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Modeling of coupling gasification and anaerobic digestion processes for maize bioenergy conversion

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Abstract

This work estimates the advantages of using maize as fuel in a power plant composed of an anaerobic digester, a gasifier and an Internal Combustion (IC) engine. The digester is fed with maize grains, while, the remaining part of the plant, the stover, is gasified. Then biogas and syngas streams are both used as fuel into the engine. The performance of this plant was evaluated coupling gasification and anaerobic digestion mathematical models. Results of the proposed solution are compared with the performance of a 100 kW biogas power plant fed with the whole crop silaged. Results show that the overall energy yield of the improved solution is 39% higher than the conventional one fed with maize silage. This method will lead to the design of small and cheap digesters as a result of the increased conversion rate. In fact, the solution proposed fully converts the high cellulose-fiber parts of the maize plant that were tough to degrade in anaerobic digesters.

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Stover, Corn grains, gasification, anaerobic digestion, modeling

1

2 **1. Introduction**

3 Maize is the energy crop most widely used for biogas power production
4 [1, 2, 3]. Most of power plants runs on a combination of maize silage and
5 livestock wastes. Even if this combination assures high conversion rate, lit-
6 erature suggests the possibility to run a power plant with almost 100% of
7 maize silage [4, 5], as modeled in this work for simplicity. During the years,
8 several attempts were made in the direction of increasing the overall power
9 plant efficiency, working on harvesting period as suggested by Bruni et al.
10 [6] or pre-treatments on the biomass used for reactors feed [7].

11 The solution proposed in this work starts from the study of the maize
12 plant , defining how it can be considered composed of different parts: stalk,
13 cob, leaves, husk and grains. These components behave differently in the
14 digester [8, 9]. Among the different parts of maize plant, grains are the
15 most degradable and even the most productive in terms of specific biogas
16 production. In fact, grains are characterized by high starch and soluble
17 sugars content, as well as low lignin [9, 10, 11]. On the other hand, the corn
18 stover, composed of cobs, leaves, husk and stalks, has a lower productivity
19 in terms of biogas as result of its high percentage of cellulose and lignin [9].

20 This suggests that a digester fed mainly with grains could theoretically be
21 smaller than a digester fed with the whole plant, but also with corn silage.
22 Furthermore, while the operation of silaging increases the productivity of

23 each specific part of the maize plant, the same procedure reduces the amount
24 of organic matter of at least 10%. This phenomenon is due to an unavoidable
25 aerobic fermentations occurring in the silaging process [12].

26 As described above, the grains are the most important part of the maize
27 plant in terms of anaerobic digestion process, while the stover is characterized
28 by low conversion rates that drastically affect the bio-chemical processes.

29 This work describes two different scenarios: 1) the conventional power
30 plant composed of an anaerobic digester fed 100% with corn silage and 2) a
31 hybrid power plant composed of an anaerobic digester fed with grains and a
32 downdraft gasifier fed with the stover.

33 Literature review revealed several studies about corn residues gasifica-
34 tion. Zijp et al. in the 1980 published a technical report with the Twente
35 University where the use of corn stover in gasifier was discussed. It was found
36 that the particulate content in the gas was one of the major issues related to
37 this application. [13]. Zijp's results were cited in one of the most important
38 manuals for fixed bed gasifier design: Woodgas as engine fuel [14]. A more
39 recent work on gasification by Mavukwana et al. [15] models the stover gasi-
40 fication process in Aspen plus finding optimal equivalence ratio and steam
41 to biomass values for this feedstock. Groeneveld and Van-Swaaij in the 1979
42 and Allesina et al. in 2015 discussed the possibility to use corn cobs gasifica-
43 tion in micro power plants. Both the works are focused on energy shortage
44 problems in African villages [16, 17]. A fixed bed gasifier of 350 kW_{th} was
45 used by Biagini et al. in 2014, it was fed with corn cobs, reporting a gasi-
46 fication efficiency of the system of 67% and a syngas heating value of 5.7
47 MJ/Nm³ [18]. Literature review shows how the stover can also be processed

48 in fluidized bed gasifiers [19, 20].

49 The basic idea of this work is depicted in Figure 1. Aim of this study is
50 to demonstrate the advantages related to the separation of the grains from
51 the corn stover and the exploitation of the grains in the digester while the
52 stover is converted into syngas by a fixed bed gasifier. Literature does not
53 include many works on the possible effect of combined anaerobic digestion
54 and gasification. Li et al. [21] modeled a coupled system aimed at biomethane
55 production, while Chen et al. couples a fixed bed gasifier working with
56 corncob and cotton straws and a typical biogas plant for fueling household
57 furnaces in rural scenarios [22]. Other studies focus on the use of anaerobic
58 digestion and thermo-chemical conversion in cascade. Two possible work
59 groups can be found in literature. The first group attempts a further energy
60 conversion of the digestate disposed by the biogas power plant [23, 24, 25], the
61 other uses anaerobic digestion for the conversion of the unwanted products
62 of the gasification and pyrolysis processes (wastewater and tar) [26, 27, 28].

63 The system is modeled as a composition of two sub-models:

- 64 • The anaerobic digestion was simulated with the Anaerobic Plant Em-
65 ulation (APE) model reported in [29].
- 66 • The stover gasification process was simulated with a black-box equilib-
67 rium model in order to estimate the steady state behavior of the gasifier.
68 Different gasification conditions were tested with the final purpose of
69 obtaining a syngas with higher heating value over 4 MJ/Nm³ and a tar
70 content lower than 2 g/Nm³. These conditions are within the typical
71 ranges reported by Milne for downdraft gasifiers [30]. However, the
72 value obtained is too high for direct feeding of the gas to an engine.

73 Therefore a filtering process is mandatory to lower the tar content value
74 under 100 mg/Nm³ [31].

75 Due to the synergy of gasification and anaerobic digestion models, precise
76 data about the chemical and physical properties of the feedstocks used as
77 inputs are required. Literature reports several studies about composition
78 and behavior in anaerobic digesters of corn and corn silage but works about
79 the behavior of the separated parts of the maize plant in bio-digestion or
80 gasification are few. For example, Hutnan et al. [32] discusses the differences
81 between maize grains and maize silage for biogas production; Getachew et
82 al. analyzes differences between grains and silage, but no data are reported
83 about the corn stover in both these works. A complete characterization
84 of the stover can be found in Evans et al. about power production from
85 substitute fuels [20]. In the next section these sources, together with other
86 literature data, are used in order to define the characteristics of the grains
87 and the stover used in the improved solution, as well as the characteristic
88 of the hypothetical 'equivalent maize silage' that can be obtained from the
89 same maize.

90 Therefore, the total chemical energy content in the syngas-biogas stream
91 was compared to the biogas chemical energy content in case of 100% silage
92 digestion. Results shown the advantages related to this approach. A power
93 production boost of about 26% was obtained not considering the advantage
94 of avoiding silaging matter losses. Considering also this contribution, the
95 advantage of the operation raises to 39%. On the other hand, the gasifier
96 is characterized by a higher conversion rate but some issues related to corn
97 stover processing have been outlined during preliminary experimental gasifi-

98 cation tests reported in the results.

99

100 **2. Material and Methods**

101 *2.1. Case study*

102 The anaerobic digestion of a 100 kW biogas plant fed only with maize
103 silage was modeled in order to evaluate the biogas production rate and the
104 biogas higher heating value HHV. Then, the corn stover was removed from
105 the model 'recipe' and the system was simulated under this new condition
106 using only grains as fuel. At the same time, the stover removed from the
107 biogas model was used in the gasification one. These two cases are depicted
108 in Figure 1 are summarized as:

109 (A) Ensilage of 100% of corn and its total exploitation in the biogas power
110 plant.

111 (B) Separation of the stover from grains, gasification of the stover and ex-
112 ploitation of the grains in the biogas plant.

113 This work does not focus on the effect of different gases on the perfor-
114 mance of the CHP engine, for this reason the two cases were compared on
115 the basis of the chemical energy content in the gas streams.

116

117 *2.2. Definition of maize characteristics from literature*

118 The methodology applied in this work is the following: the grains and
119 the stover were characterized on the data reported by Evans [20] and by

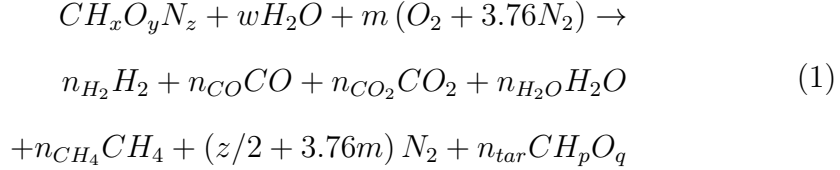
120 Getachew [33]. These data are summarized in Table 1 and Table 4. Once
121 the data about the maize components are known, it is possible to define an
122 "equivalent maize silage" obtained as a composition of the values previously
123 cited. Its properties are defined here as the weighted mean of their respective
124 components values. This approach is effective if the following assumptions
125 are verified:

- 126 1. The mass balance of the corn plant is equal to the sum of the compo-
127 nents masses.
- 128 2. The final characteristics of "equivalent maize silage" are in line with
129 those found in actual practice (i.e. [34]).

130 Basically, the method proposed allowed to back calculate the character-
131 istics of the silage (usually collected in milky-waxy stage) from the data
132 reported for grains and stover all referring to the complete maturation of the
133 feedstock. In results section the effectiveness this methodology is discussed

134 *2.3. Gasification process modeling*

135 Corn cobs gasification is not a newness. Literature reports ongoing re-
136 searches focused on using maize cobs or stovers as fuel in fixed bed gasifier
137 [16, 13] as well as in fluidized bed gasifiers [19, 20]. In this work the gasi-
138 fication process was simulated using a black-box model based on Barman's
139 work [35]. The model generally works for downdraft gasifiers; it is based on
140 the following generic gasification equation:



141 where $CH_xO_yN_z$ is the equivalent chemical formula of "dry and ash
 142 free" (daf) biomass; CH_pO_q is the equivalent chemical formula of tar [36]; w
 143 $[mol/mol_{bio}]$ is the specific molar amount of the biomass moisture calculated
 144 by Equation 2; m $[mol/mol_{bio}]$ is the specific molar amount of oxygen cal-
 145 culated by Equation 3; $n_{H_2}, n_{CO}, n_{CO_2}, n_{H_2O}, n_{CH_4}, n_{tar}$ $[mol/mol_{bio}]$ are the
 146 specific molar amount of $H_2, CO, CO_2, H_2O, CH_4$ and tar which constitute
 147 the syngas.

$$w = \frac{MW_{bio,daf} * M}{MW_{H_2O} (1 - M/100 - ASH/100)} \tag{2}$$

$$m = ER * (1 + x/4 - y/2) \tag{3}$$

148 where M [%] is the total moisture; ER [ad] is the equivalence ratio as
 149 defined by Reed and Das [37] and $MW_{bio,daf}$ [g/mol] is the molecular weight
 150 of biomass in "daf" conditions. Equation 1 can be multiplied by the molar
 151 biomass flow in "daf" conditions $\dot{n}_{bio,daf}$ $[mol_{bio}/s]$ in order to assess the molar
 152 flow of each component of the syngas as well as the syngas composition in
 153 wet and dry conditions. The molar flow of tar is given by Equation 4, the
 154 tar production versus the "daf" biomass input x_{tar} [% wt. "daf" biomass] is
 155 calculated by Equation 5. Furthermore, Equation 6 can be used to evaluate
 156 the volumetric tar amount $g_{tar,vol}$ $[g/Nm^3]$ in the syngas.

$$\dot{n}_{tar} = n_{tar} * \dot{n}_{bio,daf} \quad (4)$$

$$x_{tar} = \frac{n_{tar} * MW_{tar}}{MW_{bio}} \quad (5)$$

$$g_{tar,vol} = \frac{n_{tar} * MW_{tar}}{\frac{\dot{n}_{tot,dry}}{\dot{n}_{bio,daf}} * 0.022414} \quad (6)$$

157 The constant 0.022414 is the volume in m^3 of 1 mol of ideal gas at the
 158 normal conditions of 101325 Pa and 273 K [38]. Moreover, assuming the
 159 syngas components as ideal gases it is possible to calculate the normal volu-
 160 metric flow of wet and dry syngas. Equations 7 and 8 allow us to estimate
 161 the "cold gas" efficiency of the gasifier and the HHV of the clean and dry
 162 syngas.

$$\eta_{g,cold} = \frac{\dot{V}_g HHV_{syngas, clean}}{\dot{m}_f HHV_{bio, ar}} \quad (7)$$

163

$$HHV_{syngas, clean} = x_{H_2} HHV_{H_2} + x_{CO} HHV_{CO} + x_{CH_4} HHV_{CH_4} \quad (8)$$

164

165 where x_{H_2} , x_{CO} , x_{CH_4} [% vol] are the volumetric fraction of H_2 , CO , CH_4
 166 in the dry syngas and HHV_{H_2} , HHV_{CO} , HHV_{CH_4} [MJ/Nm³] are the higher
 167 heating values of H_2 , CO and CH_4 .

168 However, the molar specific amount of the syngas components have to
 169 be estimated. An algorithm similar to the one suggested in [39] is adopted
 170 here. The first step is to choose an initial temperature T [K] and calculate
 171 the equilibrium constant of the following reactions:

172 • **K1:** Water-gas shift $CO + H_2O \leftrightarrow CO_2 + H_2$

173 • **K2:** Hydrogasification $C + 2H_2 \leftrightarrow CH_4$

174 • **K3:** Methane steam reforming $CH_4 + H_2O \leftrightarrow CO + 3H_2$

175 Equations 9 and 10 are reported in [40] and are used here to calculate K_1
176 and K_2 while Equation 11 is used to evaluate K_3 and it is taken from [41]:

$$K_1 = e^{\frac{4276}{T} - 3.961} \quad (9)$$

$$\ln(K_2) = \frac{7082.842}{T} - 6.567 * \ln(T) + \frac{7.467 * 10^{-3} * T}{2} - \frac{2.167 * 10^{-6} * T^2}{6} + \frac{0.702}{2 * T^2} + 32.541 \quad (10)$$

$$K_3 = 1.198 * 10^{13} * e^{\frac{-26830}{T}} \quad (11)$$

177 The System 12 is composed of three chemical balances calculated from
178 Equation 1 (carbon, hydrogen and oxygen) and the three equilibrium con-
179 stants for water-gas, hydrogasification and methane reforming reactions. The
180 system is solved with the Newton-Raphson method.

$$\left\{ \begin{array}{l} n_{CO} + n_{CO_2} + n_{CH_4} + n_{tar} - 1 = 0 \\ 2n_{H_2} + 2n_{H_2O} + 4n_{CH_4} + pn_{tar} - x - 2w = 0 \\ n_{CO} + 2n_{CO_2} + n_{H_2O} + qn_{tar} - w - 2m - y = 0 \\ K_1 = \frac{n_{CO_2} * n_{H_2}}{n_{CO} * n_{H_2O}} \\ K_2 = \frac{n_{CH_4} * \frac{\dot{n}_{tot, wet}}{\dot{n}_{bio, daf}}}{n_{H_2}^2} \\ K_3 = \frac{n_{CO} * n_{H_2}^3}{\left(\frac{\dot{n}_{tot, wet}}{\dot{n}_{bio, daf}} \right)^2 n_{H_2O} n_{CH_4}} \end{array} \right. \quad (12)$$

181 Once the molar specific amount of the syngas species are evaluated, it is
 182 possible to solve the thermodynamic energy balance of the system reported in
 183 Equation 13. In order to find the equilibrium temperature T_{new} , the system
 184 is considered adiabatic and the the Newton-Raphson method is applied to
 185 the equations.

186 As reported in [39], if $abs(T - T_{new}) < 0.1$ K then the calculated equi-
 187 librium temperature and molar specific gases amounts are the final results;
 188 instead, a new iteration is done in order to satisfy the previous condition.

$$\sum_{j=react} n_j * HF_j^0 = \sum_{i=prod} n_i * (HF_i^0 + \Delta H_{T,i}) \quad (13)$$

189 where n_j [moles] and HF_j^0 [kJ/kmol] are the specific moles amount and
 190 standard heat of formation of the j-th reagent (biomass, air and moisture); n_i

191 [moles] and HF_i^0 [kJ/kmol] are the specific moles amount and the standard
 192 heat of formation of the i-th product (H_2 , CO , CO_2 , H_2O , CH_4 and N_2) and
 193 $\Delta H_{T,i}$ is the enthalpy difference between any given state and the standard
 194 state for the i-th product. $\Delta H_{T,i}$ can be calculated starting from the specific
 195 heat of the product:

$$\Delta H_{T,i} = \int_{298.15}^T C_p(T) dT = \left| aT + b\frac{T^2}{2} + c\frac{T^3}{3} + d\frac{T^4}{4} \right|_{298.15}^T \quad (14)$$

196 where the coefficient a,b,c and d are defined for each gas in [39]. The
 197 model was implemented in Python. In this way once the biomass equivalent
 198 molecule is defined, the model works with the only definition of a ER and a
 199 temperature. The temperature input is used only as a starting point for the
 200 iterating system, after few cycles the temperature converges to the ones that
 201 satisfy both the chemical and thermal sub-systems.

202 2.4. Biogas modeling

203 The mathematical sub-model designed to simulate the anaerobic digestion
 204 was developed in a previous works [29]. This model is useful to design wet (or
 205 semi-wet) anaerobic digestion plants in steady state conditions. The input
 206 data are the characteristics of the feedstock and few basic parameters such
 207 as the CHP efficiency and the process temperature.

208 The APE model [29] consists of several different interlaced sections which
 209 can be grouped into two fundamental modules: the biological module used
 210 in this work and the heat module. The biological module goals are:

- 211 1. Estimating the degradation of selected biomasses.

- 212 2. Calculating the production of bio-methane and, consequently, the power
213 output of the plant.
- 214 3. Selecting the optimal Hydraulic Retention Time (HRT) on the basis of
215 the chosen degradation efficiency.
- 216 4. Designing the digester tanks as function of the selected layout and
217 water content of the substrate.

218 Assuming hydrolysis as a limiting step of the anaerobic digestion reactions
219 chain, the biomass degradation can be described as a first order kinetic model
220 [42]. The mass balance of the substrate for a generic reactor with constant
221 volume and flow rates can be written as follows [43]:

$$\frac{d\hat{S}_e}{dt} = \frac{Q_i}{V}\hat{S}_t - \frac{Q_e}{V}\hat{S}_e - k\hat{S}_e \quad (15)$$

222 where \hat{S}_e is the biomass concentration in the effluent flow rate [$\text{kg}_{ts}/\text{m}^3$],
223 \hat{S}_t is the biomass concentration in the in-fluent flow rate [$\text{kg}_{ts}/\text{m}^3$], Q_i is
224 the influent flow rate [m^3/day], Q_e the effluent flow rate [m^3/day], V is the
225 digester active volume [m^3] and k is the hydrolysis kinetic constant [day^{-1}].

226 Starting from the concentration of the effluent flow, it is possible to cal-
227 culate the efficiency of the degradation process and, from this, to trace back
228 the HRT. The amount of reacting mass in the digester is also calculated con-
229 sidering the partial degradation of the substrate and the degree of dilution.
230 The latter is evaluated in terms of water flow rate or recirculation flow rate
231 as a function of the desired water content of the substrate and the desired
232 organic loading rate (ORL).

233 To increase the accuracy of the results, each biomass used as input is
234 broken into its constituents: sugars, proteins, fats, cellulose, hemicellulose,

lignin, ash, and non-degradables parts according to the Van Soest method (also called NDF method) [9]. A specific hydrolysis kinetic constant is assigned to each constituent type, in order to take into account the different degradation rates which typically occurs in different substrates. Specific aspects of the modeling approach were inspired by several other works [43, 9, 42, 44].

The methane productivity estimation of the matrices was carried out by giving to each class of substance (carbohydrates, proteins, lipids) a particular methane yield. This method is in accordance with the specific technical standard [45] which recalls the initial works of Buswell [46] and Boyle [47]. The share of non-degradable organic matter do not produces biogas due to its tough-fibers structure which is abiotic for microorganisms (i.e. lignin and the part of cellulose closely linked to it). In order to take into account this issue, thus avoiding overestimation of biogas production, the model calculates the proportion of non-degradable NDF (iNDF) starting from the known iNDF/ADL ratio [48]. Every biomass has a specific iNDF/ADL ratio, that can be deduced from the other parameters once the methane yield is know.

2.5. Evaluation collecting and processing costs

This work gives an overall energy balance evaluation of the proposed solution. Thanks to this evaluation is possible to demonstrate the advantages related to the improved utilization of maize. On the other hand it is important to assure that the proposed implementations an changes in the harvesting process do not affect the economy of system. The first step that needs to be taken is the evaluation of the cost differences between the two solutions

260 applied to a medium-size farm with more than 10 ha cultivated, fair degree
261 of mechanization and corn productivity about 60 t/ha (wet) [49, 50, 51]. The
262 next paragraph reports the results obtained from literature review about the
263 cost of the two solutions.

264 **3. Results**

265 *3.1. Evaluation collecting and processing costs*

266 Literature suggests small cost differences between collecting or leaving
267 the stover on the fields in these conditions [49, 50, 51, 52, 53] as explained
268 below:

- 269 • Case A: the average cost for the cultivation of maize silage is about 30
270 \$/t with 65% moisture [49]. If the humidity of the silage is theoretically
271 reduced to the moisture content of the stover in field (12.5 %), the silage
272 cost rises to 75 \$/t. Silage harvesting does not leave enough organic
273 substance on the field, therefore it is necessary to integrate nutrients
274 in the soil for a cost of 6.50 \$/t [50].
- 275 • Case B: grains harvest is carried out by a combine harvester which
276 separates grains from the plant and leaves the stover in the field. The
277 average cost of the cultivation of the grain starts from 50 \$/t [51].
278 The stover harvesting into bales is similar to the process done for the
279 straw. It costs an average of 30 \$/t considering the cost of nutrient
280 replacement. The mechanical operations required are: flail shredding
281 and raking followed by baling without crop processor [50].

282 On the other hand, leaving the stover on the field is not sufficient for
283 assuring that its organic substance is properly transferred to the soil. In fact,
284 the process required extra mechanical operations such as straw chopping and
285 soil plowing which contribute to costs raising.

286 The focus of this paper was kept on chemical and physical changes of
287 the matrices during their fate from the initial conditions. From this point of
288 view, corn silage is subject to significant energy losses during the lactic fer-
289 mentation (and often exceeding what reported in this work); these losses do
290 not occur in the same entity during the drying of the grains. For this reason
291 some auxiliary sources of energy consumption or losses were not taken into
292 account. For example, while in Case A was neglected the energy consump-
293 tion for the silaging process (stacking the trenches, pressing, covering), in
294 Case B was neglected the energy consumption for drying corn grains. These
295 losses will affect similarly both the solutions proposed.

296 3.2. Biogas modeling

297 The "equivalent maize silage" method is effective due to the good simi-
298 larity with literature (i.e. [8, 54]) as reported in Table 4. With this approach
299 the two cases have all the inputs required for their modeling as reported in
300 Tables 4, 4 and 5. The higher differences are the ones related to the fiber
301 composition. In particular, the "equivalent maize silage" shows higher lignin
302 content compared to literature and real data [54, 9]. The main cause of this
303 deviation is that Evans's data presents high fiber content values in the first
304 place.

305 The results of the biogas simulations are reported in Table 5. The model
306 gives the specific power output in terms of m_{biogas}^3/kg_{ts} . This value is used

307 to calculate the equivalent silage specific primary energy e_A [kWh_{PE}/kg_{ts}]
 308 that is the primary energy produced (biogas chemical energy) by one kg of
 309 dry maize silage. The model also calculates the methane productivity of the
 310 feedstocks which it is compared with literature data as reported in Table 5.
 311 The average error of 12% is considered acceptable for the model validation.

312 3.3. Gasification modeling

313 Table 4 resumes the major results obtained considering a wet flow of syn-
 314 gas. Due to the composition of the feedstock, a working point characterized
 315 by low tar content was found with an ER slightly higher than the value
 316 suggested for wood chips gasification [31, 37]. The stover resulted a suitable
 317 biomass for gasification with a cold gas efficiency of 71.2 %. The tar content
 318 resulted 1.32 g/Nm³, this value is slightly lower than literature review values,
 319 for example Milne reports downdraft gasifiers that produce up to 5 g/Nm³
 320 of tars. It is important to consider that the gasification power plant imple-
 321 mented in this solution consists in the reactor only. The syngas produced in
 322 the reactor can be directly sent into the biogas gasometer. In so doing there
 323 is no need for filtering process. There are few studies about the behavior of
 324 tars into the biogas gasometer, Torri and Fabbri, [28] suggested how some
 325 oils and tars can be upgraded to hydrogen through anaerobic digestion, while
 326 the work of Hübner [27] already integrates a biogas reactor for upgrading the
 327 liquid phase of a pyrolysis power plant. Anyway, within the gasometer, the
 328 syngas can be effectively cooled down and slowed. Under these conditions
 329 tars are able to condense flowing into the reacting biomass in the digester.

330 The gasifier conversion rate is evaluated in terms in dry stover specific
 331 primary energy e_{stover} [kWh_{PE}/kg_{ts}]. In case of electrical power output eval-

uation, it is important to take into account the generator and Internal Combustion (IC) engine efficiencies. These values lead to a new conversion rate value $e_{plant,model}$ [$kWh_{el}/kg_{ts,stover}$].

3.4. Chemical power output

Table 6 contains the comparison between the conversion rates of the two solutions. Table 6 points out the overboost of 39% that can be reached in case B. This value derives from the higher efficiency of the gasification process and from its capability to exploit ligno-cellulosic matter. While the productivity of the maize silage is known ($e_A = 3.079 kWh_{PE}/kg_{ts}$), the value for the combined effect of gasification of the stover (dried to $M = 5\%$ of moisture) and the anaerobic digestion of the grains is evaluated starting from mass share value of grains ($f_{ts,grains}$) and its complementary value for the stover ($1 - f_{ts,grains}$):

$$\begin{aligned} e_B &= f_{ts,grains} * e_{grains} + (1 - f_{ts,grains}) * e_{stover} = \\ &= 0.46 * 4.051 + (1 - 0.46) * 3.758 = 3.89 \end{aligned} \tag{16}$$

This value is 1.264 times higher than the silage one. Furthermore the silage losses (about 10% [12]) increase the value to 1.39. This means that a 100 kW, 100% silage power plant can be boosted to 139 kW through the adoption of a gasifier. In case A the primary energy yielded for hectare of soil is calculated considering a productivity of 26.41 tons per hectare of dried maize plant (type FAO 500: milky-waxy) as suggested by [9, 34]. As previously discussed, the value obtained needs to be resumed due to silaging matter losses. The calculation of the primary energy in Case B considers a

353 productivity of 83.98 tons per hectare of as-received maize plant (type FAO
354 700: full ripeness stage) [5]. The moisture of Case B is 68.14 % as suggested
355 by Blandino et al. [54]. The final remark need to be addressed to the cost of
356 the two proposed plants. The costs of the refer 100 kW power plant can be
357 found in literature, in particular in Italy, in 2013 the cost for maize power
358 plants is almost 10 €/W [55] considering:

- 359 • Approximately 900 m³ digester tank with gasometer
- 360 • 100 kW combine heat and power system
- 361 • Auxiliary systems such as mixers, blowers, sensors and control systems
- 362 • Automatic feeding
- 363 • Storage tank

364 More difficult is the estimation of the cost of the improved solution. In
365 fact, on one hand, the biogas part of the combined power plant is going to
366 be cheaper due to smaller tanks and digesters, on the other hand the gasifier
367 reactor and its auxiliary equipments are going to increase the price as well as
368 the bigger engine required for this solution. As rough approximation it can
369 be possible to assume the cost linear, fixing it at 10 €/W.

370 The cost of the final plant will be proportional (roughly 1.4 millions of
371 euros) because on one hand the biogas part is reduced in terms of volumes
372 of tanks, digesters and auxiliary equipments but, on the other hand the
373 new system is provided whit a gasification reactor. No filtering system is
374 required. Figure 2 resumes the energy conversion effectiveness in the two
375 cases analyzed.

376 4. Conclusions

377 This work demonstrates the advantages related to the combination of
378 anaerobic digestion and gasification technologies. The costs of new solution
379 proposed are similar to the conventional solution. The model predicts the
380 behavior of the system with an error of 12% compensated by silaging matter
381 losses of the conventional solution. Therefore, the minimum performance
382 increase is 26% for the improved solution. Such a power increase justify
383 the higher complexity of the improved solution even more considering that
384 the dimension of the new digester would be almost half of the conventional
385 one. Future work will focus on collecting data for a model validation. Lastly
386 this work suggests the use of a singular engine instead of two. This solution
387 requires an engine with higher power and presumably higher efficiency. All
388 these features of the improved solution compete to increasing the overall
389 efficiency, assuring the effectiveness of this method to boost the performance
390 of existing facilities as well as new biogas power plants. Finally it is important
391 to outline that a secondary result derived from this study. The models used
392 here required coherent data about the maize feedstock under two different
393 ripening conditions: full ripeness and silage. The solution proposed for this
394 problema is the definition of a methodology able to give the properties of
395 the silage starting from the chemical characteristics of the plant parts. The
396 method chose was found to be effective and the results are in line with typical
397 literature data about maize silage.

398 Nomenclature

399	$\Delta H_{T,i}$	enthalpy difference [kJ/kmol]	420	HF^0	standard heat of formation
400	\dot{m}	mass flow [kg/s]	421		[kJ/kmol]
401	\dot{n}	molar flow [mol/s]	422	HHV	higher heating value
402	\dot{V}	volumetric flow [Nm ³ /s]	423		[MJ/Nm ³ or MJ/kg]
403	\hat{S}_e	biomass concentration in the	424	HRT	hydraulic retention time
404		effluent flow rate [kg _{ts} /m ³]	425	$iNDF$	non-degradable neutral de-
405	\hat{S}_t	biomass concentration in the	426		tergent fiber
406		in-fluent flow rate [kg _{ts} /m ³]	427	K	equilibrium constant [ad]
407	ADL	acid detergent fiber/lignin	428	k	hydrolysis kinetic constant
408	ASH	ash content of the biomass [%]	429		[day ⁻¹]
409	C	carbon	430	M	total moisture content of the
410	C_p	specific heat [J/(mol K)]	431		biomass [%]
411	CHP	combined heat power	432	m	specific molar amount of oxy-
412	E	energy [kWh]	433		gen [mol/mol_{bio}]
413	e	specific biomass energy pro-	434	MW	molecular weight [g/mol]
414		ductivity [kWh_{PE}/kg_{ts}]	435	N	nitrogen
415	ER	equivalence ratio [ad]	436	n	specific molar amount of gases
416	f	mass fraction [%]	437		and tar [mol/mol_{bio}]
417	g	volumetric tar amount	438	NDF	neutral detergent fiber
418		[g/Nm^3]	439	O	oxygen
419	H	hydrogen	440	ORL	organic loading rate
			441	Q_e	effluent flow rate [m ³ /day]

442	Q_i	influent flow rate [m^3/day]	454	p	hydrogen coefficient of tar
443	T	temperature [K]	455	$prod$	product
444	V	digester active volume [m^3]	456	q	oxygen coefficient of tar
445	w	specific molar amount of	457	$react$	reactant
446		biomass moisture [$\text{mol}/\text{mol}_{bio}$]	458	ts	total solid
447	x_{tar}	tar production versus daf	459	vs	volatile solid
448		biomass input [% wt.]	460	x	hydrogen coefficient of the
449	Subscripts		461		biomass
450	ar	as received	462	y	hydrogen coefficient of the
451	bio	biomass	463		biomass
452	daf	dry ash free	464	z	nitrogen coefficient of the
453	g	gas	465		biomass

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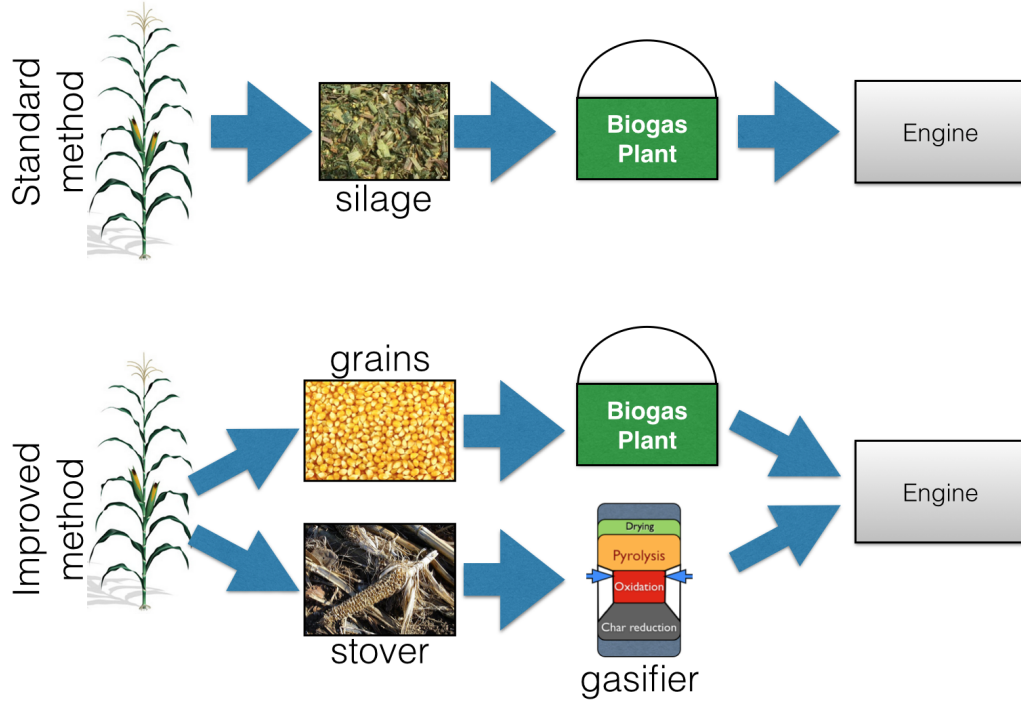


Figure 1: System layout

Table 1: Corn plant total solid composition and soil productivity (full ripeness) [52]

	Grains	Straw	Leaves	Cobs	Husk
Total Solids distribution f_{ts}	46%	27%	12%	8%	7%
Dry matter/ha [ton _{ts} /ha]	6.13	3.58	1.58	1.08	0.93

Table 2: Corn grains and stover properties

Parameter	Symbol	Value
Stover parameters for gasification process [20, 52]		
Carbon amount [% wt.]	C_{ar}	44.18
Nitrogen amount [% wt.]	N_{ar}	0.53
Hydrogen amount [% wt.]	H_{ar}	5.52
Sulfur amount [% wt.]	S_{ar}	$\simeq 0.1$
Oxygen amount [% wt.]	O_{ar}	37.69
Moisture [% wt.]	M	5 (dried on field)
Ash amount [% wt.]	ASH	6.98
Higher heating value [MJ/kg]	HHV_{ar}	19 MJ/kg
Stover parameters for anaerobic digestion process [20, 52]		
Total solids [% wt.]	ts	21.8 (full ripeness)
Ash amount [% wt.]	ASH	6.98
Volatile solids [% of ts]	VS	91.8
Crude protein [% of ts]	XP	4.8
Crude fat [% of ts]	XL	4.27
Non fiber carbohydrate [% of ts]	NFC	3.60
Neutral detergent fiber [% of ts]	NDF	79.1
Acid detergent fiber [% of ts]	ADL	16.9
Non degradable fiber ratio	iNDF/ADL	2
Grains [33, 52]		
Total solids [% wt.]	ts	66 (full ripeness)
Ash amount [% wt.]	ASH	1.2
Volatile solids [% of ts]	VS	98.8
Crude protein [% of ts]	XP	8.2
Crude fat [% of ts]	XL	3.4
Non fiber carbohydrate [% of ts]	NFC	76.6
Neutral detergent fiber [% of ts]	NDF	10.7
Acid detergent fiber [% of ts]	ADL	0.5
Non degradable fiber ratio	iNDF/ADL	2

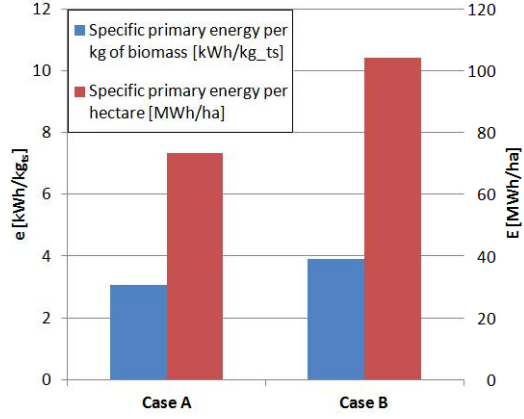


Figure 2: Energy conversion balances in the two cases

Table 3: Equivalent maize silage properties

Equivalent maize silage	Symbol	Value	Comparison with [54]
Total solids [% wt.]	ts	31.86	31.89
Ash amount [% wt.]	ASH	4.46	5.13
Volatile solids [% of ts]	VS	95.09	94.87
Crude protein [% of ts]	XP	6.42	7.44
Crude fat [% of ts]	XL	3.86	3.86
Non fiber carbohydrate [% of ts]	NFC	38.31	43.3
Neutral detergent fiber [% of ts]	NDF	46.95	40.24
Acid detergent fiber [% of ts]	ADL	8.96	4.97
Non degradable fiber ratio	iNDF/ADL	2	/

Table 4: Results of the stover gasification

Variable	Symbol	Value
Equivalence ratio	ER	0.365
Biomass moisture	M	5%
H_2 molar fraction	H_2	17.29 %
H_2O molar fraction	H_2O	5.7 %
CO molar fraction	CO	17.19 %
CO_2 molar fraction	CO_2	11.74 %
CH_4 molar fraction	CH_4	0.78 %
N_2 molar fraction	N_2	47.31 %
Specific volumetric tar amount	$m_{tar,vol}$	1.32 g/Nm ³
Volumetric syngas flow	\dot{V}_{syngas}	47.0 Nm ³ /h
Wet syngas higher heating value	$HHV_{syngas,w}$	4.68 MJ/Nm ³
Dry syngas higher heating value	$HHV_{syngas,d}$	4.93 MJ/Nm ³
Cold gas efficiency	η_{cold}	71.2 %
Dry stover specific primary energy	e_{stover}	3.758 kWh_{PE}/kg_{ts}
IC engine efficiency	η_{engine}	0.3
Electrical generator efficiency	η_{gen}	0.95
Power plant conversion rate	$e_{plant,model}$	1.07 $kWh_{el}/kg_{ts,stover}$

Table 5: Results and validation of the anaerobic digestion model

	Literature methane production [32, 52] [m ³ /kg _{vs}]	Model methane production [m ³ /kg _{vs}]	Absolut error [%]	Model biogas production [m ³ /kg _{ts}]	Model specific primary energy [kWh _{PE} /kg _{ts}]
Grains	0.360	0.410	14	0.771	4.051
Corn Stover	0.274	0.234	14	0.403	2.148
Equivalent Silage	0.350	0.326	7	0.582	3.079
Mean value	-	-	12	-	-

Table 6: Comparison between case (A) and case (B)

Variable	Symbol	Value
Case (A) specific primary energy	e_A	3.079 kWh_{PE}/kg_{ts}
Case (B) specific primary energy	e_B	3.890 kWh_{PE}/kg_{ts}
Increase	Δe	26%
Increase considering silaging matter losses	Δe_{sml}	39 %
Case (A) specific primary energy per hectare	E_A	73.173 MWh_{PE}/ha
Case (B) specific primary energy per hectare	E_B	104.08 MWh_{PE}/ha