including

77    corn stover, wheat straw, poplar, eucalyptus and waste papers amongst others have been widely

78    reported in the literatures (Borrion et al., 2012; Michael et al., 2012; Mohammad et al., 2013;

79    Zhang et al., 2010b). Few studies by Chester & Martin (Chester and Martin, 2009), Schmitt et

80    al. (Schmitt et al., 2012) and  Kalogo et al. (Kalogo et al., 2007) evaluated ethanol production

81    from MSW via dilute acid pretreatment and hydrolysis and presented the life cycle

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82  environmental impacts of the conversion. It showed MSW derived ethanol can reduce energy

83  use and GHG emissions compared to gasoline and other cellulosic ethanol production. But

84  environmental impacts are highly dependent on conversion technology, process conditions

85  used, and waste classification and its overall impact of MSW to ethanol is limited due to

86  availability of MSW.

87  Autoclaving is a new pretreatment technology replacing conventional dilute acid

88  pretreatment to process unsorted MSW. Prior LCA study considered autoclaving unsorted

89  MSW with subsequent composting in tunnels/in confined windrow/ in turning windrow, or

90  anaerobic digestion of biogenic fibres (Quirós et al., 2015). The results showed that autoclaving

91  with sorting, digesting anaerobically and composting had the lowest environmental impact

92  values for eutrophication and global warming potential. However, there is no consideration of

93  higher value uses for this biogenic fibre materials, such as liquid biofuels (e.g., butanol).

94  To address the gaps in technical and environmental aspects of acetone, butanol, ethanol

95  (ABE) production from pretreated MSW, in this study, we develop process models for ABE

96  production from autoclaved MSW feedstock. The overall technical performance and

97  environmental impacts (i.e., primary energy demand and global warming potential) are

98  evaluated across the integrated processes, including autoclave, hydrolysis, fermentation, and

99  distillation.

100  **2   Method**

101  The study models in detail the production of ABE and hydrogen from autoclaved municipal

102  solid waste feedstock. The overall process design converts MSW into ABE and hydrogen by

103  autoclave, hydrolysis, fermentation and distillation. Product recovery, energy recovery,

104  wastewater treatment and utilities are also included in the design. The recovery of non-biogenic

105  content of MSW after autoclave, including plastics, metal, and glass materials, are excluded in

5

106    this study. The input and output mass and energy flow of the system are extracted from

107    experimental data and process modelling as discussed below. Inventory data is also

108    supplemented by Ecoinvent database (Wernet et al., 2016) and literature data where available,

109    e.g., enzyme production for hydrolysis (Nielsen et al., 2006) (see Table 1). The LCA is

110    undertaken in GaBi 8.2 (2017) using Ecoinvent 3.3 inventory databases. Two environmental

111    impacts are quantified: primary energy demand (PED) in terms of MJ and global warming

112    potential (GWP), based on the most recent IPCC 100-year GWP factors to quantify GWP in

113    terms of $CO_2$ equivalents ($CO_2$ eq.) (Stocker et al., 2013). Direct $CO_2$ emissions from the

114    fermentation and combustion of butanol and ethanol fuel are excluded as the emitted carbon

115    from renewable biomass resources can be counted as "carbon neutral". Avoided emissions

116    from diverting waste to butanol and ethanol production from other conventional waste

117    treatment routes (e.g., landfill, incineration) are also excluded.

118    **2.1    Scope and functional unit**

119    We develop an LCA model of MSW-ABE following the ISO Standards 14040 and 14044

120    (International Organization for Standardization, 2006a, b). The functional unit is defined as

121    one MJ of liquid biofuels (butanol and ethanol)) used as a reference to quantify all inputs and

122    outputs of the process steps. A schematic process flow diagram defining the system boundaries

123    is shown in Fig. 1. The system boundary begins with the sorting and separation of MSW

124    (energy use and environmental burdens of the processes and products generating MSW are

125    excluded from the study) and ends with the combustion of the fuel in a light duty vehicle.

126    System expansion method is used to consider the co-products' benefits where liquid biofuels

127    (butanol and ethanol) are the main product and acetone, hydrogen, and excess electricity are

128    considered as co-products thereby allocating their impacts to main product liquid biofuels.

129

130 **2.2 Waste composition**

131 The waste composition used is representative of the UK MSW with the following wet

132 composition by mass: paper and cardboard (22%), food waste (17%), wood (8.7%), plastic

133 (22%), glass (1%), garden waste (3%), metals (4%), textiles (6.6%) and others (15.7%)

134 (Department for Environmental Food and Rural Affairs (Defra), 2017a).

135 **2.3 Life Cycle inventory**

136 **2.3.1 Autoclave Pretreatment**

137 The autoclave system is a mechanical heat treatment process developed by Wilson Bio-

138 Chemical (Wilson Bio-Chemical, 2017), based on existing autoclaving and steam boiler

139 technologies. The autoclave is a front-loading and rotating pressure vessel in which the MSW

140 is treated with high pressure saturated steam in a batch process. The organic fraction is broken

141 down to a cellulose-rich fibre, which has a high sugar composition (40–50%) and thus could

142 be suitable for biofuel production via fermentation. Untreated wastes such as plastic, glass,

143 textiles and metals are sterilised and able to be recovered post-autoclave.

144 Based on the best performance running of the autoclave process, processing parameters of

145 160°C for two hours for each batch have been determined. Thus the energy requirement of 43

146 MJ electricity and 274 MJ natural gas and 245 L water is determined from plant operation to

147 pretreat one tonne of MSW (Wilson Bio-Chemical, 2017).

148 **2.3.2 Hydrolysis**

149 The waste stream has been subjected to high temperature processing and this is similar to the

150 pretreatment normally required to overcome the inherent recalcitrance of biomass feedstocks

151 to subsequent enzymatic saccharification to sugars. Preliminary studies have previously

152 demonstrated that between 30-40% of the fibre sugar can be released by subsequent enzyme

153 hydrolysis (Ibbett, 2018). A commercially available enzyme cocktail - Novozymes Cellic

154    CTec2 (Novozymes, 2018) - is used in this study. Samples of the MSW fibre are milled to a

155    consistent particle size (0.5mm) and then loaded into the hydrolysis vessel where it is diluted

156    with water from the mains water tank into a dilute slurry (20% solids assumed in this study but

157    a range of 20–30% solids are evaluated in the sensitivity analysis). At this point, adjustments

158    may also be made to process conditions such as pH. The slurry is then dosed with an enzyme

159    solution (5% wt/wt) (15–60 filter paper units (FPU) per gram cellulase) which is stored in its

160    own separate storage tank, causing hydrolysis of the biogenic fibre to a solution of fermentable

161    sugars. There will also be solids remaining in suspension which are either un-hydrolysable or

162    have not been fully hydrolysed. All of this mixture is transferred downstream to the filtration

163    unit. The efficiency of hydrolysis is assessed by monitoring glucose release into the media,

164    over a period of 48h at the temperature of 50°C, by high pressure ion chromatography.

165    The composition of biogenic fibre transported from the Wilson System as stated above can

166    be evaluated by analysis of the monosaccharides liberated by total acid hydrolysis of the

167    polysaccharides present in the fibre cell-wall matrix (Ibbett et al., 2011). This method gave a

168    monosaccharide content as follows: glucose (40-45%), xylose (4-5%), galactose (0.7%) and

169    arabinose (2.9%), as shown in Fig. 2, where glucose is mainly derived from cellulose and the

170    other three monosaccharides are derived from hemicellulose.

171    The net enthalpy change for each reaction (see the reactions outlined below) is calculated

172    using the heat of formation ($\Delta H_f$) (Humbird et al., 2011), see eq (1) as below.

173    *(Glucan)$_n$ + nH$_2$O → nGlucose*

174    *(Xylan)$_n$ + nH$_2$O → nXylose*
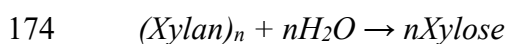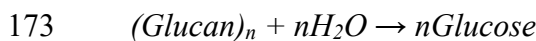
$$Q_{reaction} = \sum \frac{\Delta H_f \; x \; (m_b cy)}{M_w} \tag{1}$$

175     where $\Delta H_f$ is the heat of formation (kJ/mol), $m_b$ is the number of moles of sugar formed from

176     1 kg MSW fibre (mol), $c$ is the sugar composition (%), $y$ is sugar hydrolysis conversion yield

177     (%), $M_w$ is the molecular weight of the sugar (kg/mol).

178     Mixing is achieved by an agitator and heat control is achieved by a centrifugal pump which

179     pumps the hydrolysate around a loop through a heat exchanger cooled with cooling water, as

180     is assumed in previous biorefinery models (Humbird et al., 2011).

181     **2.3.3    Fermentation**

182     After hydrolysis, the sugary solution is adjusted (as required) with antifoam, pH altering

183     agents and other required additions (such as nutrients) in preparation for fermentation. The

184     microorganism is *Clostridium acetobutylicum* ATCC 824 and the medium of all fermentations

185     contain (per L) $KH_2PO_4$ 1 g, $K_2HPO_4$ 0.76 g, $CH_3COONH_4$ 2.9 g (of which $CH_3COO^-$ is 2.2

186     g), yeast extract (Duchefa) 2.5 g, $FeSO_4 \cdot 7H_2O$ 6.6 mg, $MgSO_4 \cdot 7H_2O$ 1 g, and *p*-aminobenzoic

187     acid (*p*-ABA) 0.1 g. Following this, the vessel is inoculated with a previously prepared

188     Clostridium culture from the seed culture vessel. The fermentation is conducted at 37°C over

189     a duration of 48 hours per batch. We assume that the inventory data of producing *Clostridium*

190     *acetobutylicum* would be similar to that of producing *Z. mobilis* as in the design (Dunn et al.,

191     2012; Humbird et al., 2011). Inventory data of nutrients are obtained from publicly available

192     data (Adom and Dunn, 2015; Edwards, 2016).

193     Fermentation then proceeds, producing ABE as well as hydrogen and $CO_2$. As the butanol

194     concentration builds, it inhibits the growth of the Clostridium. Therefore, nitrogen gas stripping

195     is used to selectively remove the ABE which escapes as a vapour to the condenser along with

196     $CO_2$, hydrogen, nitrogen and some water vapour. The hydrogen and $CO_2$ are collected during

197     the fermentation and purified by Pressure swing adsorption in the subsequent distillation stage.

198     Totally, ABE fermentation yield can be achieved at 33% of which has been validated

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199  experimentally by a 30% yield and hydrogen yield is 1.6% based on molar ratio shown in Table

200  2. The relative ratio of produced solvents acetone, butanol and ethanol is 28%, 62% and 10%.

201  The reactions represent a qualitative measure rather than stoichiometric quantitative

202  relationships for the ABE conversion process. Based on eq (1) above, reaction energy shows

203  the conversion is mildly exothermic; as such, we assume fermentation unit does not require

204  thermal management (i.e., heat loss to surroundings is balanced by heat release from

205  fermentation).

### 2.3.4  Distillation

207  The acetone, butanol, ethanol and water vapours are condensed in the beer column and are

208  subsequently transferred to rectification column for separation. The un-condensable hydrogen,

209  nitrogen and $CO_2$ continue through the condenser to pressure swing adsorption. Pressure swing

210  adsorption technology (HyGear, 2017) is used to purify hydrogen from the gaseous mixture

211  leaving the condenser. This hydrogen can be pressurised and stored in a tank, whilst the

212  remaining $N_2$ and $CO_2$ are discarded. The acetone, butanol, ethanol and water are distilled

213  based upon their relative volatilities into pure streams of each component by a gas stripping

214  procedure. This concentrated solution of solvent will then be distilled to obtain the three distinct

215  compounds: butanol, acetone and ethanol to meet the requested biofuel specifications.

216  Recirculation of the stripping gas will reduce the costs. Firstly, acetone is assumed to be

217  extracted in the first distillation column with a purity of 99 wt%. After separation of acetone,

218  the remaining liquid goes through a decanter before going to the second distillation column to

219  separate ethanol which is then dehydrated through the molecular sieve adsorption to a purity

220  of 99.5 wt%. The bottom stream which is mainly butanol and water after separation of ethanol

221  goes to the third distillation for butanol separation (99.7 wt%) (Baral and Shah, 2016; Grisales

222  Díaz and Olivar Tost, 2017). These pure products are finally stored in tanks, ready for

223    distribution or analysis. The waste biofuels and water mixture are assumed to be discharged to

224    the lignin separator and wastewater treatment system mixed with stillage from hydrolysis and

225    fermentation units.

226    **2.3.5   Wastewater Treatment**

227    Wastewater treatment process in previous model (Humbird et al., 2011) is adapted in this

228    study. After hydrolysis, fermentation and distillation, the stillage contains unfermented sugars,

229    organic acids and solid residuals, e.g., lignin. They are sent to a press filter to separate solids

230    (mainly lignin) to the combustor while the liquid fraction is sent to wastewater treatment .

231    Wastewater treatment consists of anaerobic and aerobic digestion treating and recycling the

232    wastewater to minimise the amount of water discharged and fresh water requirement. The total

233    chemical oxygen demand is assumed to be proportional to the solid content concentration in

234    the wastewater and is calculated to be 245 g/L. In anaerobic digestion, 91% of organic content

235    is converted into biogas (86%) and microorganism cell mass (5%). The biogas from the digester

236    has a composition of 51% $CH_4$/49% $CO_2$ on a dry molar basis. Methane is produced on the

237    basis of the organic content at a yield of 228 g biogas/kg chemical oxygen demand while the

238    cell mass is produced at 45 g cell mass/kg chemical oxygen demand (Humbird et al., 2011).

239    The liquid after anaerobic digestion is further treated in aerobic digestion where 96% of the

240    remaining soluble organic content is digested, with 76% converting into water and carbon

241    dioxide and 22% producing cell mass. Chemicals such as caustic soda must be added to adjust

242    the pH for digestion. After this step, the liquid is sent to a membrane bioreactor clarification

243    system where the aerobic biomass sludge is separated to sludge centrifuge mixed with

244    anaerobic sludge for dewatering. The centrifuge solid is dewatered and sent to the combustor

245    for energy recovery and the remaining water is recycled to aerobic digester for additional

246    treatment. The clarified water is pumped to the reverse osmosis for salt removal. About 79%

247　water is assumed to pure and recycled to the process and 21% of the water rejected from reverse

248　osmosis is further concentrated in an evaporator system. In the evaporator, about 7% dry brine

249　content (mainly sodium nitrate) is sent for disposal while the concentrated water is assumed to

250　be clean and recycled to the process.

251　**2.3.6　Energy recovery**

252　　The lignin from hydrolysis and fermentation residue and biogas and sludge produced from

253　wastewater treatment are fed to the combustor for heat and power generation. A grate

254　incinerator was modelled with electricity and heat production efficiency of 18.7% and 21.6%

255　of the waste's lower heating value, respectively (Veolia, 2012). The cogenerated heat is

256　assumed to be used to meet process heat requirements; the excess could be used for sterilization

257　or for cooling generation via absorption refrigeration plant on site, or exported via a heat

258　network, but such uses are not considered in the present study and excess heat is assumed to

259　not have a practical use. The electricity is used to supply the process and any surplus electricity

260　is assumed to be exported to the grid. The electricity system is assumed to be representative of

261　the UK average mix in 2015, composed of nuclear (20.9%), coal (22.5%), natural gas (29.7%),

262　hydro (1.9%), heavy fuel oil (0.6%), wind (14.2%), other renewables (8.7%), and other (1.4%)

263　(Digest of UK Energy Statistics (DUKES), 2017).

264　**2.4　Sensitivity analysis**

265　**2.4.1　Sensitivity analysis of background systems**

266　　Relative environmental performance of MSW derived liquid biofuels depends on reference

267　fuels system, enzyme production and which electricity types (i.e., renewable content of the

268　electricity) the exported electricity is displacing. It arises from regional variability of electricity

269　generation sources and associated impacts. Thus we conducted sensitivity analyses to study the

270　influence of background systems on life cycle emissions of MSW derived liquid biofuels.

271 **2.4.2 Sensitivity analysis of process variables**

272 The overall yield of ABE from MSW depends on the biogenic fibre content of MSW, the

273 conversion efficiencies from cellulose to glucose and xylose during hydrolysis, glucose and

274 xylose yield and glucose and xylose conversion during fermentation. The ultimate ABE

275 concentration is also dependant on the solid concentration during hydrolysis. Distributions are

276 fitted where sufficient data are available (e.g., hydrolysis yields) or assigned based on

277 minimum/maximum values to model parameters. Monte Carlo simulations (Ruth and Jechura,

278 2003; Tu and McDonnell, 2016) enable an investigation into how input uncertainty propagates

279 through the mass and energy balance model and LCA model. These distributions and

280 underlying data sources are summarised in Table 4 for processing parameters including

281 hydrolysis yield and solid content. Triangular distributions are used for these parameters where

282 the peak values – indicating highest probability - are those from experiments, with the

283 probability decreasing linearly until reaching zero at the upper and lower bounds considered.

284 The number of iterations for the Monte Carlo analysis to estimate the probability of different

285 results was set to 10,000 as a general rule of thumb (Barreto and Howland, 2005) using Crystal

286 Ball (Oracle, 2016). Results are shown in Section 3.3.

287 **3   Results and Discussion**

288 **3.1   Material and Energy Balance**

289  Fig. 3 indicates the flows of MSW into the main processing system including mass and

290 energy balance. The total input is one tonne MSW, of which 53% of wet mass is lignocellulosic

291 content. It has a moisture content of 40%, with remaining components broken down by sugar

292 dry content as 45% glucose and 5% xylose as measured experimentally (totally 31.8% dry

293 convertible lignocellulosic content). Sugar levels are key as they are the molecules that react

294 within the hydrolysis and fermentation stages to produce ABE. Hydrolysis yield was previously

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295    found to be 38% for glucose from experimental measurement and 70% for xylose. Thus the

296    lignocellulosic feedstock can produce 54.4 kg glucose and 11.1 kg xylose per tonne MSW after

297    hydrolysis reaction. The outputs from the conversion are 12.2 kg butanol (7.6 kg gasoline

298    equivalent on energy basis), 1.5 kg ethanol (0.9 kg gasoline equivalent), 5.7 kg acetone, and

299    0.9 kg hydrogen as well as 0.3 kg acetic acid and 1.0 kg butyric acid. ABE product yield

300    achieved in this study is relatively low compared to other lignocellulosic feedstocks which have

301    been subjected to higher severity hydrothermal deconstruction pretreatments (Ibbett et al.,

302    2011) (3.2 wt% in this study versus 11.8–14.9 wt%, on a dry substrate basis) (Baral and Shah,

303    2016; Montano, 2009), primarily because of the lower hydrolysis yield (38% for glucose)

304    achieved. However, it should be noted that hydrolysis yields could be improved up to 85% and

305    more details are discussed in Section 3.3.2. These mass transfers from MSW to biorefinery

306    products (ABE and hydrogen) are used as the bases of LCA analysis.

307      The energy recovery and process energy (i.e., electricity and heat) required for each step of

308    ABE production system are also shown in Fig. 3, which are obtained from plant operation data

309    and process modelling. Enthalpy of materials in hydrolysis and fermentation depends on the

310    mass and temperature of the materials. The autoclave process is the most energy intensive step

311    accounting for about 42% of the total heat requirement and 41% total electricity requirement.

312    The hydrolysis requires about 32% of the heat requirement and only 0.4% electricity use for

313    mixing compared to 0.7% electricity use for fermentation. About 26% of the total heat and 4%

314    of the total electricity use are required for distillation process for ABE product recovery.

315    Wastewater treatment process also consumes about 54% of the total electricity to recover

316    process water, separate lignin solid, produce biogas via equipment such as water pump, digester

317    blower, anaerobic basin, sludge centrifuge and evaporator.

318    Wastewater produced during the MSW-to-ABE process can be treated into 94% clean water

319    through anaerobic and aerobic digestion. The wastewater treatment unit can produce 389 kg

320    lignin (35% moisture content) and 21 kg biogas and 8 kg sludge (79% moisture content) to the

321    energy recovery unit. Considering the calorific values of lignin, biogas (51% $CH_4$/49% $CO_2$),

322    and sludge (16 MJ/kg (Demirbas, 2017), 14 MJ/kg, and 4 MJ/kg (Humbird et al., 2011),

323    respectively), energy recovery unit totally produces 266 kWh electricity and 1108 MJ

324    heat(Veolia, 2012). These energy sources are used to provide energy use for autoclave and

325    ABE biorefinery onsite. Excess electricity can be sold to the grid which can contribute to the

326    grid to reach the target of 15% electricity using renewable sources by 2020 as regulated by the

327    Renewable Obligation produced from (Department for Environmental Food and Rural Affairs

328    (Defra), 2013). Due to lack of integrated district heating system in UK, excess heat is assumed

329    to be discarded to the environment.

330    As shown in Fig. 3, the biogenic portion of MSW has a calorific value of 13018 MJ. For a

331    plant capacity of 150000 t MSW/yr with operating hours of 8000, the total energy content is

332    28.4 MW/yr. The total products have energy values of 3.6 MW/yr from main products of ABE

333    (37.3 MJ/kg butanol, 31.8 MJ/kg acetone and 29.7 MJ/kg ethanol) and hydrogen (141.7 MJ/kg)

334    (The Engineering Toolbox, 2019) and 4.5 MW/yr from excess electricity. Therefore, the total

335    energy efficiency of 28% can be obtained through the MSW derived ABE conversion system

336    (see Table 3). In this study, electricity co-product is higher compared to other feedstocks, as a

337    greater share of biomass is not converted to fuels and thus is available for energy recovery.

338    Excess heat is available and, if it could be utilised (e.g., by co-located industrial process and/or

339    district heating, for sterilization, or for cooling generation) then total energy yield could

340    improve to 37% compared to 47% presented for ethanol production from corn stover (Humbird

341    et al., 2011).

342    **3.2    Life Cycle Assessment Results**

343    LCA evaluation based on the mass and energy balance data is performed to quantify the life

344    cycle PED and GWP associated with converting one tonne of MSW feedstock into ABE (see

345    Fig. 4). Excluding the impact of further treating the non-biogenic content of MSW, the ABE

346    production from MSW shows a net PED of -1.11 MJ/MJ liquid biofuels  (-559.69 MJ/t MSW)

347    and net GHG emission of -12.57 g $CO_2$eq/MJ liquid biofuels (-6.32 kg $CO_2$eq/t MSW),

348    including co-products credits of acetone, excess electricity, and hydrogen. MSW to BE can

349    thus achieve better PED as bioethanol produced from agricultural residues (–0.1 – 0.6 MJ/MJ

350    fuel) (Michael et al., 2012), achieving reductions in fossil energy use by 2.3 MJ/MJ fuel

351    compared to conventional gasoline (1.2 MJ/MJ) (Michael et al., 2012). If excess heat could be

352    utilised, additional credits would result in net PED of -2.13 MJ/MJ liquid biofuels and net GWP

353    of -17.56g $CO_2$eq/MJ liquid biofuels (40% further emission reduction).

354    As seen in Fig. 4, the largest energy and GHG emissions source arising from ABE production

355    is the manufacture of enzymes, contributing approximately 2.31 MJ PED/MJ liquid biofuels

356    and 186.7 g $CO_2$eq./MJ liquid biofuels. Other process inputs (pH control; *C. acetobutylicum*

357    bacterium) and fermentation nutrients have substantially smaller impacts, totalling

358    approximately 10% of autoclave/biorefinery GHG emissions. Process energy (electricity and

359    heat) related emissions have been avoided through the energy recovery from the unconverted

360    biomass (primarily lignin solids), biogas generated by the wastewater treatment plant and waste

361    sludge. Transport of ABE to depot and to filling station account for less than 1% of the total

362    emission.

363    It is noted that a low glucose hydrolysis yield of 38% has been considered, based on the

364    experimental evidence from this study. However, a lower sugar hydrolysis and ABE yield

365    results in more residual biomass available for co-product electricity production, thereby

16

366 providing a larger co-product GHG credit when displacing grid electricity. The impacts of these

367 process variables on product yield and environmental impacts are discussed further in Section

368 3.3.

369 **3.3    Sensitivity Analysis**

370 **3.3.1    Sensitivity analysis of background systems**

371    The life cycle GHG emissions per MJ MSW derived liquid biofuels is compared to results

372 of gasoline (the EU fossil fuel comparator, US Environmental Protection Agency (EPA) and

373 US oil shale based on Energy Research Architecture (ERA)), and bioethanol (i.e., ethanol

374 produced from ethanol, sugarcane, corn stover, switchgrass, and miscanthus). Various life

375 cycle GHG emissions are also present for various electricity replacement of electricity mix,

376 electricity from hard coal, natural gas, hydro power, wind power in UK and electricity mix in

377 US and China (see Fig. 5).

378    Overall GHG emission of MSW derived liquid biofuels provides 115%, 114% and 109%

379 reduction compared to the transportation gasoline based on EU RED (84 g $CO_2$eq/MJ) for the

380 base case, US EPA (93 g $CO_2$eq/MJ) and US ERA (139 g $CO_2$eq/MJ) (Pieprzyk et al., 2009),

381 respectively. MSW to bioethanol can give 14.5–56.4 g $CO_2$eq/MJ ethanol (Chester and Martin,

382 2009; Kalogo et al., 2007; Schmitt et al., 2012; Zhang et al., 2010a); therefore MSW to BE can

383 achieve over 100% relative GHG reduction than MSW to bioethanol only. The difference is

384 primarily because of the different system boundaries (e.g., waste collection and hauling,

385 classification, coproducts considerations, and landfill treatment of residual waste) and

386 assumption (e.g., enzyme production and fermentation microorganism) made in the studies.

387 MSW derived liquid biofuels has smaller GHG emissions than other lignocellulosic ethanol

388 pathways (corn stover, switchgrass, miscanthus) and reduction of over 100% relative to corn

389 and sugarcane (Michael et al., 2012).

390    The GHG emissions assigned to enzyme production in the current study are 5.9 g $CO_2$eq/g

391    of produced enzyme (commercially Novozymes Cellic CTec2) (Kløverpris, 2018) while some

392    onsite enzyme production process using glucose as a feedstock have been reported to emit 4.1–

393    11.5 g $CO_2$eq/g cellulose (Hsu et al., 2010; McKechnie et al., 2015). However, the newly

394    produced Cellic 1.0 series (0.64 g $CO_2$eq/g enzyme) have achieved significant reduction in

395    GHG emissions. We also considered different Novozymes Cellic CTec series enzyme

396    products: Cellic CTec in 2009 (7.25 g $CO_2$eq/g), Cellic CTec3 in 2012 and 2014 (5.1 g

397    $CO_2$eq/g), and assumed Cellic X in 2022 (0.32 g $CO_2$eq/g) but their respective dosage is not

398    described here due to commercial confidentiality. Their relative impacts have been shown in

399    Fig. 5 (MSW- liquid biofuels 2), indicating a range of –135 to 22.13 g $CO_2$eq/MJ liquid

400    biofuels. Furthermore, improved potency of enzyme will lead lower dosages of enzyme in

401    hydrolysis in the future, achieving further GHG emission reductions but beyond the scope of

402    this study.

403    Due to the low GHG intensity of 1.7 g $CO_2$eq per MJ electricity produced from wind power,

404    1 MJ MSW derived liquid biofuels emits 201 g $CO_2$eq compared to –248.88 g $CO_2$eq using

405    coal electricity source of which the GHG intensity is 266.3 g $CO_2$eq per MJ electricity (see Fig.

406    5). This is due to different credits of fixed excess electricity can achieve via electricity

407    displacement. GHG intensity of China electricity mix (240.8 g $CO_2$eq/MJ electricity) lead the

408    largest GHG reduction of –205.54 g $CO_2$eq/MJ liquid biofuels compared to –96.74 g $CO_2$eq/MJ

409    liquid biofuels using US electricity mix (176.9 g $CO_2$eq/MJ electricity) and -12.57 g $CO_2$eq/MJ

410    liquid biofuels using UK electricity mix (112.1 g $CO_2$eq/MJ electricity).

411    **3.3.2   Sensitivity analysis of process variables**

412    Across various parameters as listed in Table 4, ABE product yield can be achieved at a range

413    of 10.73–82.14 kg/t MSW(see Fig. 6a) while a certainty of 90% in the range of 18.3–48.8 kg

414    /t MSW. The composition of incoming MSW feedstock varies but the biogenic content

415    including paper, card, food waste, garden waste, wood, and other organic lies in the range of

416    30-85%. The maximum 85% of biogenic content is assumed for residue MSW exiting material

417    recycling facility where non-biogenic content such as plastics, ferrous and non-ferrous metals

418    are removed. By applying Defra average data, lignocellulosic content of MSW is about 82%

419    (paper 21.6%, card 17.3%, food waste 31%, garden waste 5.3%, wood 3.2%, and other organic

420    3.5%) after going through material recycling facility. A hypothetical lower bound of 30% is

421    considered to evaluate the impact of low biogenic content on the product yield. We have

422    conservatively assumed a glucose hydrolysis yield of 38% based on the current experimental

423    evidence, but we also analyse scenarios where the efficiencies of theoretical glucose ranges of

424    30–85% and xylose ranges of 60–90% (Kalogo et al., 2007). Solid concentration rate ranges

425    from 20% to 30%; the base case is 20%. It should be noted that the variability with product

426    yield would have a large impact on associated financial aspects, where the trade-offs need to

427    be addressed in future optimisation. But before considering the optimisation, how process

428    parameters affect the product yield needs to be understood as follows in the next section.

429    The impacts of process parameter variability on the product yield are evaluated as in Fig. 7a.

430    As biogenic fibre content and glucose hydrolysis yield determines the quantity of total inputs

431    of the conversion, it has the largest impact on the product yield. It indicates the importance of

432    selection of higher biogenic content of MSW from collection facilities or materials recycling

433    facilities. Also optimisation of hydrolysis yield is also the key in future research focus as this

434    is the main barrier to maximising product output. Solid concentration in hydrolysis does not

435    have any direct impact on the absolute product yield but affects the final product concentration

436    as discussed below.

437    Under these scenarios, the ABE product concentration lies in the range of 15.1–79.6 g ABE/L

438    (9.4–47.5 g butanol/L) while the base case is 17.8 g ABE/L (11.2 g butanol/L) (see Fig. 6b)

439    compared to 6.2–64.2 g ABE/L (~10 g/L) as reported (Bankar et al., 2013; Grisales Díaz and

440    Olivar Tost, 2017). However, the high concentration of substrate and ABE products can be

441    toxic to microorganisms that the fermentation can be inhibited completely at butanol

442    concentration of approximately 15 g/L (Grisales Díaz and Olivar Tost, 2017). Glucose

443    hydrolysis yield and solid concentration contribute to the largest variance of the results (88%)

444    (see Fig. 7b). Therefore, future optimisation also needs to consider trade-offs amongst

445    increasing product yield and product concentration level and reducing growth inhibition effect,

446    for instance, by continuous removal of solvents (Brito and Martins, 2017).

447    Under the parameters considered as in Table 4, the net GWP ranges from –26.68 to 6.61 g

448    $CO_2$eq/MJ liquid biofuels while the base case is -12.57 g $CO_2$eq/MJ liquid biofuels (see Fig.

449    6c). With 90% certainty the GWP of conversion from MSW to liquid biofuels lies in the range

450    of -16.82–2.60 g $CO_2$eq/MJ liquid biofuels. Compared to the gasoline, MSW derived liquid

451    biofuels can reduce GHG emissions by 92%% to over 100%, which can significantly contribute

452    to GHG emission reductions of transport fuels by a minimum of 6% by 2020 compared to the

453    2010 level as regulated by EU Fuel Quality Directive (European Union Fuel Quality Directive,

454    2009), and meet the sustainability criteria for biofuels by EU Renewable Energy Directive

455    (GHG savings of at least 60% in comparison to fossil fuels in 2018) (European Union

456    Renewable Energy Directive, 2009). Glucose hydrolysis yield and biogenic fibre content has

457    the largest impact on the quantity of total GWP as in Fig. 7c.

458    Unlike the impact on product yield, uncertainty of process parameters shows different

459    impacts on GHG emissions. Although the increase of sugar yield/sugar content can be

460    beneficial to the increase of product yield, it is detrimental to the GWP reduction. High

461    biogenic content with relatively low ABE product yield (e.g., low sugar content/yield) can

462    minimise overall GWP per MJ liquid biofuels. This is primarily because more unconverted

463    biogenic fibre residue goes to energy recovery unit and generates more co-product electricity

464    as discussed in Section 3.2.

465    **4    Conclusions**

466    The study presents the conversion of ABE from municipal solid waste feedstocks via

467    autoclave, enzymatic hydrolysis, and ABE fermentation based on experimental data and

468    process modelling, demonstrating the conversion to be a promising way to valorise organic

469    wastes in the production of liquid biofuels. The mass and energy balance results show the

470    overall conversion process is energy self-sufficient as process energy demand (steam and

471    electricity) is fully covered by the energy recovery from lignin from hydrolysis and

472    fermentation residue and biogas and sludge produced from wastewater treatment while surplus

473    electricity be exported to the grid as co-product benefits. In total, the integrated process can

474    produce 12.2 kg butanol (7.6 kg gasoline equivalent), 1.5 kg ethanol (0.9 kg gasoline

475    equivalent), 5.7 kg acetone, and 0.9 kg hydrogen as well as 0.3 kg acetic acid and 1.0 kg butyric

476    acid from each tonne raw MSW. It should be noted that hydrolysis yield can be potentially

477    improved up to 85% for glucose conversion as discussed which would increase ABE solvent

478    output to about 39 kg.

479    MSW-derived liquid biofuels can contribute to reduce GHG emissions by over 100% %

480    compared to gasoline base on EU RED standard and conventional bioethanol. Monte Carlo

481    simulations indicate the ABE product yield with a certainty of 90% in the range of 18.3-48.8

482    kg /t MSW. Correspondingly, the net GWP ranges from -16.82 to 2.60 g $CO_2$eq/MJ liquid

483    biofuels with a 90% certainty while the base case is -12.57 g $CO_2$eq/MJ liquid biofuels.

484     Sensitivity analysis results indicate high biogenic content with relatively low ABE product

485     yield (e.g., low sugar content/yield) can minimise overall GWP per MJ liquid biofuels.

486       However, key technology challenges still need to be addressed in improving hydrolysis yield

487     which has already showed the potential to be up to 90% as this is the main barrier to maximising

488     product output for future commercialisation. Ongoing investigation is studying the non-

489     biogenic content of MSW recycling such as metal and plastic recycling benefits in order to

490     comprehensively quantify the waste management of MSW. Future work also goes for waste

491     supply chain investigation and facility design optimisation (e.g., capacity; colocation).

492

493    **Nomenclature**

| | |
|---|---|
| GHG | Greenhouse gas |
| MSW | Municipal solid waste |
| LCA | Life cycle assessment |
| ABE | Acetone, butanol, ethanol |
| PED | Primary energy demand |
| GWP | Global warming potential |
| RED | Renewable Energy Directive |
| US EPA | US Environmental Protection Agency |
| US ERA | US Energy Research Architecture |

494

495    **Notes**

496     The authors declare no competing financial interest.

Word count: 5973

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**Figure Captions**

627    Fig. 1 Overall diagram for MSW to ABE conversion (dashed line means outside the system

628    boundary)

629    Fig. 2 Sugar composition in MSW fibre by total acid hydrolysis as measured by ion

630    chromatography (weights determined in the monomer form, against total dry weight of

631    sample). Residual is difference from 100, which accounts for all other organic and non-organic

632    material present in the biofiber, which is not suitable for fermentation.

633    Fig. 3 Diagram showing the inputs into and outputs from the process of ABE production

634    from MSW. Dashed line shows the excluded flow in this analysis

635    Fig. 4 a) Primary energy demand and b) Global warming potential of MSW derived liquid

636    biofuels

637    Fig. 5 Comparison of life cycle global warming potential per MJ fuels amongst gasoline,

638    MSW derived liquid biofuels, and bioethanol.

639    Fig. 6 Monte Carlo analysis of the values of a) ABE product yield; b) ABE product

640    concentration; c) life cycle GWP of MSW derived liquid biofuels; at various process

641    parameters. Dashed lines show the base case.

642    Fig. 7 Relative contribution of processing parameters on the sensitivity of a) ABE product

643    yield; b) ABE product concentration; c) life cycle GWP of MSW derived liquid biofuels.

644    Table 1 Process data of MSW to ABE conversion.

645    Table 2 Parameters of ABE fermentation of MSW hydrolysates.

646    Table 3 Overall mass and energy balance of ABE production from MSW.

647    Table 4 Parameters for Monte Carlo simulation.

Word count: 5973

## 648 Tables and Figures

### 649 Table 1

650 Process data of MSW to ABE conversion.

| | Input | | | Quantity of product | | |
|---|---|---|---|---|---|---|
| Feedstock | MSW | 1 | t MSW | | | |
| | Moisture content of MSW | 40% | | | | |
| | | | | | | |
| Autoclave | Fibre yield ex autoclave+ sieve | 53% | | Autoclaved fibre_dry | 318 | kg |
| | Energy consumption | | | | | |
| | Electricity | 43 | MJ/t MSW | | | |
| | Heat | 274 | MJ/t MSW | | | |
| | Process water | 245 | kg/t MSW | | | |
| Hydrolysis | Glucose content | 45% | | Sugar | 65.51 | kg |
| | Xylose content | 5% | | | | |
| | Glucose hydrolysis yield | 38% | | | | |
| | Xylose hydrolysis yield | 70% | | | | |
| | Solid content in hydrolysis slurry | 20% | | | | |
| | Energy consumption | | | | | |
| | Electricity | 0.41 | MJ/t MSW | | | |
| | Heat | 214.63 | MJ/t MSW | | | |
| | | | | | | |
| | Enzyme loading, w enzyme/w sugar | 15.90 | kg/t MSW | | | |
| | volume 6M H2SO4 (for pH control) | 8.59 | kg/t MSW | | | |
| | | | | | | |
| | Weight of water added for slurry | 1035.51 | kg | | | |
| | Clean water usage | 5366.25 | kg | | | |
| Fermentation | Sugar use efficiency | 90% | | | | |
| | ABE yield | 33% | | | | |
| | Energy consumption | | | | | |
| | Electricity | 0.68 | MJ/t MSW | | | |
| | *Clostridium acetobutylicum* | 0.16 | kg | | | |
| | Monopotassium phosphate | 1.09 | kg | | | |
| | Dipotassium phosphate | 0.83 | kg | | | |
| | Ammonium acetate | 3.17 | kg | | | |
| | Yeast extract (Duchefa) | 2.73 | kg | | | |
| | FeSO4.7H2O | 0.01 | kg | | | |
| | MgSO4.7H2O | 1.09 | kg | | | |
| | Process water | 4509.87 | kg | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Distillation | Energy consumption | | | Acetone | 5.716 | kg |
| | Electricity | 3.31 | MJ/t MSW | Butanol | 12.24 | kg |
| | Heat | 125.30 | MJ/t MSW | Ethanol | 1.52 | kg |
| | | | | Acetic acid | 0.28 | kg |
| | | | | Butyric acid | 1.02 | kg |
| Gas stripping | Energy consumption | | | $H_2$ | 0.93 | kg |
| | Electricity | 0.56 | MJ/t MSW | $CO_2$ | 30.66 | kg |
| | Heat | 46.15 | MJ/t MSW | | | |
| | | | | | | |
| | Process water | 10.75 | kg | | | |
| Wastewater Treatment | Energy consumption | | | Clean water recovered | 10871.18 | kg |
| | Electricity | 56.55 | MJ/t MSW | Net water required | -296.20 | kg |
| | Heat | 0.02 | MJ/t MSW | | | |
| Energy recovery | Electricity | 959.03 | MJ/t MSW | | | |
| | Heat | 1107.76 | MJ/t MSW | | | |
| | | | | | | |
| | Excess Electricity | 854.51 | MJ/t MSW | | | |
| | Excess Heat | 447.66 | MJ/t MSW | | | |
| Transport of ABE to depot | Transport per | | | | | |
| | Truck for liquids (diesel) | 150 | km | 2.92 | ton·km / t MSW | |
| | Fuel | Diesel | | | | |
| | Energy consumption depot | | | | | |
| | Electricity UK mix | 0.00084 | MJ/MJ liquid biofuels | | | |
| Transport to filling station | Transport per | | | | | |
| | Truck for liquids (diesel) | 150 | km | 2.92 | ton·km / t MSW | |
| | Fuel | Diesel | | | | |
| | | | | | | |
| | Energy consumption depot | | | | | |
| | Electricity UK mix | 0.0034 | MJ/MJ liquid biofuels | | | |

651

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652    **Table 2**

653    Parameters of ABE fermentation of MSW hydrolysates.

| Type | Formula | Molar ratio | Weight percentage |
|---|---|---|---|
| Glucose | $C_6H_{12}O_6$ | 1 | - |
| Acetic acid | $CH_3COOH$ | 0.014 | 0.5% |
| Butyric acid | $C_4H_8O_2$ | 0.035 | 1.7% |
| Acetone | $C_3H_6O$ | 0.3 | 9.8% |
| Butanol | $C_4H_9OH$ | 0.5 | 20.8% |
| Ethanol | $C_2H_5OH$ | 0.1 | 2.6% |
| Carbon dioxide | $CO_2$ | 2.1 | 52.0% |
| Hydrogen | $H_2$ | 1.4 | 1.6% |
| Microbial cells | $CH_{1.8}O_{0.5}N_{0.2}$ | - | 11% |

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656   **Table 3**
657   Overall mass and energy balance of ABE production from MSW.

| Inputs | Tonne/year | MW |
|---|---|---|
| MSW  (40% moisture)* | 150000 | 28.4/yr |
| **Total input** | | 28.4/yr |
| **Outputs** | | |
| Acetone | 947 | 0.9/yr |
| Butanol | 2028 | 0.2/yr |
| Ethanol | 252 | 2.4/yr |
| Hydrogen | 139 | 0.001/yr |
| Heat generation | | 5.8/yr |
| Electricity generation | | 5.0/yr |
| **Total output** | | 14.4/yr |
| Process heat demand | | 3.2/yr |
| Process electricity demand | | 0.5/yr |
| **Net heat surplus** | | 2.4/yr |
| **Net electricity surplus** | | 4.5/yr |
| **Energy efficiency (main product + net electricity surplus)** | | 28% |
| **Energy efficiency(main product + net electricity surplus)- ethanol from corn stover  (Humbird et al., 2011)** | | 47% |

658   * (Excluding non-biogenic content)

659

660 **Table 4**

661 Parameters for Monte Carlo simulation.

| Parameter | Distribution |
|---|---|
| Biogenic fibre content | Triangular (Min: 30%, Max: 85%, Mode: 53%) |
| Glucose content | Triangular (Min: 40%, Max: 65%, Mode: 45%) |
| Xylose content | Triangular (Min: 5%, Max: 15%, Mode: 5%) |
| Glucose hydrolysis yield | Triangular (Min: 30%, Max: 85%, Mode: 38%) |
| Xylose hydrolysis yield | Triangular (Min: 60%, Max: 90%, Mode: 70%) |
| Solid concentration in hydrolysis | Triangular (Min: 20%, Max: 30%, Mode: 20%) |

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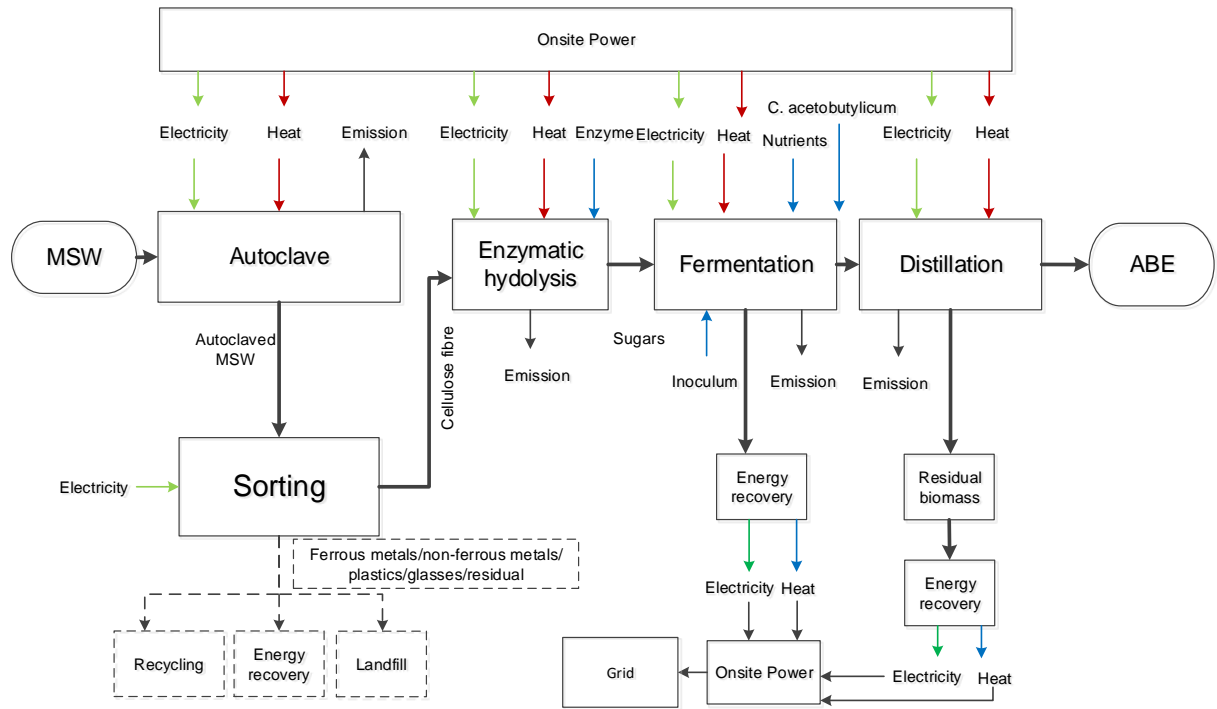


664

665    Fig. 1 Overall diagram for MSW to ABE conversion (dashed line means outside the system

666    boundary)

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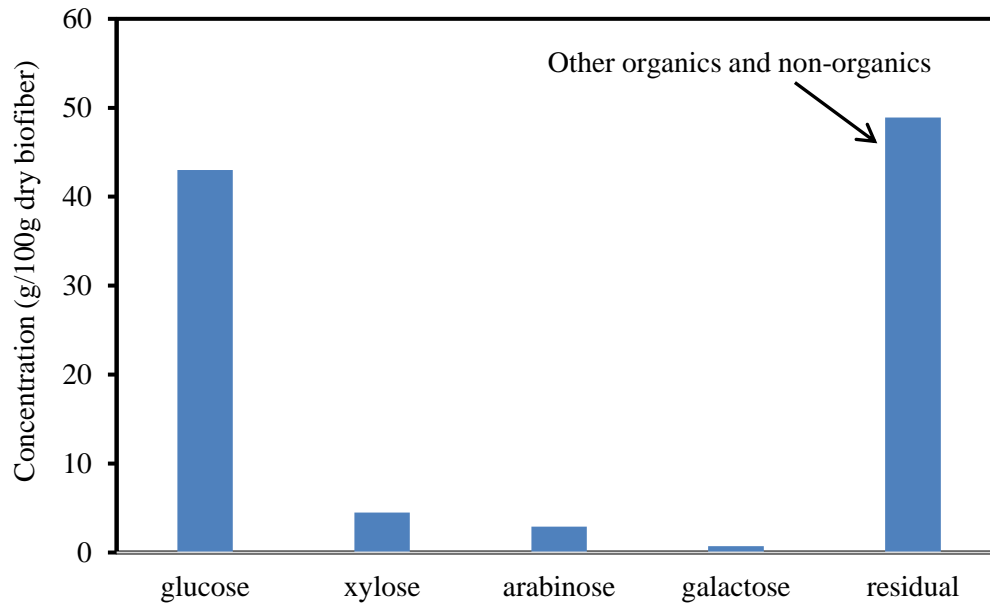


670

671   Fig. 2 Sugar composition in MSW fibre by total acid hydrolysis as measured by ion
672   chromatography (weights determined in the monomer form, against total dry weight of
673   sample). Residual is difference from 100, which accounts for all other organic and non-organic
674   material present in the biofiber, which is not suitable for fermentation.
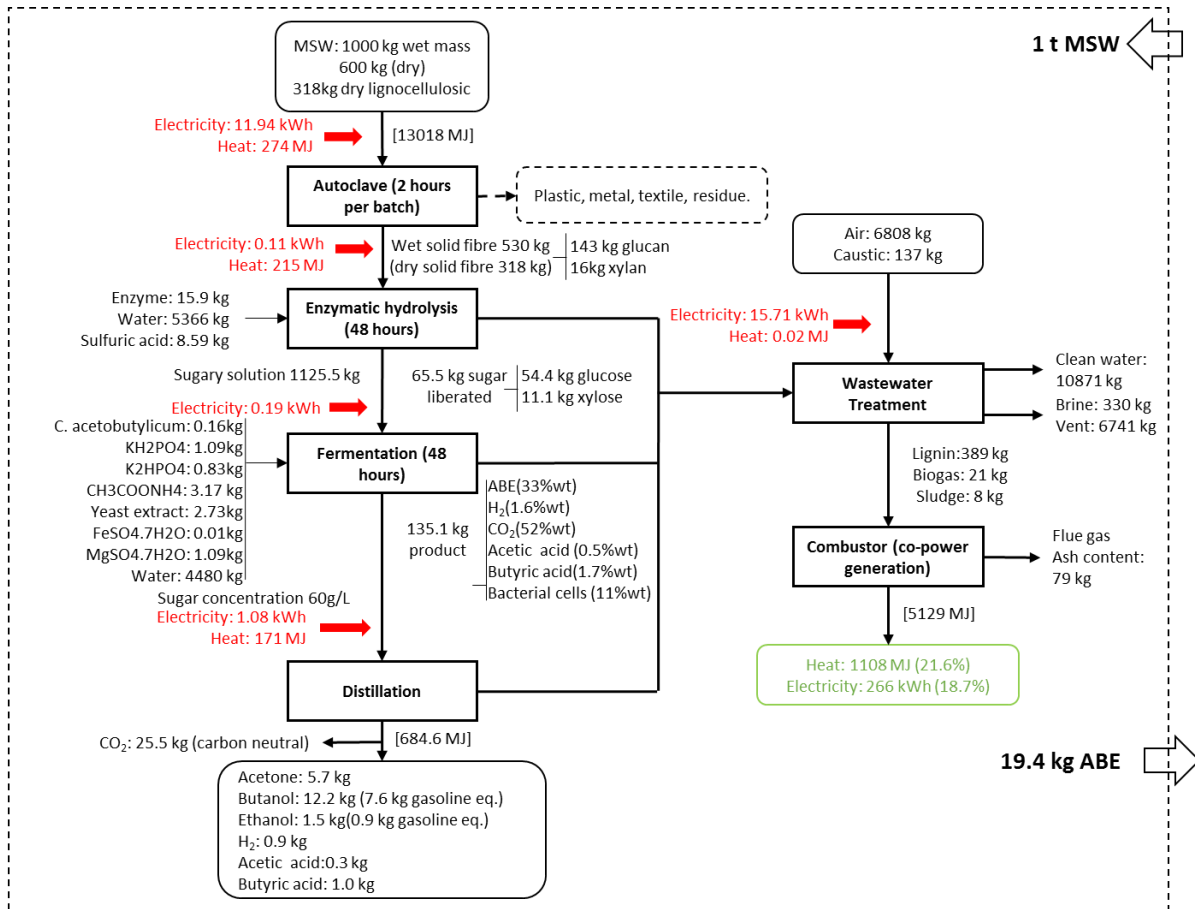
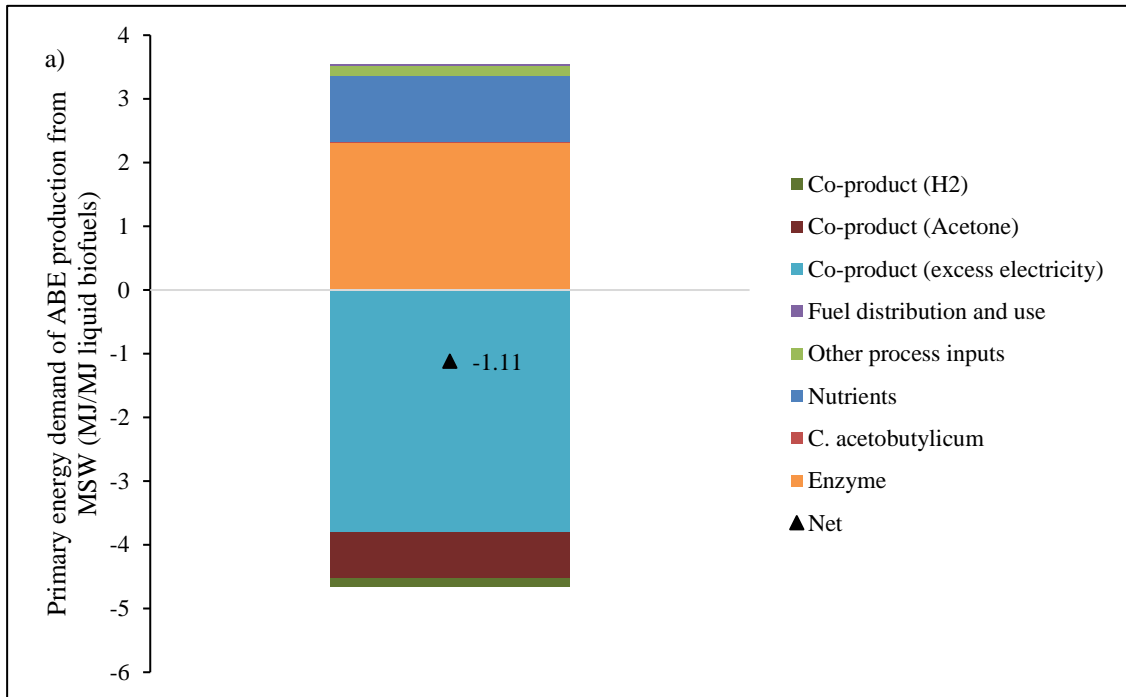Fig. 3 Diagram showing the inputs into and outputs from the process of ABE production from MSW. Dashed line shows the excluded flow in this analysis.

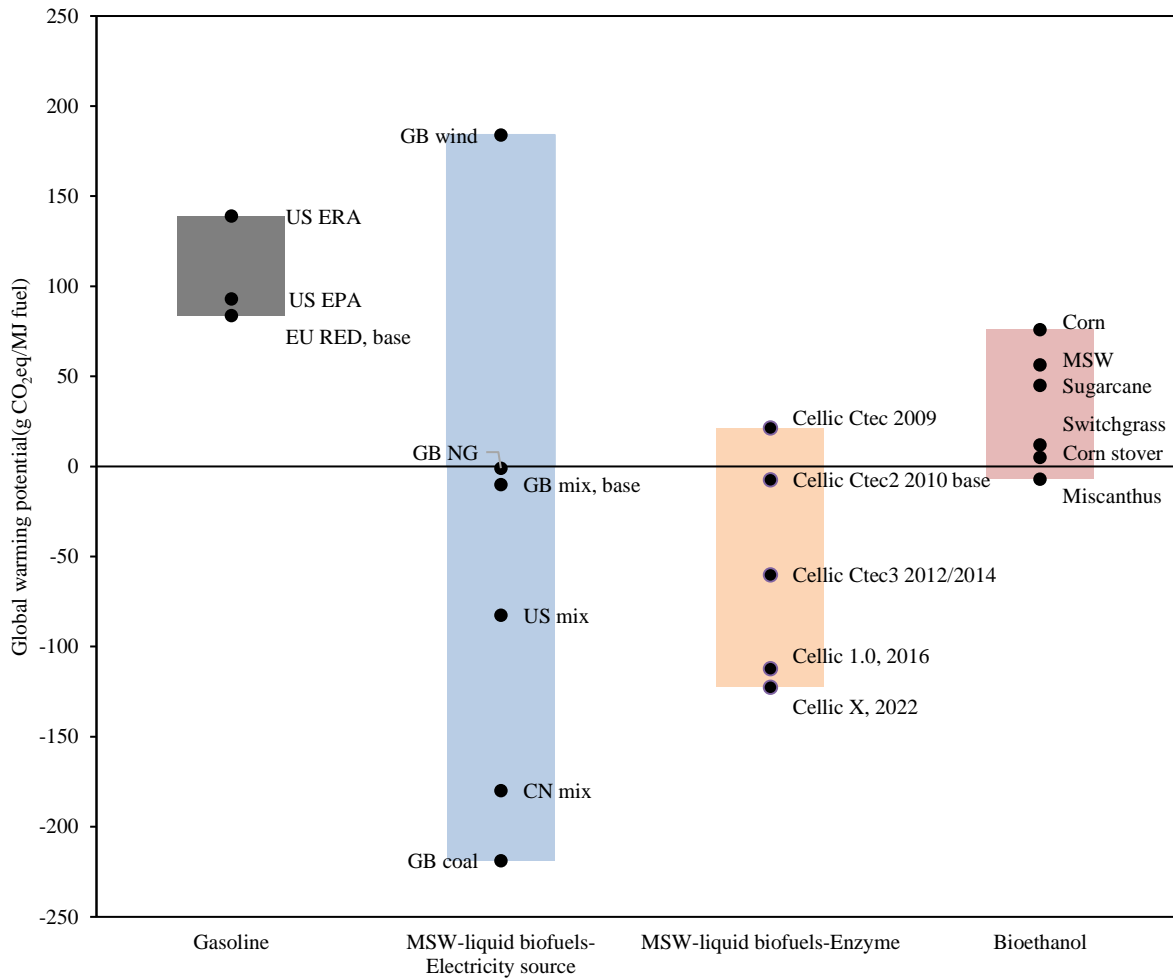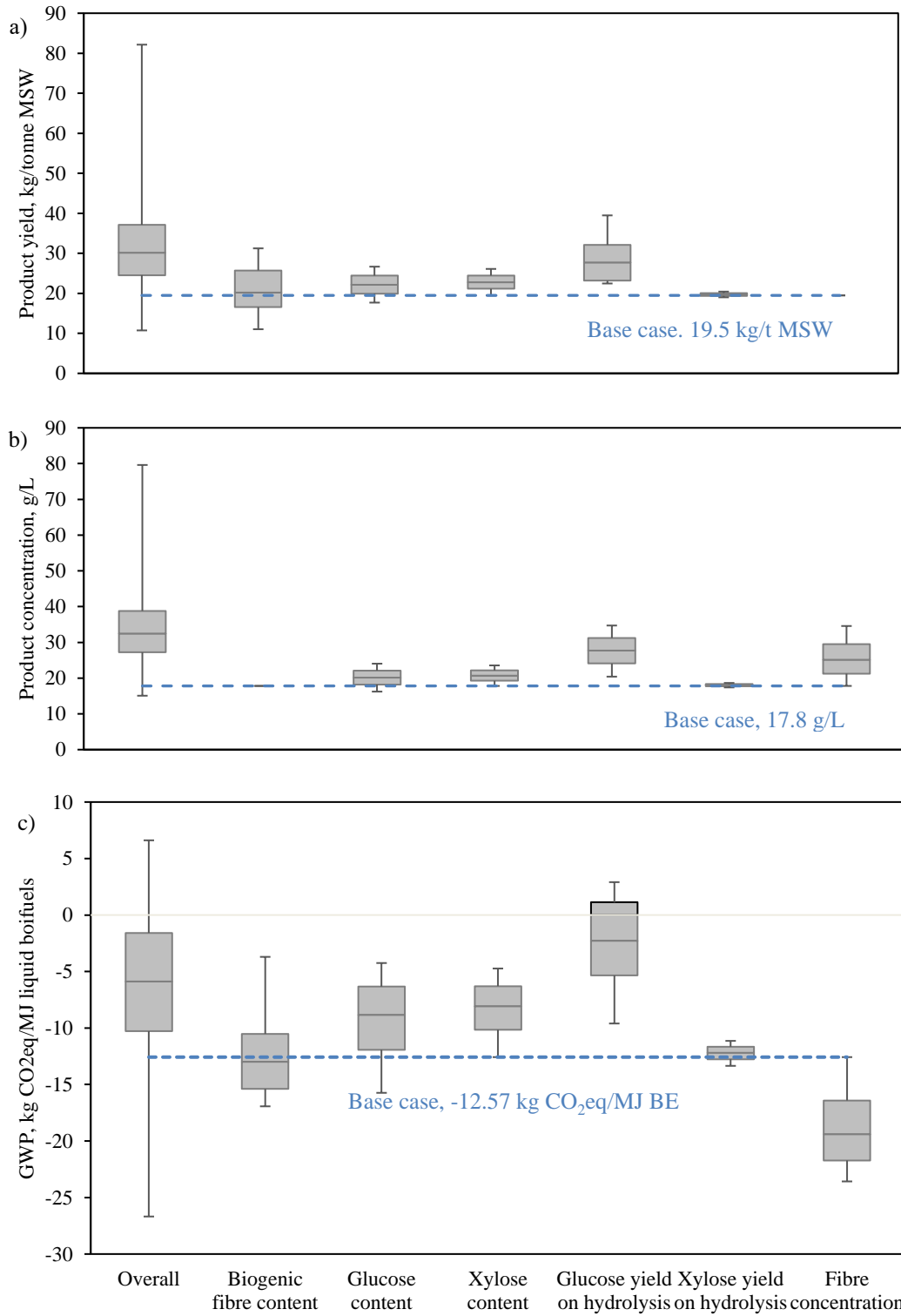Fig. 4 a) Primary energy demand and b) Global warming potential of MSW derived liquid
biofuels.

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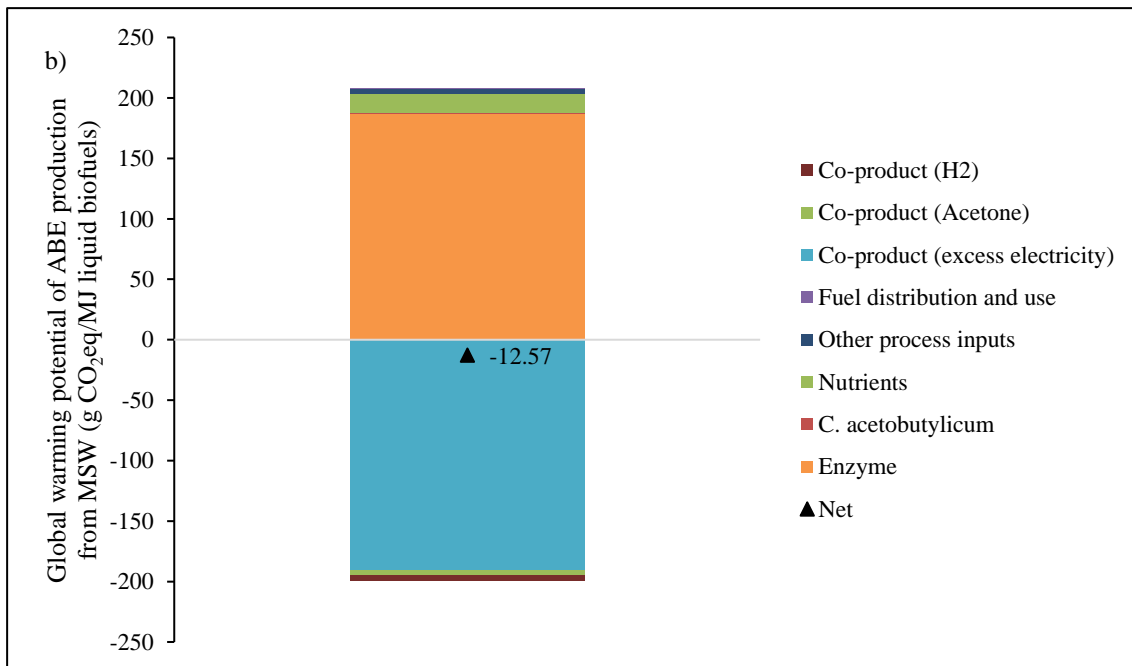
Fig. 5 Comparison of life cycle global warming potential per MJ fuels amongst gasoline, MSW derived liquid biofuels, and bioethanol[1].
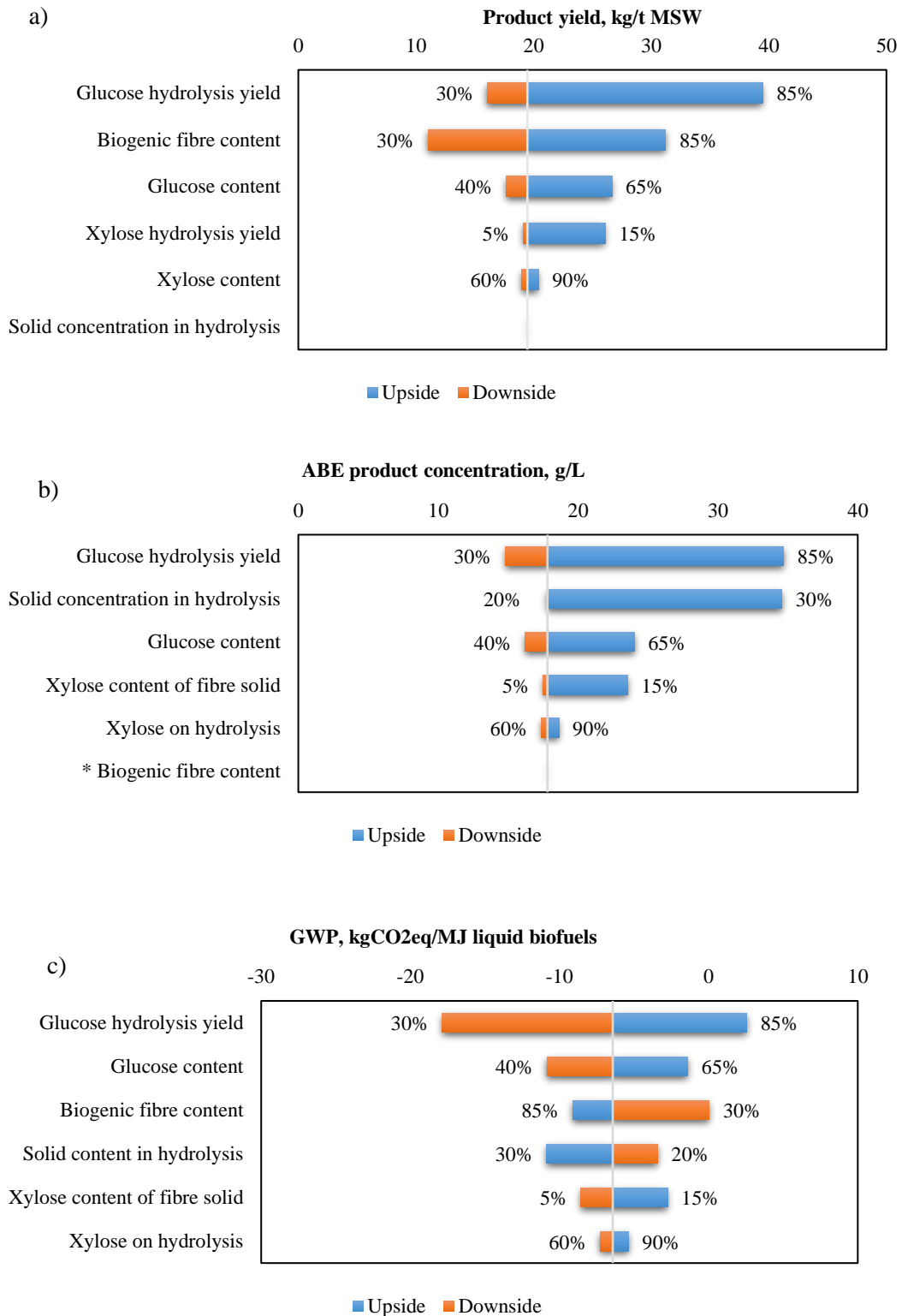
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[1] Notes: MSW-BE Electricity source (sensitive coproduct credits from electricity replacement of electricity mix, electricity from hard coal, natural gas (NG), wind power in UK and electricity mix in US and China); MSW-BE Enzyme (various series of enzyme production); gasoline (the EU fossil fuel comparator, US EPA and US oil shale based on ERA); bioethanol (cellulosic ethanol produced from ethanol, sugarcane, corn stover, switchgrass, and miscanthus)

a) Product yield, kg/tonne MSW. Base case. 19.5 kg/t MSW

b) Product concentration, g/L. Base case, 17.8 g/L

c) GWP, kg CO2eq/MJ liquid boifuels. Base case, -12.57 kg $CO_2$eq/MJ BE

Overall | Biogenic fibre content | Glucose content | Xylose content | Glucose yield on hydrolysis | Xylose yield on hydrolysis | Fibre concentration

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688     Fig. 6 Monte Carlo analysis[2] of the values of a) ABE product yield; b) ABE product

689     concentration; c) life cycle GWP of MSW derived liquid biofuels; at various process

690     parameters. Dashed lines show the base case.

691

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[2] Note: For the box plot, the ranges are calculated as follows: The box, from bottom to top, indicates the 25th (Q1), 50th and 75th (Q3) percentile values from the data plotted. The interquartile range (IQT) is Q3 – Q1. The whisker below is defined as minimum and the whisker above is defined as maximum.

Fig. 7 Relative contribution of processing parameters on the sensitivity of a) ABE product yield; b) ABE product concentration; c) life cycle GWP of MSW derived liquid biofuels.