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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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1. Introduction

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

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

This suggests that a digester fed mainly with grains could theoretically be smaller than a digester fed with the whole plant, but also with corn silage. Furthermore, while the operation of silaging increases the productivity of each specific part of the maize plant, the same procedure reduces the amount of organic matter of at least 10%. This phenomenon is due to an unavoidable aerobic fermentations occurring in the silaging process [12].

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

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

Literature review revealed several studies about corn residues gasification. Zijp et al. in the 1980 published a technical report with the Twente University where the use of corn stover in gasifier was discussed. It was found that the particulate content in the gas was one of the major issues related to this application. [13]. Zijp's results were cited in one of the most important manuals for fixed bed gasifier design: Woodgas as engine fuel [14]. A more recent work on gasification by Mavukwana et al. [15] models the stover gasification process in Aspen plus finding optimal equivalence ratio and steam to biomass values for this feedstock. Groeneveld and Van-Swaaij in the 1979 and Allesina et al. in 2015 discussed the possibility to use corn cobs gasification in micro power plants. Both the works are focused on energy shortage problems in African villages [16, 17]. A fixed bed gasifier of 350 kW_{th} was used by Biagini et al. in 2014, it was fed with corn cobs, reporting a gasification efficiency of the system of 67% and a syngas heating value of 5.7 MJ/Nm^3 [18]. Literature review shows how the stover can also be processed in fluidized bed gasifiers [19, 20].

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

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

- The anaerobic digestion was simulated with the Anaerobic Plant Emulation (APE) model reported in [29].

- The stover gasification process was simulated with a black-box equilibrium model in order to estimate the steady state behavior of the gasifier. Different gasification conditions were tested with the final purpose of obtaining a syngas with higher heating value over 4 MJ/Nm^3 and a tar content lower than 2 g/Nm^3. This conditions are within the typical ranges reported by Milne for downdraft gasifiers [30]. However, the value obtained is too high for direct feeding of the gas to an engine.

Therefore a filtering process is mandatory to lower the tar content value under 100 mg/Nm^3 [31].

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

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

2. Material and Methods

2.1. Case study

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

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

(B) Separation of the stover from grains, gasification of the stover and exploitation of the grains in the biogas plant.

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

2.2. Definition of maize characteristics from literature

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

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

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

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

2.3. Gasification process modeling

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

$$\begin{aligned} CH_xO_yN_z + wH_2O + m\left(O_2 + 3.76N_2\right) \rightarrow \\ n_{H_2}H_2 + n_{CO}CO + n_{CO_2}CO_2 + n_{H_2O}H_2O \\ +n_{CH_4}CH_4 + \left(z/2 + 3.76m\right)N_2 + n_{tar}CH_pO_q \end{aligned} \quad (1)$$

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

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

$$m = ER * \left(1 + x/4 - y/2\right) \quad (3)$$

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

$$\dot{n}_{tar} = n_{tar} * \dot{n}_{bio,daf} \tag{4}$$

$$x_{tar} = \frac{n_{tar} * MW_{tar}}{MW_{bio}} \tag{5}$$

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

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

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

$$HHV_{syngas,clean} = x_{H_2} HHV_{H_2} + x_{CO} HHV_{CO} + x_{CH_4} HHV_{CH_4} \tag{8}$$

where x_{H_2}, x_{CO}, x_{CH_4} [% vol] are the volumetric fraction of H_2, CO, CH_4 in the dry syngas and HHV_{H_2}, HHV_{CO}, HHV_{CH4} [MJ/Nm^3] are the higher heating values of H_2, CO and CH_4.

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

- **K1:** Water-gas shift $CO + H_2O \leftrightarrow CO_2 + H_2$
- **K2:** Hydrogasification $C + 2H_2 \leftrightarrow CH_4$
- **K3:** Methane steam reforming $CH_4 + H_2O \leftrightarrow CO + 3H_2$

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

$$K_1 = e^{\frac{4276}{T} - 3.961} \tag{9}$$

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

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

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

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

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

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

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

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

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

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

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

2.4. Biogas modeling

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

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

1. Estimating the degradation of selected biomasses.

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

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

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

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

Starting from the concentration of the effluent flow, it is possible to calculate the efficiency of the degradation process and, from this, to trace back the HRT. The amount of reacting mass in the digester is also calculated considering the partial degradation of the substrate and the degree of dilution. The latter is evualuated in terms of water flow rate or recirculation flow rate as a function of the desired water content of the substrate and the desired organic loading rate (ORL).

To increase the accuracy of the results, each biomass used as input is 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 applied to a medium-size farm with more than 10 ha cultivated, fair degree of mechanization and corn productivity about 60 t/ha (wet) [49, 50, 51]. The next paragraph reports the results obtained from literature review about the cost of the two solutions.

3. Results

3.1. Evaluation collecting and processing costs

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

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

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

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

3.2. Biogas modeling

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

The results of the biogas simulations are reported in Table 5. The model gives the specific power output in terms of m^3_{biogas}/kg_{ts}. This value is used to calculate the equivalent silage specific primary energy e_A $[kWh_{PE}/kg_{ts}]$ that is the primary energy produced (biogas chemical energy) by one kg of dry maize silage. The model also calculates the methane productivity of the feedstocks which it is compared with literature data as reported in Table 5. The average error of 12% is considered acceptable for the model validation.

3.3. Gasification modeling

Table 4 resumes the major results obtained considering a wet flow of syngas. Due to the composition of the feedstock, a working point characterized by low tar content was found with an ER slightly higher than the value suggested for wood chips gasification [31, 37]. The stover resulted a suitable biomass for gasification with a cold gas efficiency of 71.2 %. The tar content resulted 1.32 g/Nm^3, this value is slightly lower than literature review values, for example Milne reports downdraft gasifiers that produce up to 5 g/Nm^3 of tars. It is important to consider that the gasification power plant implemented in this solution consists in the reactor only. The syngas produced in the reactor can be directly sent into the biogas gasometer. In so doing there is no need for filtering process. There are few studies about the behavior of tars into the biogas gasometer, Torri and Fabbri, [28] suggested how some oils and tars can be upgraded to hydrogen through anaerobic digestion, while the work of Hübner [27] already integrates a biogas reactor for upgrading the liquid phase of a pyrolysis power plant. Anyway, within the gasometer, the syngas can be effectively cooled down and slowed. Under these conditions tars are able to condense flowing into the reacting biomass in the digester.

The gasifier conversion rate is evaluated in terms in dry stover specific primary energy e_{stover} $[kWh_{PE}/kg_{ts}]$. In case of electrical power output evaluation, it is important to take into account the generator and Internal Combustion (IC) engine efficiencies. This values lead to a new conversione 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 productivity of 83.98 tons per hectare of as-received maize plant (type FAO 700: full ripeness stage) [5]. The moisture of Case B is 68.14 % as suggested by Blandino et al. [54]. The final remark need to be addressed to the cost of the two proposed plants. The costs of the refer 100 kW power plant can be found in literature, in particular in Italy, in 2013 the cost for maize power plants is almost 10 €/W [55] considering:

- Approximatively 900 m^3 digester tank with gasometer
- 100 kW combine heat and power system
- Auxiliary systems such as mixers, blowers, sensors and control systems
- Automatic feeding
- Storage tank

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

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

4. Conclusions

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

Nomenclature

$\Delta H_{T,i}$	enthalpy difference[kJ/kmol]
$\dot{m}$	mass flow [kg/s]
$\dot{n}$	molar flow [mol/s]
$\dot{V}$	volumetric flow [Nm^3/s]
$\hat{S}e$	biomass concentration in the effluent flow rate [kg$_{ts}$/m^3]
$\hat{S}t$	biomass concentration in the in-fluent flow rate [kg$_{ts}$/m^3]
ADL	acid detergent fiber/lignin
ASH	ash content of the biomass [%]
C	carbon
C_p	specific heat [J/(mol K)]
CHP	combined heat power
E	energy [kWh]
e	specific biomass energy productivity [kWh_{PE}/kg_{ts}]
ER	equivalence ratio [ad]
f	mass fraction [%]
g	volumetric tar amount [g/Nm^3]
H	hydrogen
HF^0	standard heat of formation [kJ/kmol]
HHV	higher heating value [MJ/Nm^3 or MJ/kg]
HRT	hydraulic retention time
$iNDF$	non-degradable neutral detergent fiber
K	equilibrium constant [ad]
k	hydrolysis kinetic constant [day^{-1}]
M	total moisture content of the biomass [%]
m	specific molar amount of oxygen [mol/mol_{bio}]
MW	molecular weight [g/mol]
N	nitrogen
n	specific molar amount of gases and tar [mol/mol_{bio}]
NDF	neutral detergent fiber
O	oxygen
ORL	organic loading rate
Q_e	effluent flow rate [m^3/day]

Q_i	influent flow rate [m^3/day]
T	temperature [K]
V	digestor active volume [m^3]
w	specific molar amount of biomass moisture [mol/mol_{bio}]
x_{tar}	tar production versus daf biomass input [% wt.]

Subscripts

ar	as received
bio	biomass
daf	dry ash free
g	gas
p	hydrogen coefficient of tar
$prod$	product
q	oxygen coefficient of tar
$react$	reactant
ts	total solid
vs	volatile solid
x	hydrogn coefficient of the biomass
y	hydrogen coefficient of the biomass
z	nitrogen coefficient of the biomass

References

References

[1] Oslaj M, Mursec B, Vindis P. Biogas production from maize hybrids. Biomass and Bioenergy 2010;34(11):1538 –45. URL: `http://www.sciencedirect.com/science/article/pii/S0961953410001431`. doi:http://dx.doi.org/10.1016/j.biombioe.2010.04.016.

[2] Gunaseelan VN. Anaerobic digestion of biomass for methane production: A review. Biomass and Bioenergy 1997;13(1–2):83 – 114. URL: `http://www.sciencedirect.com/science/article/pii/S0961953497000202`. doi:http://dx.doi.org/10.1016/S0961-9534(97)00020-2.

[3] Golkowska K, Greger M. Anaerobic digestion of maize and cellulose under thermophilic and mesophilic conditions – a comparative study. Biomass and Bioenergy 2013;56(0):545 –54. URL: `http://www.sciencedirect.com/science/article/pii/S0961953413002924`. doi:http://dx.doi.org/10.1016/j.biombioe.2013.05.029.

[4] Fabbri C, Shams-Eddin S, Bondi F, Piccinini S. Efficienza e problematiche di un impianto di digestione anaerobica a colture dedicate. IA Ingegneria Ambientale 2011;40(1):29–40.

[5] Negri M, Bacenetti J, Manfredini A, Lovarelli D, Fiala M, Maggiore TM, et al. Evaluation of methane production from maize silage by harvest of different plant portions. Biomass and Bioenergy 2014;67(0):339 –46. URL: `http://www.sciencedirect.com/science/article/pii/S0961953414002864`. doi:http://dx.doi.org/10.1016/j.biombioe.2014.05.016.

[6] Bruni E, Jensen AP, Pedersen ES, Angelidaki I. Anaerobic digestion of maize focusing on variety, harvest time and pretreatment. Applied Energy 2010;87(7):2212–7.

[7] Sambusiti C, Monlau F, Ficara E, Carrère H, Malpei F. A comparison of different pre-treatments to increase methane production from two agricultural substrates. Applied Energy 2013;104:62–70.

[8] Raposo F, la Rubia MD, Fernandez-Cegri V, Borja R. Anaerobic digestion of solid organic substrates in batch mode: An overview relating to

methane yields and experimental procedures. Renewable and Sustainable Energy Reviews 2011;16:861–77.

[9] Amon T, amon Vitaliy Kryvoruchko BA, Zollitsch W, Mayer K, Gruber L. Biogas production from maize and dairy cattle manure—influence of biomass composition on the methane yield. Agriculture, Ecosystems & Environment 2007;118:173–82.

[10] Shinners KJ, Binversie BN, Muck RE, Weimer PJ. Comparison of wet and dry corn stover harvest and storage. Biomass and Bioenergy 2007;31(4):211 –21. URL: `http://www.sciencedirect.com/science/article/pii/S0961953406001826`. doi:http://dx.doi.org/10.1016/j.biombioe.2006.04.007.

[11] Shinners KJ, Binversie BN. Fractional yield and moisture of corn stover biomass produced in the northern {US} corn belt. Biomass and Bioenergy 2007;31(8):576 –84. URL: `http://www.sciencedirect.com/science/article/pii/S0961953407000530`. doi:http://dx.doi.org/10.1016/j.biombioe.2007.02.002.

[12] Weinberg ZG, Chen Y. Effects of storage period on the composition of whole crop wheat and corn silages. Animal feed science and technology 2013;185:196–200.

[13] Zijp T, Stassen HEM. The gasification by partial combustion project in tanzania. Tech. Rep.; Twente University of Technology Report; Enschede, The Netherlands; 1980.

[14] Mechanical Wood Products Branch FFD. Woodgas as engine fuel; vol. ISBN 92-5-102436-7. F.A.O.; 1986.

[15] Mavukwana AE, Jalama K, Harding K. Simulation of South African Corncob Gasification with Aspen Plus: A Sensitivity Analysis; vol. 492. Applied Mechanics and Materials; 2014.

[16] Groeneveld MJ, Van-Swaaij WPM. Gasification of solid waste - potential and application of co-current moving bed gasifiers. Applied Energy 1979;5(3):165–78.

[17] Allesina G, Pedrazzi S, Sgarbi F, Pompeo E, Roberti C, Cristiano V, et al. Approaching sustainable development through energy management, the case of fongo tongo, cameroon. International Journal of Energy and Environmental Engineering 2015;6(2):121–7. URL: `http://dx.doi.org/10.1007/s40095-014-0156-7`. doi:10.1007/s40095-014-0156-7.

[18] Biagini E, Barontini F, Tognotti L. Gasification of agricultural residues in a demonstrative plant: Corn cobs. Bioresource Technology 2014;173(0):110 –6. URL: `http://www.sciencedirect.com/science/article/pii/S0960852414013455`. doi:http://dx.doi.org/10.1016/j.biortech.2014.09.086.

[19] Damartziz T, Michailos S, Zabaniotu A. Energetic assessment of a combined heat and power integrated biomass gasification–internal combustion engine system by using aspen plus. Fuel Processing Technology 2012;95:37–44.

[20] Evans RJ, Knight RA, Onischak M, Babu SP. Development of biomass gasification to produce substitute fuels. Tech. Rep. PNL-6518; Pacific Northwest Lab.; 1988.

[21] Li H, Larsson E, Thorin E, Dahlquist E, Yu X. Feasibility study on combining anaerobic digestion and biomass gasification to increase the production of biomethane. Energy Conversion and Management 2015;100(0):212 –9. URL: `http://www.sciencedirect.com/science/article/pii/S0196890415004549`. doi:http://dx.doi.org/10.1016/j.enconman.2015.05.007.

[22] Chen G, Xia Z, Yang M, Yan B, Zhou W, Tian X. Decentralized heating in a rural village using biomass gasification and anaerobic digestion: Economic and environmental analysis. Energy Procedia 2014;61(0):2367 –70. URL: `http://www.sciencedirect.com/science/article/pii/S1876610214030355`. doi:http://dx.doi.org/10.1016/j.egypro.2014.12.006; international Conference on Applied Energy, {ICAE2014}.

[23] ping XIE L, LI T, dong GAO J, ning FEI X, WU X, guang JIANG Y. Effect of moisture content in sewage sludge on air gasification. Journal of Fuel Chemistry and Technology 2010;38(5):615 –20. URL: `http://www.sciencedirect.com/science/article/pii/S1872581310600485`. doi:http://dx.doi.org/10.1016/S1872-5813(10)60048-5.

[24] Pedrazzi S, Allesina G, Belló T, Rinaldini CA, Tartarini P. Digestate as bio-fuel in domestic furnaces. Fuel Processing Technology 2015;130(0):172 –8. URL:

`http://www.sciencedirect.com/science/article/pii/S0378382014004214`. doi:http://dx.doi.org/10.1016/j.fuproc.2014.10.006.

[25] Neumann J, Binder S, Apfelbacher A, Gasson JR, García PR, Hornung A. Production and characterization of a new quality pyrolysis oil, char and syngas from digestate – introducing the thermo-catalytic reforming process. Journal of Analytical and Applied Pyrolysis 2014;(0):–. URL: `http://www.sciencedirect.com/science/article/pii/S0165237014003489`. doi:http://dx.doi.org/10.1016/j.jaap.2014.11.022.

[26] Wang W, Ma W, Han H, Li H, Yuan M. Thermophilic anaerobic digestion of lurgi coal gasification wastewater in a {UASB} reactor. Bioresource Technology 2011;102(3):2441 –7. URL: `http://www.sciencedirect.com/science/article/pii/S0960852410017967`. doi:http://dx.doi.org/10.1016/j.biortech.2010.10.140.

[27] Hübner T, Mumme J. Integration of pyrolysis and anaerobic digestion - use of aqueous liquor from digestate pyrolysis for biogas production. Bioresource Technology 2015;183(0):86 – 92. URL: `http://www.sciencedirect.com/science/article/pii/S0960852415002060`. doi:http://dx.doi.org/10.1016/j.biortech.2015.02.037.

[28] Torri C, Fabbri D. Biological upgrading of pyrolysis oil and gas to methane and hydrogen by means of adapted anaerobic bacteria consortium. In: European Biomass Conference & Exibition, Milan. 2AO.4.5; 2012,.

[29] Bavutti M, Guidetti L, Allesina G, Libbra A, Muscio A, Pedrazzi S.

Thermal stabilization of digesters of biogas plants by means of optimization of the surface radiative properties of the gasometer domes. Energy Procedia 2014;45:1344–53.

[30] Milne T, Evans R, Abatzoglou N. Biomass gasifier" tars": their nature, formation, and conversion. National Renewable Energy Laboratory Golden, CO; 1998.

[31] Basu P. Biomass Gasification and Pyrolysis: Practical Design and Theory. Academic Press, Elsevier; 2010.

[32] Hutnan M, Spalkova V, Bodik I, Kolesarova N, Lazor M. Biogas production from maize grains and maize silage. Polish J of Environ Stud 2010;19(2):323–9.

[33] Getachew G, Robinson P, DePeters E, Taylor S. Relationships between chemical composition, dry matter degradation and in vitro gas production of several ruminant feeds. Animal feed science and technology 2004;111:57–71.

[34] Oslaj M, Mursec B, Vindis P. Biogas production from maize hybrids. Biomass and Bioenergy 2010;34(11):1538–45.

[35] Barman NS, Ghosh S, De S. Gasification of biomass in a fixed bed downdraft gasifier – a realistic model including tar. Bioresource Technology 2012;107:505–11.

[36] Yamazaki T, Kozu H, Yamagata S, Murao N, Ohta S, Shiya S, et al. Effect of superficial velocity on tar from downdraft gasification of biomass. Energy & Fuels 2005;19:1186–91.

[37] Reed TB, Das A. Handbook of Biomass Downdraft Gasifier Engine Systems. The biomass energy foundation press; 1988.

[38] Cengel YA. Introduction to thermodynamics and heat transfer. McGraw-Hill; 1997.

[39] Jarungthammachote S, Dutta A. Thermodynamic equilibrium model and second law analysis of a downdraft waste gasifier. Energy 2007;32(9):1660 –9. URL: `http://www.sciencedirect.com/science/article/pii/S0360544207000199`. doi:http://dx.doi.org/10.1016/j.energy.2007.01.010.

[40] Zainal Z, Ali R, Lean C, Seetharamu K. Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials. Energy Conversion and Management 2001;42(12):1499 –515. URL: `http://www.sciencedirect.com/science/article/pii/S0196890400000789`. doi:http://dx.doi.org/10.1016/S0196-8904(00)00078-9.

[41] Bottino A, Comite A, Capannelli G, Felice RD, Pinacci P. Steam reforming of methane in equilibrium membrane reactors for integration in power cycles. Catalysis today 2006;118:218–22.

[42] Husain A. Mathematical models of the kinetics of anaerobic digestion—a selected review. Biomass and Bioenergy 1998;14(5–6):561 –71. URL: `http://www.sciencedirect.com/science/article/pii/S0961953497100472`. doi:http://dx.doi.org/10.1016/S0961-9534(97)10047-2.

[43] Vavilin V, Rytov S, Lokshina L. A description of hydrolysis kinetics in anaerobic degradation of particulate organic matter. Bioresource Technology 1996;56(2–3):229 –37. URL: `http://www.sciencedirect.com/science/article/pii/096085249600034X`. doi:http://dx.doi.org/10.1016/0960-8524(96)00034-X.

[44] Angelidaki I, Ellegaard L, Ahring B. A comprehensive model of anaerobic bioconversion of complex substrates to biogas. Biotechnology and Bioengineering 1999;63:363–72.

[45] VDI4630:2006-04 . Fermentation of organic materials - characterisation of the substrate, sampling, collection of material data, fermentation tests. Tech. Rep.; Verein deutscher Ingenieure; 2006.

[46] Buswell AM, Hatfield W. Anaerobic fermentations. Tech. Rep. No. 32, 1-193; State of Illinois Dept. of Registration and Education, Div. of the State Water Survey; Urbana, Il; 1936.

[47] Boyle WC. Energy recovery from sanitary landfills – a review. Tech. Rep.; Schlegel, H.G. und Barnea, S. (Hrsg.): Microbial Energy Conversion Oxford, Pergamon Press; 1976.

[48] Traxler MJ, Fox DG, Soest PJV, Pell AN, Lascano CE, Lanna DP, et al. Predicting forage indigestible ndf from lignin concentration. Journal of Animal Science 1998;76:1469–80.

[49] Komleh SP, Keyhani A, Rafiee S, Sefeedpary P. Energy use and economic analysis of corn silage production under three cultivated area levels in tehran province of iran. Energy 2011;36(5):3335 –41. URL:

http://www.sciencedirect.com/science/article/pii/S0360544211001952. doi:http://dx.doi.org/10.1016/j.energy.2011.03.029.

[50] Graham RL, Nelson R, Sheehan J, Perlack RD, Wright LL. Current and potential u.s. corn stover supplies 2007;:1–11URL: https://www.agronomy.org/publications/aj/abstracts/99/1/1.

[51] Ceral money: cost prediction software - un progetto stima i costi di produzione dei cereali. Bologna, Italy; 2010.

[52] Sokhansanj S, Turhollow A, Cushman J, Cundiff J. Engineering aspects of collecting corn stover for bioenergy. Biomass and Bioenergy 2002;23(5):347 –55. URL: http://www.sciencedirect.com/science/article/pii/S0961953402000636. doi:http://dx.doi.org/10.1016/S0961-9534(02)00063-6.

[53] Thompson JL, Tyner WE. Corn stover for bioenergy production: Cost estimates and farmer supply response. Biomass and Bioenergy 2014;62(0):166 –73. URL: http://www.sciencedirect.com/science/article/pii/S0961953413005333. doi:http://dx.doi.org/10.1016/j.biombioe.2013.12.020.

[54] Blandino M, Calcagno M, Ferrero C, Fabbri C, Vanzetti C, Reyneri A. Tutolo, sottoprodotto del mais per uso energetico. L'informatore Agrario 2013;43:11–5.

[55] Ragazzoni A. Biogas, analisi della redditività al variare di taglia e dieta. Informatore Agrario 2013;11:17–21.

Figure and tables captions

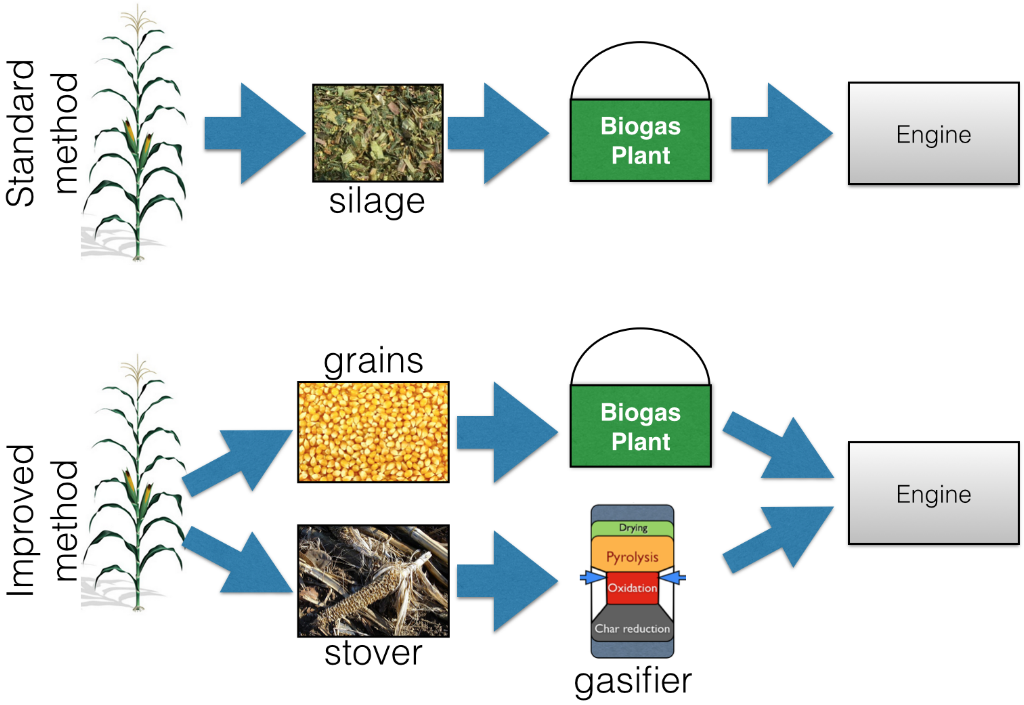

Figure 1: System layout

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

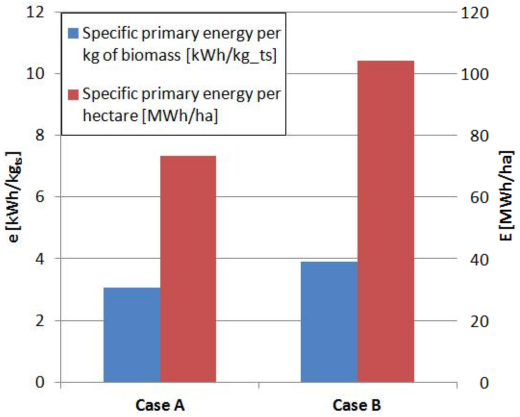

Figure 2: Energy conversion balances in the two cases

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