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20 **A new process concept for highly efficient conversion of sewage sludge by**
21 **combined fermentation and gasification and power generation in a hybrid**
22 **system consisting of a SOFC and a gas turbine**

23

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30

31 **Abstract**

32

33 **Sewage sludge** can be disposed of by fermentation, incineration or **gasification**.
34 Conversion of the resulting **biogas**, combustion heat or **gasification** gas into
35 electricity is often employed. Since **sewage sludge** cannot be fermented completely
36 and due to the significant heat requirements for drying it in the incineration plant or
37 before the gasifier, the electrical output in all cases is very low. Consequently, this
38 work seeks to investigate a combination of fermentation and **gasification** in which
39 dried fermentation waste is converted in a gasifier. With the aim of combining these
40 two **biomass** conversion processes with power generation in an efficient manner, a
41 hybrid system consisting of a **SOFC** and a **gas turbine** is investigated. This

42 combination of a **biogas** plant and a gasifier has the advantage that waste heat can
43 be used as a heat source in drying the fermentation waste. Another advantage is the
44 combined conversion of **biogas** and **gasification** gas in the **SOFC**. As steam from
45 **gasification** gas is used for internal reforming of methane out of **biogas** at the anode
46 of the **SOFC**, the complexity of the plant is reduced and the efficiency is increased. A
47 configuration including a pressurized **gasification** process was identified as most
48 efficient in terms of electrical output.

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50 **Keywords**

51 Biomass, sewage sludge, biogas, gasification, SOFC, gas turbine

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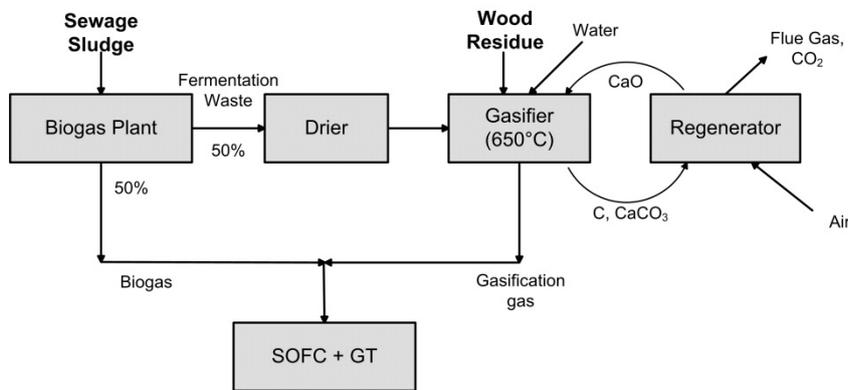
54 **1. Introduction**

55

56 The disposal of sewage sludge is difficult due to the pollutants it contains. As there
57 are high quality requirements for its deployment as fertilizer in agriculture, its use has
58 stagnated at 30 % in Germany in the years 2006 to 2010. Most sewage sludge
59 (50 %) is disposed of by incineration [1] (after a fermentation step). The first step in
60 sewage sludge conversion is always fermentation. Mechanical dewatering of
61 fermented sewage sludge reduces the water content to approximately 70 %. The
62 biogas formed during fermentation is flared or converted in a combined heat and
63 power plant, whereafter the fermented and mechanically dewatered sewage sludge
64 can be disposed of in a waste incineration plant [2]. Only little or no heat is supplied

65 by the combustion process and additional fossil fuel is required due to the high heat
 66 demand of evaporating the humidity in the sludge. Another option is to co-fire the
 67 fermented and dewatered sewage sludge in a coal-fired power plant [3, 4]. An
 68 advantage of this concept is that the sludge can be dried by the waste heat of the
 69 power plant and thus the dried sludge can replace part of the coal. A disadvantage is
 70 the energy expenditure for the transportation of un-dried sludge.

71



72

73 **Figure 1: Innovative process concept of combined fermentation and**
 74 **gasification of sewage sludge and wood**

75

76 This work proposes an innovative concept of combined fermentation and gasification
 77 of sewage sludge and wood as seen in Figure 1 [5]. With a two-stage, high-
 78 performance digestion [6-8], an energy conversion of 50 % of the sewage sludge into
 79 biogas is attainable. Fermentation waste (fermented sewage sludge) is dried and
 80 subsequently converted in a gasifier into a gas with high hydrogen content [9, 10].
 81 Since gasifiers are built for higher energy flows, wood residue has to be added to the
 82 sewage sludge in the gasifier. Both the biogas from the fermentation and the
 83 gasification gas are converted in a SOFC (solid oxide fuel cell), which has a high
 84 electrical efficiency potential [11, 12]. Fermentation and gasification are combined, as

85 waste heat from the gasification process can be used to dry the fermentation waste.
86 The absorption-enhanced reforming (AER-) process is based on a fluidized bed
87 gasification where CO_2 is absorbed at the bed material CaO [13-18]. Thus, high H_2
88 concentrations of about 75 vol% (based on dry gas) and small CO_2 and CO
89 concentrations are achieved. The reforming process consists of two reactors. In one
90 reactor, the endothermic gasification of biomass (dried sewage sludge and wood)
91 with steam takes place, while in the other reactor, the bed material is heated by
92 burning the coke, which is not converted in the gasification reactor. Thus the loaded
93 bed material CaCO_3 is regenerated to CaO and the formed CO_2 leaves the reactor
94 with the flue gas. Converting the gases in a SOFC, an electrical efficiency of
95 approximately 45 % (from gas to electrical energy) can be achieved at a fuel
96 utilization rate of 80 %. A hybrid system consisting of a SOFC and a gas turbine
97 raises the electrical efficiency to approximately 70 % [19-26]. An important difference
98 in comparison with conventional fuel natural gas is that there is less of a cooling
99 effect from the internal reforming of methane at the SOFC anode, and therefore more
100 air is required for cooling the SOFC.

101

102 Several experimental investigations combining two of the above mentioned
103 components can be found in literature: gasification of fermentation waste [27], power
104 generation in SOFC from biogas [28] and gasification gas [29, 30] as well as power
105 generation in a hybrid system of SOFC and gas turbine with natural gas [31].

106

107 Gas quality is important to prevent degradation of the electrodes of the SOFC. For
108 biogas, desulfurization with a charcoal filter is sufficient. Gas treatment of gasification

109 gas is more complex. Particles, chlorine, sulfur and undesired higher hydrocarbons,
110 so called tars [32], must be removed. State of the art is cold gas cleaning in filters
111 and scrubbers. Thus, the steam in the gas is also condensed. Hot gas cleaning,
112 however, has the potential to improve energetic efficiency by using the energy
113 content of the tars and preventing the loss of sensible energy in the scrubber. It also
114 has the potential to reduce the complexity of the system by eliminating heat
115 exchangers and other components. Although hot gas cleaning is not state of the art,
116 there are several research activities in this field. The Fraunhofer UMSICHT report
117 [33] gives an overview of gas cleaning processes for both biogas and gasification gas
118 in general. Aravind [34] summarizes several possibilities for hot gas cleaning of
119 gasification gas for fueling a SOFC. The present work implements hot gas cleaning.

120

121 The aim of the present work is a concept that maximizes the utilization of the energy
122 content of sewage sludge. Therefore, three main concepts are presented with
123 combined fermentation and gasification and conversion of the product gases, either
124 in a SOFC or in a hybrid system consisting of a SOFC and a gas turbine. The
125 advantages of heat and stream integration are shown by comparing electrical
126 efficiencies. For the most efficient concepts with power generation in SOFC and gas
127 turbine, different options for compressing the gasification gas for the gas turbine are
128 discussed.

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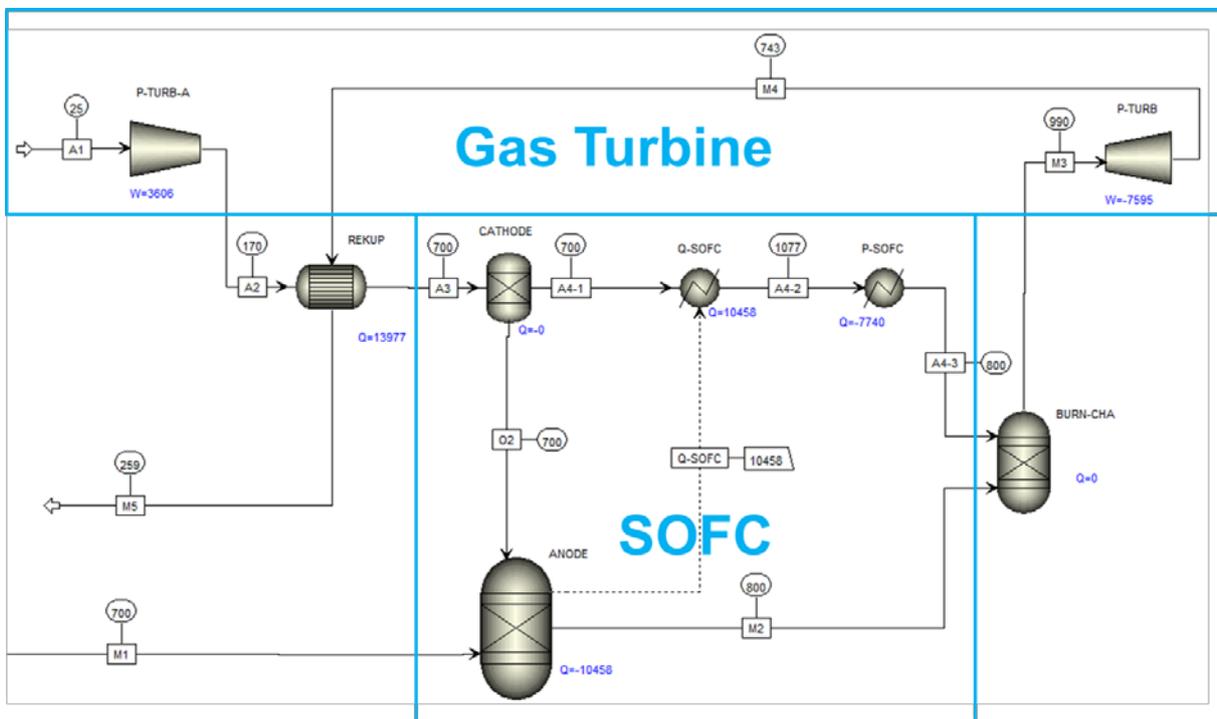
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133 **2. Modelling Aspects and Assumptions**

134

135 Aspen Plus is the software used for process simulation, which includes gas treatment
136 and conversion to electricity. Fermenter and gasifier are treated as black boxes with
137 conversion rates, efficiencies and product gas concentrations taken from literature
138 and project partners [15, 35-37].

139



140

141 **Figure 2: Flowsheet in Aspen Plus for power generation using SOFC and gas**
142 **turbine**

143

144 The power generation part of the Aspen Plus model is shown in Figure 2. Preheated
145 air at 700 °C (compare stream A3 in Fig. 2) is fed into the cathode. The required
146 amount of oxygen for the electrochemical reaction in the fuel cell (stream O2) is

147 separated and fed together with the cleaned product gases from fermentation and
148 gasification (compare stream M1) into the anode which is modeled as Gibbs reactor.
149 First all the released heat at the anode-reactor (stream Q-SOFC) is used to heat up
150 the air (stream A4-1). In a second step the generated electrical power in the SOFC is
151 extracted from stream A4-2 in block P-SOFC reaching the actual temperature of the
152 cathode off-gas of 800 °C (stream A4-3). The electrical power is calculated as
153 followed:

$$P_{el,SOFC} = U_f \cdot V \cdot \dot{n}_{M1} \cdot (y_{H_2} \cdot y_{CO} \cdot 4 y_{CH_4}) \cdot 2F$$

154 U_f is the fuel utilization in the SOFC, V the voltage, \dot{n}_{M1} the mole flow at the inlet of
155 the SOFC-anode, y_i the appropriate mole fractions and F the faraday constant. In
156 order to calculate the cell voltage, a one-dimensional simulation tool in Excel is used
157 with respect to local gas concentrations, electrical resistance and temperature along
158 one cell of the SOFC in co-flow configuration. As input from Aspen Plus, the gas
159 concentration, pressure and temperature at the inlet of the anode (stream M1) are
160 required. The tool provides a look-up table for cell voltages, which are dependent on
161 operating pressure, temperature, gas concentration and fuel utilization. The SOFC is
162 standardized to 0.7 V for a typical non-pressurized, reformed gasification gas, which
163 enters the anode of the SOFC at 700 °C and exits at 800 °C. All simulations are
164 based on the same stack size. The anode and cathode off-gas are mixed, burned
165 and used for power generation in the gas turbine.

166

167 The simulations in Aspen are based on the following assumptions:

168 - Peng-Robinson is used as equation of state.

- 169 - The tar reformer and burning chamber of the gas turbine are modeled as
170 Gibbs reactors for which chemical equilibrium is assumed.
- 171 - The gas turbine and the compressors are modeled as isentropic (isentropic
172 efficiency of gas turbine: 85 % and compressor: 78 %).
- 173 - All component-related heat losses are not taken into consideration.
- 174 - The entry and exit air temperatures for the SOFC are 700 °C and 800 °C,
175 respectively.
- 176 - 50% of the energy content of sewage sludge is converted to biogas with gas
177 composition of 60 vol% CH₄ and 40 vol% CO₂ [37].
- 178 - Gasification gas composition (dry): 73 vol% H₂; 11.5 vol% CH₄; 7.5 vol% CO;
179 6 vol% CO₂; 2 vol% C₂H₆ [15] (875 ppmv C₁₀H₈); 33.3 vol% H₂O.
- 180 - Fermentation waste is dried from 70 % to 25 % water content at 850 kWh per
181 ton water.

182

183 It is further assumed that the heat demand for pre-heating the air for the gasification
184 process regenerator and for the steam generation for the gasifier is covered by the
185 waste heat of the regenerator flue gas [35]. Cold gas efficiency of the gasification
186 process is assumed to be 70 % [36]. Gas cleaning of the gasification gas concerning
187 particles, chlorine and sulfur is assumed to take place at a temperature of 650 °C
188 [34]. Energy losses are not taken into consideration. Tars are reformed at 900 °C
189 [38]. Sensible energy of the reforming product gases is partly used for heating the
190 gas before reforming.

191

192

193 **3. Combined Fermentation and Gasification Process**

194

195 Three main process configurations are investigated to illustrate the potential of
196 combined fermentation and gasification of sewage sludge and the conversion of
197 biogas and gasification gas into electricity. In the first configuration, the conversion of
198 gas takes place exclusively in the SOFC, whereas the second and third
199 configurations rely on a hybrid system consisting of a SOFC and a gas turbine. The
200 third configuration differentiates itself by introducing the use of a pressurized gasifier.
201 In order to illustrate the advantages of the combined processes, configurations with
202 separated processes are also introduced at the end of the chapter.

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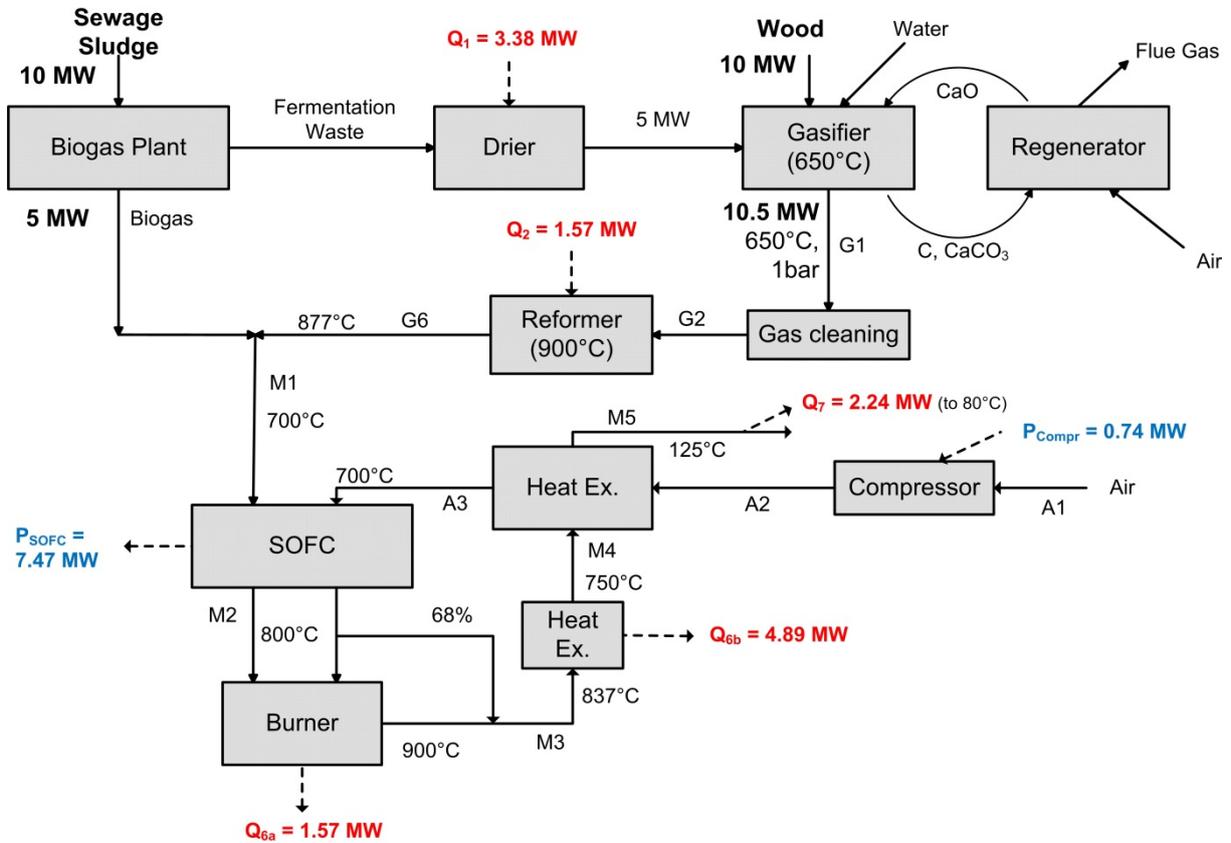
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3.1. Process Configuration with Gas Conversion in the SOFC only

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216

217 **Figure 3: Combination of fermentation and gasification – conversion of biogas**
 218 **and gasification gas in SOFC (Configuration 1) [5]**

219

220 Figure 3 contains Configuration 1, in which biogas and gasification gas are converted
 221 in a SOFC. Sewage sludge with an energy flow of 10 MW is fermented. This energy
 222 flow, which is based on the lower heating value, corresponds to the capacity of a
 223 sewage treatment plant for a city of about 500,000 inhabitants. The fermentation
 224 waste, with a water content of more than 90 %, still contains 50 % of primary energy
 225 input. After mechanical dewatering to 70 % humidity, the fermentation waste is dried
 226 thermally to 25 % humidity. Therefore, a heat flow rate of 3.38 MW is needed (stream

227 Q_1). The 5 MW fermentation waste (fermentation waste with an energy flow rate of
228 5 MW based on the lower heating value) is combined with a 10 MW wood feed and
229 converted in the fluidized bed of the gasifier. Absorption-enhanced reforming
230 provides a gas at 650 °C with 73 vol% H_2 in the dry gas (stream G1). After being
231 cleaned of particles, chlorine and sulfur, the product gas reaches the tar reformer at a
232 temperature of 650 °C (stream G2). In order to maintain the high quality of the gas
233 with high concentrations of H_2 , low concentrations of CO_2 and no N_2 , an allothermal
234 reforming process is considered. Since tars are present, a reforming temperature of
235 900°C is required [38], which is also sufficient to reform any other hydrocarbons
236 present (methane, ethane, etc.) as well. As the reforming reaction is endothermic,
237 heat at a high temperature level is required (stream Q_2). Subsequently, the reformed
238 gasification gas is mixed with biogas and the resulting mixture (stream M1) is
239 converted at the anode of the SOFC at a temperature of 700 °C. Methane from the
240 biogas is reformed directly at the anode with steam from the gasification gas and the
241 products CO and H_2 are converted into electricity. A fuel utilization rate of 80 % in the
242 SOFC is assumed which leads to a cell voltage of 0.68 V. Air (stream A3) is required
243 at the cathode of the SOFC in order to provide the oxygen for the electrochemical
244 reaction and to cool the stack. Because of these cooling requirements, an excess of
245 air is supplied to the SOFC ($\lambda = 9.5$).

246

247 The SOFC off-gases (stream M2 and parts of the cathode off-gas) are burned in a
248 combustion chamber. Thus energy at a high temperature level is available, which is
249 used for the energy demand of the tar reformer (Q_2) and for pre-heating air for the
250 SOFC. An additional heat flow rate of 4.89 MW at more than 750 °C (stream Q_{6b}) is
251 also available and has a high potential, but remains largely unleveraged in this

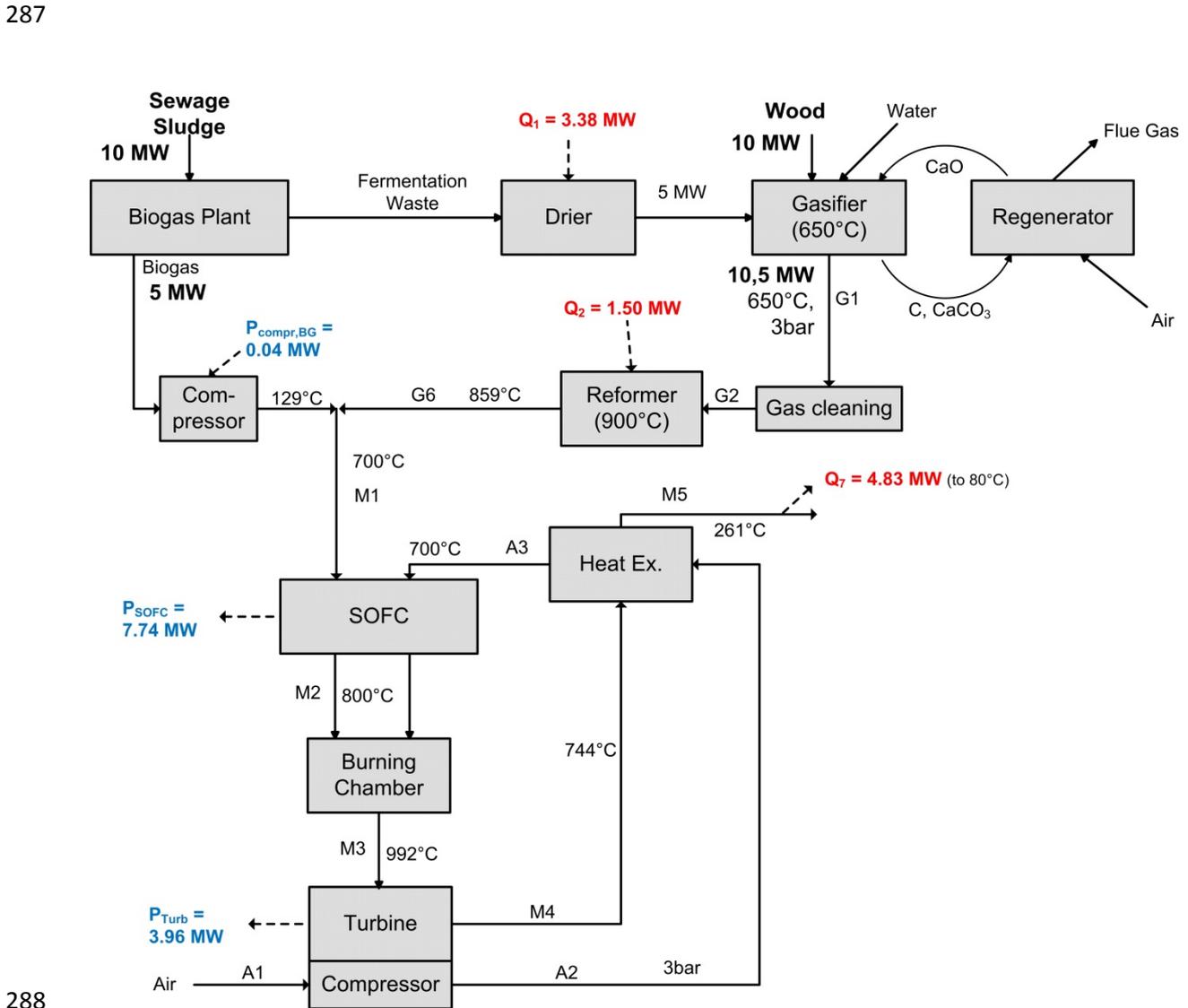
261 **Figure 4: Combination of fermentation and gasification – compression of**
262 **biogas and gasification gas to 3 bar absolute pressure and combined**
263 **conversion in a hybrid system of a SOFC and a gas turbine (Configuration 2)**
264 **[5]**

265

266 In Configuration 2 the gases are converted to electricity in a hybrid system consisting
267 of a SOFC and a gas turbine (Fig. 4). In order to increase the efficiency of the
268 combined plant, the off-gas of the SOFC is expanded in a gas turbine. This requires
269 a pressurized operation of the SOFC at 3 bar absolute pressure, which also
270 increases the efficiency of the SOFC itself [21]. Fuel utilization in the SOFC is
271 reduced in order to reach a sufficiently high temperature before and especially after
272 the turbine (stream M4) in order to heat the compressed air (stream A2) to 700 °C for
273 the SOFC. The temperature before and after the gas turbine (streams M3 and M4)
274 increases with reduced fuel utilization in the SOFC because less air is required for
275 cooling purposes (stream A3) and because the SOFC off-gas contains more
276 chemical energy, which is converted in the burning chamber. Based on material
277 properties, a temperature of 990 °C is assumed before the gas turbine, resulting in a
278 fuel utilization rate of 67.5 % in the SOFC for Configuration 2. The cell voltage is
279 calculated to 0.835 V. The difference in gas treatment between Configuration 2 and
280 Configuration 1 is that the gasification gas must be cooled for compression.
281 Gasification gas is compressed to 3 bar absolute pressure at 120 °C in order to
282 prevent the steam in the gas (streams G5 and G6) from condensing. The steam is
283 required for the internal reforming of methane from biogas at the anode of the SOFC.

284

285 **3.3. Process Configuration with Pressurized Gasification and Gas**
 286 **Conversion in a Hybrid System of SOFC and Gas Turbine**



289 **Figure 5: Combination of fermentation and pressurized gasification at 3 bar**
 290 **absolute pressure – conversion of biogas and gasification gas in a hybrid**
 291 **system of a SOFC and a gas turbine (Configuration 3) [5]**

292

293 In Configuration 3, a pressurized gasifier [39] is implemented (Fig. 5). Gas treatment
 294 is simplified, since the gas does not need to be cooled and compressed and the

295 energy required for compression to 3 bar absolute pressure is saved. The following
296 assumptions are made:

- 297 - Energy demand for the compression of liquid water before evaporation in the
298 gasifier is negligible.
- 299 - Energy demand for pre-heating the air for the regenerator and for vaporizing
300 the water for the gasification process is covered by the regenerator flue gas.
- 301 - Energy demand for compressing the air for the regenerator is covered by
302 expansion of the regenerator flue gas.
- 303 - Cold gas efficiency, gas composition and gas temperature are the same as in
304 the case of atmospheric gasification.

305

306 In reality, the temperature of the gasification process will be higher and the product
307 gas composition will vary at 3 bar absolute pressure. For example, several more
308 hydrocarbons will exist [40]. After mixing the gasification gas with compressed
309 biogas, the mixture can be converted in the SOFC and the gas turbine as described
310 for Configuration 2.

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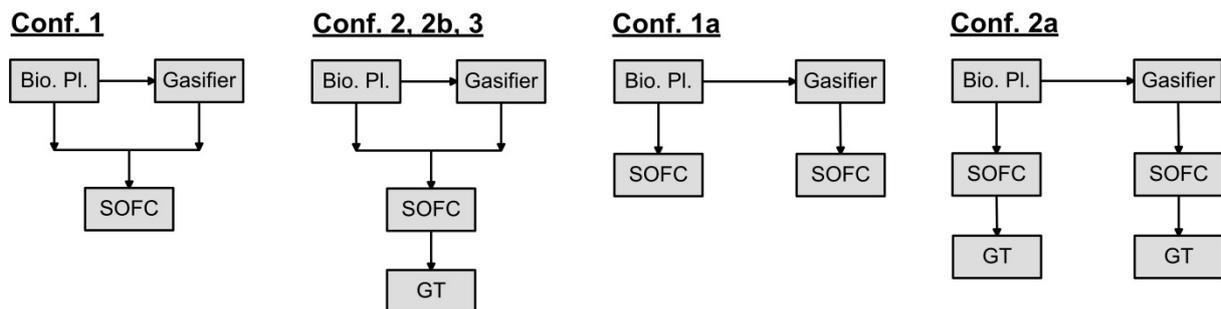
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317 **3.4. Overview of Process Configurations**

318

319 In contrast to Configurations 1, 2 and 3, as described in the previous sections, in
320 Configurations 1a and 2a, the conversion of the dried fermentation waste takes place
321 in a separate process. No heat integration is possible and each gas is converted
322 separately. In Figure 6 an overview of all Configurations is shown. In Configuration
323 2b the steam in the gasification gas is condensed and the gas compressed at lower
324 temperatures than in Configuration 2.

325



326

327 **Figure 6: Overview of all configurations: combined-process (Confs. 1, 2, 2b, 3)**
328 **and separated-process (Confs. 1a, 2a)**

329

330 Figure 7 shows the fermentation part of Configuration 2a, which consists of the
331 fermentation and conversion of biogas in a hybrid system of a SOFC and a gas
332 turbine. The fermentation waste is dried before being transported to the gasification
333 process. Steam is supplied for internal reforming of methane out of the biogas at the
334 anode of the SOFC and the steam-biogas-mixture is heated to 700 °C (Q3).

335

346 **4. Results and Discussion**

347

348 This chapter comprises two sections. The first section underlines the advantages of
349 combined fermentation and gasification (Configurations 1 and 2) resulting from heat
350 and stream integration compared to two separate processes (Configurations 1a and
351 2a). In the second part the results for power generation in a hybrid system consisting
352 of a SOFC and a gas turbine are discussed, with special consideration given to the
353 different possibilities of pressurization (Configurations 2, 2b and 3).

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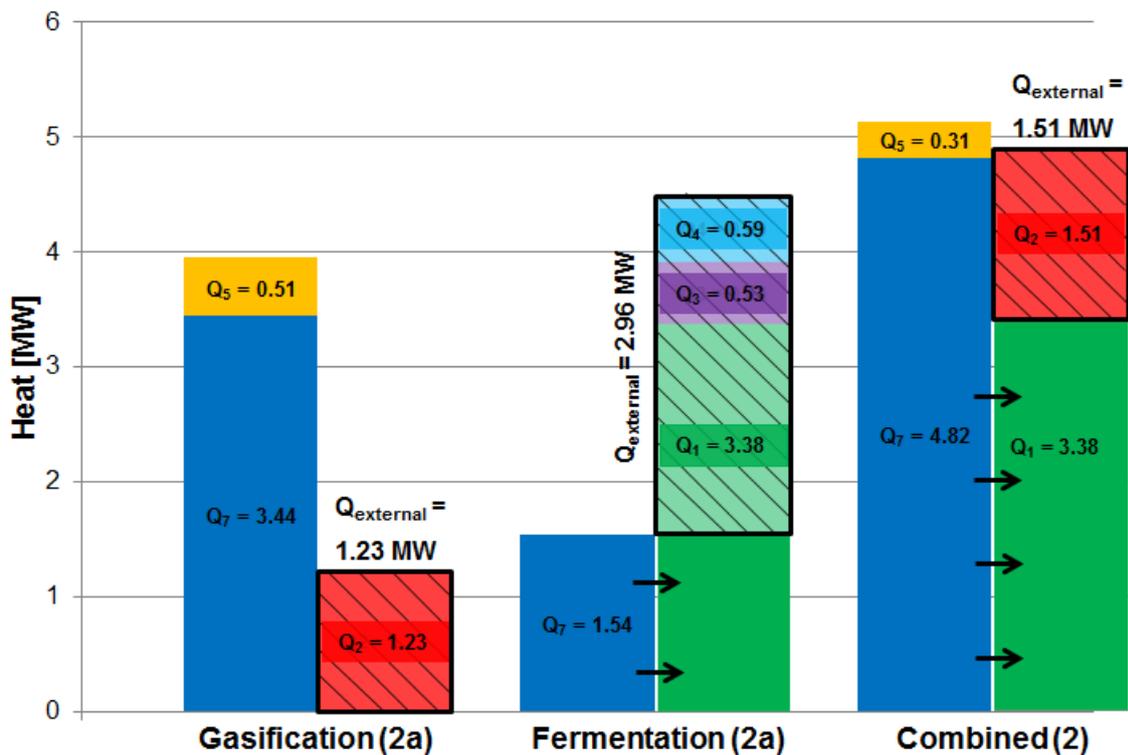
4.1. Advantages of Combined Fermentation and Gasification

366

367

368 An advantage of combined fermentation and gasification is that waste heat from the
 369 gasification process can be used to dry the fermentation waste.

370



371

372 **Figure 8: Waste heat (Q_5 , Q_7 at the left) and heat demand (Q_1 , Q_2 , Q_3 , Q_4 at the**
 373 **right) for Configuration 2: With separated processes for gasification and**
 374 **fermentation (Conf. 2a) and the combined process (Conf. 2)**

375

376 Figure 8 illustrates the heat streams for Configuration 2, as well as for Configuration
 377 2a, which consists of two separate processes for fermentation and gasification. For
 378 the combined process, heat streams Q_5 and Q_7 are sufficient for covering the heat

379 demand of drying the fermentation waste (Q1). Operating with separate processes
380 produces significant waste heat during gasification, which cannot be used in
381 concurrent or subsequent processes. The heat required for drying the fermentation
382 waste in the fermentation process cannot be covered completely, requiring the
383 addition of supplementary external heat. This extra heat has to be supplied by a
384 burner, which may be fired with fossil fuels, for example. In all cases, extra heat for
385 the tar reformer in the gasification process (Q2) cannot be provided internally,
386 because the heat requirements exceed 900 °C.

387

388 Another advantage besides heat integration is stream integration. The approximately
389 19 % steam in the 4800 m_N³/h stream of reformed gasification gas (stream G6 in
390 Confs. 1, 2 and 3) is sufficient to reform the 60 % methane contained in the 840
391 m_N³/h biogas stream, which happens at the anode of the SOFC. Containing 9 %
392 methane and 16 % H₂O, there is sufficient steam in the mixed gas to inhibit
393 thermodynamic carbon formation at the anode of the SOFC. If biogas and
394 gasification gas are converted together in the SOFC, neither an evaporator providing
395 steam for the internal reforming of methane, nor a heat exchanger for heating the
396 biogas-steam-mixture is required. No supplementary heat (Q3 and Q4 of the
397 separate fermentation process in Figure 7) is required, which also increases overall
398 electrical efficiency. Comparing Configuration 2 with Configuration 2a demonstrates
399 the effect of heat and stream integration. Additional heat flows of 0.59 MW for
400 vaporizing (Q₄ in Figure 7) and 0.53 MW for heating the biogas-steam-mixture (Q₃)
401 are required. Requiring external heat for Q₃, Q₄ and parts of Q₁ (for the drier) causes
402 the overall electrical efficiency to be reduced from 52.8 % (Conf. 2) to 46.4 % (Conf.

403 2a). In the case of exclusive use of a SOFC, as in Configuration 1, the overall
404 electrical efficiency is reduced from 33.7 % (Conf. 1) to 29.7 % (Conf. 1a).

405

Configuration	1		2	
Processes	separated (a)	combined	separated (a)	combined
η_{el} [%]	29.7	33.7	46.4	52.8

406

407 **Table 1: Comparison of electrical efficiencies with separated and combined**
408 **processes of fermentation and gasification (for Confs. 1 and 2)**

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4.2. Pressurized Operation of SOFC and Gas Turbine and Pressurization of Gasification Gas

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422
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424 With the advantages of stream and heat integration shown in section 4.1, an
425 electrical efficiency of over 30 % (33.7 % for Conf. 1) is achieved. In the case of
426 exclusive conversion in a SOFC, however, a significant amount of energy is
427 inefficiently used or lost as waste heat. As described in section 3.1, not all of the
428 chemical energy in the mixed gas (stream M1 in Fig. 3) can be converted in the
429 SOFC. Due to the fuel utilization rate of 80 %, the high amount of air used for cooling
430 ($\lambda = 9.5$) and the conversion of the remaining chemical energy in a burning chamber,
431 there is a surplus of energy available in the form of heat at over 900 °C. Even after
432 covering the heat requirements for reforming the gasification gas (stream Q2), an
433 excess of 4.89 MW is available at over 800 °C, which is not used efficiently by district
434 heating in Configuration 1. Since this potential is used more efficiently by a gas
435 turbine in Configurations 2 and 3, the electrical efficiency increases from 33.7 %
436 (Conf. 1) to 52.8 % (Conf. 2). In order to maintain a sufficiently high temperature at
437 the turbine off-gas to heat the air to 700 °C for the SOFC, fuel utilization in the SOFC
438 has to be reduced to 67.5 % in Configuration 2. Thus, less air is required to cool the
439 SOFC ($\lambda = 5.0$). At the given conditions – pressure ratio of 3 in the turbine and low
440 cooling effect of internal reforming of only 9 % methane in the gas – the gas turbine
441 contributes approximately 34 % to electrical output. The more methane in the gas,
442 the bigger the cooling effect in the SOFC, the less air required and the more fuel can
443 be converted in the SOFC. Thus, less air in the compression and expansion part of
444 the turbine leads to a smaller contribution of the turbine to electrical output.

445

446 If converted in a turbine, the gas must be compressed to 3 bar absolute pressure
447 before the SOFC and the SOFC itself must work under pressure. Therefore, different
448 routes for compressing the gas for conversion in a hybrid system of a SOFC and a
449 gas turbine are discussed. Biogas exists at low temperatures and can be
450 compressed easily. Gasification gas exists at high temperatures and has to be cooled
451 for compression. Thus, there are two options to compress the gas, Configuration 2
452 and 2b, compared in Table 2.

453

Configuration	2	2b	3
Evaporator required	no	yes	no
Gas cooling required	yes	yes	no
$T_{\text{compr,g}}$ [°C]	120	53	-
P_{compr} [MW]	0.37	0.28	0.04
P_{turb} [MW]	3.99	3.98	3.96
P_{SOFC} [MW]	7.74	7.74	7.74
P_{overall} [MW]	11.73	11.72	11.70
Q_{biomass} [MW]	20	20	20
$Q_{\text{extern-required}}$ [MW]	1.51	1.51	1.50
η_{el} [%]	52.8	53.2	54.2
$Q_{\text{district-heating}}$ [MW]	1.75	1.25	1.45

454

455 **Table 2: Comparison of Configurations 2, 2b and 3 with different options for**
456 **pressurizing the gasification gas to 3 bar absolute pressure**

457

458 T_{Compr} in Table 2 is the temperature of the gasification gas before compression
459 (compare stream G5 in Fig. 4 for Configuration 2). P_{Compr} is the electrical power
460 required for compression of biogas and gasification gas (compare $P_{\text{Compr,BG,a}}$ and
461 $P_{\text{Compr,BG,b}}$ in Fig. 4). $Q_{\text{extern-required}}$ is the required heat input which cannot be covered
462 by internal heat integration (compare Q2 in Fig. 4 and 5). $Q_{\text{district-heating}}$ is the waste
463 heat down to 80 °C which can be used for district heating (compare in Fig. 4 or Fig. 8
464 for Configuration 2: $Q5 + Q7 - Q1$).

465

466 In the case of Configuration 2b, the gas is cooled to 25 °C before being reheated to
467 60 °C, mixed with biogas and compressed to 3 bar absolute pressure at a
468 temperature of 53 °C. Therefore, most of the steam is condensed and the electrical
469 energy demand for compression is small, due to the small volume flow (see P_{Compr} in
470 Table 2). An evaporator is required, however, for providing steam for the internal
471 reforming of methane in the SOFC, as are heat exchangers for cooling gasification
472 gas and heating biogas, steam and gasification gas.

473

474 In Configuration 2, the gas is cooled to 120 °C (see stream G5 in Fig. 4) before
475 compression. Thus, due to the higher steam content in the gas and the higher
476 temperature, more electrical energy is required for compression. No evaporator is
477 required, though, resulting in a reduction in the complexity of the whole plant and an
478 increase in the amount of waste heat, which can be used for district heating (see
479 Table 2).

480

481 Using a pressurized gasifier as a third option allows the energy required for
482 compressing the gasification gas to be saved. Configuration 3 offers an increase in
483 electrical efficiency from 52.8 % (Conf. 2) to 54.2 %. After hot gas cleaning,
484 pressurized gasification gas is mixed with compressed biogas and converted in a
485 SOFC and a gas turbine at 3 bar absolute pressure. No evaporator and no heat
486 exchangers are required for gas treatment. Configuration 3 is identified as the most
487 promising configuration concerning the electrical efficiency of converting sewage
488 sludge (and wood residue).

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502 **5. Conclusion**

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504 It was illustrated that the combination of fermentation and gasification coupled with
505 the combined product gas conversion in a hybrid system consisting of a SOFC and a
506 gas turbine enables an highly energetic utilization of sewage sludge. With this
507 innovative concept, sewage sludge is not only disposed of but can also partially
508 replace fossil fuels. Additionally, with wood residue being converted in the gasifier,
509 fossil fuel use is further reduced. In each of the three investigated configurations with
510 combined fermentation and gasification, the waste heat produced by the combined
511 plant is sufficient for drying the fermentation waste. If the fermentation process and
512 the gasifier are considered separately, however, the waste heat from the
513 fermentation part is not sufficient for drying purposes, requiring an external heat
514 source. An hybrid SOFC-gas turbine system, which is investigated at 3 bar absolute
515 pressure in this work, enables high electrical efficiencies. Since gasification gas
516 contains no methane after tar reforming and there is only 9 % of methane in the gas
517 after mixing it with biogas, there is only a small heat sink resulting from internal
518 reforming at the SOFC anode and, as a consequence, a high amount of air is
519 required for cooling the SOFC. Therefore, the SOFC off-gas contains significant
520 amounts of sensible and chemical energy, which are optimal for conversion in a gas
521 turbine. Approximately 34 % of the electrical output is produced by the gas turbine.
522 With the combined conversion of biogas and gasification gas in the SOFC, a heater
523 for the biogas and an evaporator for providing steam for internal reforming of the
524 biogas at the SOFC anode are not needed, because the gasification gas contains
525 sufficient steam. In the case of atmospheric gasification and gas conversion in a
526 hybrid system, this advantage of saving an evaporator however leads to the

527 disadvantage that more electrical energy is required for the hot compression. Overall,
528 a process-wide electrical efficiency of 53 % is calculated, excluding any heat losses.
529 Pressurizing the gasifier to 3 bara maximizes the overall electrical efficiency to 54 %
530 and reduces the complexity of the gas treatment process.

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