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Highlights of the article " Solid oxide fuel cells powered by biomass gasification for high efficiency power generation"

- Design and operation of a gasification-SOFC system with minimal gas cleaning
- Experimental results from full load, part load and long-term tests with product gas
- Electric efficiencies around 40% biomass-to-power for small-scale power generation
- Modeled gasification-SOFC combined cycle concepts with efficiencies up to 62%

1 **Solid oxide fuel cells powered by biomass gasification for high** 2 **efficiency power generation**

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9 **ABSTRACT**

10 Increased use of bioenergy is a very cost-effective and flexible measure to limit changes in the
11 climate and the infrastructure. One of the key technologies toward a higher implementation of
12 biomass is thermal gasification, which enables a wide span of downstream applications. In
13 order to improve efficiencies, flexibility and possibly costs of current biomass power
14 generating systems, a power plant concept combining solid oxide fuel cells (SOFC) and
15 gasification is investigated experimentally. The aim of the study is to examine the commercial
16 operation system potential of these two technologies. Investigations are done by combining
17 the commercial TwoStage Viking gasifier developed at the Technical University of Denmark
18 and a state-of-the-art SOFC stack from Topsoe Fuel Cell for high efficiency power
19 generation. A total of 5 tests were performed including polarization tests at various gas flows
20 to study part-load operation; and a longer test to investigate stability. The study shows
21 experimentally the potential and feasibility of a SOFC-gasification system with a commercial
22 gasifier and a SOFC stack by measuring the highest reported values of such a system, with
23 biomass-to-electricity efficiencies up to 43%. Results from related modeling studies are also

24 presented, showcasing the intriguing potential of the system with modeled cycle electric
25 efficiencies up to 62%.

26

27 Keywords: Bioenergy, Biomass, Gasification, Fuel cell, SOFC, Power generation

28 **1 INTRODUCTION**

29 The most cost-effective path to reduce climate change is through increasing the share of
30 bioenergy significantly, because biomass to a large extent can directly substitute fossil fuels in
31 the present infrastructure [1,2,3]. Currently, biomass is mainly utilized as a substitute to fossil
32 fuels in large (>50 MW_{th}), efficient, and modern steam power plants that reach electric
33 efficiencies up to about 40-50% [1]. However, such plants are limited to high capacities, if
34 high efficiencies are to be maintained. In smaller typical biomass power plants (10-50 MW_{th})
35 electrical efficiencies drop to 18-33% and will require flexible operation on cheap, local
36 feedstock to be competitive in the future [1]. So, the future energy system will require
37 advanced biomass conversion and power generating technologies to ensure environmental as
38 well as economic sustainability.

39 Solid oxide fuel cell (SOFC) technology is an interesting option for high-efficient power
40 generation in future energy systems. SOFC technology is currently under extensive research
41 as one of the most promising near-future power technologies. Fuel cells convert gaseous
42 chemical energy directly into electric energy through electrochemical reactions and are thus
43 subject to less loss than traditional power generation technologies. The SOFC's are especially
44 interesting for smaller scale power systems, as they offer high fuel flexibility (CO, H₂, CH₄),
45 compared to other fuel cell types and can maintain their very high electric efficiency at
46 smaller scales and part load operation. The high operating temperatures of 700-900°C in the
47 SOFC allows internal reforming of e.g. hydrocarbons in the stack, which increases its fuel
48 flexibility greatly. SOFC operation is however limited by its nickel containing anode, which

49 requires a reducing atmosphere to stay active and forces the fuel cell to exhaust excess fuel.
50 The fraction of fuel used is called the *fuel utilisation* (FU).
51 In order to utilize biomass as a fuel for fuel cells, a conversion from solid to gaseous fuel is
52 required, this can be achieved via gasification. At high temperatures, thermal gasification
53 offers a very flexible and highly efficient platform to convert solid carbonaceous matter into a
54 combustible *product gas*. This gas typically consists of lower hydrocarbons, CO, CO₂, H₂, N₂,
55 inorganic impurities and tars. State-of-the-art gasification plants reach cold gas efficiencies of
56 80-93% (biomass to product gas [LHV]) [4]. The produced gas can afterwards be processed
57 for a variety of applications including power, heat, chemical and fuel production applications.
58 As a joint technology platform, SOFC-gasification systems that combine the fuel flexibility
59 and conversion efficiency of gasification and the high electric efficiency of fuel cell
60 technology have very high potential. Recent modeling studies from the Bio-SOFC project
61 have shown that SOFC-gasification systems can reach electric efficiencies of 42-62% with
62 proper design – see e.g. [5,6,7]. However, product gas quality and capital costs pose a
63 challenge to further development and commercialization [8]. Product gas quality relates
64 specifically to tars, inorganics, and particulates that can terminate fuel cell operation and thus
65 strict gas conditioning is typically required.
66
67 SOFC-gasification systems are still on the laboratory scale and limited tests have been
68 performed on real product gas from a gasifier [9,10,11,12,13,14]. In addition, most of these
69 tests have only been on single cells, at low loads and/or for short time periods. The focus of
70 these studies has mostly been on gas quality. Hofmann et al. [9,10,11] and Jewulski et al. [12]
71 discussed and tested internal reforming of tars and lower hydrocarbons in the SOFC, and
72 concluded that these compounds can be utilized as a component in the fuel if sufficient steam
73 is added to the gas stream to avoid carbon deposition. Tests with product gas above 10 g/nm³

74 of tars from a circulating fluid bed were found to be feasible at low loads [11] and tests with
75 product gas from an updraft gasifier showed tolerance to tars up to 85 g/nm³ at low loads [14].
76 While product gas with no tars, low levels of steam and light hydrocarbon levels above 9
77 vol% caused carbon deposition and mechanical fracture as a result of internal endothermic
78 reforming reactions [12]. Caution should be taken when evaluating tar concentrations, as both
79 composition and concentration will depend on the gasifier design and applied conditions.
80 SOFC operating on product gas at high load (fuel utilization of >70%) have shown high
81 electric efficiencies of up to 38% [10,13]. Hofmann et al. [10] operated a downdraft gasifier
82 with low tar levels (<0.2g/nm³), but found that the high load caused anode oxidation. Oudhuis
83 et al. [13] employed a pyrolyzer with extensive gas cleaning and thus obtained a clean gas that
84 proved stable operation with the SOFC.

85
86 As mentioned, studies of SOFC-gasification systems are mainly focus on gas quality
87 investigations and do therefore not represent a commercially operating system. Such a system
88 will be operated at high loads, at various gas flow rates, and with limited gas cleaning to
89 lower costs. Also, the gasifier will have to be very efficient in retaining as much of the
90 chemical energy in the solid fuel into gas with a high cold gas efficiency, as the chemical
91 energy is a main bottleneck for electrochemical combustion.

92 The TwoStage biomass gasifier at the Technical University of Denmark are a proven and
93 commercial gasification system that can achieve a very high cold gas efficiency of 93%, while
94 producing only an insignificant amount of tars and around 1 vol% light hydrocarbons
95 (methane) with only a bag filter for gas cleaning [15][16][17]. Given the challenges of the
96 previous cited works within SOFC's with product gas, it is expected that the proposed system
97 will provide a clean gas that will minimize risk of carbon deposition and be technically
98 feasible on commercial terms, including a relatively low level of complexity. Therefore it is

99 expected that the coupling of the TwoStage gasifier and a state-of-the-art fuel cell stack will
100 provide a system that will move the joint technology platform closer to commercialization and
101 feature: 1) very high electric efficiency; 2) low levels of gas cleaning; 3) stable operation.

102

103 In 2007, the TwoStage gasifier was operated with a single-cell SOFC continuously for 150
104 hours at low load and showed potential for stable operation [9]. This project continues the
105 investigations previously started in [9] and will investigate commercial terms of operation.

106 The current study operates an 800 W_e state-of-the-art SOFC stack at high load on real product
107 gas from the TwoStage gasifier. Specifically, this study examines the full- and part-load
108 performance of the stack when varying flow rates and load and performs long-term tests of
109 the stack at high load. The study shows experimentally the potential and feasibility of a
110 SOFC-gasification system with a commercial gasifier and a SOFC stack, coupled using only a
111 bag filter, activated carbon filter, a humidifier, and a desulphuriser.

112 **2 MATERIALS AND METHODS**

113 The study was carried out at the facilities at the Technical University of Denmark (DTU),
114 Risø Campus. The experimental equipment included the TwoStage ‘Viking’ gasifier,
115 necessary fuel cell gas conditioning and the SOFC stack.

116 **2.1 TwoStage gasifier**

117 The TwoStage gasification concept has been developed at DTU over several decades and it
118 has been upscaled several times and commercially up to 1.5MW_{th} [15]. The gasifier is a
119 staged downdraft concept, where the pyrolysis and gasification are carried out in separate
120 reactors with a partial combustion zone in between. The gasifier is unique in its ability to
121 produce gas with virtually no tars (<1 mg/nm³), using only a simple bag house filter and while
122 still obtaining a high cold gas efficiency of 93% [16]. The applied TwoStage gasifier plant is a

123 80 kW_{th} Viking plant, which is fully automated, have been operated for more than 3000 hours
124 and have shown very stable operating characteristics with regards to continuous operation ,
125 gas composition and engine operation [17].

126 A flow diagram of the Viking gasifier is shown in Figure 1. The gasifier is operated at
127 atmospheric pressure levels. Pine wood chips of ≈40% humidity are fed into an externally
128 heated screw conveyor that dries and pyrolyzes the fuel up to 600°C. No fuel analysis was
129 made, but the fuel is very similar to the fuel used in previous tests, which is shown in Table 1.
130 The screw conveyor is heated using superheated engine exhaust. The pyrolysis products are
131 led to the second reactor and are partially oxidized by air, raising the temperature above
132 1100°C. Hereby, the tar content is reduced by 99%. The gas and char then pass through a hot
133 fixed char bed, where the char is gasified and the temperature is subsequently lowered to
134 800°C at the bed outlet. The hot char bed acts as a tar cleaning unit, removing 99% of the
135 remaining tars [17,18], yielding a near tar-free gas. The obtained product gas then flows
136 through a series of heat exchangers and a bag house filter that removes small amounts of
137 particles, tars and water. Afterwards, the gas enters a mixing tank, where a slipstream of about
138 2 kW_{th} was directed to the fuel cell setup.

139

140 **2.2 Fuel cell gas conditioning**

141 Gas conditioning is essential when using fuel cells, as this technology is highly sensitive to
142 several gas components. Levels of hydrocarbons have to be monitored, as they will be
143 reformed internally in the anode and cause thermal stresses by cooling and can cause carbon
144 deposition. The reforming of hydrocarbons needs a sufficient water vapor pressure in order to
145 avoid carbon deposition and thus the gas needs to be humidified. Inorganic compounds,
146 including sulphur, need to be completely removed to avoid anode deactivation.

147 The product gas initially flowed through two active carbon filters at room temperature with a

148 retention time of 53 seconds. These filters act as guard beds, removing inorganic compounds
149 and tars.

150 Afterwards, the gas passed through an electrically heated water spray tower, where it was
151 humidified to reach an oxygen-carbon molar ratio of 2. The humidification temperature was
152 60°C, which correspond to a water molar fraction of about 19.5% in the humidified product
153 gas.

154 The humid product gas was electrically heated to 245°C and led through a fixed guard bed
155 with ZnO pellets that removed remaining sulphur compounds up to 10 ppm. Afterwards the
156 gas was heated electrically to 670°C before being fed to the SOFC. An overview of the gas
157 conditioning is shown in Figure 2.

158
159 The gas composition was measured at dry and tar-free conditions with an Advance Optima
160 2020 Modular continuous process gas analyzer system, with an Caldos 15 cell for H₂ analysis
161 and an Uras 14 cell for CO, CO₂ and CH₄ (ABB, Switzerland). The O₂ content was measured
162 with an PMA 10 O₂-analyzer. The uncertainty of the gas analyzer is ±1% of the measured
163 value. The continuous gas flow for the analyzer system was taken via a twist filter following
164 the carbon filters.

165 Tars and sulphur compounds were measured at the inlet and outlet of the carbon filters. For
166 tar analysis, solid phase adsorption (SPA) samples were taken during the experimental work
167 with tubes from Supelco with an aminopropyl adsorbent. Three samples were taken before
168 and after the carbon filter. The samples were analysed by gas chromatography/mass
169 spectrometry (GC/MS) with acetone as the solvent with the modification of using stable
170 isotopes of polycyclic aromatic hydrocarbon standards as the internal standards – see further
171 details in reference [17]. Sulphur was measured using 250mL gas probes and GC/MS with
172 three measurements before and after the carbon filter.

173

174 **2.3 SOFC stack**

175 The SOFC stack is produced by Topsoe Fuel Cell. The stack is made of 50 planar, anode
176 supported cells. The anode is made of yttrium-stabilized zirconia (YSZ), nickel catalysts and a
177 mechanical support structure. The electrolyte is made of YSZ and the cathode of lanthanum
178 strontium manganite. The stack is an 'S 1-02' type, with a footprint of 12x12 cm and a
179 nominal capacity of 800 W_e. It was operated at near atmospheric pressure and the operation
180 was designed for 700°C fuel exhaust. The stack was fed with air as oxidizer at 670°C. The
181 SOFC stack was placed in an electrically heated oven at 700°C, as the stack was not insulated.
182 The SOFC was heated at 200K/h to minimize thermal stresses. The start-up was carried out at
183 open-circuit conditions with Formier10 gas (10v% H₂, 90v% N₂) and as 700°C was reached,
184 the stack was stabilized for 30min before switching to product gas. After switching to product
185 gas the SOFC was similarly left for 30min before drawing power from the stack. A picture of
186 the mounted SOFC stack is shown in Figure 3.

187

188 **2.4 Experimental procedure**

189 The experimental work was carried out over 3 campaigns for a total operating time of 145
190 hours with real product gas as described in [19]. An overview of reported tests is shown in
191 Table 2. Tests started when the SOFC voltage was stabilized after the warm-up (usually after
192 6 hours). Measurements of voltage, power and gas composition were taken as averages over
193 3-10 minutes, except values at maximum current that were taken as an average over 60
194 minutes of operation. National Instruments' LabView 2015 software via a Siemens Step 7
195 PLC system was used for the data acquisition.

196

197

198 Flow rates were measured using manual measurements with a flow meter during the tests and
199 are therefore a calculated average value. The SOFC stack load was controlled by increasing
200 the current to specified values on an electric load box. The current was held to a maximum of
201 25 A, as specified by Topsoe Fuel Cell. During all tests, air was fed non-pressurised at 90
202 l/min (measured at 20°C).

203 3 RESULTS AND DISCUSSION

204 3.1 Product gas and SOFC stack temperature

205 The product gas was examined three times for tars and sulphur. No tars could be detected
206 using the SPA tar analysis, which is expected as shown in previous campaigns with the
207 gasifier [17]. The SOFC's tolerance towards tars are discussed several places and as
208 mentioned, several tests have been made e.g. [9,10,11]. As rough estimate, Aravind and de
209 Jong [19] gave a threshold value of 2g/Nm³ tars in order to avoid carbon deposition, but states
210 that it naturally depends on the tar species, temperature and gas composition. These findings
211 indicate that the TwoStage gasifier design could be altered to reduce the tar conversion, in
212 order to obtain other benefits (e.g. using a smaller char bed/reactor or increasing fuel
213 flexibility by using a fluid bed for char conversion) as a slightly higher tar concentration will
214 not affect the SOFC performance.

215 Sulphur was analysed for the COS and H₂S compounds, but only COS could be detected with
216 an average value before the carbon filter of 3.7ppm and <0.1ppm after the carbon filters [20],
217 displaying the relatively simple carbon filters effectiveness. The SOFC's tolerance towards
218 sulphur species is extremely depending on gas composition and temperature, but Rostrup-
219 Nielsen et al. [21] found that a SOFC stack at 800°C using partially oxidized jet fuel (gas
220 composition similar to TwoStage product gas) was not affected by 10ppm H₂S, and while

221 50ppm decreased performance 10%, the SOFC could easily be regenerated to original
222 performance levels. These findings indicate that the already simple gas condition applied in
223 Figure 2 might be further reduced, so that only the integrated gasifier bag filter (and possibly
224 humidifier depending on the hydrocarbon/tar level) remains upstream of the SOFC, while also
225 allowing the gasifier to increase its tar production if needed.

226

227 During the campaigns, only small fluctuations in the product gas composition from the
228 TwoStage gasifier were seen. Average gas compositions during the tests are shown in Table
229 3. Figure 4 shows as reference, the gas composition fluctuations during Test 5.

230

231 Some gas fluctuations were observed during the tests: the bag filter was cleansed and back
232 flushed with nitrogen to reduce pressure drop; and pressure spikes occurred regularly. The
233 pressure spikes occurred probably because of water droplet evaporation from the humidifier.
234 Voltages were affected by the pressure increases, resulting in negative spikes until the
235 pressure was reset shortly after – see Figure 8.

236 The temperature of the stack increased as the current increased, due to generated waste heat.

237 During Test 5, temperatures were constant as the current was not varied. Results from the
238 measurements of product gas, exhaust gas and air temperatures are shown in Table 4.

239

240 **3.2 Performance of SOFC stack**

241 The performance of the SOFC stack is evaluated based on power output, voltage and electric
242 efficiency (power to fuel input [LHV]). The FU is an appropriate dimensionless base of
243 comparison value across fuel flows and gas compositions. As the FU increases, so does the
244 internal losses in the SOFC, due to mass transfer and concentration losses as the load
245 increases. The FU can be defined using the current, I , as the ampere value is a measure of

246 conducted electrons (and thus proportional to the number of conducted oxygen-ions). As the
 247 steam reforming and water-gas-shift (WGS) reactions by the nickel catalysts at the anode of
 248 CO and CH₄ are faster than the electrochemical reactions [22,23], a molar hydrogen
 249 equivalent, n_{H2-eq} , is calculated based on complete steam reforming and WGS of CO and CH₄
 250 , shown in Equation 1. The FU is defined in Equation 2 on a molar basis. N_c is the number of
 251 cells in the stack and F is Faradays constant.

$$253 \quad n_{H2-eq} = n_{H2} + n_{CO} + 4 \cdot n_{CH4} \quad (1)$$

$$254 \quad FU = \frac{\frac{I}{2 \cdot F} N_c}{n_{H2-eq}} \quad (2)$$

255
 256 The SOFC performance was tested in a large operating area in order to simulate part- and full-
 257 load conditions. Voltage, power density and voltage standard deviation as a function of
 258 current density for Test 2 is shown in Figure 5 and the power outputs of the SOFC stack for
 259 Test 1-4 are shown in Figure 6. The corresponding electric efficiencies for Test 1-4 are shown
 260 in Figure 7. During testing, it was seen that one of the 50 SOFC's in the stack was not
 261 producing any power.

262
 263 Even though the FU was up to 90.2%, there was no significant decline in power in following
 264 tests due to internal losses in the stack (see Figure 7) and tests at different flows yielded
 265 nearly equal electrical efficiencies across FU. This means that part-load operation down to
 266 55% flow (Test 1 compared to Test 4) does not reduce the efficiency of the stack, which is an
 267 important factor in an energy system with large fluctuations from e.g. wind and solar power.
 268 The peak values for Test 1-4 are shown in Table 5, showing the data for the measurements at
 269 max FU. The maximum efficiency value (46.4%), power (875 W) and FU (90.2%) achieved

270 are, to the authors knowledge, the highest values found in literature for product gas operation.
 271 These efficiencies are markedly higher than previous tests in which 38% was reached [10,13].
 272 Previous tests with the TwoStage gasifier and a single-cell SOFC showed electric efficiency
 273 of 24% at a fuel utilization of 30% [9], which is higher than the roughly 18% obtained here at
 274 the same FU. Even though the gas was similar it should be noted that the previous test
 275 operated at 850°C and a current density of 260mA/cm² – compared to 700°C and ≈50-100
 276 mA/cm² (depending on test and gas flow). An evaluation of the increased temperature with
 277 higher efficiency versus shorter SOFC lifetime should be made when designing such a
 278 system.

279
 280 Considering the gasifier-SOFC system, a plant efficiency η_{plant} can be estimated based on the
 281 present results. Using Equation 3, the combinations of SOFC efficiency at maximum FU and
 282 gasification efficiency gives TwoStage-SOFC electrical efficiencies of 38-43%. TwoStage
 283 cold gas efficiency is denoted with η_{cg} and the SOFC stack efficiency with η_{SOFC} . The range
 284 of this approximation is confirmed through mathematical modeling of the system [24].

$$286 \quad \eta_{plant} = \eta_{cg} \cdot \eta_{SOFC} \quad (3)$$

287
 288 The TwoStage-SOFC system is thought as a decentralised constellation in the <20MW_{th}
 289 range, as downdraft gasifiers have limitations with regards to scaling [25,26]. The efficiencies
 290 of this system are significantly higher than typical competing decentralised biomass power
 291 plants at 18-33% [1]. The obtained efficiencies are comparable with those of biomass power
 292 plants with capacities above 100 MW_{th} [1]. Gasification systems typically have electrical
 293 efficiencies of 18-33% [26], similar to those of decentralised power plants, with the typically
 294 engine operated TwoStage gasifier of 29% (gross) [17]. Two of the most efficient

295 demonstrated biomass gasification systems, not using fuel cells, are the Värnamo combined
296 cycle and Skive engine plants. These plants reach electrical efficiencies of 33% and 30%
297 respectively [27,28] and are significantly outperformed in comparison to these tests.

298

299 **3.3 Long-term performance of SOFC stack**

300 In order to investigate any decline in the performance of the SOFC stack when continuously
301 using product gas, the results of the 62 hour-test (Test 5) have been used. During the test, the
302 gasifier stopped for 1 hour due to a fuel feeding fault and the SOFC stack was consequently
303 stopped. The SOFC stack did however assume full-load operation at 20.1 A again after 2.5
304 hours after the stop. The performance of the stack is shown as stack voltage on Figure 8 and
305 key data are presented in Table 6.

306

307 The SOFC operation during the 62 hours was generally stable throughout the test, with power
308 fluctuating within $\pm 10\text{W}$, which is to be expected with slightly varying gas flow and
309 composition (see Figure 4). As seen in Figure 8 and as mentioned earlier, the voltage did
310 however experience some spikes during operation, which is likely caused by droplets that are
311 carried over from the humidifier and in turn evaporates when reaching the heat exchangers.
312 The sudden evaporation will cause the local steam concentration to increase and lower the
313 heating value of the gas locally, which decreases the stack voltage. The drop in voltage was
314 very short and voltage was stabilized quickly after.

315

316 In order to assess the SOFC performance, the voltage is calculated independently of product
317 gas fluctuations as these will affect the voltage. By evaluating the stacks overpotential using
318 the Nernst equation, the internal losses can be assessed. The data for Test 5 is divided into
319 sections of 30 minutes that are averaged. The overpotential V_{OP} can then be calculated as in

320 Equation 4 from the measured voltage, V_{exp} , using the Nernst equation [22], assuming
 321 complete steam reforming of CO and CH₄. E^0 is the electrode potential at standard conditions
 322 for hydrogen and P is the average partial pressure of the product gas in the stack. P_{H2-eq} is the
 323 accumulated partial pressures of H₂, CO and four times CH₄ as in Equation 1.

324 It can be challenging to model a precise SOFC performance using a zero-dimensional model
 325 as chosen here. Multiple factors as varying temperature, gas composition, and pressure across
 326 the electrode structure causes relatively simple models to rely on estimates. This is discussed
 327 by Bang-Møller [24], where the approach taken here with Equation 4 is evaluated against a
 328 more precise form, which caused the Nernst and cell voltage to be 4% and 19% lower
 329 respectively at similar conditions. However, as the calculations of this project focuses on a
 330 trend in voltage and because the gas composition is very stable (see Figure 4), the error in
 331 modeling will only affect the trend to a minor degree.

$$333 \quad V_{exp} = \left(E^0 - \frac{R \cdot T}{2 \cdot F} \ln \left[\frac{P_{H2O}}{P_{H2-eq} \cdot P_{O2}} \right] - V_{OP} \right) N_c \quad (4)$$

334
 335 The calculated overpotential for the SOFC stack is shown in Figure 9. The value fluctuates
 336 slightly, which is due the discussed modeling assumptions above and to minor disturbances in
 337 the system, namely the gas pump was found to fluctuate. The overpotential of the stack is split
 338 into two sections: before and after the 2.5 hour fall-out. Before, the overpotential is increasing
 339 at a low rate, indicating that the stack performance is declining. After the stop, however, the
 340 overpotential is stable, but with a higher value, indicating that the stack has been damaged by
 341 the sudden stop in operation. This effect is likely due to the thermal cycling that the SOFC
 342 experiences during the sudden stop in operation - the SOFC control was designed to shut off
 343 power when the gasifier stopped, meaning that the current went from 20.1A to 0A in an

344 instance. This immediate shut-down, can decrease the contacting between electrodes and
345 electrolyte/interconnect and hence increase losses as the remaining contact sites are forced to
346 increase load, resulting in increased overpotential – this phenomenon is discussed in e.g. [29].
347 Hence, future tests should implement a revised control strategy that gradually lowers the
348 drawn current from the stack in order to limit degradation. Following the stop, the continuous
349 operation with product gas did not affect the stack after the stop. As the test showed some
350 increase in overpotential before the stop and constant operation after, there is not enough data
351 to conclude whether long-term operation is feasible and longer tests are recommended.

352
353 In all, a total of 145 hours of operation was however carried out on product gas, without
354 significant decline in SOFC performance that indicates loss of performance when combining
355 these two technologies. However, two aspects should be kept in mind when evaluating these
356 results: 1) the stack performance has not been tested before and after the tests with a reference
357 gas, so specifics on a possible performance decline has not been investigated – for instance
358 could the high fuel utilization have caused a decline in performance that cannot be assessed
359 over the operating time of this project; 2) the stacks initial condition is unknown by Topsoe
360 Fuell Cell and the stack might have decreased performance compared to an unused stack.
361 Following the test campaigns, the gas separation of the stack was tested at room temperature
362 with gas tracing and it was found that there was a leak between anode and cathode, which will
363 lead to either anode oxidation and/or loss of fuel, but in all cases a loss of performance.

365 **3.4 Comparison with modeling studies**

366 Within the BioSOFC project, the coupling of the TwoStage gasifier and SOFC's has been
367 studied by mathematical modeling in other publications [5,6,7,8,24,30,31]. The main results
368 from these publications are discussed here in relation to the experimental data and the system

369 potential.

370 The TwoStage-SOFC system is projected as a decentralised plant with capacities below
371 10MW_e. The system were modeled to have an electrical efficiency of 44.9% with a FU of
372 85% [5], which is within range of the results presented here. The modeled results for the
373 SOFC fit well with the obtained experimental results in e.g. [5].

374 However, as the SOFC is subject to a certain FU, there are high quality heat and excess fuel
375 available downstream that can heighten the system efficiency. Therefore, combined cycle
376 (CC) concepts that enhance the electrical efficiency have been modeled. The efficiencies for
377 various CC configurations are shown in Table 7, showcasing the very high potential of
378 decentralised power based on biomass gasification and SOFC technologies. The results stress
379 the need to utilize the SOFC off-gases in order to be as competitive on efficiency as possible
380 and design some of the most efficient systems available. Downstream power generation could
381 also be implemented as a cost reduction measure as lower FU also leads to lower maintenance
382 costs of the SOFC.

383

384 Thermo-economic studies were also included in [8,30]. Both studies concluded that the main
385 expense of the system is the investment cost. Specifically the SOFC capital cost was found to
386 be the main bottleneck for commercialization. Electricity prices were found to be close to
387 competitive with other biomass power generation, but not sufficiently high to justify the high
388 investment. Thus continued technology maturation and SOFC cost reduction will be needed if
389 the plant will be competitive without incentives.

390

391 **4 CONCLUSIONS**

392 Experimental studies were performed on an 800 W_e SOFC stack, operated on real product gas
393 from the TwoStage gasifier. The test setup featured the TwoStage biomass gasifier, the SOFC

394 stack and simple gas cleaning consisting of only a bag filter, two carbon filters, a humidifier
395 and a desulphuriser. No tar could be detected. Only small amounts of sulphur compounds
396 were found, enabling both the carbon filters and desulphuriser to remove them, which can
397 reduce complexity even further. Thus the TwoStage gasifier is very well suited for operating
398 SOFC with only a minimum of gas conditioning.

399 The SOFC was operated at 700°C and was subject to 4 tests with different flows from 15-28
400 l/min and currents from 0-24.1 A for up to 62 hours. The 4 tests displayed the SOFC stacks
401 excellent part-load performance down to 55% flow, without loss of efficiency. The tests
402 achieved the highest reported values of such a system globally, with a SOFC stack electric
403 efficiency of 46.4% at 90% fuel utilisation. A gasifier-SOFC system electric efficiency was
404 estimated to be around 40%, which is considerably higher than those from traditional
405 decentralised biomass power plants and showcases the systems intriguing potential.
406 A total of 145 hours of operation was achieved without significant losses in SOFC
407 performance.

408

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412 Polygeneration (ForskVE-12205) projects. The authors would like to thank Topsoe Fuel Cell
413 for delivering the SOFC stack and the DTU Energy department for technical assistance.

414

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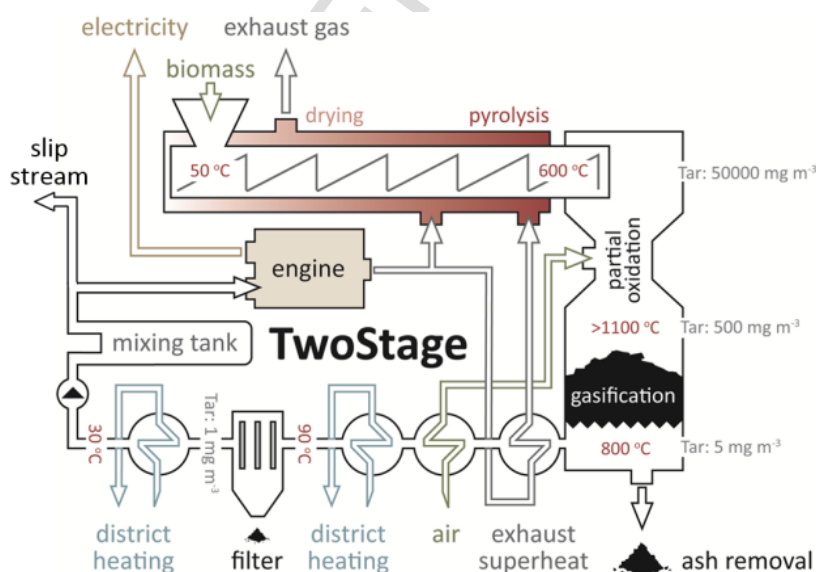
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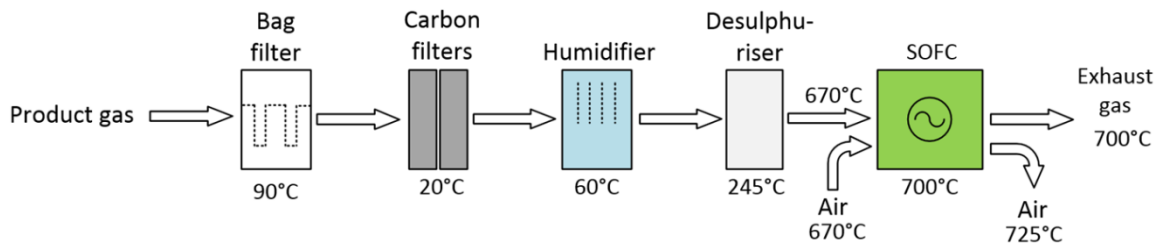
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506

507 **Figure 1:** Flow diagram of TwoStage gasification with an engine.

508



509

510 **Figure 2:** Overview of fuel cell gas conditioning with approximate operating temperatures.

511 Electric heaters are not shown.

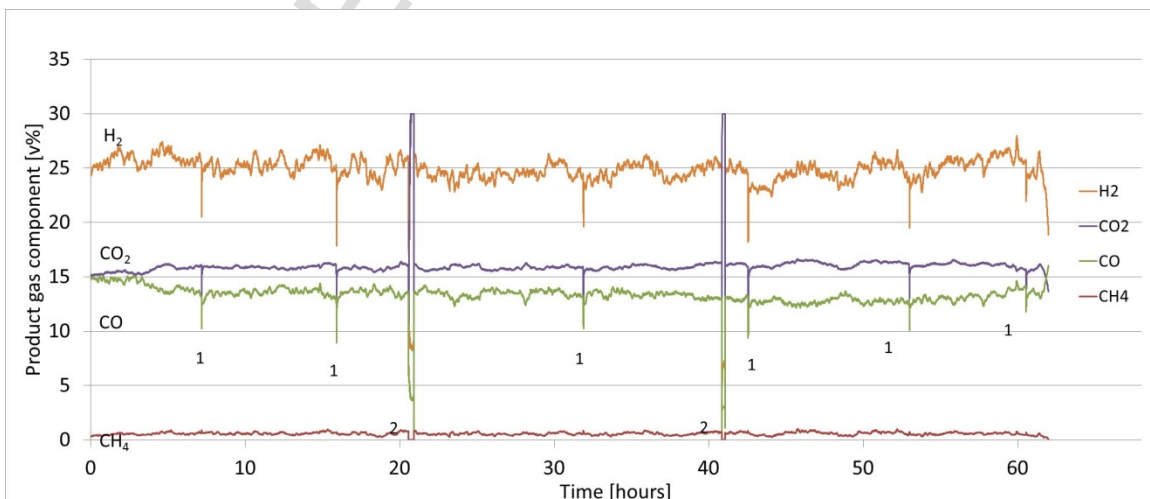
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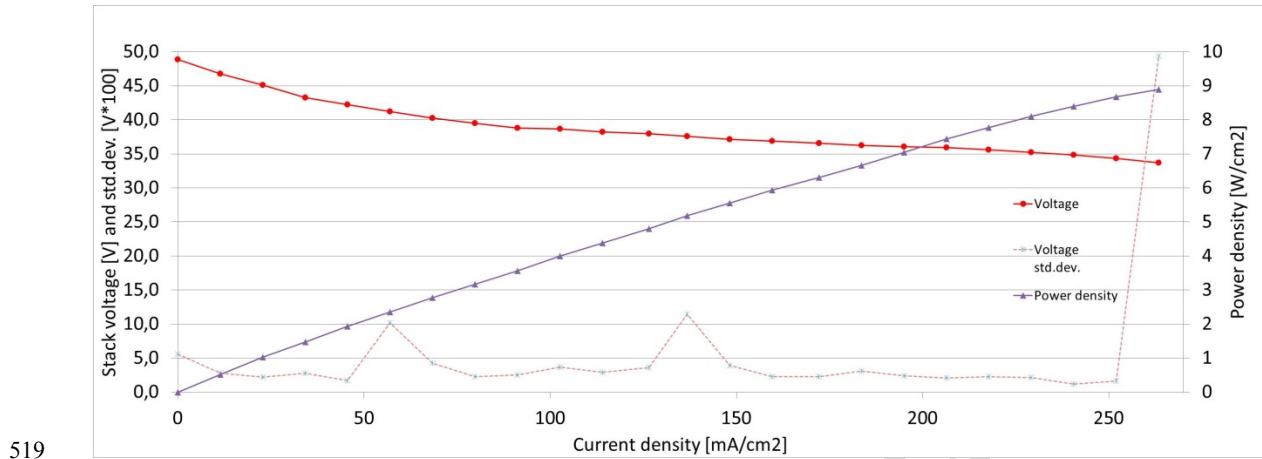
514 **Figure 3:** SOFC stack mounted in oven

515



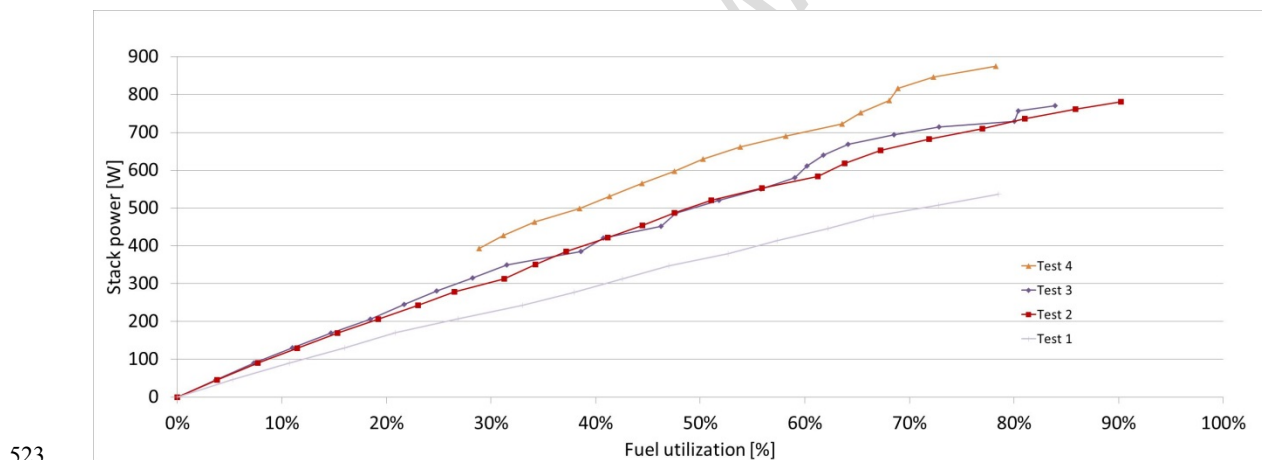
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517 **Figure 4:** Gas composition during Test 5 for 62 hours. Incidents marked '1' are during
 518 flushing of the bag filter and '2' are measurements of SOFC exhaust.



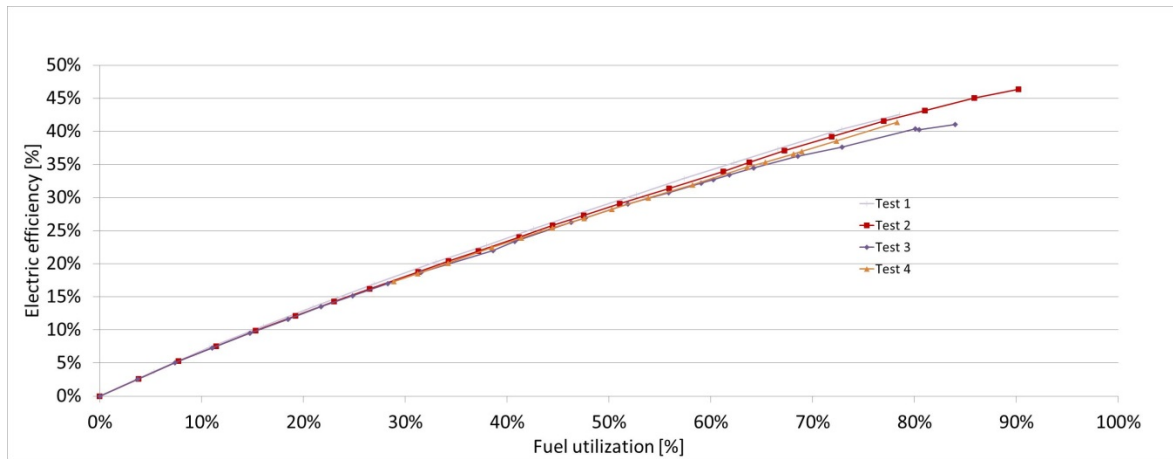
519
 520 **Figure 5:** SOFC stack voltage with standard deviation and power density shown as a function
 521 of current density for Test 2.

522



523
 524 **Figure 6:** SOFC stack power output shown as a function of fuel utilisation for Test 1-4.

525

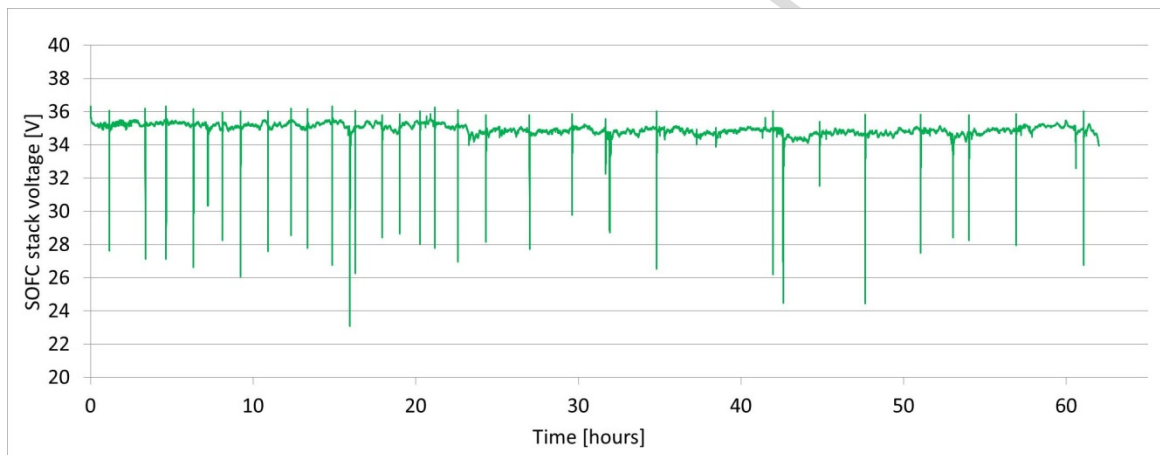


526

527 **Figure 7:** SOFC stack electric efficiencies shown as a function of fuel utilisation for Test 1-

528 4.

529

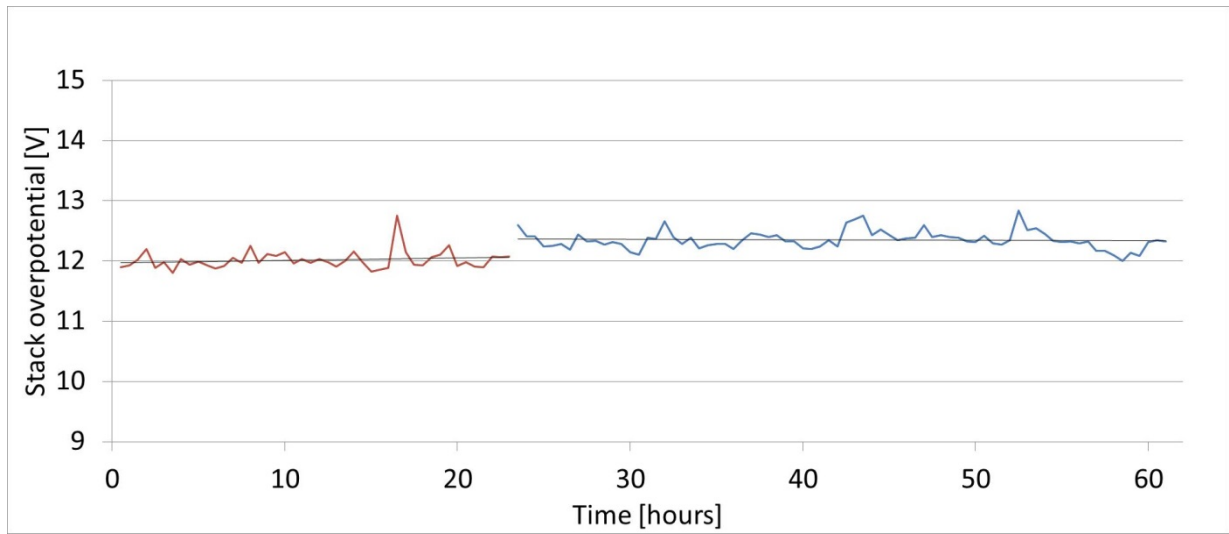


530

531 **Figure 8:** SOFC stack voltage during Test 5 for 62 hours. Spikes are caused by sudden

532 pressure increases upstream of the SOFC. A stop of 2.5 hour is marked, but not shown.

533



534

535 **Figure 9:** Overpotential, V_{OP} during Test 5 for 62 hours, as described by Equation 4. The
 536 curve is split where there was a 2.5 hours stop in operation. Trendlines are added for each
 537 curve.

538

Component	Method	Measure 1	Measure 2
Ash [wt%, dry]	550°C, app. 20h	-	-
HHV [MJ/kg, dry]	ISO 1928	19.60	-
LHV [MJ/kg, dry]	ISO 1928	18.28	-
C (wt%, dry)	ASTM 5373	48.90	49.00
H (wt%, dry)	ASTM 5373	6.20	6.00
N (wt%, dry)	ASTM 5373	0.17	0.40
S (wt%, dry)	ASTM 4239C	0.022	0.07
Cl (wt%, dry)	ASTM 4208, IC	0.063	-
O (wt%, dry)	-	-	44.00
Moisture (wt%)	-	-	32.20

539 **Table 1:** Fuel measurements of wood chips from previous tests with the Viking gasifier [17]

540

Test #	Gas flow* [l/min]	Duration [hours]	Range of current values for tests [A]
1	15.9	1.5	0 - 15.1
2	22.5	3.5	0 – 23.1
3	23.0	7	0 – 24.1
4	28.8	2	10.0 - 25.1
5	22.4	62**	20.1

541 **Table 2:** Overview of tests performed. *Flow measured at 20°C and atmospheric pressure.

542 **Test 5 were stopped for 2.5 hours due to a 1-hour gasfier failure during the test.

543

Test #	CH ₄ [vol%]	CO [vol%]	CO ₂ [vol%]	H ₂ [vol%]	N ₂ (rest) [vol%]	Sum [vol%]	Gas energy flow (LHV)* [W]
1	0.6	15.2	15.4	27.2	41.6	100.0	1245
2	0.7	14.1	15.1	26.3	43.8	100.0	1723
3	0.7	15.6	14.1	26.7	42.8	99.9	1826
4	0.5	14.9	15.3	26.0	43.3	100.0	2200
5	0.6	13.3	16.0	24.8	45.3	100.0	1588

544 **Table 3:** Overview of average dry product gas compositions during the different tests.

545 Compositions are calculated as average values over 3-10 minutes. Nitrogen content is

546 calculated by difference. *Gas energy calculated based on average LHV of gas and flow

547 during the experiment

548

Test #	Product gas [°C]	Exhaust gas [°C]	Air in [°C]	Air out [°C]

1	658-666	676-688	657-668	684-711
2	649-670	672-698	654-671	680-732
3	650-670	675-700	655-675	680-730
4	651-682	687-706	663-675	700-733
5	661-683	691-705	663-677	719-731

549 **Table 4:** Gas temperature measurement ranges during tests in and out of the SOFC stack
 550 caused by changes in load and gas compositions.

551

Test #	Flow compared to Test 4 [%]	Power [W]	Electric efficiency [%]	FU [%]
1	55.2	537	42.6	78.5
2	78.1	780	46.4	90.2
3	79.9	771	41.0	84.0
4	100	875	41.4	78.3

552 **Table 5:** Data for max fuel utilisation (FU) measurements. Data are taken as averages over 60
 553 min.

554

Gas flow* [l/min]	Current [A]	Power [W]	Electric efficiency [%]	FU [%]
22.4	20.1	704 ±9.8	44.3	83.0

555 **Table 6:** Key data for Test 5 taken as an average over 62 hours with standard deviation for
 556 power as primary measurement. *Gas flows are measured at 20°C and atmospheric pressure.

557

Power system configuration	Scale	Electric efficiency
----------------------------	-------	---------------------

	[MW _e]	[%]
SOFC [5]	1.4	44.9
SOFC-Stirling engine [8]	0.12	42.4
SOFC-Organic rankine cycle [6]	0.1	54-62
SOFC-Gas turbine [24]	0.3	55-58
SOFC-Kalina cycle [31]	8	49-58
SOFC-Steam cycle [7]	10	48-56
SOFC-Steam injected gas turbine [30]	10	48-50

558 **Table 7:** Main results of modeling studies with TwoStage gasifier, SOFC and further
 559 downstream power generation.

560